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PROCEEDINGS

FOURTH NATIONAL MEETING

OF THE

UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

June 28-29, 1976
The University of British Columbia

Sponsored by
National Science Foundation

Report No. UCEER-4

UCEER

Universities Council for
Earthquake Engineering Research

California Institute of Technology
Mail Code 104-44 Pasadena, California 91125

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FOREWARD

This volume contains the Proceedings of the Fourth National Meeting of the Universities Council for Earthquake Engineering Research which was held on the campus of the University of British Columbia, June 28-29, 1976. The purpose of this meeting was to provide a vehicle for the exchange of information related to current and projected university research in earthquake engineering and to evaluate progress in specific areas of research and establish goals and priorities for future work. All university researchers with an active interest in earthquake engineering were invited to participate. Participants were encouraged to present brief oral and written summaries of their research activities or those of their particular organization.

One hundred and ten individuals attended the meeting representing 39 universities, various government agencies and industries. Travel grants were awarded to 61 individuals.

There were six sessions consisting of brief five minute research reports. Sixty-four individuals gave reports. The written summaries of these reports are contained in this volume. These summaries are arranged according to university.

In addition to the research presentations, there were two panel discussions. The subject of the first panel was "Earthquake Prediction and Earthquake Engineering Research" and that of the second was "Current Capabilities and Future Needs in Experimental Earthquake Engineering Research." Copies of position papers by each panel member along with summaries by the panel recorders are included in this volume.

Local arrangements for the meeting were very ably handled by Professor Sheldon Cherry and his colleagues at the University of British Columbia. The banquet on Monday night in the Faculty Club was a highlight of the meeting. It was attended by 96 individuals.

A special note of thanks is due Miss Sharon Vedrode for her invaluable assistance in looking after the many details in the planning and execution of the meeting as well as the preparation of this volume.

W. D. Iwan
Executive Secretary
UCEER

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FOURTH NATIONAL MEETING
UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

University of British Columbia, June 28-29, 1976

FINAL SCHEDULE

Registration/Information

June 27 - 6:00-10:00 PM - Lobby, Gage Residence
June 28, 29 - 7:30 AM - 5:30 PM - Room 104 Angus Building

June 28 (All regular conference sessions will be held in Room 104 Angus Building)

8:00 - 8:30	Opening Remarks, Announcements
8:30 - 10:00	Research Reports, Session I
10:00 - 10:30	Coffee Break
10:30 - 12:00	Research Reports, Session II
12:00 - 1:30	Lunch
1:30 - 3:30	Panel Discussion, Earthquake Prediction and Earthquake Engineering Research
3:30 - 4:00	Coffee Break
4:00 - 5:00	Research Reports, Session III

Conference Dinner - Faculty Club

6:30 - 7:30	No Host Social Hour
7:30 - 9:30	Dinner - Speaker: Miss Madeline Bronsdon, Curator of the Museum of Anthropology, University of British Columbia

June 29 (All regular conference sessions will be held in Room 104 Angus Building)

8:00 - 9:30	Research Reports, Session IV
9:30 - 10:00	Coffee Break
10:00 - 12:00	Panel Discussion, Current Capabilities and Future Needs in Experimental Earthquake Engineering Research
12:00 - 1:30	Luncheon, Hosted by the Government of the Province of British Columbia
1:30 - 3:00	Research Reports, Session V
3:00 - 3:30	Coffee Break
3:30 - 4:30	Research Reports, Session VI
4:30 - 5:00	Conference Summary, Closing Remarks

PRESENTATION SCHEDULE

SESSION I (Ch., W.D. Iwan)

G.V. Berg, U. Mich.
S.C. Goel, U. Mich.
R.D. Hanson, U. Mich.
W.S. Rumman, U. Mich.
T.S. Vinson, Mich. St.
K. Aki, MIT
J.M. Becker, MIT
C.A. Cornell, MIT
D. Boore, Stanford
J.M. Gere, Stanford
H.C. Shah, Stanford
G.A. Hegemier, UCSD
J.E. Luco, UCSD
R.K. Miller, UCSB
W.T. Thomson, UCSB
A.S. Veletsos, Rice U.

SESSION II (Ch., W.D. Liam Finn)

W.J. Hall/N.M. Newmark, U. Ill.
W.C. Schnobrich, U. Ill.
M.A. Sozen, U. Ill.
T. Ariman, U. Notre Dame
J.E. Goldberg, Purdue
A. Schiff, Purdue
J.T.P. Yao, Purdue
P.L. Gould, Wash. U., Mo.
A. Pauw, U. Mo., Columbia
F.Y. Cheng, U. Mo., Rolla
W.O. Keightley, Montana St. U.
A. Askar, Princeton U.
R.H. Scanlan, Princeton U.
F. Kozin, Polytech. Inst. of NY
P.C. Wang, Polytech. Inst. of NY
G.C. Lee, St. U. of NY
I.J. Oppenheim, Carnegie-Mellon

SESSION III (Ch., G.V. Berg)

M. Aslam, Berkeley, by D.T. Scalise
V. Bertero, Berkeley
R.W. Clough, Berkeley
G. Dasgupta, Berkeley
J.M. Kelly, Berkeley
R. Mayes, Berkeley, by Y. Omote
H. D. McNiven, Berkeley
W.L. Schroeder, Oregon St. U.
A. Peyrot, U. Wisconsin
J.R. Benjamin, EDAC

SESSION IV (Ch., A.S. Veletsos)

G.C. Hart, UCLA
K.L. Lee, UCLA
A.K. Mal, UCLA
B. Mohraz, So. Meth. U., by A.S. Veletsos
J.O. Jirsa, U. Texas, Austin
G.W. Housner, Caltech
D.E. Hudson, Caltech
W.D. Iwan, Caltech
P.C. Jennings, Caltech
H.L. Wong, Caltech
N.M. Hawkins, U. Washington
S.W. Smith, U. Washington
Le-Wu Lu, Lehigh U.
J.B. Scalzi, NSF

SESSION V (Ch., G.C. Hart)

K.S. Pister, Berkeley
E.P. Popov, Berkeley
H.B. Seed, Berkeley, by J.R. Booker
W.E. Wagy, Berkeley
N.D. Walker, Jr., Berkeley
D. Williams, Berkeley
P.M. Byrne, U. British Columbia
W.D. Liam Finn, U. British Columbia
A. Motsonelidze, U. British Columbia
N.D. Nathan, U. British Columbia
R.A. Spencer, U. British Columbia
A. Ghali, U. Calgary
A. G. Davenport, U. West. Ontario
M. Novak, U. West. Ontario
D.V. Reddy, Mem. U. Newfoundland

SESSION VI (Ch., E.P. Popov)

S. Masri, USC
F.E. Udwadia, USC
V.I. Weingarten, USC
J. Humar, Carleton U.
J. Boatwright, Lamont-Doherty
S. Uzumeri, U. Toronto
G. Ayala, UNAM
R.B. Matthiesen, USGS
T.C. Hanks, USGS, by A.G. Brady
R.L. Sharpe, Appl. Tech. Council
M. Fintel, Portland Cement Assoc.

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(By Affiliation)

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W. D. Iwan
P. C. Jennings
B. D. Westermo
H. L. Wong

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J. L. Humar

Carnegie-Mellon University

I. J. Oppenheim

Lamont-Doherty Observatory

J. Boatwright

Lehigh University

Le-Wu Lu

Massachusetts Institute of Technology

K. Aki
J. M. Becker
C. A. Cornell

McGill University

D. Mitchell

Memorial University of Newfoundland

D. V. Reddy

Michigan State University

T. S. Vinson

Montana State University

W. O. Keightley

Oregon University

W. L. Schroeder

Polytechnic Institute of New York

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P. C. Wang

Princeton University

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Rice University

A. S. Veletsos

Stanford University

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State University of New York

G. C. Lee

University of Auckland

G. R. Martin

University of British Columbia

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P. M. Byrne	A. Motsonelidze	Y. Vaid
S. Cherry	N. D. Nathan	E. Varoglu

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A. Ghali

University of Colorado

J. E. Haas | C. Kisslinger

University of California, Berkeley

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K. L. Lee		

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W. S. Rumman

University of Missouri, Columbia

A. Pauw

University of Missouri, Rolla

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UNAM

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P. E. Gilbert D. Hickman

Kinemetrics

K. L. Benuska

M & M Protection Consultants

J. D. Morin

<u>Portland Cement Association</u>

M. Fintel

<u>Terra Technology Corporation, Seattle</u>

E. H. Hernandez

PANEL NO. 1

Title: Earthquake Prediction and Earthquake Engineering Research

Chairman: S. Cherry, University of British Columbia

Recorder: C. A. Cornell, Massachusetts Institute of Technology

Panel Members:

J. E. Haas	University of Colorado, Boulder
G. W. Housner	California Institute of Technology
C. Kisslinger	University of Colorado, CIRES
N. M. Newmark	University of Illinois
P. Ward	USGS, Menlo Park

C. A. CORNELL, Recorder

Massachusetts Institute of Technology

Earthquake prediction is a physical possibility, but much effort and possibly time remain before forecasting is an operational tool. Difficult political and legal problems are involved, many associated with the interim period before the reliability and accuracy of earthquake forecasts are established. The implications to earthquake engineering practice and research are perhaps fewer than might be expected. Some believe that design practice would be unchanged and that practicing engineers would be affected only when called in after a prediction to evaluate the capabilities of existing buildings relative to the anticipated earthquake effects. The primary influence of prediction on earthquake engineering research would be its creation of a natural laboratory experiment.

The panel discussion was initiated by five ten-minute presentations by panel members; they summarized and supplemented the prepared written material. These presentations were followed by a question and answer period involving both the audience and the panel.

In his initial presentation, Dr. Haas described a scenario of an earthquake prediction-public response situation. The scenario was based on responses in interviews of members of the business, professional, and government communities. A major effect--one connected with the long lead time associated with large magnitude prediction--would probably be a broad economic slowdown.

In their initial presentations Dr. Ward and Dr. Kisslinger described the current scientific basis for earthquake predictions. Both emphasized the practical need to quantify the accuracy and reliability of such predictions. This requirement in turn demands not only better understanding of the physical relationships between precursors and events, but also a significant number of test cases for larger events. Dr. Kisslinger amplified his written statements by discussing briefly a number of the measurable precursors of current interest (e.g., from leveling data; from tide data; the tilt, radon, sea-level, and lake-level anomalies used in recent China events; and changes in the ratio of p and s wave velocities). Location prediction is based on such information as migration of epicenters and in-situ stress monitoring. Time-to-occurrence accuracy is poor (a factor of 2 or 3), being poorer for larger events, but there is hope of finding means of improving the accuracy as the event approaches in time. Both scientists appreciate the engineering/disaster-mitigation need to predict effects (e.g., an iso-seismal map) not simply a magnitude, epicentral location, and date. Our current ability to predict strong motion intensity given magnitude and distance is weak.

Earthquake engineers Housner and Newmark reviewed their opinions on the implications of prediction. Earthquake prediction might not much effect new buildings unless all events could be predicted (life safety remaining an issue until this total capability is possible). Dr. Newmark would like to improve the benefits of predicted earthquakes as research laboratories by developing the ability to initiate at will controlled earthquakes. The cost effectiveness of waiting for natural events is low.

The audience of earthquake engineering research investigators showed relatively little interest in the implications of prediction on their own specialty. With the exception of one question regarding the existence of any plans to instrument and test buildings in the areas of predicted earthquakes (answer: only some acceleration of instrument placement in the Palmdale area), the questions centered on two broad areas: (1) the social/political/economic implications of prediction and (2) the current focus of the public and their politicians on prediction (relative to their concern for engineered mitigation measures).

Questions about public information predominated. In light of negative economic implications, should not the public be warned only shortly before the event? Answers: different individuals and organizations have different "optimal" warning times, but in any case suppression of such information is impossible and unwise in the current political climate. What is the nature of the channels of information to the public? Answers: they include various government organizations as well as the press. The state of California has a committee to certify predictions; the U.S.G.S. is considering establishing a prediction review council. Public information brochures are available and in preparation. Critical problems include false-alarms, credibility, etc. The public must be made to recognize that this is a period of development of prediction capability. Whereas predictions made now must be made public in order to test them adequately, it must be expected that many will be wrong.

Questions regarding the effects of predictions on various individuals included: (1) the liability of an engineer asked to review a building in a threatened zone (answer: public officials will not risk not calling for evacuation from even "approved" buildings, but liability issues to many involved must be addressed now); (2) the effects on a nuclear power plant [answer: they could be shut down prior to the predicted event, but (a) security of the capability to cool the core must be maintained through the event (as now) and (b) shut-down means a large financial loss implying that it will only be done when the credibility of the prediction is above some threshold (a similar problem exists for dams: the value of stored water can be tens of millions of dollars; it cannot be released casually)]; and (3) the economic effects of a prediction [answer: it is recognized that they may be strongly negative by some micro-economic (e.g., community level) accounting schemes and much less so from a macro-economic view].

Specific questions to Dr. Haas included the reliability of the interview technique for predicting actual individual and organizational responses (answer: it is a concern, but care was taken to use double interviews, etc.) and the existence of plans for a sociological study of the current Palmdale situation (answer: "I don't know").

Finally, several engineers in the audience questioned the high level of publicity associated with earthquake prediction. One answer proposed that prediction is a fad; extreme public interest can be expected to pass in a matter of months. Whereas it was admitted that it is prediction itself which has caught the attention of many of the public, we can be assured that existing programs and new legislation will be balanced scientific and engineering programs.

J. EUGENE HAAS

Institute of Behavioral Science
University of Colorado

An earthquake prediction will have little impact on the normal way in which land use controls and seismic resistant construction are used by a city to mitigate the earthquake hazard. It will cause some increase in actions designed to prevent secondary impacts. The earthquake prediction will be the dominant driving force in increasing by far the scope and intensity of efforts related to preparedness for emergency response and planning for relief, restoration and reconstruction.

In no case does the earthquake prediction produce a diminished application of any adjustment mechanism with the possible exception of insurance, an adjustment which is seldom used anyway.

A credible earthquake prediction serves as a catalyst in the entire adjustment process for the community, as we have seen. But quite apart from that relationship an earthquake prediction has direct effects of its own, negative as well as positive, on the community. Because a prediction contains specific information regarding time, location and magnitude, a host of specific actions can be taken that otherwise would make no sense. Most of those actions deal with the reduction of deaths and injuries. Highly accurate earthquake prediction permits the human habitation of a seismically active area with relative impunity insofar as casualties and emotional trauma are concerned. In addition, earthquake prediction makes possible the avoidance of loss of highly valued objects such as records, art works and certain kinds of equipment. Many such objects simply cannot be replaced. With earthquake prediction they may be used and enjoyed with relative impunity until the coming of the earthquake.

But all knowledge also has its cost. The severe local economic depression produced by the earthquake prediction may represent economic loss as great as that produced by the earthquake itself. There are steps that could be taken to soften the negative economic impact of the prediction but it is not clear yet whether those steps will be taken.

What actions, if any, might be appropriate <u>prior to</u> the release of the first prediction for a damaging earthquake?

1. Some measures designed to stabilize property values after the earthquake prediction should be given priority consideration. Most frequently mentioned is some form of Federally subsidized earthquake insurance, perhaps modeled after the current National Flood Insurance Program.

2. Clarification of the legal liability of predictors, public officials and property owners (National Academy of Science).

   A. To what extent is the seismologist or his employer liable for the consequences of a prediction if "normal professional standards" are used in developing and releasing the prediction?

   B. To what extent are public officials liable if they take only limited action, e.g., ordering evacuation only of very clearly unsafe buildings, in the face of an earthquake prediction? Does the degree of liability change as the estimated probability goes up from say 25% to 60%? What liability is inherent in taking more drastic action?

   C. Does the employer or property owner face increased liability as a result of an earthquake prediction? If he fails to vacate his property well in advance of the expected earthquake can he be sued successfully for damages and wrongful death?

3. How can drastically increased mitigation and preparedness measures be financed by local government? With tax revenues dwindling and legitimate demands for budget increases expanding, local government will be in severe financial straights. Should special state and Federal "predisaster" financial assistance be made available? Under what circumstances? Should the aid be comparable to the postdisaster financial assistance normally given?

   There are a number of interlinked issues which come into play here. All of them need immediate attention.

4. Should residents of the "target" community be encouraged to leave the area? How about leaving areas designated as "higher risk" zones?

   Especially for the first few predictions there may be a concern that the earthquake may come earlier or be larger than predicted. From a strictly economic perspective residents for the most part should be encouraged to stay and many business leaders may well take that stance. From strictly a safety standpoint most persons should be encouraged to leave for safer areas well in advance of the predicted time. Under exceptional circumstances perhaps forced evacuation would be called for.

   For each potential target community there ought to be careful examination of the pros and cons and the probable consequences of different courses of action.

5. Should there be some attempt at controlling the tactics of land speculators?

   There is considerable concern among knowledgeable officials that some unethical land speculators will use scare tactics akin to "block busting" to drive down property values. Is there a legal, feasible basis for dealing with such activities?

Earthquake prediction is an emerging technology. Its application in the near future is a near certainty. It is becoming clear that a number of "negative forces" will be set in motion by an earthquake prediction with an extended lead time. If we wish to avoid some of these negative consequences it is high time to consider and adopt some strategies to counterbalance the negative trends. It is also necessary to consider with care how best to utilize the opportunities provided by an earthquake prediction.

REFERENCE

NATIONAL ACADEMY OF SCIENCES (1975). Earthquake Prediction and Public Policy. Printing and Publishing Office, National Academy of Sciences.

EARTHQUAKE PREDICTION AND EARTHQUAKE ENGINEERING RESEARCH

G. W. Housner
California Institute of Technology

Earthquake prediction, if developed to the point of adequate reliability, will certainly have important social, financial, economic, and political effects, but can be expected to have less effect on earthquake engineering. The earthquake engineering design of new buildings will be relatively unaffected except, possibly, for pressures to reduce earthquake design requirements because weaker buildings could be evacuated prior to an earthquake and thus would not be a hazard to the public. Successful earthquake prediction will have an influence on engineering for during the interval between the making of the prediction and the occurrence of the earthquake many decisions relating to engineering must be made, and many problems can be expected to arise where the correct engineering decision will not be obvious. Successful earthquake prediction can be expected to have a significant influence on earthquake engineering research, particularly on experimental research.

Successful earthquake prediction would enable earthquake engineering research workers to treat earthquakes as full scale laboratory experiments. It has often been said in the past that strong earthquakes should be considered as opportunities for full-scale laboratory research, but not knowing when and where earthquakes will occur it is necessary to disperse instruments throughout the strong seismic zones thus using a shotgun approach. However, if the location, magnitude and time of occurrence of earthquakes could be predicted it would be possible to use a rifle approach and concentrate instruments and effort and truly make use of the earthquake as a full-scale laboratory experiment. In this regard, it is of interest that the visiting team of Chinese earthquake engineering research workers that were in the United States in May 1976 explained that in China they were already prepared to do just this. They said that they had several mobile units outfitted so that when a prediction was made they could quickly move instruments into the area and record the forthcoming earthquake. However, they missed obtaining any records during the 4 February 1975 Haicheng earthquake, which had been predicted by seismologists, because insufficient lead time had been given to move the mobile units into the area. In 1970 Liaoning Province had been identified as a region of special seismic risk and in December 1975 a false alarm was issued which kept the populace out of doors for two days and nights. The main Haicheng shock (magnitude 7.3) was preceded by 527 preshocks which started February 1st. Three hundred and eighty-eight occurred between midnight and noon of February 4th with the largest being magnitude 4.7. This prompted the issuance of a general warning at 2:00 p.m. and the main shock occurred at 7:36 p.m. *

It appears from the foregoing, that what the Chinese are doing is not prediction in the sense that U.S. seismologists are using the word. The Chinese seismologists monitor many precursory phenomena: geological, biological, chemical, seismological, etc., and when it seems appropriate, inform the local seismological brigades who then decide when to warn the populace. This differs from the way earthquake prediction is being discussed in the United States where it is expected that on the basis of observations the seismologists will make a prediction of a forthcoming earthquake that will specify, in a probability sense, the magnitude, location and time of occurrence. This information, in the case of California, will be forwarded to the State Office of Emergency Services which will call into session its Advisory Committee which will recommend how much credence to give to the prediction. If the prediction is accepted, the Office of Emergency Services will presumably take certain precautionary steps of its own to mitigate the effects of the earthquake should it occur and will inform the appropriate State and Local government agencies of the prediction. These agencies must then make some decisions as to what steps they will take to prepare for the earthquake and what information and recommendations they will issue to the local inhabitants. Presumably all these actions will be reported by newspapers, TV and radio as they take place. The crucial difference between the U.S. and the Chinese approaches is that the U.S. seismologists will announce their prediction of time, place and magnitude together with an estimate of the accuracy. The Chinese seismologists, on the other hand, communicate directly with the local population, telling them to get out of the building because an earthquake is expected.

A procedure similar to that of the Chinese was involved prior to the 1 August 1975 Oroville, California, earthquake. Beginning on 28 June 1975 there was a marked increase in seismic activity in the Oroville region with a general increase in numbers of and magnitudes of small earthquakes during the following month. A week before the main shock Bruce Bolt concluded that this increase in activity was sufficiently alarming to warrant alerting the Department of Water Resources and he telephoned me to recommend that I, as Chairman of the Earthquake Advisory Board inform the Department of Water Resources that a larger potentially damaging shock might occur in the vicinity of Oroville Dam. This information was then relayed to DWR.

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*A detailed description is given in the paper "The Haicheng, China, Earthquake of 4 February 1975," Bulletin of New Zealand National Society for Earthquake Engineering, March 1976, by R. D. Adams, who visited the Haicheng area in September 1975.

When a reliable earthquake prediction is made, earthquake engineering research workers should immediately prepare to treat the forthcoming earthquake as a full-scale laboratory experiment. That is, install strong-motion instruments to record ground motions, install suitable instruments to record building motions and deformations, install suitable instruments on special structures such as major dams, large bridges, tall towers, nuclear powerplants, liquid natural gas tanks, etc., and be prepared to measure the behavior of soils and soil structures, and if the earthquake is predicted to occur near the oceanfront, preparation should be made to record possible tsunami.

We may ask, what will constitute a satisfactory prediction? In the U.S. this will certainly depend largely on the reliability and accuracy of the prediction. Two different approaches can be taken, a) the scientific approach and b) the black box approach. The scientific approach might proceed in a fashion similar to weather forecasting where by means of various observations some atmospheric anomaly is detected and some estimate made of its travel path and its intensity and what the implications are. On this basis predictions are made as to the probability of rain. The black box approach on the other hand does not depend on identifying a particular atmospheric anomaly and estimating its consequences but, rather, direct correlation is made between observations and the occurrence of the predicted event. In the case of weather prediction, the black box approach if carried to an extreme might lead to predicting the same weather tomorrow as today, and over a year's time this would give a rather high level of success. The success of the black box approach can only be judged on a statistical basis, that is, what is the ratio of successful predictions to unsuccessful predictions. The black box approach must be treated very cautiously, especially in the beginning, so that public confidence is not destroyed.

What earthquake engineering research workers would like would be to have the prediction identify the causative fault, the location, the magnitude and the time of occurrence of the event. Presumably, this is the sort of prediction that the scientific approach would ultimately lead to. On the other hand, the black box approach seems now to be subject to large uncertainties in time, space, and energy release. We would like to avoid the situation in which following a prediction a considerable effort is made to install instruments and prepare for the event only to find that it occurs 50 miles away. Or, after installing the instrumentation and waiting with no earthquake occurring to have the earthquake occur after the instrumentation has been removed. It certainly would be unacceptable to predict destructive earthquakes and then have nothing occur. This would be too much like the situation in which the end of the world is predicted by the leader of a cult and all the members dispose of their wordly possessions and assemble on a mountain top only to find that doomsday does not arrive.

If prediction becomes successful, it certainly will have some far reaching implications for engineering. It seems to me that much careful thinking is required before the engineering community will be ready for earthquake prediction.

CARL KISSLINGER

CIRES
University of Colorado/NOAA

Current Status of Prediction Technology

An earthquake prediction is a statement of the time, place, and magnitude of a future event, including some measure of the confidence the predictor associates with his specification of each of these parameters. Research to achieve the ability to make predictions is in its early stages, and all predictions made at the present time should be viewed as tests of hypotheses rather than applications of proven technology. Many more theoretical analyses, laboratory studies, and field investigations must be completed before we can determine the extent to which earthquakes are predictable, which methods of prediction are most effective, and how probabilities are to be assigned to a given prediction.

There is no doubt that some earthquakes have been preceded by diagnostic changes in observable geophysical quantities, and we are confident that earthquakes in some geological settings are predictable on the basis of precursory anomalous changes. We do not know if all earthquakes, or even all crustal earthquakes, the ones of principal practical concern, exhibit premonitory behavior. We need to know if the occurrence of precursors is a function of the mode of faulting (strike-slip vs. dip-slip), the tectonic settings (e.g., plate margins vs. intraplate settings), or some other circumstances.

The places of occurrence of future earthquakes are indicated first by past seismic history, about which we know a fair amount, and by the location of a precursory anomaly if one is detected. Seismic gaps seem to be diagnostic in plate margin settings, and the suggestion that hypocenters migrate merits further study. Migration of events was the first clue used by the Chinese in predicting the Haicheng earthquake. We are in much worse shape with regard to intraplate earthquakes, for example those in eastern North America. We do not understand at all why these earthquakes occur, and we are struggling to learn the correct way in which to use seismicity information to assess future hazard. In the absence of a repetition of any of the very large earthquakes within the historical record, we have no sound basis for judging the recurrence rates at any of the sites of past great events in the eastern part of the continent.

We have two clues to the magnitude of an impending earthquake from observations of precursors: the size of the area within which anomalous behavior occurs and the time duration of the anomaly. The direct relation of anomalous area to magnitude is best supported for geodetic data, especially from Japan. The dependence of anomaly duration on magnitude has been observed for many kinds of precursors.

We need to know the spatial pattern of the formation and disappearance of anomalies, as this pattern will yield important information about the physics of the processes involved.

We have little data for major earthquakes, the ones that are important from the social viewpoint. The Haicheng earthquake in China, M 7.3, is the only example, and we are trying to learn the details of that successful prediction. Some great earthquakes clearly appear as a sequence of breaks along a fault, each triggered by the arrival of the adjacent one. We are left with the question, do we scale precursors to levels like M 8.5, or do we attempt to predict a runaway 6.5 for which the precursors look only like those for a moderate event?

Time Table for Future Prediction Research

It is a mistake for politicians to ask for and for scientists to claim a target date for the achievement of successful prediction technology, even given large amounts of financial and human resources to work toward that goal. At this point, we don't even know if the problem is generally solvable. Prediction should be recognized as an important research goal with the potential for enormous social benefits,and then governments should proceed in an orderly way, spending money at a sensible rate commensurate with the importance of the problem and the relevant research capabilities, until we either achieve the goal or decide that it cannot be done.

We will not know if we have a useful technology for predicting large earthquakes until we have had a chance to test it on at least one real case, and few of us will be satisfied with the results of one such test, whether they be positive or negative. We may very well have learned how to predict big earthquakes within a decade or so, and still not know that for sure. A major event at any one place is a rare event, so we must optimize our chances of capturing one by prudent selection of experimental area, and then wait until nature provides us with the definitive experiment. We must take advantage of all opportunities for international cooperation in order to increase the rate of data accumulation and acquisition of experience with major events.

Lead-Time and Accuracy of Earthquake Predictions

At present, every prediction must be considered to be an experiment, a test of a hypothesis. I don't know how we convey this to the public and avoid the negative consequences of experimental predictions, but we cannot make progress otherwise. We do not know the efficacy of various postulated precursors in all tectonic settings, we do not know the false alarm rate. We need experience with failures as well as successes if we are ever to be able to assign meaningful probabilities to predictions. We must encourage serious investigators to get their predictions into the record before the fact, even if this means publicizing their "mistakes".

With regard to lead-time, the evidence indicates that precursors fall into two populations. One group is characterized by an anomaly duration that scales with magnitude. The other, apparently accompanying only moderate to large earthquakes, magnitude 5 and greater, begin very shortly before the event, the duration not depending on the magnitude. If further experience shows that both intermediate and short-term precursors do exist, we will have lead times of some years for major events, but with large uncertainty as to the actual data, and warning signals just before (days to hours) the occurrence. A number of useful things can be done during the long interval, such as strengthening weak structures, eliminating obviously hazardous conditions, and reducing inventories of vulnerable goods in storage. If proper planning has been done, the short-term signals can be used to initiate immediate measures to reduce injuries and deaths.

Relation of Prediction to Earthquake Engineering Research

The best time to take positive action to reduce the disastrous effects of earthquakes is when building sites are selected and structures are designed and constructed. In highly developed countries, the ability to predict accurately specific events, if ever achieved, should not change the requirements or the practices of good earthquake engineering. The same hazards have to be resisted, and the possibility of knowing, after construction is complete, the day on which the earthquake will strike does not change the design requirements. Of course, if analysis of the precursory data indicates that the impending earthquake will produce ground motion substantially in excess of the design earthquake, i.e. the magnitude will exceed that expected from hazard assessment, steps should be taken to strengthen vulnerable elements.

In less developed countries, the needs are no different, but the practical realities are. A good example is China, where the quest for a reliable prediction technology has been given the highest priority. In that country, hundreds of millions of inhabitants of seismically active areas are housed in structures that have no provision for earthquake resistance. The systematic replacement of all of this housing is rejected for economic reasons, and in this situation, the emphasis on prediction makes a lot of sense. The approach is to get the people out of the dangerous buildings, let the buildings fall down with minimal injuries, and then go back and clean up the mess. This approach requires good planning for the recovery period, so that temporary shelter, food, medical care, sanitation and other basic needs can be provided promptly. The Chinese are a well-diciplined society, and from their limited experience, as we know it, the approach works for them. Even false alarms leading to considerable disruption appear to be acceptable at present. Certainly the number of injuries and deaths in Guatemala could have been greatly reduced by a good prediction followed by appropriate action.

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NATHAN M. NEWMARK

University of Illinois at Urbana-Champaign

Earthquake prediction and earthquake engineering are closely related topics that, in many respects, cannot be considered separately. Prediction involves estimates not only of when an earthquake might occur, but also of its magnitude of occurrence and the intensity of ground shaking at a particular site that might result from the expected earthquake. Earthquake engineering involves mitigation of the effects of an earthquake by selecting design levels of motion intensity, choosing allowable levels of structural response, and developing the knowledge necessary to permit the design to be made so that damage is limited to permissible or allowable levels. Among these topics are the selection of design levels for earthquakes that have a reasonable probability of occurrence during the lifetime of a building, to avoid extensive costs for repairs or reconstruction; and of even more importance, to provide for an extreme earthquake by designing important buildings in such a way that they will not collapse or fail in a manner that (a) will bring serious injury or loss of life to personnel, or (b) cause serious economic disruption and unacceptable sociological consequences.

Another related topic involves earthquake intensity mitigation, but this is a more difficult and more tenuous possibility which may well occur in the long range future but is not likely to occur in the period of time during which we can have some assurance of major improvements in our ability to forecast or predict earthquakes and to design to resist their consequences.

The present interest in earthquake prediction arises from the fact that the possiblity for saving lives, providing temporary measures to avoid serious economic consequences, and providing for the safeguard of critical facilities in such a way that damage from expected earthquakes might be greatly limited, appear to have great potential. However, property damage in general, and the performance of vital functions such as water supply, sanitary systems, power distribution systems and the like, might not be greatly helped by ability accurately to predict earthquakes.

A great many physical phenomena have been associated with earthquakes, and some of them appear to have a reasonably good physical correlation with subsequent earthquakes. However, at the present time no single set of physical phenomena appear to be sufficient as a sole measure for accurate prediction techniques. Most of the models that are used to study precursory phenomena are crude, and improvement of the models will require considerable fundamental research and effort as well as theoretical studies. These methods run the gamut from measurement of the change in the ratio of shear wave to compressive wave velocities in ground, to observation of the response of animals to precursory motions or noise levels that precede earthquakes.

Basically, it appears necessary to consider the whole range of phenomena that might be indicative of future earthquake activity, and to correlate these in some way, in part empirically and in part with various techniques that might be developed from operations research methods. Nevertheless, although earthquakes of moderate intensity and magnitude have been predicted accurately in some cases, with more success in China, apparently, than elsewhere, there is some question whether the extremely large earthquakes that occur occasionally in certain parts of the world, and notably on the West Coast of the United States on some of the major faults on which activity occurs only at great intervals, can be predicted accurately in terms of the time when they might occur.

The statement has often been made that along certain regions of the San Andreas fault, for example, a major earthquake with motions of as much as 20 feet of strike slip movement will occur about once in a century. However, the predictive techniques that are available now do not appear to give any assurance that one could predict such a large earthquake within a period of time in the future less than several years, and possibly not even that accurately. Consequently, disruptions in economic activity and in the general course of life might be greater than is acceptable from predictions of the occurrence of major earthquakes. The question might even be raised as to what would be the best response to a prediction that a major earthquake in San Francisco along the San Andreas fault would occur within a week or ten days.

The values to be obtained from earthquake engineering research are somewhat more definable and possibly more positive. It appears possible now, for example, to provide design criteria that would prevent the destruction of or serious damage to major dams, nuclear reactors, or other major, expensive, and dangerous or hazardous structures. It also seems likely that, within the next few years, the design criteria for buildings will have reached the point that in general the engineering and architectural professions can design with some assurance to avoid collapse or major loss of life in buildings of various heights and designs in all parts of the country.

The problem that remains, however, in both of these types of situations is the very large amount of conservatism that is required to give a reasonable degree of assurance of the success of such design criteria. It will only be after a great deal of additional research that we can reduce this excessive conservatism to a level that will make it more nearly economically feasible to provide the proper design criteria without excessive costs.

We have yet to explore adequately the possible correlation between earthquake prediction and provisions in the design to provide safety or mitigation of earthquake response or earthquake damage effects. This approach might well consist of designs that would permit taking account of the likelihood that an earthquake might occur in the near future, say within several hours to several weeks, in such a way that less complex and expensive provisions could be made in the design that would depend in part on the predictive techniques to lessen the possible damage to the structure. These might consist, in the case of nuclear reactors, for example, simply of providing for shutdown and standby modes to avoid damage from the earthquake motions; or in the case of dams, by providing a lowering of the water level behind the dam. In the case of buildings, the alternatives appear to be primarily evacuation of the buildings or of proceeding to a place of safety where objects could not fall upon inhabitants. Just how these interactions might be provided for have not yet been studied in enough detail to indicate what all of the possibilities might be. However, at present earthquake engineers have the responsibility of making sure that regardless of the state of earthquake prediction they can and will design structures and other facilities in such a way that collapse, with loss of life and major economic destruction, will not occur.

Although extensive progress has been made recently in earthquake engineering, and much more extensive and improved results can be expected in the future, as we improve the accuracy of our knowledge through additional research, there are many areas, particularly concerned with earthquake hazards and with earthquake hazard prediction, that remain extremely difficult to assess. If we had knowledge of the earthquake hazard at a particular site, a successful design would not be difficult to achieve. At present, our knowledge is imperfect and imprecise. One of the major problems in earthquake prediction is to improve knowledge of the intensities of motion that are likely to occur at different sites. This appears to be a longer range program than any other aspect of the topics associated with this Panel's assignment. Much of what we are likely to learn about earthquakes will be valuable only to the extent that it agrees with observations, and observations take a long while. We can improve our capability of learning from observations by extensive theoretical work and laboratory experiment, but the final test will be the comparison of our results with observations made in earthquakes. Since earthquakes occur rarely at any particular site, and cannot yet be accurately predicted in advance, the proper deployment of instruments is still a matter of great uncertainty, and the cost effectiveness of instrumentation deployment remains very low.

Finally, one of the major problems facing the earthquake engineer is the matter of the hazards from old structures or existing structures. Even when we can improve our knowledge to the point that we can design with a great deal of assurance against future earthquakes, there will be many buildings and other structures which will not have been designed in accordance with these more advanced standards and criteria. How these can be improved in performance and capability is a matter that involves a great deal of study, expense, judgment, and willingness to face hard economic facts.

As a measure of the importance of the topic assigned to this Panel, I should like to point out that the Director of the National Science Foundation has appointed an Advisory Group, of which I have the honor to be chairman, on earthquake prediction and hazard mitigation, which has the responsibility for reviewing the Federal Agencies programs in these areas and of advising the Director of NSF and the President's Science Advisor on the priorities for research, the appropriate budgeting for the necessary research in these fields, and the formation of a sound technical basis for decisions to be made by the Federal Government on the responsibilities, budget, and limitations to achieve an appropriate basis of knowledge for earthquake prediction and hazard mitigation. The Advisory Group is directed to consider the following topics:

The role of the federal and other governmental and private organizations and individuals for research support and program result implementation.

Potential use of research projects.

Competition for limited funds among many worthy programs.

Capability and interest of the potential users to absorb and implement the results of the program.

The Advisory Group had a meeting on June 14 and another meeting is scheduled for August 12 and 13 in Washington to consider working papers presented to it by the NSF and the U. S. Geological Survey. It is expected that the work of the group will have been completed by mid 1977, during which time at least four meetings of the group will have been held.

The Advisory Group has a wide representation including seismologists, geophysicists, sociologists, earthquake engineers, and building code officals from all parts of the country. Meetings are attended by representatives of the various governmental agencies involved in the topics. We shall be glad to have the benefit of your advice and suggestions. The discussion at this meeting will be most helpful to the Advisory Group and to me personally.

EARTHQUAKE PREDICTION AND EARTHQUAKE ENGINEERING RESEARCH

Peter L. Ward
U.S. Geological Survey, Menlo Park

Earthquakes appear to be predictable on a scientific basis. Such predictions of varying reliability will be issued with increasing frequency in the future. We know what earthquakes are, why most occur, and where most occur. A wide variety of physical precursors have been reported prior to earthquakes including measurements of strain (e.g. leveling, trilateration, sea level, creep, seismicity, and tilt) and the effects of strain (e.g. changes in velocity, radon content, resistivity, telluric currents, and magnetic fields). The reliability of these observations varies, and many more observations, particularly within dense networks of similar instruments, are needed to establish clearly the occurrence and source of these precursors as well as their temporal relation to pending earthquakes. Models exist for the earthquake source that provide a physical basis for many of these precursors but there are significant questions still to be answered. Thus, while earthquake prediction appears feasible and much progress has been made in recent years, considerable research still is needed before a reliable prediction system can be implemented. The rate of progress depends primarily on how soon forerunners to earthquakes of magnitude greater than 4 can be monitored within dense networks of a wide variety of instruments. Under the present program, a proven prediction system may be decades away.

Now is a very awkward time for seismologists. While a proven prediction capability does not exist, anomalies suggestive of a damaging earthquake could be recorded at any time. When lives are at stake, such indications, even if quite incomplete, will need to be released to the public. Thus there is a significant chance of false alarms during the present phase of this developing technology.

Prediction offers many benefits including reductions in life-loss, damage and disruption. For the engineer, even a generalized prediction provides a chance to increase instrumentation in an area prior to a large event. The first earthquake of magnitude 6 or greater that is predicted well enough to allow installation of dense strong-motion instrumentation, should provide a major leap forward in studies for predicting ground motion as well as for understanding the earthquake source and the effects of earthquakes on structures. Earthquake predictions, if made months or years in advance, will probably provide a major impetus to repair or condemn weak buildings, and take other actions to lessen the potential for loss.

Earthquake predictions may cause a major problem for engineers by suddenly spurring thousands of requests for evaluation of how specific structures will respond in the predicted earthquake. The engineering profession needs to be in a position to respond rapidly and not be hampered by unresolved issues of undue liability for these responses.

PANEL NO. 2

Title: Current Capabilities and Future Needs in Experimental Earthquake Engineering Research

Chairman: R. W. Clough, University of California, Berkeley

Recorder: Le-Wu Lu, Lehigh University

Panel Members:

V. V. Bertero	University of California, Berkeley
R. D. Hanson	University of Michigan
P. C. Jennings	California Institute of Technology
R. B. Matthiesen	USGS, Menlo Park
J. B. Scalzi	NSF
D. Rea	University of California, Los Angeles
M. A. Sozen	University of Illinois

LE-WU LU, Recorder

Lehigh University

Part 1. Presentation of Panel Members

All panel members made brief presentations based on the material they had prepared for the session. Dr. J. B. Scalzi, whose report did not appear in the document issued to the conference participants, explained his views of the purpose of laboratory and field testing and mentioned the potentials that exist for international cooperation in this area. The U.S. now has already installed strong-motion instruments in the Soviet Union. Also there is the U.S.-Japan Panel on Wind and Earthquake which can foster cooperation with Japanese institutions and research workers.

Part 2. Discussions Among Panel Members

Matthiesen to Jennings

Q: You mentioned the need to have our own buildings for experimental research. Are they to be underdesigned structures?

A: Buildings that are not intended for occupancy can be designed and constructed the way we want them to be. They can have certain dynamic characteristics or weaknesses and non-typical design details.

Bertero to Scalzi

Q: With regard to international cooperation, we need to consider the differences in construction method and design philosophy in overseas countries. Also there is the problem of "how to conduct and maintain the research facilities."

A: Careful planning is needed.

Rea to Sozen

Q: I want to add to your statement, "think more, test less," one of my own -- "think better after test."

Hanson to Rea and Others

Q: How to build a six component shaker?

A: State-Of-Art has to be carefully studied.

Considerable discussion then followed on the merit of installing strain and/or deformation meters in buildings.

Clough, Jennings and Rea emphasized the importance of having, in addition to the strong motion records, strain and displacement records which can be used in a more direct way to check the theory. Cost of strain gaging and the necessary equipment will be high, but it may be comparable with that of the strong-motion instrumentation (considering the amount of data that a strain recording system will give). It is desirable to have close cooperation with the manufacturers in the construction of the instruments.

Matthiesen: The strain gages installed at a UCLA building in the fifties did not yield useful results.

Jennings: The instrument might be something different from the ordinary strain gage. Something more reliable but installed at fewer locations.

Sozen: On metallic skeletal structures -- strain gage works OK. On reinforced concrete structures -- results are less reliable.

Clough: Experience from earthquake similator work at Berkeley shows that consistent results can be obtained with scratch gages.

Bertero to Rea, Jennings and Matthiesen: In reinforced concrete research, we have to test the type of buildings we want. Otherwise we wouldn't know what is in these buildings.

Rea: UCLA had a bad experience. But this doesn't mean that the idea will never work.

It is easier and more useful to get strain gage readings directly. The strong-motion record represents the integrated effect, local behavior can not be observed.

Need to test buildings before and after earthquake.

Matthiesen: There is some existing work on strain meters triggered by strong motion.

Future records should be digitized.

Part 3. Open Discussion

Mains: SR-4 gages seem to work on reinforcing bars (4-5 weeks). Does the scratch gage give good long term results?

Clough: Scratch gages work well in long term studies.

Hawkins: The University of Washington has had good experience with acoustic gages. Readings can be digitized.

Housner: The name of scratch gage is "Pruitt."

Hegemier to Bertero: If there is so much lack of understanding in material behavior under multiaxial state of stress, then are we really ready for full scale tests?

Bertero: At the micro level much research is still needed, but reasonably good predictions can be made based on our understanding at the macro level. Analytical and experimental work must be continued on steel, concrete and masonry at both levels.

Sozen: Doesn't think everything has to start at "Step 1" of his chart. As far as concrete slab problems are concerned, single slab is OK. Interaction problem is not completely solved.

Newmark: We had considerable success in instrumenting the Latino Americana Tower in Mexico City. Old type of scratch extensometers was used. What happens to an actual building during earthquake is very important because considerable judgements are usually exercised in the design. What is the response of the building foundation, and how is it affected by the building? Need to compare foundation response with the free fielding response.

What we want to be sure of is that laboratory experiment be conducted on specimens similar to what we use in actual practice. Instrument buildings -- We should always think before, during and after tests. A true test is a test that agrees with actuality.

McNiven: Experiments in engineering and in physics are so different. In physics, theory preceeds experiments. In engineering, we study test data first, then develop theory.

Matthiesen: Actually, observation always comes before theory.

Spencer: We should try to learn from other engineers and should encourage construction of buildings modelled after those which have performed successfully in the past.

Newmark: I want to know more about the explosion test being conducted in the Soviet Union.

Matthiesen: The Russians try to create earthquake-like inputs by explosion. A series of explosive charges is set off with delay periods in order to produce the combined wave fronts. The explosives are strong enough to cause damage to buildings. Four-story, two bay (some have three bays) building frames, representative of typical Soviet construction, have been built and free vibration tests have been conducted. Dynamic tests of increasing intensity have also been conducted by blast.

Higgins: Generation of earthquake-like ground motion has been tried elsewhere. The cost/benefit ratio of this type of testing needs to be examined. No source mechanism is involved in the explosive-generated ground motion. It is a useful way to study soil behavior under dynamic load, subway systems, mines, etc., where we can not separate soil from the structure. Cost is usually high. Experiments are best planned with a number of structures constructed at the same site.

Matthiesen: Soviets have tested dams and other types of earth structures by explosives.

Berg: The cost of building a National Laboratory should be examined from its potential benefit. We want to know, "How much reduction in the cost of future buildings can we expect (after research is done by using the facilities in the Laboratory) with the same reliability." Or, "How much improvement in performance can we expect for the same cost."

Bertero: Engineered buildings didn't suffer too seriously during the recent Guatemala earthquake. But damage to non-structural elements was very serious indeed.

Popov: Quality control in the field is a very critical problem. Another problem is the enforcement of building regulations or specifications.

Bertero: About quality control, what can we do in the laboratory is usually quite different from what can be achieved in the field. Control of quality of reinforced concrete masonry in the field is particularly difficult.

Schiff: We should also consider instrumentation for equipment or other contents in the structure.

Williams: We need to consider spatial variation in the installation of instruments.

Matthiesen: At four places in California, this factor was considered in the installation.

The session was consluded at 12:10 PM after the chairman thanked the panelists for their presentations and also the people who participated in the discussions.

VITELMO V. BERTERO

University of California, Berkeley

INTRODUCTION

This summary is devoted to the discussion of experimental research in the area of aseismic design and construction of buildings. This does not mean that this is the only area in the field of earthquake engineering which requires experimental research. Such research is also urgently needed in the general area of lifeline earthquake engineering. From the structural point of view, it can be stated that the ultimate objective of earthquake engineering research is to develop methods of design and construction that will result in earthquake-resistant structures both functional and economical. To achieve this goal, fully integrated analytical and experimental studies should be conducted.

Although no new revolutionary experimental techniques has been developed in the last five years, these years have witnessed major advancements in the area of aseismic design of buildings. These advancements were triggered by the occurrence of the San Fernando earthquake of February 1971. Investigations of this event have not only produced valuable data but have led to post earthquake laboratory studies, all of which have resulted in considerable improvements in seismic codes. In a series of papers presented at the ASCE-EMD Specialty Conference on Dynamic Response of Structures [1], several authors have summarized the present status of experimental research on earthquake-resistant structures.

Objectives and Scope. - The main objectives of this paper are to determine the greatest needs in the area of aseismic design of buildings and, accordingly, to find out if there is a need for a National Laboratory for large-scale experimentation. The greatest needs in this area are identified by reviewing the general aspects involved in achieving an economical, serviceable, and safe aseismic design and construction. A detailed discussion of these aspects and research needs is presented in Ref. 2. The flow diagram of Fig. 1 summarizes these aspects. It can be seen from this diagram that to achieve a reliable design, it is first necessary to establish the design earthquake (critical ground motion, X_3) and then to predict the mechanical behavior (dynamic response, D) of the structure--more specifically, of the whole soil-structure system--to X_3. Unfortunately, there are, at present, great uncertainties involved in the determination of X_3 and D. This paper summarizes the research needs in these two areas.

RESEARCH NEEDS FOR ESTABLISHING DESIGN EARTHQUAKES

At present the main source of uncertainties in the whole aseismic design procedure lies in the establishment of the design earthquake(s). Studies of past earthquake damage have been severely hampered by the lack of ground motion records. Strong-motion seismographs should be installed in all zones where severe shaking can occur. At any given site, the arrangement of such seismometers should be such that it will provide adequate information for determining the six components of the ground motion. Study of the response of buildings to these components will throw some light on the information needed to establish reliable design earthquakes. This is not an easy problem because, even for a given site, the critical ground motion can vary according to the limit state controlling the design of the structure. While information on the intensity and frequency content of a ground motion is sufficient for service limit state design earthquakes, it is not so for cases where safety (ultimate limit states) controls design. This information should be complemented with data on the duration of strong ground shaking and the number, sequence and characteristics of intense, relatively long acceleration pulses that can be expected [3]. There is a need to estimate at least the maximum incremental velocity and the associated acceleration that can be developed for different soil conditions taking into account the mechanical characteristics of each type of soil [3]. If this can be established, the structural designer will be able to design the structure according to the upper bound of the energy that can be transmitted to the foundation of the structure.

Present difficulties of predicting critical ground motions can be overcome through experimental research in the field, rather than in the laboratory. Studying the problem of soil-structure interaction by means of earthquake simulators would require a shaking table facility so tremendous that it would be both technically and economically unfeasible at this time. The largest table (100 ft. x 100 ft.) whose feasibility study has been carried out at present permits the testing of only three- or four-story buildings at full-scale without the foundation material [4]. Special three-dimensional arrays of seismometers and strain meters should be designed and placed throughout the building, the building foundation, and on the surrounding ground to obtain sufficient data for studying the interaction between the structure and the soil and the relationship between the free-field motion and the motion at the building foundation.

Because there is a low probability that any of the instrumented building sites will be subjected to severe ground motions due to a real earthquake in the very near future, it is necessary to supplement the above sources of information by trying to generate an earthquake-like environment by means of controllable sources. The utilization of underground nuclear explosions seems most promising [1,5]. Underground nuclear explosions may also be useful as a source for testing actual buildings to complete destruction (collapse), which is needed to improve aseismic design.

RESEARCH NEEDS TO PREDICT MECHANICAL BEHAVIOR UP TO COLLAPSE

In discussing the research needs in this area it is convenient to distinguish between non-engineered and engineered buildings. The main purpose of this discussion is to justify the need for a National Laboratory for large-scale experimentation that should consist of a combination of both the largest possible earthquake simulator facility and the largest loading facility. These types of facilities have been defined and described by Clough and Bertero in Ref. 1.

<u>Non-engineered Buildings</u>. - The construction of earthquake-resistant low-cost housing is a serious problem in those seismic regions of the world where the only economical material available for walls is adobe or bricks. This problem may be solved by the proper detailing, particularly by providing adequate anchorage to the various components of the building. New

methods of anchoraging should be developed through full-scale testing of building components in loading facilities. The reliability of these new techniques and possible improvements of established methods can be studied by final tests of the whole building using medium- or large-scale earthquake simulator facilities.

Engineered Buildings. - In these cases, buildings have definite structural systems. Inspection of Fig. 1 reveals that in the case where safety requirements control design, there are two possible paths for determining the design loads and/or deformations for a preliminary design of the structure. At present the design forces are derived through the use of a reduced elastic response spectra (ERS). The reduction is achieved using a selected ductility, μ. The main drawback of this method is that it is based on the assumption that the same type of ground motion that is critical for the elastic response of the structure is also critical for an inelastic response; that this might not be the case, particularly for near-fault sites, has been shown in Ref. 3. Furthermore, the method of reducing ERS through μ is based on results obtained in single degree-of-freedom systems having ideal elasto-perfectly plastic mechanical behavior. No real structural system enjoys such ideal behavior, and each structure has a different hysteretic behavior. Thus, the rational path for inelastic design is the one using information derived from the actual hysteretic behavior of the structure.

To predict analytically the hysteretic behavior of a building, it is necessary to study experimentally the behavior of the building and its components subjected to earthquake-like actions so that appropriate mathematical models may be devised. Despite increased knowledge on the hysteretic behavior of structural elements and planar subassemblages, there are still not sufficient data to predict the three-dimensional inelastic behavior of most buildings. Although the response of actual buildings to severe ground shaking would be the most reliable source of information on hysteretic behavior, such information is unlikely to be obtained in the near future. Even if tests could be coordinated with underground nuclear testing programs, only a few buildings could be tested to complete destruction. Thus, other ways of obtaining the needed information should be investigated. One possibility is to test small-scale models of buildings on medium-size shaking tables or on "dynamic loading facilities" [1]. However, the dynamic testing of models in their nonlinear range in compliance with the requirements imposed by the laws of dimensional similarity is difficult and costly. For comprehensive studies of the hysteretic behavior of all types of structures, it is more convenient to replace the dynamic excitations by equivalent pseudo-static excitations [2]. The use of earthquake simulators can be reserved for verifying the adequacy of the mathematical modeling of the whole building.

Studies of Behavior of Actual Buildings under Equivalent Pseudo-static Forces. - The advantages and disadvantages of this method of testing have been discussed in Refs. 1 and 2. Unfortunately, there are too few opportunities to do field tests of actual buildings up to failure, and because of the difficulty of instrumenting and loading the buildings, only simple or isolated frames of their structures are usually tested. Therefore, efforts should be devoted to developing pseudo-static facilities that will permit testing of full- or large-scale models of buildings and/or subassemblages of their main structural elements.

LABORATORY TESTS UNDER EQUIVALENT PSEUDO-STATIC FORCES AND ADDITIONAL AMBIENT AND FORCED VIBRATION TESTS

Full-size Buildings or Large-scale Models. - Since 1967, Japanese researchers have been carrying out pseudo-static tests on full-size apartment buildings up to five stories high [2]. In most of the tests repeated reversed lateral forces of a preselected fixed pattern were used. The magnitude of the forces was increased in steps. The advantage of using this method is that after each step, the building can be subjected to free and/or forced vibration by means of shakers, thereby making it possible, at each time step, to obtain the variation of period and damping with the amount of damage induced in the building. The results of these tests have clarified the probable seismic behavior of highly complex structures fabricated from cast-in-place reinforced concrete, precast reinforced concrete, and precast concrete with prestressed construction systems. It is doubtful that the observed interaction between the different components of these structures could have been predicted analytically or by means of separate tests of their individual structural components. Problems similar to these are being confronted by researchers throughout the world. In the U. S., for example, large panel precast concrete buildings are now considered economically and architecturally viable systems of construction. Although these types of buildings are potentially able to resist severe ground motions with controllable damage, realization of this potential will require extensive research. MIT researchers who are involved in the development of advanced dynamic modeling techniques capable of estimating the full range of potential seismic response of these panelized structures have concluded, after preliminary studies [6], that the successful evolution of these techniques depends on the availability of reliable test data. It is believed that only tests on full-size or large-scale models of buildings and on their components can produce the required data. The need for large-scale, rather than small-scale, models is due to the fact that the inelastic behavior of structures--particularly when reversal of deformations occurs--is very sensitive to the detailing, which is very difficult to simulate at reduced scales. Thus, a large pseudo-static facility that will permit the application of multi-directional deformations or loadings should be developed. This can be accomplished with the arrangement illustrated schematically in Fig. 2. This type of facility would permit the application of horizontal biaxial deformations, as well as of vertical loading by simply attaching auxiliary steel frame elements to the permanent walls and the tie-down slab. The variation of the dynamic characteristics at the different levels of damage induced during the pseudo-static test of a model can be determined by conducting ambient and force vibration tests. To obtain the variation of dynamic characteristics with a large amplitude of vibrations, it is necessary to develop shakers more powerful than those presently available.

Static and Dynamic Tests on Subassemblages. - Comprehensive studies of the hysteretic behavior of large buildings by means of destructive pseudo-static testing will still be very costly. Thus, such studies should be conducted on the basic subassemblages of such buildings. The type of subassemblage to be studied depends on the structural system used. Significant and steady advances in the knowledge of the hysteretic behavior of moment-resisting frames, infilled frames, braced frames, and wall-frame systems have been witnessed in the past five years by testing of planar subassemblages of these systems. Versatile loading facilities have been developed [1] which permit highly sophisticated and precise pseudo-static, and even dynamic, loading tests to be conducted on such planar subassemblages.

Now that the technology has been developed and applied to loading facilities for testing of planar subassemblages, the time is right for extending its application to the development of the large, three-dimensional pseudo-static testing facility discussed above. This facility will permit single and multiple story space subassemblages to be tested by subjecting them to forces in the vertical and two horizontal directions. The hysteretic behavior of columns under biaxial bending and associated shear and that of joints under three-dimensional actions; the effect of the interaction between perpendicular wall elements and floor systems in the lateral stiffness and strength of the whole building; and the interaction between structural and nonstructural elements to determine what controls the amount of acceptable ductility, are just some of the problems that need to be investigated and which require such a large, three-dimensional loading facility.

CONCLUDING REMARKS

For rapid improvements in the field of aseismic design, there is an urgent need for conducting integrated experimental and analytical studies to establish more reliable design earthquakes and to predict the hysteretic behavior of buildings up to collapse. This last need will necessitate the development and construction of a laboratory for large-scale experimentation.

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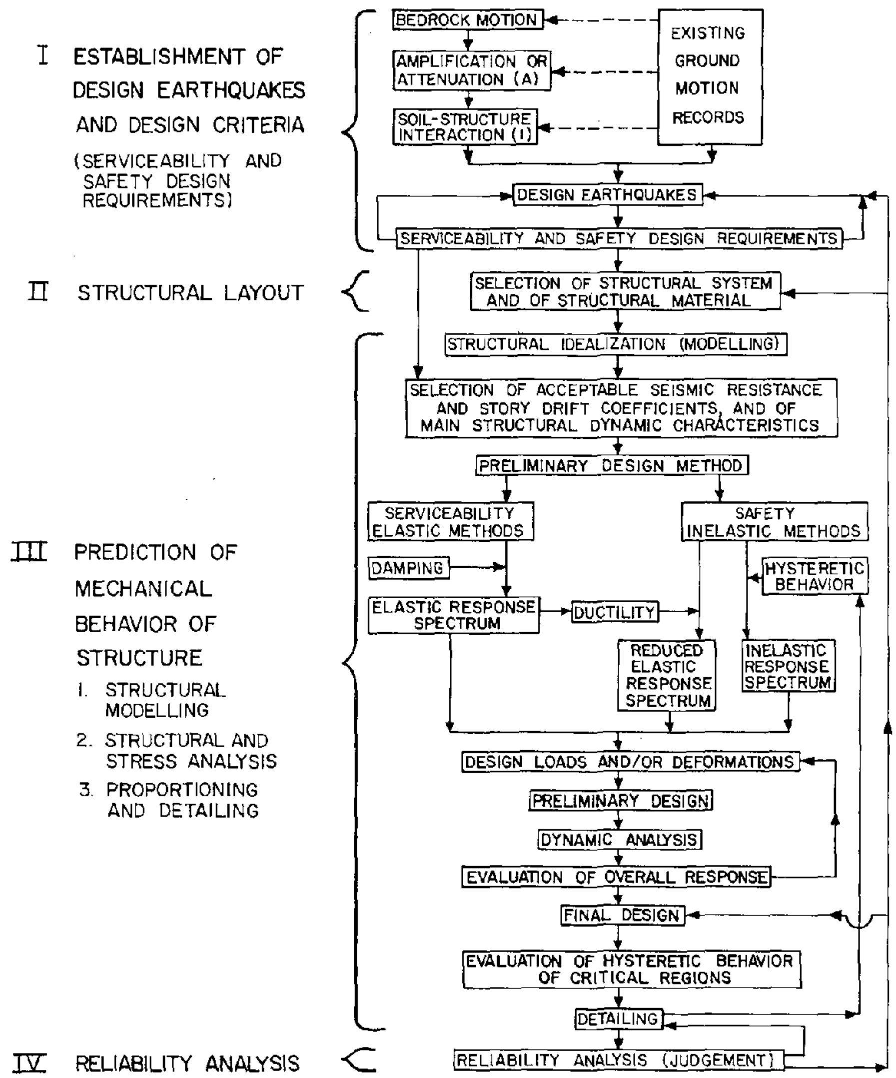
FIG. 1 FLOW DIAGRAM OF GENERAL ASPECTS AND STEPS INVOLVED IN ASEISMIC DESIGN



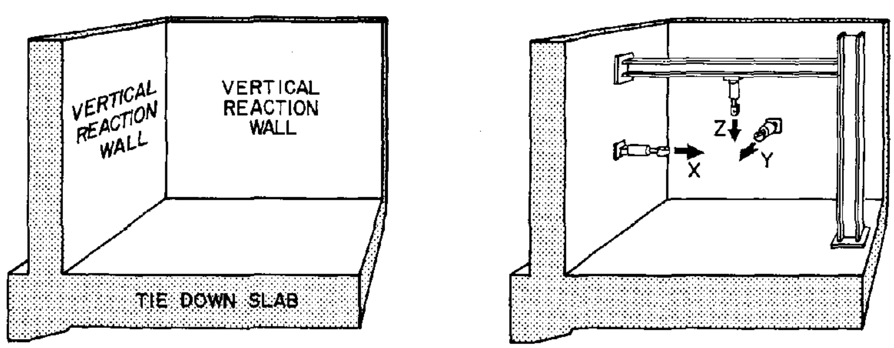


FIG. 2 PSEUDO-STATIC FACILITY FOR TESTING LARGE-SCALE SPECIMENS UNDER THREE-DIRECTIONAL DEFORMATIONS

Panel No. 2

CURRENT CAPABILITIES AND FUTURE NEEDS IN EXPERIMENTAL EARTHQUAKE ENGINEERING RESEARCH

Robert D. Hanson
The University of Michigan

Great advances have been made in the last ten years in developing an understanding of the earthquake phenomena and of the behavior of man-made structures during earthquakes. Most of these advances have been made through coupling of theoretical, mathematical, and experimental efforts. However, I am concerned at the present time that the theoretical and mathematical efforts are surging so far ahead of experimental verification, that potential difficulties may be overlooked. I do not suggest that we should slow these developments, rather that a great deal more effort must be directed toward appropriate experimental studies.

It is understandable that the distribution of effort and results favors the theoretical and mathematical procedures. The uncertainties in cost, time and results are much larger for experimental work. Control of important parameters and variations of these parameters are much more difficult experimentally. This tale of woe is meant not only to make the theorists feel that they did select the correct field of work, but also so that they will recognize the difficulties inherent in verifying their basic assumptions. The assumptions were made for mathematical simplicity to represent, as well as was known, actual behavior. But, how many large scale experiments were studied to arrive at those assumptions? How important are these assumptions to the computed results?

With my prejudices exposed, let me direct my comments to two of the questions suggested for discussion by this panel.

1. <u>What are the greatest needs in this field?</u>

The greatest need is large size realistic three dimensional experimental results. Most members of a structure can be adequately represented as a two dimensional body. However, the junction of these members usually occurs in a three dimensional configuration. Multiaxial loading must be studied in more detail. Total structures must be tested. Does the sum of the members equal the whole as in our assumed simplistic way - for inelastic response?

Consider "realistic" by itself. Most of our past experimental efforts have been directed to achieving an unspecified level of seismic resistance. I believe it is time to evaluate what the researchers have suggested as the best design and compare them with current practice. How much better are the new designs and what is the difference in cost of constructing them? It has been expressed by several people, most notably by Glen Berg, that all buildings are <u>not</u> built in California. What design details should we recommend for lower levels of seismic risk? What experimental data do we have available to substantiate that conclusion?

Techniques and procedures for repairing and strengthening existing structures needs much more work.

2. <u>What are the specific experimental investigations which could have the greatest impact on actual structural design?</u>

I will limit my discussion of this question to structural steel buildings. I believe that the greatest impact will come from studies of braced frame systems, bracing members, and brace connection details. The braced frame is not the answer for all systems, however, this type of framing has been ignored by many people because some unfortunate details have resulted in early failure of the bracing members. The excellent results obtained with elevated water tanks shows what can be accomplished.

June 22, 1976

Panel No. 2

Current Capabilities and Future Needs in Experimental Earthquake Engineering Research

P. C. Jennings
California Institute of Technology

Introduction

In my discussion I have chosen to respond briefly to a few of the questions posed in the charge to the Panel. The status of the experimental research and the major accomplishments in the field are not addressed; it is assumed that these are generally known to this audience.

What are the greatest needs in this field?

The experimental research in earthquake engineering can be divided roughly into two categories: measurement of the characteristics of strong ground motion; and measurement and experimentation directed toward understanding the earthquake response of structures and their capacity to resist strong shaking without hazardous failure. In the first category the greatest need, in my opinion, is for measurements which delineate the characteristics of the strong ground shaking in great (Magnitude 8+) earthquakes. The next greatest need in this area is for measurements which clarify the effects of source mechanisms, travel paths, and local soil conditions upon the features of strong ground motion. In the second category, the greatest need is for experimental research which establishes the capacity of structures of different types to withstand intense ground motion without collapse. This second need is obviously a broad one, requiring instrumentation of full-scale structures, shaking table studies, repeated load tests of structural members and joints, etc.

What are the future needs in strong-motion instrumentation, data collection and analysis?

In this field I think the strongest need is to assure the stability and growth of existing instrumentation programs. If this is done, we should be able to take advantage of recent advances in instrumentation, to encourage the development of special purpose instruments and networks, and to install more instruments on structures other than buildings. Examples include buried pipelines and tunnels, electrical and mechanical equipment, fluid storage tanks, bridges, etc. In the case of buildings, a strong-motion strain meter would be a useful complement to standard instrumentation in a few instances.

What are some of the low cost, high yield investigations which could be performed?

One such example is the installation of strong-motion strain meters noted above. Another possibility would be ambient vibration tests on a large enough number of buildings to allow statistical studies to be made of the observed dynamic properties. It is time, however, that we should also be thinking of high yield investigations that are not necessarily of low cost. Unless some relatively costly experimentation is done, it is my assessment that the pace of advancement of earthquake engineering experimentation will be controlled to a large extent by the occurrence of strong-motion earthquakes in heavily instrumented areas of the world.

What are the specific experimental investigations which could have the greatest impact on actual structural design?

The experimental investigation that I believe would have the most impact on structural design is the measurement of the earthquake response of a modern structure shaken so hard that it either collapsed or failure was imminent. Of almost equal value would be the measured response of modern structures that survived what measurements could show to be intense motion approaching the strongest credible.

It would also be of direct benefit to earthquake resistant design if we could build test buildings of several types and conduct detailed forced vibration tests on the bare structural frames (including measurements of strain and deformation as well as dynamic properties). These tests could be conducted at large amplitudes not achieved in previous tests because of the possibility of incurring damage or excessively disturbing the occupants. The buildings could next be completed non-structurally and architecturally and then the tests repeated to determine the effects of these elements. Properly executed experiments of this type would provide a much-needed benchmark for evaluating the accuracy of analytical modeling of structures for dynamic loads.

Is there a need for a National Laboratory for large scale experimentation?

The type of experimentation mentioned above would require a National Laboratory, in my opinion, as would a very large shaking table (in the 60 to 100 foot class). A National Laboratory would be relatively expensive to operate, obviously, and its establishment would require a substantial increase in the total funding directed toward earthquake engineering research. Although I favor the establishment of a National Laboratory, it should be brought into existence in such a way that it does not dominate the funding of research in the field by its very size. Secondly, it seems to me that a National Laboratory should be an operating agency and should not be involved in funding research.

R. B. Matthiesen

U.S. Geological Survey

The following discussion emphasizes the current capabilities and future needs in strong-motion instrumentation used as a research tool to solve significant problems in earthquake engineering. Some problems can be solved only from strong-motion data, and the solutions to other problems require verification that can be demonstrated only with strong-motion data. Significant strong-motion records from any one site are obtained infrequently and at considerable expense. Hence, careful planning is required to optimize the return of data for the investment required.

The impetus behind most earthquake engineering research is the application of the research results to the reduction of earthquake hazards through engineering design. Of primary importance in this research is an understanding of the spectral characteristics of potentially damaging ground motions in all seismically active regions. Regional differences and local variations of ground motion are important, but the level of motion is significant only if it is potentially damaging to reasonably well designed structures or systems. Lower levels of motion are important only if interpretations based on them may be extrapolated to the higher, potentially damaging levels of ground motion.

For many years, the stated engineering design philosophy has been that structures should survive frequently occurring levels of motion without damage and should survive the most extreme levels of motion without collapse. Design procedures, however, tend to emphasize the lateral forces associated with the frequently occurring levels of ground motion, not those that may cause damage. Furthermore, the performance of real structures during motions that cause significant damage is inadequately understood. A considerable amount of information on structural response at damaging levels can be obtained from laboratory and shake table tests, but confirmation of such results will be required from structures that are damaged in major earthquakes.

The types of studies that utilize strong-motion data may be classified as follows:

- Studies of the source mechanism.

- Studies of the spectral characteristics of strong ground motions and of the variations of these characteristics with the nature of the source, travel path, and local site conditions.

- Studies of soil failures through liquefaction or landslides.

- Studies of the response of representative types of structures and systems at potentially damaging levels of response and of the influence of the foundation conditions on this response.

- Studies of the response of equipment that is free-standing or mounted on structures.

Basic to all of these studies is the need to plan the instrument arrays so as to solve the important problems that can best be solved with strong-motion data from actual earthquakes. This requires an optimization of the location of networks and arrays and of the numbers and locations of instruments within arrays with the objective of obtaining data to evaluate analytical solutions for each specific problem.

Source mechanism studies represent a relatively recent use of the strong-motion data, and significant results have been achieved in determining source spectra and displacement characteristics from near-field records. A basic problem in source mechanism studies is that the instruments must be located "close" to the source of future events whose location and time of occurrence cannot be accurately predicted at the present time. Numerous instruments may have to be located in all significantly active areas in order to insure that the near-field records required to conduct source mechanism studies will be obtained.

Most of the significant strong-motion records obtained to date have been obtained in California, and the techniques for estimating the spectral characteristics and attenuation of strong ground motion are based largely on these records. Preliminary evaluations of the seismicity of other regions suggest that several other areas may provide as much data in the same time frame as some of the less active areas of California. Regional networks should be designed to obtain data on the differences in the spectral attenuation of ground motion in these regions. Numerous instruments may be required in each region if the spacing and location of the instruments in these networks are optimized relative to the nature of the source and in view of the anticipated amount of scatter in the attenuation data.

Local site effects include the influence of: 1) the amplification and filtering of motion by near-surface layers, 2) variations in the motion with depth even in the absence of noticeable layering, and 3) variations of ground motion over short distances. In none of these cases have adequate instrumentation arrays been designed and installed so as to obtain the data needed to verify the models that have been developed. General information about the influence of local site conditions on the spectral amplitudes of ground motion may be obtained from regional networks by placing instruments in different geologic settings or at sites with different soil conditions. More detailed studies will require an extensive instrumentation program including down-hole instruments. A few down-hole installations have provided data from low-level events, and a few more are being installed at the present, but meaningful data at potentially damaging levels of motion are nonexistant. Several three-dimensional instrumentation arrays should be installed in regions where the seismic activity is sufficiently high to insure an adequate return on the investment in instrumentation, its installation, and its maintenance. The location and spacing of instruments in these arrays need to be optimized with respect to the seismicity of the different regions, and the nature of the near-surface layering.

Instrumentation to study soil failures through liquefaction or landsliding is virtually nonexistant. These instruments can be incorporated into regional arrays if potential areas of soil failure are identified. Data from transducers placed in the area of potential soil failure as well as on nearby stable ground can be recorded remotely to obtain some meaningful data even though a soil failure occurs. Optimization of the spacing and location of transducers in areas of potential soil failure must await additional analytical studies of the problem. Extensive instrumentation for these studies should be installed only in highly active regions, however.

Although the San Fernando earthquake produced 60 sets of records of building response, most of these data are marginally significant. Only two buildings that incurred structural damage were instrumented, and only one of these was damaged significantly. On the other hand, data from at least twenty other buildings are of some importance in understanding the nonlinear behavior of typical buildings prior to the initiation of damage. No significant records have been obtained from any structures other than buildings. There are no cases in which instrumentation has been specifically designed to study soil-structure interaction, although two cases are known in which records have been obtained from buildings in which soil-structure interaction may have been an important factor. Optimization of the location of the instruments in each type of structure must be based on the dynamic characteristics of the particular structure. Allowing for the fact that many different types of structures are being instrumented for both operating and regulatory agencies, a total research program of instrumentation of representative types of structures should be optimized with respect to the seismicity of different regions and the relative importance of different types of structures.

Recurrence relations have been obtained from the strong-motion records obtained at installations that have been in place for about 40 years. In three cases (Ferndale, Hollister, and El Centro) the data are sufficient to provide statistically meaningful recurrence times for peak accelerations up to 100 cm/sec/sec, whereas in most cases the data are sufficient only to estimate the recurrence time at 10 cm/sec/sec. Of equal importance, however, is the fact that at several sites in "seismically active" areas, no estimate of recurrence could be made.

For example, no estimate could be made for Golden Gate Park, San Jose, Westwood, or Pasadena, although maximum accelerations of 100 cm/sec/sec have been recorded at each of these sites. Furthermore, although 12 records have been obtained at Helena, only three have been recorded since 1940 and none since 1960. These results are an indication of the serious difficulties that arise in any attempt to provide a rational plan to obtain the desired strong-motion data in a reasonable length of time.

From the recurrence data and the average cost of instrumentation and its maintenance ($400 per year), the costs to obtain records with peak accelerations greater than specified levels have been estimated. For peak accelerations that are potentially damaging, the results imply that, except in the three most active areas mentioned above, costs of the order of $10-20,000 per record must be anticipated in most areas of California. In areas less active than California, even higher costs must be anticipated.

The benefits that will be derived from the data also must be estimated to assess the proper significance of the costs. Obviously, the first set of data that will provide insight to some of the unanswered questions regarding the nature of the strong ground motions from earthquakes in the eastern parts of the United States will be of considerable value, whereas additional records at 50 cm/sec/sec obtained at any of the sites in California are of little added value. To maximize the benefit to be derived, it is clear that those studies that can be accomplished in the more active areas should be planned for those locations. Studies of local site conditions should be planned for Cape Mendocino (Ferndale), the San Benito Valley (Hollister), and the Imperial Valley (El Centro). Studies of low-rise buildings and freeway bridges also can be planned for these regions, whereas studies of high-rise buildings or dams can be conducted only in somewhat less active areas of California. A careful study of the seismicity of other regions must be made to determine the extent of instrumentation that is optimum in structures in those regions.

DIXON REA

University of California, Los Angeles

Currently, equipment and facilities of varying sophistication are available for experimental research in earthquake engineering:

(1) Strong motion recorders are used to record ground motion and the response of structures during earthquakes.
(2) Ambient and vibration generator equipment is used to determine the dynamic properties of full scale structures vibrating at small amplitudes of motion.
(3) Cyclic loading facilities are used to determine the properties of structural elements and assemblages of elements as they are deformed into the nonlinear and inelastic range of behavior.
(4) Shaking tables are used to determine the response of small structures to realistic earthquake type motions.

Each type of equipment suffers from some limitations. Strong motion recorders must wait for the occurrence of an earthquake that will produce significant response, and then the data is limited to acceleration-time histories. Ambient and vibration generator equipment provide information for small amplitudes of motion only. There are difficulties in providing proper boundary conditions for elements and assemblages and in prescribing appropriate deformation histories in cyclic loading tests. Shaking tables produce only limited deformation in relatively small structures. Since no single type of equipment can supply all the information required to improve earthquake resistant design, it will be necessary to continue to obtain as much information as possible from each type of equipment.

Much of the equipment has been built within the past ten years. With the exception of strong motion recorders, there are only a few pieces of each type. The quantity of experimental data is relatively small and the work done so far has been a good beginning. It has provided data for use in design and revealed some inadequacies in analytical models used in design.

Existing types of equipment can be improved for use in the future. Strong motion instrumentation may be expanded to include measurement of deformations and strains. The performance of forced vibration generators, cyclic loading equipment and shaking tables may be improved. In addition, significant benefits may result from the use of digital data acquisition systems. Data obtained directly in digital form may be processed easily with the result that a maximum amount of information can be extracted from a particular experiment.

The need for coordination between experimental and analytical research is well recognized. Greater coordination between various types of experimental work would be beneficial. For example, a relatively small number of structures in suitable locations should be selected for extensive instrumentation in anticipation of earthquakes. These structures should be subjected to complete ambient and forced vibration tests in order that their properties at small amplitudes of motion are fully documented for use when earthquake response records are obtained. Complementary research programs should be undertaken at shaking table facilities of differing sizes and performances. Similarly, complementary programs should be undertaken by different cyclic loading facilities. Finally, coordination is required between some programs at shaking table and cyclic loading facilities.

As well as the need for more equipment of existing types, equipment of greater capacity and higher performance will be required. A workshop on Simulation of Earthquake Effects on Structures (1) has outlined the need for larger shaking tables and larger, more universal, cyclic loading facilities. In addition to increased size and performance these facilities will have to be able to simulate at least the three translational components, if not all six components, of earthquake ground motions.

The cost of this larger equipment will be significantly greater than the cost of current generation equipment. There would be economic advantages in placing such a larger shaking table and a cyclic loading facility of comparable size together in one laboratory. The facilities could share the same manpower, workshops and computers. In addition, coordination between the shaking table and cyclic loading experiments would be more easily accomplished.

The work of such a laboratory would have to be coordinated with some of the work being conducted at smaller facilities in the universities. It might even provide a forum for the coordination of such programs. However, the laboratory should not be constructed at the expense of experimental research in the universities. Thus if such a laboratory were constructed to house a 30 ft x 30 ft shaking table with three translational components of motion and a cyclic loading facility of comparable size, it would require an increase in funding for experimental earthquake engineering of approximately \$5-10 million for construction costs and approximately \$1 million per year for operating costs.

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(1) Proceedings of a Workshop on Simulation of Earthquake Effects on Structures, San Francisco, September, 1973. Published by National Academy of Engineering, 1974.

NOTES FOR UCEER PANEL #2 ON EXPERIMENTAL RESEARCH (Vancouver, B.C., June 1976)

by

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The diagram in Fig. 1, reproduced from reference 1, provides a convenient if Procrustean format for a few comments related to experimental research on earthquake resistance of reinforced concrete.

Object of the hierarchy in Fig. 1 is to understand (or to reproduce analytically starting from "first" principles) the response of a reinforced concrete structure to an earthquake motion of any intensity or complexity, assuming tentatively that such a goal can be or needs to be attained.

Types of experiments at Level 1 establish the unit force-displacement ("constitutive") relations which acquire a new dimension with respect to earthquake effects because information obtained at a constant rate and direction of strain seldom suffices.

Level 2 refers to tests of externally determinate elements under actions which change in proportion to each other or remain constant as the other(s) change(s). A simple example is a cantilever subjected to biaxial shears with a constant axial load. Level 3 differs from 2 in that the external actions change at different independent rates.

Levels 4 and 5 refer to structures including a number of discrete elements as well as those including putatively nonstructural components, at any scale and tested statically (4) or dynamically (5) to any limits of response. Studies of actual buildings, preferably instrumented before the fact, may be included in this category.

Ideally, phenomena observed at each level are to be organized in intelligible statements of as wide an application as possible to create conceptual models which will make prediction by synthesis of more complex phenomena (at higher levels) possible.

The success, in obtaining conceptual models which stood the test of time, of early experimenters in concrete such as Abrams and Talbot rested on their systematic variation of the critical parameters in extensive series of tests with multiple replications as well as on their choice of preliminary hypotheses by which the tests were planned. With that as a basis for operation, it is instructive to speculate about what is entailed for a nearly complete package at, say, Level 2.

Consider the domain of Level 2 as a three-dimensional space (Fig. 2) with the main somewhat arbitrary groupings of the parameters being variations in (1) cross-sectional properties, (2) properties along the longitudinal axis, and (3) loading. Figuratively, the enclosed space needs to be filled with confirmed data. But the main dimensions selected for Fig. 2 have dimensions within themselves. The resulting space is one of multiple dimensions. To fill it would exhaust any conceivable research budget even without replication. It would appear that for earthquake-resistant design, the comforts of systematic investigation of <u>all</u> the variables are not to be had. The planning of experimental investigations at each level have to rely more heavily on preconceptions. The same is true for "moving" the information from Level 1 to 5 and from the laboratory to practice.

Accepting the premise that only the apparently essential need be investigated, a superficial and unscholarly (because of lack of references cited) review of some of the needs at the five levels of Fig. 1 follows.

Level 1: It would be inconceivable to base practice across the country on a few tensile tests of reinforcing bars. Currently, knowledge on the behavior of reinforcing bars cycled well into the inelastic range in both compression and tension is limited to data from a handful of tests of medium size bars. The same weakness exists for stress-strain properties of confined concrete under repetitions of large strains. There is an acute need for further direct investigations of bond under cyclic loading.

Level 2: The encounter of problems with shear not anticipated by static or unidirectional tests has tended to relegate to the background the fact that systematic testing is still required to define a versatile set of rules for hysteresis of elements not failing in shear or bond. The state-of-the art would suggest that the question of the strength and stiffness of frame and wall connections will require many years of experimental work.

Level 3: This is virtually a no man's land. Consider a condition as idealized as that of a column in a planar frame. Where does one obtain the information for checking a hypothetical hysteresis relationship if the axial load varies from a small tension to a compression as the shear changes? If the point of contraflexure moves back and forth in a girder during the vibration of the frame, are calculations of the end rotations based on concepts derived from standard tests applicable? One can formulate an impressively long list of such questions with very little experimental data to answer them.

Level 4: It has often been said that experimentation is more important for earthquake-resistant design as opposed to "gravity design" because much real estate accumulates before a particular and possibly vital error is discovered. Component testing does not necessarily reveal such errors in structural concept. Behavior of connections and interaction of the structure with architectural elements provide past examples. "Static" testing of structures, even with simplified loading patterns, is likely to provide a substantial portion of our knowledge on the behavior and design of reinforced concrete. It is hoped that occasions will arise in the immediate future and in the U.S. or Canada of loading actual buildings to complete failure, after a few selected displacement reversals, under the action of a set of loads simulating critical conditions for the estimated dynamic response of the buildings.

Level 5: The reliability of earthquake simulation tests using structural models has been demonstrated through experiments with "uniform" models preparing the background for investigation of abrupt changes in mass and/or stiffness distribution and with torsional moments which are yet to be attempted.

Unless one has an axe to grind, it is difficult to single out a particular type of test or group of experiments at particular level (Fig. 1) as the main domain of future activity. If the commitment is truly to understand the behavior of reinforced concrete, with the hope that this investment will yield substantial returns in cost and safety of construction, experimental activity ought to be expanded at all levels. A rather elaborate test at, say, Level 4 may introduce new information, but without the basic behavioral knowledge to analyze this information it is likely to be of very limited use.

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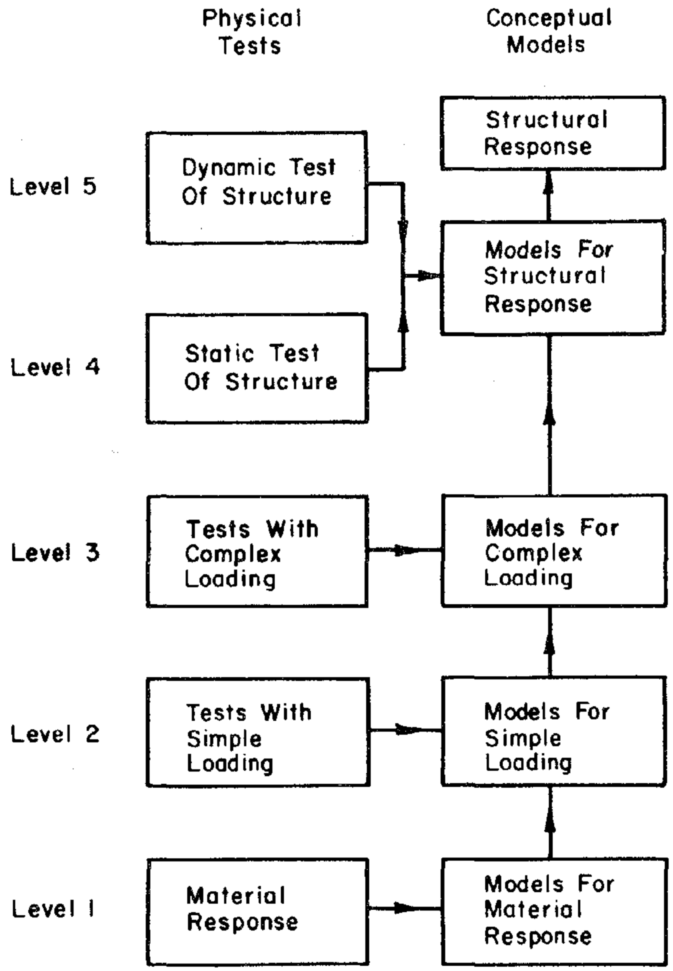
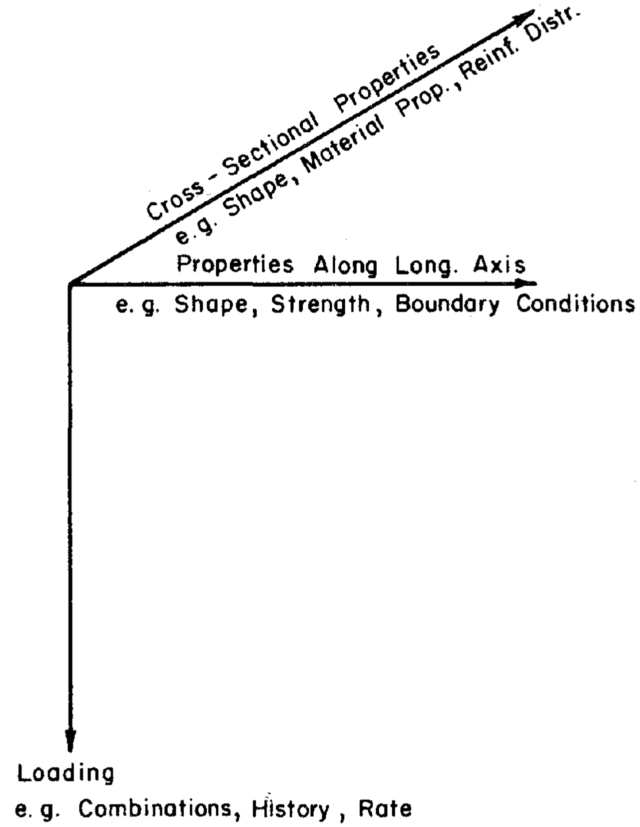


Physical Tests
Conceptual Models
Level 5
Level 4
Level 3
Level 2
Level 1
Dynamic Test Of Structure
Static Test Of Structure
Tests With Complex Loading
Tests With Simple Loading
Material Response
Structural Response
Models For Structural Response
Models For Complex Loading
Models For Simple Loading
Models For Material Response

FIG. 1



Cross - Sectional Properties
e.g. Shape, Material Prop., Reinf. Distr.
Properties Along Long. Axis
e.g. Shape, Strength, Boundary Conditions
Loading
e.g. Combinations, History, Rate

FIG. 2

RESEARCH SUMMARIES

G. W. HOUSNER

California Institute of Technology

National Science Foundation-sponsored Earthquake Engineering Research is being conducted in three areas: the dynamics of suspension bridges, capability of strong ground motions to cause damage to structures, and ground motion characteristics correlated with epicenter distance and local geology.

Dynamics of Suspension Bridges

A theoretical analysis has been made of the linear vibrations of vertical, horizontal, and torsional modes of vibration, and an equivalent finite element formulation has been made taking into account the elasticity of the cables and the deformations of the towers. An energy analysis has been made to clarify the distribution of strain energy in the various parts of the bridge. Measurements have been made of the traffic excited vibrations of the Vincent Thomas suspension bridge at Los Angeles Harbor and good agreement was found between the measured and the calculated modal periods of vibration. It is planned to make additional measurements on the bridge and to study the response of the bridge to earthquake-type ground motions.

Capacity of Strong Ground Motions to Cause Damage to Structures

Studies are being made of the capability of ground motions to feed vibrational energy into structures and how this energy input leads to damage. Correlations are being made between energy input and beyond yield point response and with observed damage where ground motions have been recorded. The approach employed is to examine energy input averaged over all frequencies and correlate this with average response behavior. It has been found that the time intergral of velocity squared is a measure of energy input averaged over periods of vibration, analogous to the way that the time integral of acceleration squared is a measure of energy input averaged over frequencies of vibration.

Ground Motion Characteristics Correlated with Epicentral Distance and Local Geology

Detailed studies are being made of the correlation of significant characteristics of ground motions and their correlation with epicentral distance and local geology. The set of ground motions recorded during the 9 February 1971 San Fernando, California earthquake is being studied.

The objective of the study is to determine which characteristics correlate with a minimum dispersion as well as to identify those characteristics whose usefulness is impaired by large dispersion.

D. E. HUDSON

California Institute of Technology

Recent work in processing strong motion accelerograph data will be summarized under the headings: (1) Completion of standard digitized data project; (2) Studies of instrumentation system characteristics and of correction procedures; and (3) Calculation and correlations of ground motion parameters.

Standard Digitized Data

The final reports in the series of standard digitized data volumes were published in the summer of 1975 and were distributed by the end of the year. This completes a 10 year National Science Foundation program aimed at supplying investigators with computer-compatible uniformly processed basic data on earthquake ground motions and structural response measurements. In looking back over this lengthy undertaking, I should like to express my great appreciation to Drs. M. D. Trifunac and A. G. Brady for the very special efforts they have devoted to all aspects of the project. The final stage of this program now under way is the preparation of a summary volume containing cross-indices, maps, location information, additional interpretive material, and a complete collection of errata for all of the volumes. Users of this data who have encountered errors in any of the volumes, or other matters requiring additional explanation or clarification, are urged to transmit this information to me in the near future so that this final volume can be as complete as possible.

A brief summary of the contents of this data bank may be of interest. Of the 381 three-component accelerograms, 187 are from ground sites, mainly basements of buildings, and the remaining are from upper floor and roof locations in buildings. The records come from 57 different earthquakes, ranging in size from M = 3 to the maximum of M = 7.7 of the Kern County earthquake. The 187 ground stations are located at a variety of site conditions, for most of which no detailed studies of local soil and geology are available. Most of the sites can only be roughly characterized as relatively soft alluvium, 60% of the records, hard (rock) 10%, and intermediate, 30%. The station recording the largest number of earthquakes is El Centro, which since 1934 has produced accelerograms from 16 events. The earthquake producing the most records is the San Fernando 1971, with 241 records, 98 of them from ground sites. This San Fernando earthquake is also the last and most recent event to appear in the standard data volumes. From 1971 on, the digitizing, processing, and dissemination of the basic accelerograph data is to be carried out under the supervision of the Seismic Engineering Branch of the U.S. Geological Survey.

Instrument Characteristics and Data Processing

Some general studies of instrument characteristics and of data processing have been continuing. For example, corrections for transducer cross-axis sensitivity and misalignment had not been included in the standard data processing procedures as it was thought that they would be of a relatively minor nature for most records. A detailed investigation of these effects has just been completed by Drs. H. L. Wong and Trifunac, and it has been shown that these corrections would in fact be negligible for most records and for most applications. Suitable instrument tests and computational techniques have been developed so that these effects can be allowed for if desired for special applications. The only difficulty of applying these corrections to past measurements is the absence of reliable information as to the condition of the transducers. Since it is not always clear when readjustments were made in the field, current measurements may not always be indicative of conditions at the time earthquake records were made. If accurate tests of each accelerograph are made in the future and suitable records are kept, such cross-axis sensitivity and misalignment corrections can easily be incorporated into standard processing programs to any desired accuracy.

In establishing filter characteristics for the standard data processing it was realized from the beginning that to use one or a few filter intervals for all of the records would represent a practical compromise which would be far from optimum for some records. In particular the low frequency cut-off limits of 16 seconds period for the paper records, and 8 seconds for the 70-mm and 35-mm film records involved some difficult decisions based on noise characteristics of the whole data processing system. In view of the special importance of the ground site records for fundamental studies in strong motion seismology, Dr. Trifunac is at present reprocessing the ground records using an individually designed optimum filter for each component. While the standard processing is believed to be satisfactory for most applications, there are some special research problems for which the optimally-filtered records will be important.

The improved knowledge of typical strong motion earthquake characteristics which has been derived from studies based on the standard data bank has in turn been useful in arriving at a more accurate assessment of the role of system noise in limiting the data-collection potentialities of current strong-motion instrumentation. In this sense instrument design is an iterative process, and the more that is known about the quantities to be measured, the closer can the instrumentation system be taylored to the job at hand. By comparing typical spectrum values of earthquake ground motions for events of different magnitudes and at different distances with system noise spectra, it has been possible to define more accurately the conditions under which the measured signals from earthquake ground motions can be expected to be significantly above the noise levels. In this way it has been found that some of the standard accelerograms having very low acceleration values must be used with caution over portions of the frequency range.

Ground Motion Parameters

The availability of the standardized data in computer-compatible form makes it easy to carry out various computational and statistical studies of ground motion parameters, and a number of papers reporting studies of this type based on the standard data have already appeared in the literature. As an example of my own efforts in this direction, I will mention an investigation of near-field accelerograms now under way. A near-field measurement is defined as one made at distances from points of significant seismic energy release of the order of the linear dimensions of the seismic source. Such measurements are of special importance for studies of source mechanisms, and hence for investigations of such key practical problems as the establishment of upper limits of expected ground motion. From the standard data set, 12 such near-field records were selected having acceleration amplitudes of engineering significance. These were supplemented by 4 records obtained since 1971 which were processed uniformly with the standard set. These are believed to be all of the records which are available from instruments which are sufficiently similar so that direct comparisons are meaningful.

It should be mentioned that for most of the earthquakes there is so little information about depth and conditions at the source that it is not possible to be sure that the measurement is in fact in the near field, and more detailed future studies may remove some of these events from the list. By reproducing these near-field accelerograms to the same scale on one figure, an interesting visual impression of the great diversity of the sample is received. This figure, taken from a paper submitted to the forthcoming Sixth World Conference on Earthquake Engineering in New Delhi, throws a new light on some familiar earthquakes. The 1940 El Centro event, for example, which has been widely used as a typical relatively severe ground motion does not loom as large compared to some other recorded ground motions as might be expected. A correlation of the records with various ground motion parameters derived from them, such as peak accelerations, velocities, and displacements, response spectrum averages, durations, and maximum energy parameters was then carried out. This suggested that the visual character may be an important indicator of significant aspects of the earthquake which may be difficult to capture in a quantitative way by any single parameter or by any simple combination of parameters. The small size and great diversity of this sample of near-field records also suggests that much of our current knowledge of strong ground motions must be considered to be of a tentative nature.

WILFRED D. IWAN

California Institute of Technology

The following is a description of some of the National Science Foundation sponsored research being conducted at the California Institute of Technology in the general area of nonlinear structural response.

Earthquake Response of Degrading Structures

A simple model has been developed which describes the deterioration of certain structures, such as those of reinforced concrete, when they are subjected to large amplitude dynamic loading. By proper selection of the model parameters, the model may be made to characterize the behavior of systems ranging from simple bilinear hysteresis to systems exhibiting progressive degradation in both stiffness and energy capacity.

The actual earthquake response of a variety of hysteretic systems ranging from nondegrading to strongly degrading has been examined. It has been found that on the average the displacement response spectrum of the hysteretic systems between periods of 0.4 to 4.0 sec closely resembles that of a linear system except for a period shift which depends only on the ductility of the response. By finding the shifted linear response spectrum which best fits the spectrum of the hysteretic system, it is possible to define an effective period and damping for hysteretic systems which depends on ductility. The results of the numerical investigation have been compared with predictions of analytical models and some significant discrepancies have been found. A new analytical technique for determining the effective period and damping has been developed.

Earthquake Response of Equipment with Motion Limiting Constraints

Mechanical and electrical equipment used in building structures is often mounted on a resiliently supported base so as to minimize the transmission of mechanical vibration into the structure. If unconstrained, such equipment isolation systems will normally undergo very large relative displacements during a strong earthquake with likelihood of broken connections, loss of isolation or other forms of failure. In order to minimize the displacement of such systems, motion limiting devices are frequently installed between the isolator base and the structure. The transient response of this type of nonlinear system cannot generally be analyzed except by means of numerical integration techniques which are costly to apply. Furthermore, the earthquake input information supplied to the isolation system designer is often in the form of design base or floor level response spectra, making the application of numerical integration techniques even more difficult.

A method has been developed whereby the response spectrum may be used to calculate the response of equipment isolation systems with motion limiting constraints. This is accomplished by defining a set of "equivalent" linear support stiffness and equating the maximum stored energy of the linearized system to that of the actual system. The results of the approximate method have been compared with the results obtained from direct numerical integration. Observations have been made on the role of various system parameters in determining the response. The design criteria specified by existing and projected codes has been found to be inadequate in many cases.

Nonstationary Random Response of Nonlinear Systems

The equivalent linearization approximate analytical technique has been extended to problems of the nonstationary response of nonlinear systems. The new method can be applied to hysteretic as well as nonhysteretic systems. It provides a valuable tool for investigating the statistics of the transient response of nonlinear structures.

The approach involves minimization with time of the difference between the equation describing the system in question and some linear system. Application of the technique gives an equation for the envelope response statistics as a function of time. This equation is of the Fokker Plank type and is solved by a series expansion technique. The response of several different nonlinear structures to bursts of white noise has been examined. The predictions of the theory have been verified using Monte-Carlo simulation techniques.

Response of Systems with Localized Nonlinearity

Nonlinearities are often localized at one point in a system. This will be the case if one portion of the system is much weaker than the rest or if nonlinear isolation devices have been intentionally incorporated at some point in the system. The composition of such systems makes them amenable to study using an extension of approximate analysis techniques.

The qualitative response behavior of a class of undamped chainlike structures with a nonlinear terminal constraint has been investigated. It has been shown that the hardening or softening behavior of every resonance peak is similar and is determined by the properties of the constraint. Also examined has been the number and location of resonance curves, the boundedness of the forced response, the loci of response extrema, and other characteristics of the response. Particular consideration has been given to the dependence of response characteristics on the parameters of the linear system, the nonlinear constraint and the load distribution.

P. C. JENNINGS

California Institute of Technology

The earthquake engineering research covered in this brief presentation is supported by the National Science Foundation and the Earthquake Research Affiliates of the California Institute of Technology. The research projects treated here are under my supervision and include the dynamic tests of buildings, studies of the dynamics of collapse of reinforced concrete structures, and analysis of earthquake response of buildings. Additional earthquake engineering research at Caltech is reported in companion presentations by other members of the staff.

Dynamic Tests of Buildings

This project is a primarily experimental effort directed toward the measurement of the dynamic properties of modern buildings and an assessment of the ability to predict these properties in detail. The work is being done as part of the doctoral research of Douglas A. Foutch. The experimental research consists of forced-vibration and ambient tests of two multistory buildings in Pasadena: the 9-story Millikan Library Building on the Caltech Campus, a reinforced concrete shear-wall structure; and the 12-story World Headquarters Building of the Ralph M. Parsons Company, a moment-resistant steel frame structure. For the forced-vibration tests, two new vibration generators and associated controls were used. The vibration generators, manufactured by Kinemetrics, Inc. are similar to those used in previous tests, but incorporate a number of improvements. The control mechanisms are solid-state equivalents of the original controls, with added features including a 0° or 180° phase option between master and slave, adjustable phase control, and a built-in frequency counter. The measurement system used in most of the tests, both forced and ambient, was a combination of Ranger Seismometers, signal conditioners, and an 8-channel recorder. In some of the forced vibration tests, the phase of the exciting force was recorded on one of the channels to help in determination of in and out-of-phase components of response. The measurements taken on the buildings included as a first step the determination of natural frequencies, dampings and some information about the mode shapes. These tests were followed by detailed measurements which delineate the three-dimensional characteristics of the more important modes. For example, at Millikan Library 50 measurements of 3 mutually perpendicular components of the motion were made on each of 6 selected floors. A similar number of measurements was taken at the Parsons Building. Measurements with this much detail have not been made before and they allow the determination of bending of floor systems, soil-structure interaction, deformation of columns, etc. to an extent where we expect to be able to comment critically upon the ability of modern methods of structural analysis to predict these effects. A finite-element model of the Parsons Building has been made for this purpose.

Mr. Foutch has completed the experimentation and is now writing up his research; we expect the report to be distributed this fall. Some of the results of the tests of Millikan appeared in the Proceedings of the U.S. National Conference in 1975, and others will appear in the Proceedings of the Sixth World Conference.

Dynamics of Collapse of Low-Rise Reinforced Concrete Structures

Dr. Haruo Takizawa of the University of Hokkaido, Japan has performed an extensive analytical study of the ultimate capacity of low-rise reinforced concrete (R/C) frame buildings subjected to intense earthquake motion. This study was done while he was a post-doctoral fellow at Caltech for a year. The intent of the study is to use recent advances in the ability to model the non-linear hysteretic behavior of R/C structures, combined with equations of motion which include the effect of gravity, to investigate the intensity of motion required to cause collapse. The studies were partly motivated by the collapse of some low-rise R/C buildings in the Tokachi-Oki earthquake of 1968. The degrading trilinear hysteretic relation used in this study and the idealization of the hinging mechanisms of multi-degree-of-freedom structures as "equivalent" single-degree-of-freedom systems are applicable to these types of R/C frames, among others. One of the features of the study was an attempt to determine the margin of safety against collapse when subjected to motions of short duration, but with high peak acceleration. Such motions are generated in the near field of small earthquakes ($M \approx 4$ to 6) and in some cases the peak accelerations have reached 50% to 60% g or more. To a degree, at least, we have been able to demonstrate quantitatively the lower destructive potential of such motions in comparison to the longer, but less intense motions recorded during earthquakes like El Centro, Taft, Tokachi-Oki, etc. The results of the study consist of numerous calculations of the response of two classes of R/C structures (soft frames and stiff frames) to three ensembles of earthquake motions, and the presentation of the results. Some related features of the problem were examined by means of pilot calculations, where extensive computations were not possible. Features of this sort included the deterioration of strength (ductility degradation) in addition to the degradation of stiffness incorporated in the hysteretic model, which proved to be quite significant; the effects of vertical excitation, which proved almost negligible; the effect of biaxial excitation and response, which gave a decrease in the critical excitation strength of the order of 10% to 15%; and example calculations showing the possible effect of a more complex, two degree-of-freedom system which modeled the effect of a localized structural failure.

One of the interesting sidelights of the research was the occasional occurrence of a structure that would collapse when the strength of motion was raised to a certain level (e.g. 2.5 times El Centro, 1940) but which would take without collapse the next increment in intensity of excitation (e.g. 3.0 times the same record).

A summary of the results of the research will be reported in the Proceedings of the Sixth World Conference on Earthquake Engineering, and a detailed EERL report is now in preparation

Analysis of Earthquake Response of Buildings

The measured response of over 50 buildings to the San Fernando earthquake is providing an opportunity to develop techniques of system identification that are particularly suited to earthquake engineering. Research on this topic is being performed by graduate student James Beck. The work is not as advanced as the two studies reported above and results are not yet available. At the present stage, the capabilities of a few selected methods of nonlinear system identification are being investigated with a view toward selecting and/or modifying the most promising approach.

Another study in this general area that is just getting underway concerns the torsional excitation and response of buildings. This work is being done by graduate student Graeme McVerry.

H. L. WONG

California Institute of Technology

The following is a brief summary of the theoretical and experimental work at Caltech in the area of seismic wave propagation. This research may be divided into two major categories: (I) Foundation dynamics and soil-structure interaction and (II) wave propagation through irregular layers and irregular surface topographies.

I. Dynamic Soil-structure Interaction

(a) Analytical Phase:

In the past, systematic investigations on various aspects of soil-structure interaction have been carried out using simple parametric studies (1); it is through these preliminary studies that the most pertinent parameters are properly identified. Two of the most important aspects of soil-structure interaction that we have studied are: the effect of non-vertically incident waves (2,3) and the effect of coupled interaction between many structures (1,4).

For non-vertically incident SH waves or surface Love waves, large torsional as well as translational response can be induced upon the foundation. Particularly at the frequencies of excitation where the wavelength is approximately twice the characteristic length of the foundation, the torsional response is of the same order as the maximum translational response. For the case of incident Rayleigh waves (3), a large rocking component accompanies the vertical and horizontal translations of the foundation; this is caused by the retrograding motion of the Rayleigh wave. From this brief account, it is clear that the response of the foundation cannot always be described by vertically incident S waves, and that the contributions from surface waves must also be considered. Generally, for an arbitrarily shaped rigid foundation, three translations and three rotations are excited by an arbitrary incident wave.

On the subject of coupled interaction for two or more structures, it was found that: in order to be realistic in modeling, three-dimensional analysis must be used; two-dimensional models simply cannot take into account all the coupling effects. For instance, the motion of a rigid foundation in three dimensions can be described by three translations and three rotations, but a model with two space dimensions can allow only two translations and one in-plane rocking component. Thus, the torsional characteristics of the structures cannot be incorporated into the analysis.

At the present time, a numerical method (5) based on an integral equation formulation is being developed for the analysis of three-dimensional soil-structure interaction problems. The computer programs and subroutines are compiled for a general computer code aimed directly at practical engineering applications.

This program will have the capabilities to solve problems which involve one or more arbitrarily shaped surface foundation bonded to an elastic or viscoelastic layered stratum; the range of configurations covered by this method can handle a certain class of design problems.

(b) Experimental Phase:

Full-scale experiments (6) have been performed on a nine-story reinforced concrete building for the purpose of evaluating (i) the flexibility of the foundation, (ii) the approximate stress distribution under the foundation, and (iii) the forces and moments exerted on the soil during the experiment. The distribution of displacements measured at the basement level during a forced-vibration test indicate that the rigid foundation assumption is excellent for one direction but not in another. This can be explained by the relative stiffness of the superstructure in the respective directions. This shows that the rigidity of the foundation is partially determined by the stiffness of the superstructure, unless the foundation slab is quite thick.

Using the distribution of displacements measured, an approximate distribution of stresses under the foundation for this particular level of shaking can be obtained by the method introduced in (5). The maximum dynamic normal and shear stresses (excluding static weight) are of the order of 5 psi and 1.2 psi, respectively; whereas, the weight of the building distributed uniformly over the foundation area gives rise to a nominal static pressure of about 35 psi. From these approximate stress distributions, one can also estimate the forces and moments exerted on the soil by the superstructure; this information can be useful for soil design problems.

II. Effects of Surface and Subsurface Irregularities on Wave Amplitudes

(a) Analytical Phase

The amplification and deamplification of ground motion by irregular layers and surface topographies have been studied by simple two-dimensional analytical models. As a continuation of the effort, numerical methods based on integral representations (7,8) are currently being used as the basis for parametric studies. Concurrent to these theoretical studies, other numerical methods are being developed for boundary value problems of this type.

(b) Experimental Phase

Due to the lack of experimental observations in this subject, full-scaled wave propagation experiments (8,9) have recently been performed over the Pasadena area. The source of excitation was created by vibrating a nine-story reinforced concrete building (the Millikan Library at Caltech) at its resonance frequencies; the distribution of monochromatic ground waves generated by the foundation was measured by Ranger type seismometers. This type of experiment provides well-controlled and ideal conditions for wave propagation testing, and the data obtained can readily be used to aid theoretical studies. As indicated by the preliminary analyses presented in (8) and (9), wave amplitudes in Pasadena are dominated by layer reflections, but the surface topographic effects are minimal.

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J.L. HUMAR

Carleton University, Ottawa, Canada.

Earthquake engineering research supported by a National Research Council grant is being carried out in two areas: seismic response of asymmetrical multistory buildings, and earthquake resistant design of regular and irregular buildings.

Response of Irregular Buildings

Dynamic irregularity in building structures may result from unsymmetrical distribution of mass and stiffness over the plan or the height of the building. Initial studies are being carried out on the response of buildings that are irregular over the height. The dynamic behaviour of multistory steel rigid-frame buildings with set-back towers has been investigated. The effects of set-backs upon building periods and mode shapes have been examined and the linear and nonlinear behaviour of such buildings when subjected to recorded ground motion has been studied [1]. The investigation is being extended to cover concrete frame and frame-shear wall structures. Both linear and non-linear response studies are planned, and it is proposed to model the nonlinear behaviour of concrete sections subjected to cyclic loading by a hysteresis loop with degrading stiffness characteristics.

Buildings with other types of dynamic irregularities will be investigated in a later phase of this study.

Earthquake - Resistant Design of Buildings

It is recognized that for regular buildings an equivalent static load approach to earthquake-resistant design is an acceptable and practical tool. It is, however, desirable that the design forces obtained by using this method be as consistent with the results of a dynamic analysis as is possible with what is an essentially simplified approach. Initial studies carried out towards this goal are related to the investigation of the distribution of shears and overturning moments throughout the height of the building. An idealized uniform moment and shear deflecting cantilever model has been developed to represent a building that is regular in its geometry and in the distribution of mass and stiffness. Based on a study of the response of this model to a simplified spectrum curve, empirical relationships have been obtained for the distribution of shears and overturning moments throughout the height of the building [2].

Seismic response studies of a number of regular buildings with different structural layouts including: steel rigid frames, steel braced frames, concrete frames, and concrete frame-shear walls are planned. The buildings will be subjected to earthquake ground motions compatible with the design spectra prescribed in the National Building Code of Canada. The distributions of shears and overturning moments obtained from the above studies will be compared with those obtained from the idealized cantilever model with a view to deriving simple but rational expressions for the equivalent static design forces in regular buildings.

Studies in the area of earthquake-resistant design of irregular buildings are being carried out initially on multistory buildings with single or multiple set-backs. The results of linear and nonlinear analyses of steel-framed set-back buildings are being examined in an effort to find a correlation between them so that it may be possible to use a linear analysis for obtaining realistic values of seismic design forces. It is proposed to extend these studies to include set-back buildings with concrete frames and shear walls. Investigation of buildings with other types of irregularities is also planned.

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IRVING J. OPPENHEIM

Carnegie-Mellon University

Earthquake engineering research is currently being conducted in five areas. The first two projects are being funded by the National Science Foundation, while the others are supported by the University.

Evaluation of Water and Transportation System Performance

This project, which involves a professional firm (GAI, Inc.) as sub-contractor, is an attempt to develop a methodology for the evaluation of lifeline performance. It proceeds on the basis that three features which distinguish lifelines from point facilities must be incorporated in the model. These features are i) the need for a rational measure of lifeline performance, ii) the need to reflect the redundancies which exist in many systems, and iii) the need to model the geographical extent of the system which represents an increased "catchment area" for damaging earthquake occurence.

Seismic failure links are those points in the system where earthquake induced failure would occur. Performance matrices correlate system performance with combinations of link failures (or states of link damage). The inverse iso-seismal zones are then generated from those links, and the envelope of those zones is retained. Integration of the local seismicity over the areas contained in the zones is a measure of the expected occurence of damaging earthquakes.

The results will be most useful when they are compared to the hazard faced by individual buildings, the risk of damage being calculated in the identical manner. This permits a relative measure of lifeline damage risk to building damage risk. Where possible, the results will be presented as a dollar loss per capita.

Formulation and Expression of Seismic Design Provisions (S. J. Fenves)

This project, performed in cooperation with the Center for Building Technology, National Bureau of Standards, is intended to assist and augment the development of Recommended Comprehensive Seismic Design Provisions for Buildings currently performed by ATC. The project is divided in two phases; in the current phase, we are cooperating with ATC to insure that the Design Provisions are clear, complete, consistent and coherent; in the second phase, we will formally document the ATC report, as well as produce alternate organizations for different categories of uses, so as to assist in the adaption of the ATC Design Provisions by various organizations.

The methodology used has been developed over a number of years on various codes and design specifications, and involves the use of decision tables, for representing individual provisions and of network concepts for representing the relationship between provisions and for their organization. These tools permit checking the draft provisions for completeness and correctness, and developing alternate organizations for clarity of exposition and ease of use.

Vibrations or Flexible Foundations (P. P. Christiano)

Although foundations deform dynamically, most previous work in the area of soil-structure interaction is premised on the condition that the structural mat or footing is either rigid or exerts a prescribed contact pressure on the foundation. We are, therefore, studying the effect of mat flexibility on the dynamic response to time-varying excitation. Specifically, we seek answers to the following questions:

1. For flexible footings of regular geometry, having uniform thickness, bearing on an elastic half-space and subjected to prescribed spatial distributions of harmonically varying loads; how does the response vary as a function of the thickness and of the excitation frequency?

2. How do internal stresses and contact pressures vary with forcing frequency, loading, and mat thickness?

3. What are the effects on response due to spatial variation of mat thickness (e. g. radial taper)?

4. What are the effects of concentrated masses and external stiffness on the responses of the mat?

The above issues are being investigated via harmonic analyses of flexible plate models bonded to the elastic half-space. The structural components are modelled by conventional finite elements, while the subgrade will be modelled as a continuum.

High Rise Masonry Buildings - Measurement of Dynamic Properties

High rise reinforced masonry construction is a building type whose earthquake response characteristics are still largely unknown. The researchers intend to measure the dynamic properties (under ambient vibrations) in a number of these buildings. They will also attempt to predict those properties by analytical means. Comparison of measured to predicted properties may permit inference of structural behavior characteristics. Of specific interest are indications of coupled-wall action (where not part of the design) and of the effect of differing wall/slab connection details. The Civil Engineering Department recently acquired a Kinemetrics vibration monitor to use in this study.

Torsional Response of Structures

The role of induced torsion in structural response is being investigated. Recently completed studies of the elastic response demonstrated the effects of varying the eccentricity. Studies which will begin shortly will focus on response in the inelastic range. Of particular interest is the fact that the eccentricity will change as corner columns yield. It is not yet known whether this migration of the shear center is a dangerous phenomenon, but further study seems to be in order.

JOHN BOATWRIGHT

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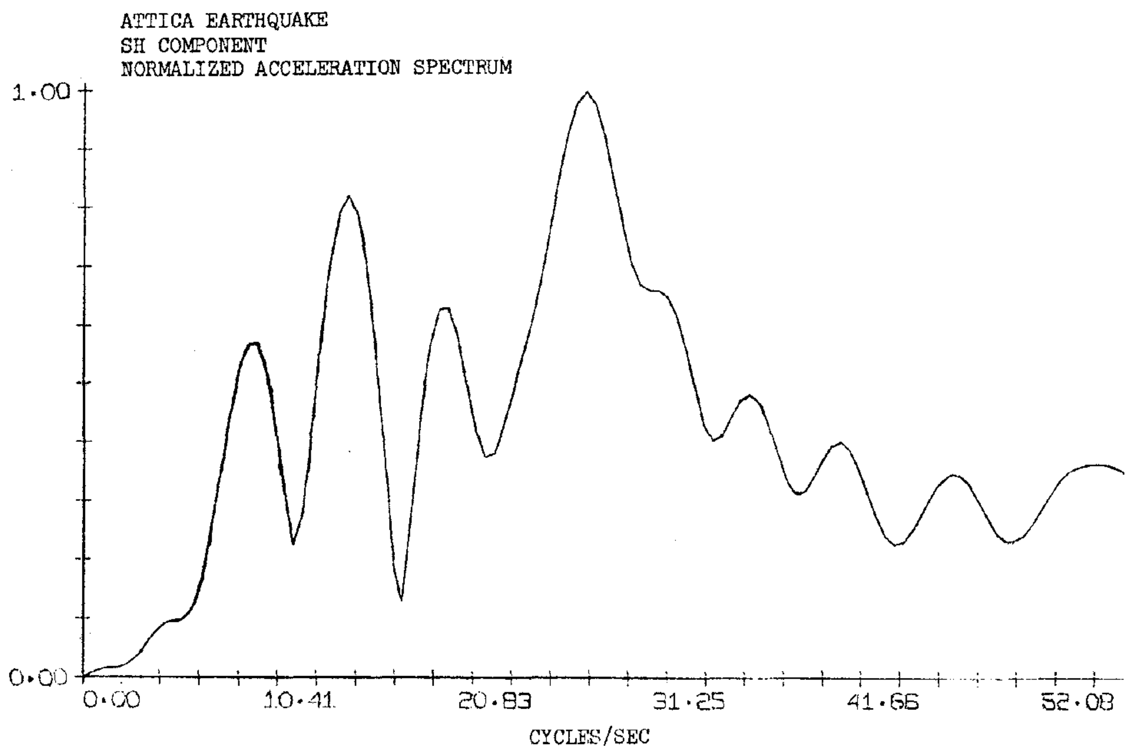
High Frequency Accelerations of Strong Ground Motion in the Eastern United States

The seismicity of the eastern United States differs substantially from that of the areas west of the Rocky Mountains. Two particular features which are of immediate importance to earthquake engineering are (1) the relatively low attenuation of the seismic motions, and (2) the liklihood of enriched high frequency content (> 10 hz) radiated from sources with high stress drop. The combination of these effects necessitates a characterization of acceleration spectra at high frequencies to be used as input to design studies for earthquake resistant structures.

We have studied strong motion records for three small earthquakes in New York State. Two of these, magnitudes 3.9 and 2.2, occurred in the Blue Mountain Lake region, and the third, magnitude 1.4, occurred beneath a brine field near Attica. The strong motion instrument, located 1.3 km from this event, recorded a maximum horizontal acceleration of 10% g. Our motivation for considering events of this size within the context of design engineering is twofold; first, it is reasonable to presume that the source behavior for these small events is considerably more simple than that of larger events and may give insight into the physical processes occurring at the focus, and second, if earthquake displacement spectra have an asymptotic ω^{-2} falloff above the corner frequency, (without attenuation), then the acceleration spectra will be flat in these frequencies and estimates for the high frequency accelerations due to larger events may be obtained by simply scaling the spectral amplitudes of the smaller events.

The acceleration spectra we will present have been calculated from short traces (~ .4 secs) of SH-component motion, obtained by rotation of the horizontal components recorded by the Kinemetrics SMA-1 instruments. These short SH traces effectively reduce P-wave contamination and echo modulation of the spectra. Because we are concerned with a higher frequency band than is normally used in ground motion studies, we have made a rigorous statistical analysis of our spectral estimation scheme, including digitization and truncation error effects.

The smooth peaked spectrum of the Attica earthquake (see Figure) appears to indicate an anomalous rupture process, where possibly a much greater stress drop occurred on a small portion of the fault surface.



The more irregular spectra of the Raquette Lake and Blue Mountain Lake events show corner frequencies of 12 hz and 30 hz, respectively. Because of the extremely low attenuation in this Adirondack region, the acceleration spectra for these two events show substantial high frequency amplitudes up to, and beyond, 40 hz.

LE-WU LU

Lehigh University

Research related to earthquake engineering is being carried out in three different subject areas: reticular concrete floor systems subjected to gravity loads and in-plane shear forces, constitutive relations of structural concrete, and steel beam-to-column web connections.

Reticular Concrete Floor Systems

This work, supported by a grant from the Division of International Programs of the National Science Foundation, is part of a cooperative research program with Escuela Colombiana de Ingenieria (ECI), in Bogota, Colombia. A typical reticular floor system consists of two series of intersecting narrow concrete joists forming a lattice pattern with retangular openings which are filled by preformed hollow boxes. The system has been used extensively in many South American countries and performed well during the several moderate earthquake shocks which occurred in Colombia and Venezuela in the recent past. It has also been used in several buildings in the U.S.

The contribution of the boxes to the overall strength stiffness of the floor system is often neglected in design. The work at ECI is concentrated on the open-grid system without the in-filling boxes, whereas the Lehigh work includes both the grid system and the boxes. The current work at both schools is concerned with the behavior under gravity loads. Small scale models are being prepared and tested, and results will be compared with theoretical calculations. Preliminary work indicates that the contribution of the precast boxes is substantial.

The principal investigators of the work are Ti Huang and Le-Wu Lu in the U.S. and Luis G. Aycardi in Colombia.

Constitutive Relations of Structural Concrete

This work is supported by the Division of Solar Energy of the Energy Research and Development Administration. The overall objective of the work is to devise a means necessary to achieve a satisfactory analysis of the type of under-sea structures which have been envisioned for use in ocean thermal power plants. The basic constitutive relations developed can be applied to any type of concrete structures and can properly take into account both the loading and unloading behavior of the material. Recent work points to the possibility of deriving elastic-plastic stress-strain relations using classical theories of plasticity. The concept of "discontinuous surface", due to micro-cracking, is introduced in the derivation. Experiments on conical shells of plain and polymer impregnated concrete have been conducted to check the validity of the theoretical results. Some emphasis is placed on the ductility and failure modes of the structures as influenced by the stress-strain properties of the concrete used in making the models.

The principal investigator of the work is Wai-Fah Chen.

Beam-To-Column Web Connections

The behavior and strength of steel beam-to-column web connections are being investigated in the project supported by the American Iron and Steel Institute. The current study centers on a study of unsymmetrical web connections where there is only a beam on one side of the column and where there is axial load applied to the column. The first phase of this study includes the testing of eight "simulated" beam-to-column web connection assemblages which have been designed to study 1) the behavior of the column web under the action of concentrated flange forces representing the beam moment, 2) different methods of attaching the beam flanges to the column in web connections, and 3) the stiffener requirements on the side of the column opposite the beam. Preliminary results indicate that the connections having beam flanges welded only to the column web have lower strength and ductility than those having beam flanges welded to the inner side of the column flanges.

The principal investigators of the project are Lynn S. Beedle and Wai-Fah Chen.

KEIITI AKI

Massachusetts Institute of Technology

At M.I.T.'s Department of Earth and Planetary Sciences, several Ph.D. theses works have been done with an ultimate purpose of predicting strong motion of an earthquake solely from physical principles, using the conditions and material properties of a given earthquake fault, without knowing past records of strong motion associated with the fault. So far, the works have been supported by the Geophysics Division of the National Science Foundation.

Effect of source mechanism and sedimentary basin structure on seismic motion near an epicenter

In the thesis by Michel Bouchon, various seismic scattering problems in the vicinity of an earthquake source have been solved by the method of discrete wave-number representation. This is a numerical method, but gives better physical insight to the scattering process than other numerical methods such as the finite difference method.

The method was applied to understand the accelerograms recorded at the Pacoima Dam during the San Fernando earthquake of 1971. A satisfactory agreement was obtained between the observed and the computed on the basis of a propagating dislocation in a half-space.

Another problem relevant to earthquake engineering studied in Bouchon's thesis is the surface motion above a sedimentary basin due to a nearby earthquake. The results show a strong effect of source mechanism on the amplitude variation with the epicentral distance. The effect of sediment basin on the amplitude variation is not simply separable from the effect of source mechanism. A general impression from these results is that classic approaches in earthquake engineering such as relating peak acceleration, velocity and displacement in terms of <u>magnitude</u> and <u>distance</u> and treating the sediment effect separately using source models of plane wave incidence may not be adequate, if we want something better than an order of magnitude estimates on ground motion. The effects of source mechanism and complex earth structure are strongly coupled and they may not be simply parametrized by magnitude and epicentral distance separately.

For a ground motion estimation better than an order of magnitude, we need to know about the mechanism and location of a future earthquake. In other words, we may need an earthquake prediction, at least in location and source mechanism, for a meaningful earthquake engineering work.

Seismic radiation from propagating shear cracks

In the thesis by Shamita Das, some progress has been made in predicting seismic motion from a model of earthquake characterized as a rupture propagation. The fault slip is calculated by a finite difference solution of an integral equation formulated using a Green's function which satisfies the stress free condition on the plane containing the crack. A finite-mesh equivalent of Irwin's fracture criterion is used to determine the motion of crack tip. A variety of propagating rupture problems for anti-plane and in-plane shear cracks were solved by this method.

The effects of initial stress distribution and obstacles along the fault plane on seismic radiation were studied in some detail. For example, it was found that a multiple rupture along a fault with obstacles which never break shows a similar corner frequency to a single smooth rupture. The difference between them shows up at frequencies higher than the corner frequency. On the other hand, a multiple rupture along a fault with obstacles which eventually break show a significantly lower corner frequency than the smooth rupture.

A convenient way of expressing seismic radiation from a fault is to show the space-time Fourier transform of slip-motion, or a w-k spectrum of source function. It is convenient because the far-field spectrum, say at angle θ from the fault plane normal, is given by a cross-section along $k = \omega \sin\theta / c$, where c is the velocity of P or S waves. This w-k diagram gives the radiation of P and S waves to all directions at a glance.

The w-k spectrum representation may also be a useful tool to combine the complex effects of source and medium on ground motion.

Future research directions

The above two thesis works provided us with methods for understanding the seismic motion near an earthquake source. With increasing distances from the fault, the effects of attenuation and scattering become more important. Understanding these complex propagation path effects on short period seismic waves will be the goal of our research in the immediate future. The thesis by Bernard Chouet, in a work supported by ERDA, has been concerned with the statistical treatment of the effect of scattering on short period seismic waves. We know now how to interpret the coda part of a local earthquake in terms of a random medium. We shall extend this line of approach to the main part of a local earthquake. We shall also study the scaling law of seismic spectrum both theoretically and experimentally using the coda method, in order to extrapolate the ground motion for a large earthquake from observation on small ones.

JAMES M. BECKER

Massachusetts Institute of Technology

A preliminary study of the "Seismic Resistance of Precast Concrete Panel Buildings" is being conducted under the sponsorship of the National Science Foundation through their Research Applied to National Needs Program. The principal investigators for this project are Professors J. M. Becker and J. M. Biggs. The current phase of this research includes a survey of design practices and available experimental data, an examination of the problems of analytical modeling, and preliminary parametric studies using response spectrum modal analysis.

Large Precast Panel Building (LPPB) Systems

In recent years LPPB systems have become economically and architecturally viable systems for use in the American construction industry. These systems were originally developed for use in regions that are essentially nonseismic in character. However, they are now being used in seismic regions in both the United States and throughout the rest of the world. The adaptation of these structural systems for use in seismic regions provides both opportunities and problems with regard to their overall structural safety.

LPPB systems existing in seismically active regions of the United States are designed on the basis of seismic criteria developed for structures employing either ductile moment-resisting frames or monolithically cast shear walls to resist lateral loads. The normal concepts of ductility, based on flexural failure modes, implicit in these codes may not be applicable to LPPB systems.

The obvious difference between monolithically cast structures and precast panel structures is the discontinuity created by the connection areas between the panels. An assessment of the state-of-the-art in panel joinery is presented in the first report issued by the project, "Joints in Large Panel Precast Concrete Structures" by Una Zeck. This report provides a general description of the role of joinery in panelized structures, a survey of different forms of joinery and a discussion of potential modes of behavior. Joint behavior can range between the extremes of hard and soft connections. A hard connection is one in which the forces to be transfered are concentrated at specific locations (e.g. welded plates) causing nonlinear behavior to occur in the panel. At the other extreme, a soft connection is one that transfers forces along its entire length and concentrates nonlinearities in the connection region.

To provide a focus for analytical research, a LPPB system developed in New England and now being used throughout the United States was chosen for detailed study. This structure is a post-tensioned cross-wall system using prestressed hollow-core floor planks. The load bearing shear walls are constructed out of precast concrete panels that are 8 feet in height and can range in length from 12 feet to 48 feet. These panels are post-tensioned together creating a horizontal connection in which grout is placed in the space left by the floor planks and the next panel is then bedded in drypack concrete. The post-tensioning force and the structures own weight act together as a prestressing force in the resistance of overturning moments and participate in developing the friction mechanism for shear transfer across the connection. These connections are considered soft, in that shear transfer may cause both distortion and slippage in the connection.

Analytical Modeling

Modeling studies have been performed in the linear elastic range to develop an initial understanding of the dynamic characteristics and potential seismic response of these panelized systems. Because of construction details, there is virtually no coupling between adjacent cross-walls in a structure. This uncoupling, along with the asumptions of a rigid floor diaphragm and base rigidity, have enabled modeling studies to be carried out on an isolated wall.

To examine the potential effects of the nonlinearities associated with soft connections, it was decided to seperate the stiffness parameters for the connection area. This seperation allowed for the independent variation of the modulus of elasticity and the shearing modulus. An effective shearing modulus could then be assumed to account for the possibilities of both distortion and slippage.

Three dynamic models were examined: a beam model, a simple finite element model and a statically condensed super element model. The beam model required the inclusion of both shear stiffness terms and rotational degrees of freedom in order to obtain results comparable to the other analysis procedures. The finite element models used isotropic plane stress rectangles (PSR) for the panels and anisotropic elements for the connection areas.

The simple finite element model used one element each for the panels and the connection areas. The unusual aspect ratio of the connection area did not seem to have a significant effect. A single PSR element is stiffer in bending than an actual structure, but this appeared to be compensated for by the exaggerated rotational mass created by the lumping the mass at the corner nodes. A 3x6 element mesh was used for the super element model. This mesh was capable of modeling all significant deformation modes. While the cost of using a super element is difficult to justify in analyzing solid walls, its use is essential when considering penetrations.

The super element model was considered to give the most realistic results. All three models, however, gave similar results when considering tolerances normally associated with design.

Parametric Study

Parametric studies are being performed to assess the dynamic characteristics and seismic response of an idealized structure. The parameters that are being examined are: height of the structure, length of panel, stiffness of connection area, response spectrum and percent of critical damping. For various combinations of the above parameters, the period and shape of the first ten modes are determined along with the shear and moments associated with the modal response.

Preliminary indications are that the response of 5 and 10 story structures is dominated by the contribution of the first mode, while 15 and 20 story structures show an increasing participation of the second and third modes. The softening of the shear stiffness in the connection area has a noticeable, but not significant, effect on the level of seismic forces. For the 5 story structure, potential joint softening may lead to a slight increase in the level of seismic forces.

The above typical observations were on the basis of an SRSS modal analysis using a smooth response spectrum. Time history analyses are currently being carried out to gain a better understanding of the cycling associated with connection areas and the possible effect it might have on joint degradation.

Work is also being done to compare results of the parametric studies to strength criteria for the structure. Initial indications are that overturning moments will cause tension across the connection area before friction mechanisms will allow slippage due to shear. For a ten story structure, this openning of the connection may occur with peak accelerations as low as 0.05g depending upon the level of post-tensioning. Once this openning or slippage does occur, the problem becomes nonlinear in nature. The safety of these large precast panel building depends upon what form of ductility exists at this point. This question of non-linear response is of major concern and forms the basis for the next phase of this research project.

C. ALLIN CORNELL

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The basic philosophy of the (NSF/RANN-sponsored) MIT project on Structural Loads Analysis and Specifications is to approach "all" loads within a single framework in order, first, to gain the advantages of transferring methods from one load to the other and, second, to develop one or more unified approaches suitable for all loads. The latter objective leads to consideration of a relatively simple time-dependent (stochastic process) model that is a sufficiently accurate representation of all loads types; such a model will encourage the broader professional understanding of loads as time-dependent phenomena, and it will facilitate parametric studies of the load combination problem (especially in relation to code specifications). The specific load types considered in detail are seismic, snow, vehicles, tornadoes, hurricanes, extra-tropical winds, and temperature loads.

The table shows one view of the project's structure and activities. We identify three levels of activity ranging from a random-variable (or even deterministic) level of description consistent with most present specifications and with most engineers' appreciation of loads, through a second level (the unified, simplified stochastic process view discussed above), to the third level of state-of-the-art representation of each type of load (this level usually includes both spatial and temporal stochastic representation of the phenomenon). The project is concerned primarily with structure-independent macro-time, macro-space load processes (as distinct from, for example, seismic response spectra, wind pressure fields on buildings, etc.).

At each level three types of activities take place for each load type considered (and in some cases for the combined loads problem). The first of these is related to understanding the phenomena through the physical laws and empirical data of the relevant field (e.g., seismology or meteorology). At the lowest level this includes direct observations of, for example, maximum annual wind speeds. At the highest level it includes phenomenological and physical information such as empirical and theoretical pressure field versus wind-velocity field relationships within hurricanes. The second type of activity, shown in the right-hand column of the table, is stochastic modeling of the problem at each particular level. At the lowest level this might simply imply *a priori* selection of distribution form (based, for example, on derivations from higher levels), but it also includes, in the case of load combinations, collecting and developing proposals for deterministic ("Level I") load combination formats. At the intermediate level this modeling activity includes proposing several alternative (relatively simple) stochastic process representations of the macro-time variation of loads and also developing a catalogue of parametric analysis results for the distribution of the sum of any pair of load processes (e.g., continuous Gaussian plus Poisson point process with random magnitudes). Finally, the third activity (located logically between the information activity and the modeling activity in the table) is that of statistical inference. The second item, model selction, is particularly important in this project and simultaneously very little studied in the literature of our profession or that of statistics. At the lowest level this problem classically includes selecting a distribution type and estimating its parameter values based on observed data. In modern Bayesian statistical terms the residual statistical uncertainty (associated with less-than-infinite sample sizes) is retained and included in the "Bayesian" or "predictive" distribution of, say, the maximum load intensity in the next 50 years. This is true in principle of both the parameter uncertainty (given the model) and the model (per se) uncertainty. Work by Professor Daniele Veneziano on this topic has been reported. A Ph.D. thesis on model uncertainty was completed in January 1976 by Mircea Grigoriu.

There are also physical and analytical issues associated with taking the highest (state-of-the-art) representation of a particular load type and transforming it into any given simpler second-level representation. A main point of the project is that because of the desire for harmonization among all loads any single second-level model determined to be the best compromise may not be the most natural second-level model for any given load type. For example, a Poisson point process with independent, instantaneous intensities is an easy-to-use model reasonably consistent with many advanced seismic and tornado representations, but it may be an awkward way to represent all occupancy loads in buildings (and it is clearly misleading if used for all loads for load combination pruposes!). Finally, at the highest level, where a state-of-the-art model has been preselected, the third activity involves primarily parameter estimation. We are seeking ways, for example, to use more statistical data than is typically available at the lowest level (e.g., 30 years of wind velocities at a nearby airport).

FIGURE 1 - PROJECT STRUCTURE

	1 INFORMATION: PHYSICAL UNDER-STANDING AND EMPIRICAL DATA	2 INFERENCE/DECISION: MODEL SELECTION AND PARAMETER ESTIMATION	3 MODELING: PROBABILISTIC MODELS AND CODE PROCEDURES
LEVEL C State-of-the-Art	*Uniform documentation of existing background *New empirical back-ground analysis studies *Loads library	*Estimation procedures for spatial models	*Unified review of existing models of particular loads *New models of particular loads *Unified temporal/spatial models
LEVEL B Unified Stochastic Process Models	*Simplification of Level C needed to square information with unified models	*Formal unified sto-chastic process model selection procedures *Role of "predictive" model (i.e., those that include explicitly model and parameter uncer-tainty)	*Catalog of potential uni-fied models; analysis of their properties (e.g., extremes *Extremes of combinations of models (load combina-tion theory)
LEVEL A Random Simple Variables Models and Deterministic Code	*Empirical (direct data analysis) of extreme loads *Comparison with model predictions *Relationship to existing code values	*As above, except for simpler random variable models	*Distributions of extremes (from Level B models) *Simplified approximate analytical procedures load combinations *Deterministic code for-mats, new and existing versus Level B

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INTRODUCTION

The extensive work on aseismic design of above-ground reactors and recent studies on missile impact effects, aircraft impact, blast effects due to chemical explosions, reactor melt-down and tornadoes indicate the advantages of underground siting with inherent general reduction in complexity of seismic amplification and benefits of structural and biological integrity. The paper describes part of a continuing study of the dynamic structural characteristics of four principal underground concepts for nuclear reactor containments:

a) Cut-and-Cover in Rock or Soil, b) Unlined Cavity in Rock, c) Lined Cavity in Rock or Soil, and d) Lined Cavity in Rock or Soil with Annular Filling of Soft Material - with respect to Shape, Backfill Material, Cavity Wall Reinforcement (Rock Bolting and Lining), Annular Filling, and Modelling Criteria.

The work was initiated by the recent participation of the first author in the Seismic Task Group of the ASCE Committee for Nuclear Structures and Materials (Ref. 1). Parametric studies are presented (Refs. 2 and 3) for the response to a step-pulse, representing a blast excitation applied horizontally, using a plane-strain finite-element analysis with triangular and rectangular elements over a sufficiently extensive finite region, restricted to the time-history free from stress wave reflection effects. As the character, intensity and frequency of earthquake and blast-inducted ground motions are roughly similar, the results have practical value in studying earthquake effects. The longer time durations in earthquake analysis can be handled without an absorbing boundary by imposing additional material damping to the soil elements as indicated in Refs. 4 and 5.

ANALYSIS

1. Cavity Shape: For the same area of opening a comparison of four different shapes, i) circular, ii) semi-circular roof with vertical walls, iii) flat circular roof with vertical walls, and iv) horseshoe, indicates the horseshoe shape to be the best with an average stress decrease of 10 to 15% compared to other shapes. An analysis of the different horseshoe configurations is also presented. Figs. 1a and 1b give typical studies.

2. Cavity Wall Reinforcement (Rock Bolting and Lining): Studies of passive and active rock bolting, reinforced and prestressed concrete liners, and steel liners indicate active rock bolting to be the best kind of reinforcement. Rock bolting, with about 80% of the amount of the steel required for a cavity liner, decreases the stress in the medium by 25% or more compared to 10% for the liner. Typical studies are presented in Figs. 2a, 2b, 2c, and 2d.

3. Isolation: A surrounding medium of soft, energy absorbing material, e.g., closed cell polyurethane foam, reduces by about 80% the liner membrane forces and bending moments and the stresses in the medium by about 10-15% (Fig. 3).

4. Backfill Material: Typical analyses of a cut-and-cover structure for six different filling materials are presented in Figs. 4a and 4b. A proper selection of the combined properties, the density and elasticity, of the backfill material can lead to a significant reduction in the stresses in the structure and the surrounding medium.

The research programme has a number of 'spin-off' applications outside the nuclear industry to tunnels, conduits, and cavities for oil and gas storage.

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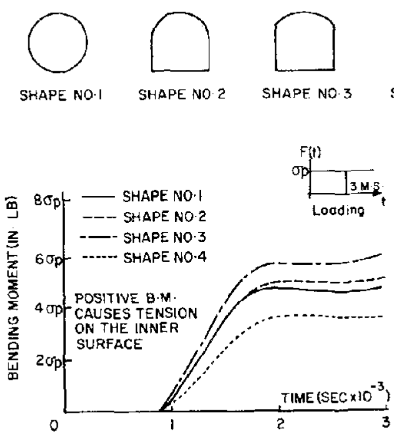
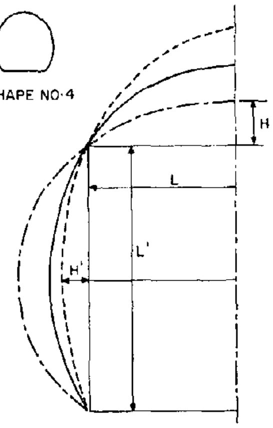
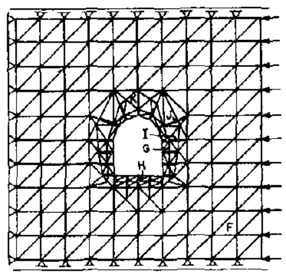


FIG· Ia BENDING MOMENT IN ELEMENT AT CROWN

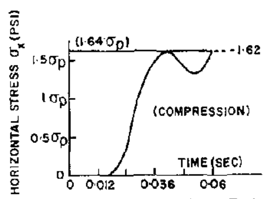


FIG· Ib DIFFERENT HORSESHOE SHAPES

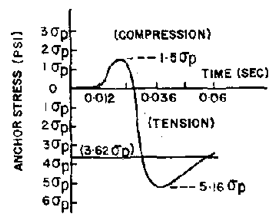


FIG· 2a MESH USED IN CASE OF ROCK BOLTING

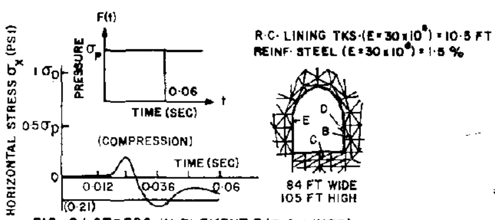
NO·OF NODES ·········· = 168
TOTAL NO·OF ELEMENTS ·········· = 316
NO·OF STEEL ANCHORS ·········· = 36
AREA OF EACH ANCHOR ·········· = 0·63 IN
INITIAL PRESTRESS ·········· = 150 KSI
ANCHOR LENGTH ·········· 21 FT (SIDEWALLS)
42 FT (ARCH ROOF)
CAVITY SIZE ·········· = 84 FT WIDE
105 FT HIGH



FIG· 2b STRESS IN ELEMENT H (ACTIVE ROCK BOLTING)



FIG· 2c STRESS IN ELEMENT I (ACTIVE ROCK BOLTING)



FIG· 2d STRESS IN ELEMENT B (R·C· LINER)

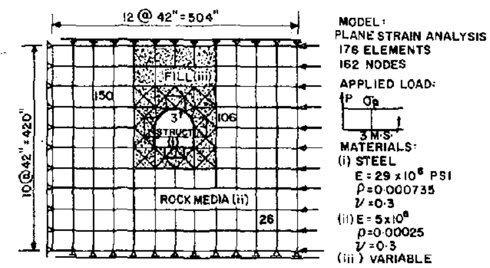
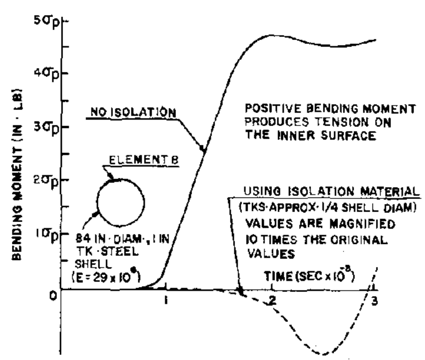
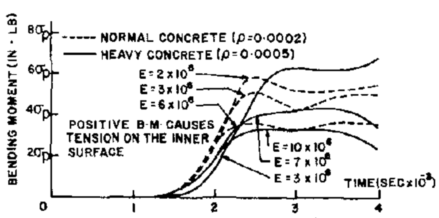


FIG 4a MODEL USED FOR CUT-AND-COVER STRUCTURE



FIG· 3 BENDING MOMENT IN ELEMENT 8 – STRUCTURE – ROCK ($E = 5 \times 10^6$, $\rho = 0{\cdot}25 \times 10^{-3}$, $\nu = 0{\cdot}3$) ISOLATED BY CLOSED CELL POLYURETHANE FOAM ($E = 1400$, $\rho = 0{\cdot}006 \times 10^{-3}$, $\nu = 0{\cdot}3$)



FIG· 4b BENDING MOMENT IN ELEMENT 3 – CUT-AND-COVER STRUCTURE·

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National Research Council of Canada sponsored earthquake engineering activities are being conducted in the following areas:-

The "worst" Direction of Excitation

Building axes orientation is generally independent of the direction in which ground distrubance propagates. Therefore, one has to design for ground disturbance that comes from a direction that will produce the most severe demand on the structure.

To study this problem, new ground motion records are synthesized based on instrument recorded ground motion through a rotational transformation. The response spectra based on these synthesized records are computed and compared with the spectra based on instrument records. In particular, comparison is made on spectra based on ground motions along the "principal directions". Principal directions are defined as the directions where the cross-correlation of the records in the three perpendicular directions are zero (see Penzien and Watabe, Int. J. Earthquake Engineering and Structural Dynamics, 1975).

The ultimate aim of this study is to provide a transformation relating the response spectra based on instrument measured records (which is readily available) to response spectra based on motions along different direction, particularly along the principal directions. Such a transformation will reveal both the worst direction and the response spectra associated with the ground motion in that direction.

Bi-Directional Excitation on Asymmetrical Structure

A study is made on the response of a class of single mass asymmetrical structure with eccentricities in both x and y direction subjected to uni-directional and bi-directional ground excitation. The El Centro 1940 records are used as a sample excitation. The class of structure considered consists of lateral resisting elements at the perimeter of the structure. Cases considered are large eccentricities in both directions,large eccentricity in one direction and small eccentricity in another direction. Comparison is made on the response spectra of the different cases. Particular attention is paid to the response at the perimeter of the structure.

TED S. VINSON

Michigan State University, East Lansing, Michigan

Earthquake engineering research at Michigan State University is presently being conducted in three areas: (1) Evaluation of the Dynamic Properties of Frozen Soils, (2) Comparison of the Cyclic Strength Characteristics of Remolded and Undisturbed Sand, and (3) Evaluation of the Dynamic Properties of Soft Rock and Stiff Clay. A considerable amount of work has been done in the first area under two National Science Foundation research grants (GK-37439 and ENG 74-13506). This work is described in detail below. Only a modest amount of work has been done in the latter two areas and it is not described herein.

EVALUATION OF THE DYNAMIC PROPERTIES OF FROZEN SOILS

Introduction. In the past decade considerable attention has been focused on Alaska and other cold regions of the world owing to their abundance of natural resources, particularly those related to our increasing demand for energy. Nearly 85 percent of Alaska lies within a permafrost region, i.e., a region of perenially or permanently frozen ground. Further, Alaska is located in one of the world's most active seismic zones. This was exemplified by the 1964 "Good Friday" earthquake and more than sixty other earthquakes that have equalled or exceeded a Richter magnitude of 7 since the 1800's. The need to determine the dynamic properties of frozen soils for use in frozen ground response analyses during earthquakes is apparent.

Objectives. The objectives of the research work are:

(1) to develop test equipment to evaluate the dynamic properties of frozen soils under simulated earthquake loading conditions
(2) to evaluate the dynamic properties of frozen soils under simulated earthquake loading conditions
(3) to investigate parameters that might influence the dynamic properties of frozen soils such as soil type, soil density, nature and amount of the ice phase, temperature, confining pressure, and amplitude and frequency of dynamic loading.

Development of Test Equipment. The criteria for the development of the test equipment were established after reviewing (1) the thermal characteristics of frozen soil deposits, and (2) test conditions associated with earthquake loadings. The criteria were:

(1) temperature control of the test specimen over a range of $0^{o}C$ to $-10^{o}C \pm 0.1^{o}C$
(2) control of confining pressure over a range of 0 to 200 psi
(3) control of shear strain over a range of 10^{-3} to 1 %
(4) control of frequency over a range of 0.05 to 5 Hz

To satisfy these criteria various combinations of three conventional dynamic test systems (cyclic triaxial, cyclic simple shear, and cyclic torsional shear) and three temperature control techniques (cold room, cold bath, and cooling coil) were considered. The test system developed for use in the research work represents a coupling of cyclic triaxial test equipment with a cold bath. The system consists of four basic components:

(1) an electrohydraulic closed loop test system (actuator, servovalve, hydraulic power supply, servo controller, hydraulic controller and function generator) which applies a cyclic axial load (deviator stress) to the frozen sample

(2) a triaxial cell which contains the sample and non-circulating coolant

(3) a refrigeration unit and cold bath which circulates the coolant around the triaxial cell

(4) transducers, and output recording and readout devices (load cell, LVDT, thermistors, X-Y and strip chart recorder, transient store, digital multimeter and oscilloscope) to monitor the load (stress), displacement (strain), and temperature of the sample.

The electrohydraulic closed loop test system and triaxial cell are similar to those used in unfrozen soil dynamics research at laboratories throughout the country. The refrigeration unit and output recording and readout devices are also conventional laboratory equipment items. The cold bath is approximately 1.2 ft x 1.2 ft x 1.5 ft and contains 1.7 cu ft of circulating coolant, excluding the volume of the triaxial cell. It is constructed so that the coolant enters at the bottom and returns to the refrigeration unit from a line at the top of the bath. The bath is insulated all around with two inch sheets of styrofoam to prevent heat loss in the cell. A linear variable differential transformer (LVDT) is attached across the sample to the cap and base to monitor displacement and a load cell is attached to the base to monitor the cyclic axial load. Two thermistors are attached to the 2.8 inch diameter and 7 inch long sample to monitor its temperature during the test.

Evaluation of Dynamic Properties. An evaluation of the dynamic properties of laboratory prepared samples of sand, silt, gravel, clay and ice with the test equipment described above has been undertaken. The research work on ice and frozen clay is complete; the work on sand, silt, and gravel is in progress.

The polycrystalline ice samples used in the research program were prepared at two densities (0.77 and 0.904 g/cm^3). The samples were tested at strain amplitudes from 3×10^{-3} to 2×10^{-2}%, temperatures from -1 to -10°C, frequencies from 0.05 to 5 cps and confining pressures from 0 to 200 psi. The values of dynamic Young's modulus over the range of material and test conditions were from 260×10^3 to 900×10^3 psi; the values of damping ratio were from 0.001 to 0.14. The test results indicate that the dynamic Young's modulus of ice increases, in general, with increasing confining pressure, density, and frequency. The dynamic Young's modulus of ice decreases with increasing temperature and increasing strain amplitude. The test results indicate that, in general, damping ratio of ice decreases as frequency increases from 1.0 to 5.0 cps. The damping ratio tends to decrease with decreasing temperature and increases with increasing strain amplitude for high density ice. It is apparently not affected by strain amplitude for low density ice. There appears to be no well-defined relationship between damping ratio of ice and confining pressure or density.

Two types of frozen clay samples were used in the research program: (1) Ontonagon clay, termed "O-clay," and (2) a mixture of Ontonagon and sodium montmorillonite clay (fifty percent each by weight), termed "M+O-clay." The O-clay (specific surface area 215 m^2/g) was prepared at different water contents (29,36,46,55%) to assess the influence of water (ice) content on dynamic properties. The M+O-clay (specific surface area 475 m^2/g) was used to investigate the influence of specific surface area (related to unfrozen water content). The samples were tested at strain amplitudes from 3×10^{-3} to 1×10^{-1}%, temperatures from -1 to -10°C, frequencies from 0.05 to 5 cps, and confining pressures from 0 to 200 psi. The values of dynamic Young's modulus over the range of test conditions were from 90×10^3 to 880×10^3 psi; the values of damping ratio were from 0.02 to 0.3. The test results indicate that the dynamic Young's modulus of frozen clay decreases with increasing strain amplitude and specific surface area. The dynamic Young's modulus of frozen clay increases with decreasing temperature and increasing water content and frequency. It is apparently not affected by confining pressure. The test results indicate that the damping ratio of frozen clay increases with increasing strain amplitude and increasing temperature. The damping ratio, in general, decreases for an increase in frequency from 0.5 to 5 cps; for frequencies greater than 5 cps, damping ratio increases as frequency increases. There appears to be no well-defined relationship between the damping ratio and water content or specific surface area. The damping ratio is apparently not affected by confining pressure.

Future Research. The test results from the current research program are associated with reconstituted samples prepared and frozen in the laboratory. It is generally recognized that the structure of these samples is significantly different from the structure of in situ frozen soil and, consequently, it may not be possible to use the dynamic properties measured to predict the response of frozen ground deposits during earthquakes. In future research work naturally frozen soil samples (undisturbed samples taken in situ from frozen ground deposits) will be tested. When sufficient data is collected design equations or curves to evaluate dynamic properties of naturally frozen soils based on a knowledge of index and classification parameters will be developed. Finally, the response of characteristic types of frozen ground deposits during earthquakes will be studied.

W. O. KEIGHTLEY

Montana State University

University sponsored research is ongoing in two areas: The use of segmented prestressed wall panels to dissipate vibrational energy in buildings through Coulomb friction, and the evaluation of a static tilting platform as a device to indicate the earthquake resistance of small buildings.

Energy Absorbing Wall Panels

Infill wall panels in building frames, composed of strips of reinforced concrete prestressed together, are presented as a means for absorbing vibrational energy. As the building frame distorts, the wall panels, which are fitted within the rectangular space formed by pairs of adjacent columns and beams, but touching only at the corners, conform to the distortion by slipping along the joints between strips, similar to the way in which a deck of cards can be distorted in shear. Energy is consumed by Coulomb friction during the slipping. The goal is to consume as rapidly as possible the kinetic energy of the structure relative to the ground without causing excessive forces at the corners of the frame.

A digital computer study is in progress to examine the earthquake response of planar multistory frames which have interfloor Coulomb dampers. To determine the size of Coulomb slip forces which will approximate 20% critical viscous modal damping, a 4-story frame of an apartment building designed for earthquake resistance was studied under excitation of the El Centro earthquake. It was assumed that at peak response the frame is distorted in the classical fundamental mode and that in one cycle of free vibration starting from this peak, the energy consumed by Coulomb friction equals the energy consumed by 20% viscous modal damping. The interfloor Coulomb slip forces thus determined, increased by 15% to allow for the effects of higher modes, varied from 8% of the floor weight in the top story to 35% in the lowest story. An iterative step-by-step computation of response showed maximum responses of the Coulomb damped building to be within a few percent of the maxima of the viscous damped building, except that top story shear was 30% greater. Residual displacement of the top floor after the earthquake was 0.1 in. When ground excitation was doubled in intensity, response was about three times as large, corresponding to about 5% viscous damping.

Further work is planned in design, in computer study, and in laboratory experiments to determine if the concept is practical for installation in buildings.

Static Tilting Platform

A tilting platform is suggested as a low cost device, especially in developing countries, for indicating the relative earthquake resistance of small buildings and pointing out their weaknesses. When the table is tilted through angle θ, a structure on the table is subjected to forces corresponding to a constant lateral ground acceleration of $g \times \sin\theta$ and a vertical acceleration of $g(1-\cos\theta)$. A static tilt does not induce dynamic amplification, activate higher modes of vibration, or produce failure in just the same way as a sequence of short triaxial reciprocating pulses. Nevertheless the facility does load structures laterally with a body force proportional to mass, is simple in construction and operation, and requires the simplest of instrumentation. The bed and hoist of a dump truck is suggested as a ready made facility.

A table 8 1/2 ft x 8 1/2 ft, of octoganal shape to permit reciprocating tilting about three axes, was built by Kenneth D. Munski, an MS student in Civil Engineering. The table was raised by a manual overhead 5-ton hoist to eliminate the jerking of electric hoists. Twenty brick structures were tested, 4 ft x 6 ft x 31 in. high, one brick thick, loaded with a 4 in. slab resting on foam rubber on top of the walls. The tests included pairs of structures laid in weak 1:5 lime-sand mortar, sand, mud, and no mortar at all, tilted about longitudinal, transverse, and diagonal axes.

General observations from the tests (some already known or obvious): 1) Collapse of end walls often triggered final failure. All walls should be tied to roof and floor. 2) These structures were weaker in the direction of the short walls by 15-30%. In the diagonal direction strengths were about the same as in the longitudinal direction. 3) Unmortared brick structures withstood about 0.4g, sand mortar about 0.2g, lime mortar about 0.5g, and mud mortar about 0.6g. Results within pairs were surprisingly consistent.

To compare the tilt tests with dynamic tests, the table was then mounted on wheels and pulsed horizontally with triangular pulses of 1/8 sec. duration, maximum acceleration the same as required for static tilt failure. Four structures were tested; results were erratic. After as few as 4 pulses, unmortared models showed diagonal cracking and loosening of bricks in end walls, but end wall collapse did not occur until 60 pulses. A second structure pulsed diagonally failed after 37 pulses. Models of lime mortar first cracked after 1 or 2 pulses, but one withstood 80 pulses and one 26 pulses till failure.

There are no immediate plans for continuing this investigation in this country, but some work is planned at the University of Roorkee, India, in the coming year.

W. L. SCHROEDER

Oregon State University

A project to assess the effectiveness of thin rock revetments in preventing flow slides on loose sand slopes, and reported on previously,[1] has been completed. The study was supported by the National Science Foundation. A limited number of summary reports is available.[2] Principal conclusions of the study, representative of submerged sand slopes 40 cm to 120 cm high, were that:

1. Thicker slope revetments result in higher pore water pressures in a slope for a given level of vibratory excitation.

2. Pore water pressures were highest in flatter slopes.

3. Slope revetments of sufficient thickness will prevent flow slides and limit slope deformations, in spite of the occurrence of liquefaction in the slope-forming material.

Three distinct behavior modes of slopes were noted during testing. Type I behavior was characterized by a flow of slope material down the face, on a plane parallel to the slope surface. Type II behavior was limited lateral flow on an essentially horizontal plane, which deformed, but did not rupture the revetment. Type III behavior was liquefaction of the slope without marked deformation. Type I behavior results from reduction of the sliding factor of safety to unity. It is not necessarily, therefore, representative of a fully liquefied condition. Flows on essentially horizontal planes, resulting from liquefaction, occurred when revetments ruptured; but generally, the effect of revetments was to restrict flow movements, resulting in Type II or III behavior.

Test measurements and observations indicate that selection of revetment thickness for flow slide control involves two considerations. First, the revetment must be thick enough to insure that Type I failure will not occur. In other words, it must be thick enough to force the behavioral mode to Type II or III. Second, for Type II or III behavior the revetment thickness must be sufficient to meet acceptance criteria, i.e., prevention of failure or restriction of deformation. If this second condition is satisfied, the first is always met. Analysis of the problem therefore reduces to consideration of Type II behavior. No analysis for meeting deformation criteria has been developed, but analysis for a failure mode has been proposed and is given below.

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[1] Schroeder, W.L., Flow Slide Control with Slope Revetments, Proc. 3rd Nat'l. Mtg., UCEER, Ann Arbor, 1974.

[2] Schroeder, W.L. and Narkiewicz, S.A., Flow Slide Control with Slope Revetments, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 97331, June 1975.

A diagram of a revetted slope, standing at an angle, β, above the horizontal, is shown on Figure 1. Liquefaction is presumed to have occurred to the right of plane GD and to a depth, h. Seepage toward the face results in a pore pressure distribution defined by BDE. The force balance on AHGD then requires that, for $\phi_1' = \phi_2'$,

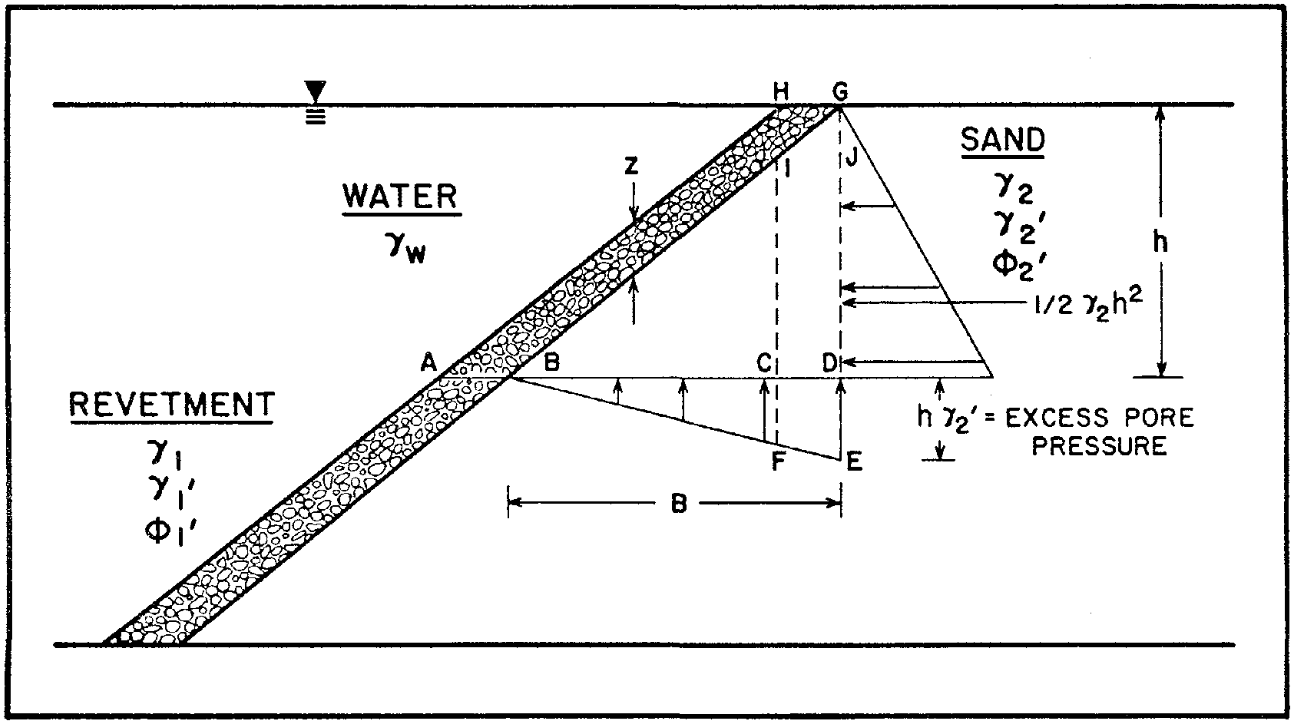

Figure 1. Assumptions for flow slide analysis.

$$z^2 - \frac{2h\gamma_1}{\gamma_w} z + h^2 \left[\frac{\gamma_2}{\gamma_w} \frac{\tan\beta}{\tan\phi'} + 1\right] = 0 \tag{1}$$

which for known values of γ_1, γ_2, γ_w, β and ϕ' reduces to

$$\frac{z}{h} = \text{constant}$$

For 4:1 to 2:1 slopes, z/h varies from about 0.45 to 0.65. Therefore, to prevent flow slides, the revetment thickness must be about one half the depth of liquefaction in the slope.

F. KOZIN

Polytechnic Institute of New York

R. GRAN

Grumman Aerospace Corporation

Our research program is sponsored by the RANN Division of the National Science Foundation under grant number GI-43095.

The main objectives of our program are:

(1) Develop statistically reliable estimation and modeling techniques for application to non-stationary time series.

(2) Apply these techniques to modeling of geophysical data, in particular, strong motion earthquake records.

(3) Relate the features of model to geophysical properties and in particular to local ground characteristics for microzonation studies.

Over the past two years we have concentrated on objectives (1) and (2).

The model that we have investigated is given by the differential equation

$$\begin{cases} \ddot{x}(t) + a\dot{x}(t) + b(t)x(t) = h(t)W(t). \\ \qquad y(t) = x(t) + N(t) \end{cases} \tag{I}$$

In this model x represents the strong motion earthquake acceleration, a is the damping term (constant), b(t) is a cubic polynomial with coefficients b_o, b_1, b_2, b_3, h(t) is an envelope function multiplying the gaussian white noise W(t), y(t) represents the observed strong motion data which is the acceleration x(t) with an additive noise term to account for noise generated by instruments as well as by digitization techniques. The envelope function h(t) is obtained by a least squares spline fit directly to the envelope of the strong motion record. A typical fit is shown in Figure I. The spline procedure fits a sequence of cubic polynomials between selected peaks of $|x|$. This yields a much smaller squared error than obtained by fitting functions such as $\alpha te^{-\beta t}$ or $k(e^{-\alpha t} - e^{-\beta t})$ to the peaks.

Determining h(t) by this procedure, we then apply optimal filtering techniques to estimate a, b_0, b_1, b_2, b_3 directly from the strong motion data.

The quality of the estimated constant coefficients are checked by making statistical tests of the residuals. Using the function h(t), and the estimated coefficients a, b_0, b_1, b_2, b_3 simulated records are generated. An example is given in Figure 2, which shows the actual earthquake and two simulations from the estimated model I. The strong motion record that generated the curves in Figures 1 and 2 is the San Fernando earthquake record taken in the first floor of 222 Figuroa Avenue.

Twenty five records of the San Fernando earthquake are presently being modeled and analyzed, and analysis is being made of the estimated coefficients.

The next stage of our program will be to relate non-stationary models to fault as well as local ground properties. Hopefully, useful characterizations of geophysical properties from the estimated coefficients will be obtained.

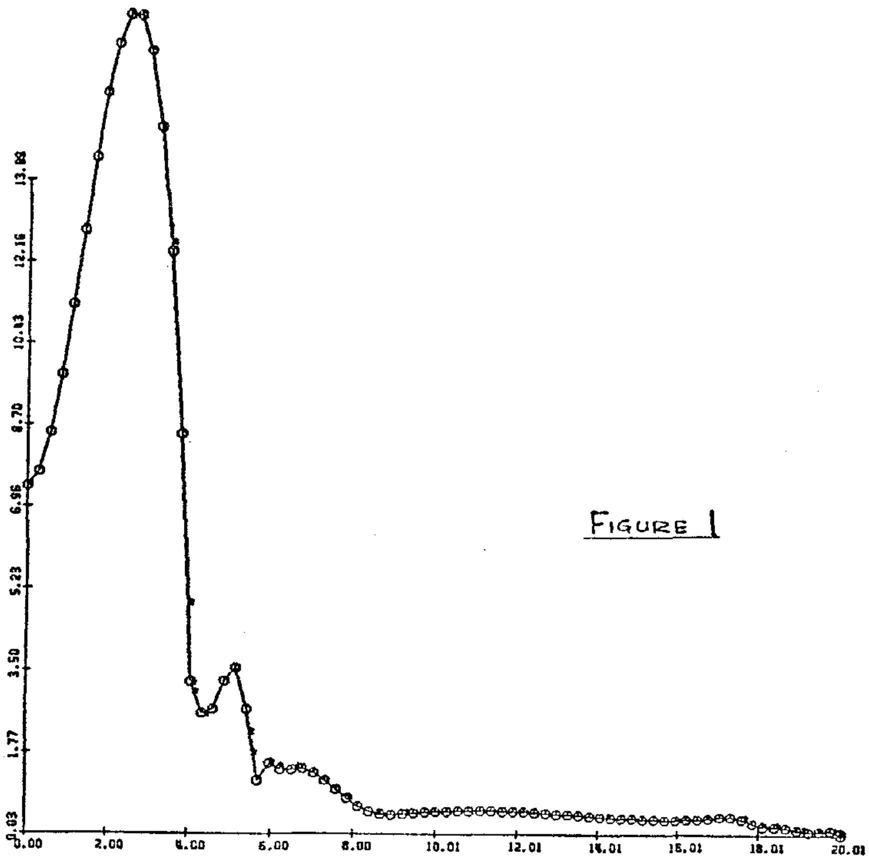

FIGURE 1

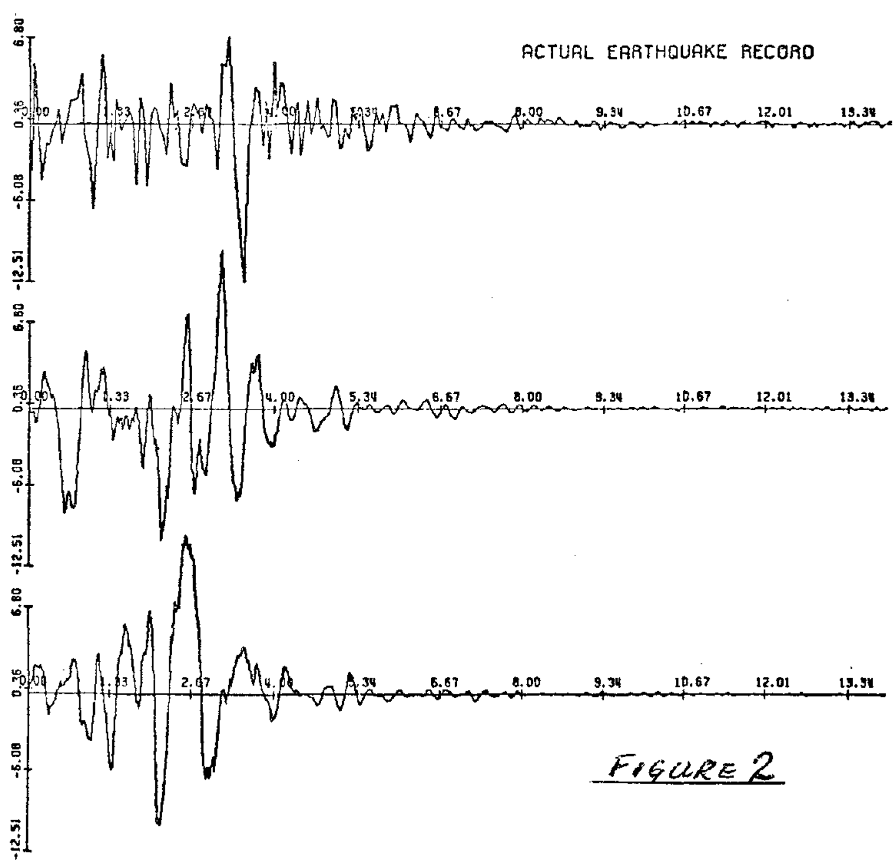

FIGURE 2

R.F. DRENICK and P.C. WANG

Polytechnic Institute of New York

The development of the so-called "critical excitation method" for the assessment of structural earthquake resistance is sponsored by the National Science Foundation. Research is being conducted in two areas: The modifications that are necessary in the basic idea of the method in order to make it applicable to the practice of earthquake engineering; and the generalizations of the method to inelastic structures, multi-dimensional excitations, etc.

Applications of the Method

The critical excitation, for a designated structural design variable (deflection, moment, shear, axial force, etc.), and for a designated set of possible ground motions of a certain intensity, is the one in the set which generates the largest response peak in that variable. In much of the work so far, only elastic structures have been considered. The main problem then developed to be the choice of the underlying set of ground motions. Ideally, it should contain all excitations which are considered "realistic" ground motions at the site of the structure, and as few others as possible.

The original idea was to admit all excitations, up to a certain intensity that is considered appropriate for the site. The "critical excitation" thus obtained is the time-reversed unit impulse response of the design variable adjusted to the required intensity. The set developed to be too large, however. It contains too many excitations that are patently unrealistic, and the critical one unfortunately often is among them. This is particularly true for structures with fundamental periods of more than 1 sec.

The set can be narrowed down in many ways, the simplest of which may be the following. Since it is to contain all "realistic" excitations one should probably insert into it all ground motions that have been recorded at sites with overburden characteristics similar to those of the site under study. This was in fact done. In addition, all those excitations were inserted into it which are linear superpositions of those recorded ones, provided only that their combined intensity did not exceed a specified maximum. The resulting set was the one used in much of the work reported here. Moreover, for computational efficiency, it was not the critical excitation proper that was determined in that set; rather, the excitation was calculated that differed least, in the mean-square sense, from the critical one obtained under the intensity constraint alone.

Eight conventionally designed or already built structures were analyzed and their responses to these excitations determined. At least on inspection, the synthetic excitations obtained in the way just described, appeared to be perfectly realistic samples of ground motions. The response peaks which they generated were compared with those produced by the 1940 El Centro SOOE, the 1971 Pacoima Dam S14W, and the 1954 N79E ground accelerations (adjusted to the same intensity). The ratios of the peaks were found to fall in the range of 1.1 to 2.9. Selected members were also checked for strength adequacy. Especially those of the structures designed by experienced engineering firms, were found to have sufficient reserve strength to sustain the synthetic excitation with the El Centro intensity, without resort to too high a ductility ratio.

The results encourage the hope that the critical excitation method, suitably modified, will lead to reliable, if somewhat conservative assessments of structural earthquake resistance. It is then most likely to be applied to structures of considerable social or economic value.

Generalization

The usefulness of the method, it is felt, would be enhanced if it could be generalized in several directions. Two such generalizations have been achieved. One is the extension from one-dimensional to multidimensional ground motions, and another is from elastic to inelastic structures. Neither extension, however, has so far been tested on existing or planned structures.

A. ASKAR AND A. S. CAKMAK

Princeton University

Although earthquakes occur with large deformations and high stress intensities which necessarily lead to nonlinear phenomena, most analytical efforts to date have been based on linear analyses in engineering seismology and soil dynamics, with only a few using numerical techniques in the study of nonlinear effects. There are, however, a wealth of problems such as the shifts in frequency, dispersion due to the amplitude, the generation of harmonics, and the coupling of shear and volumetric waves which are primarily nonlinear in nature and cannot be accounted for by a linear theory. The aim in this report is to present a methodology that would allow one to relate the microtremor measurements to strong earthquake spectra at the same location.

In this paper equations involving these nonlinear phenomena are developed, and the method introduced in earlier papers [1-3] for the solution of the resulting nonlinear equations for an infinite medium is generalized to the case of a finite region as it pertains to the phenomena mentioned above.

Consider a nonlinear stress-strain relation for the soil as:

$$\tau = G_o \frac{\partial v}{\partial x} + G_1 \left(\frac{\partial v}{\partial x}\right)^3 \tag{1}$$

where v is the shear displacement perpendicular to the direction of propagation x, τ is the shear stress, G_o and G_1 are respectively the linear and nonlinear shear moduli.

Corresponding to the nonlinear stress-strain relations in (1), the field equation is obtained as

$$\rho \frac{\partial^2 v}{\partial t^2} = G_o \frac{\partial^2 v}{\partial x^2} + 3G_1 \left(\frac{\partial v}{\partial x}\right)^2 \frac{\partial^2 v}{\partial x^2} \tag{2}$$

Above ρ is the mass density and t is the time.

The problems presented here are those of propagation of free waves in an unbounded medium as well as the standing waves in an elastic layer where one of the boundary is forced with harmonic motion. In the first problem, the frequency Ω for the nonlinear case is found to be

$$\Omega = \Omega_0 \left[1 - \frac{9G_1}{8G_0} q^2 \, v^2(x,0)\right] \tag{3}$$

where q is the wave number and $\Omega_o = \sqrt{G_0/\rho}\, q$ is the frequency of the linear case. Similarly the nonlinear wave comprises the fundamental mode and the third harmonics and is of the form:

$$v(x,t) = \frac{1}{2} v(x,0) \; [1 + \frac{1}{32} \frac{G_1}{G_0} q^2 \; (\frac{v(x,0)}{d})^2] \; \exp \, i \; (qx-\Omega t)$$

$$- \frac{1}{64} \frac{G_1}{G_0} q^2 \; (\frac{v(x,0)}{d})^3 \; \exp \; 3i(qx-\Omega t) \qquad (4)$$

+ harmonics of opposite sign

As for the second problem of a forced layer, in addition to the same features of the preceding problem, the resonance singularities of the linear analysis are seen to disappear through the frequency shifts through nonlinear coupling. Figure 1 illustrates the disappearance of the resonance infinity of the energy spectrum near the (nondimensionalized) frequency $\Omega = \pi/2$, for the case when one face is traction free, the other is given a harmonic displacement.

The present method is valid for any type of polynomial nonlinearity and may be extended to multilayer systems by means of transfer matrix methods. Furthermore, the nonlinear dispersion relation may be used to obtain frequency spectra under random inputs.

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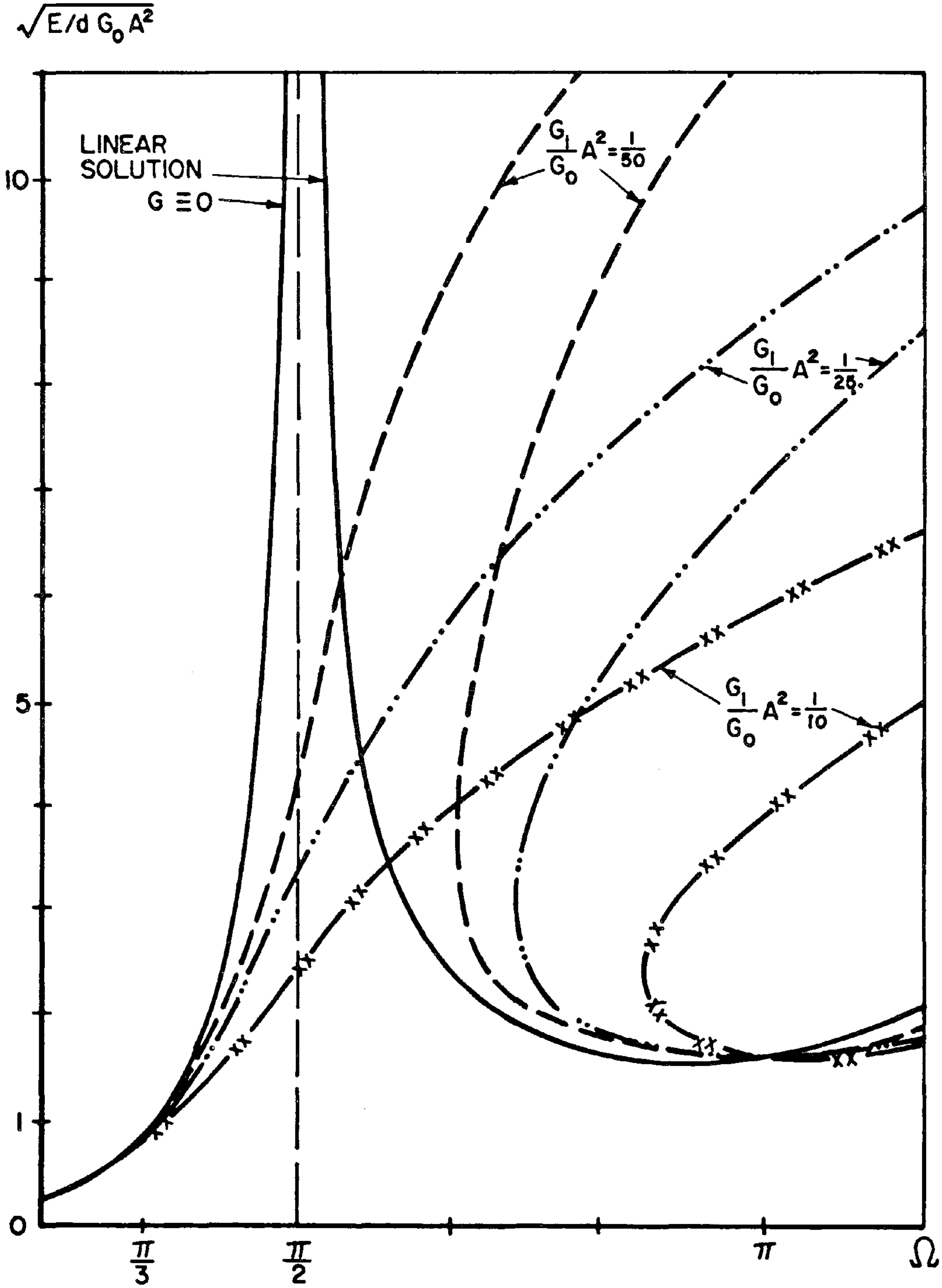
Fig. 1. Energy Spectrum: Linear and Nonlinear Solutions.



R. H. SCANLAN

Princeton University

Two problems concerned with aseismic design are currently under investigation:

1. For structures dealt with as elastic, means are under development for the economical derivation of secondary spectra from specified primary design spectra. The methods employed specifically avoid the intermediate use of detailed time histories.

2. For a broader class of structures, comprehensive means are sought to replace the commonly specified design spectrum as the definition of the earthquake input for aseismic analyses.

These two problem areas will be briefly discussed below.

1. Secondary Spectra from Primary Design Spectra

Specification of a "target" or "ground" response spectrum $S^T(\omega_s)$ for design may be considered the starting point of this problem. The usual first step is to recreate one or more examples of earthquake acceleration time histories which can cause maximum structural responses just enveloping the target spectrum (as in Refs. [1], [2]). The details of this step are avoided by the following process.

Let the desired input earthquake acceleration be specified by

$$\ddot{z}(t) = \sum_{n=1}^{N} Z_n \cos\left(\frac{2\pi nt}{T} + \phi_n\right)$$

where Z_n are to be determined, and ϕ_n are independent random on $(0, 2\pi)$. Define

$$A_n = \left|1 + \omega^2 H_T(\omega_s, \omega)\right| Z_n$$

where the A_n are structural response coefficients associated with a response Fourier series analogous to the input $\ddot{z}(t)$, H_T being defined as the structural transfer function

$$H_T(\omega_s, \omega_n) = [\omega_s^2 - \omega_n^2 + 2i\zeta_T\omega_s\omega_n]^{-1}$$

wherein ω_s is the structure natural frequency and ζ_T is a time-averaged damping function defined by

$$\zeta_T = \frac{\zeta^2\omega_s T}{\zeta\omega_s T - 1 + \exp[-\zeta\omega_s T]}$$

for a structure of actual damping ζ and an earthquake duration T. Then defining σ^2 as

$$\sigma^2_{(\omega_s)} = \frac{1}{2} \sum_{n=1}^{N} A_n^2(\omega_s)$$

an iterative process

$$Z_n^{(i+1)} = \frac{S^T(\omega_s)}{R\sigma(\omega_s)} Z_n^{(i)}$$

is set up which adjusts the coefficients Z_n until a specified multiple R of the response standard deviation σ meets the target spectrum. Selection of R is made following lines of Ref. [2], or, alternatively, R may be specified by an implicit scheme.

Secondary response Fourier coefficients B_n are then defined from the converged set Z_n by

$$B_n = \left|1 + \omega_n^2 H_{eT}\right| \left|1 + \omega_n^2 H_{str}\right| Z_n$$

where H_{str} is a generalization of H_T and H_{eT} is a transfer function of secondary equipment with time-averaged damping. The desired secondary response spectrum S_e is then a chosen factor R_e times the standard deviation of the set B_n. Many details are necessarily omitted here.

Fig. 1 (Ref. [3]) compares two secondary response spectra, one obtained in the above manner for a multi-degree system, without recourse to time histories, and the other by conventional time-history methods. Further studies are underway.

2. Broadened Specification of Strong-Motion Earthquake Input

As is well known, the usual "target" design spectra suffer from the following shortcomings for application to design: 1) they do not explicitly deal with "knowable" earthquake details, such as duration and overall "envelope" form; 2) they do not account for phasing between separate response degrees of freedom; 3) smoothed design spectra are usually mutually inconsistent among different damping values; 4) they are applicable only to elastic structures; 5) they do not separate excitation input from structural response thereto; 6) they do not provide direct access to secondary response spectra associated therewith.

The present study focuses upon the parameters: duration, envelope, acceleration level, and Fourier amplitude spectrum in an attempt to specify the anticipated design earthquake in a manner inclusive of these ascertainable data, and to provide a direct route to secondary response spectra.

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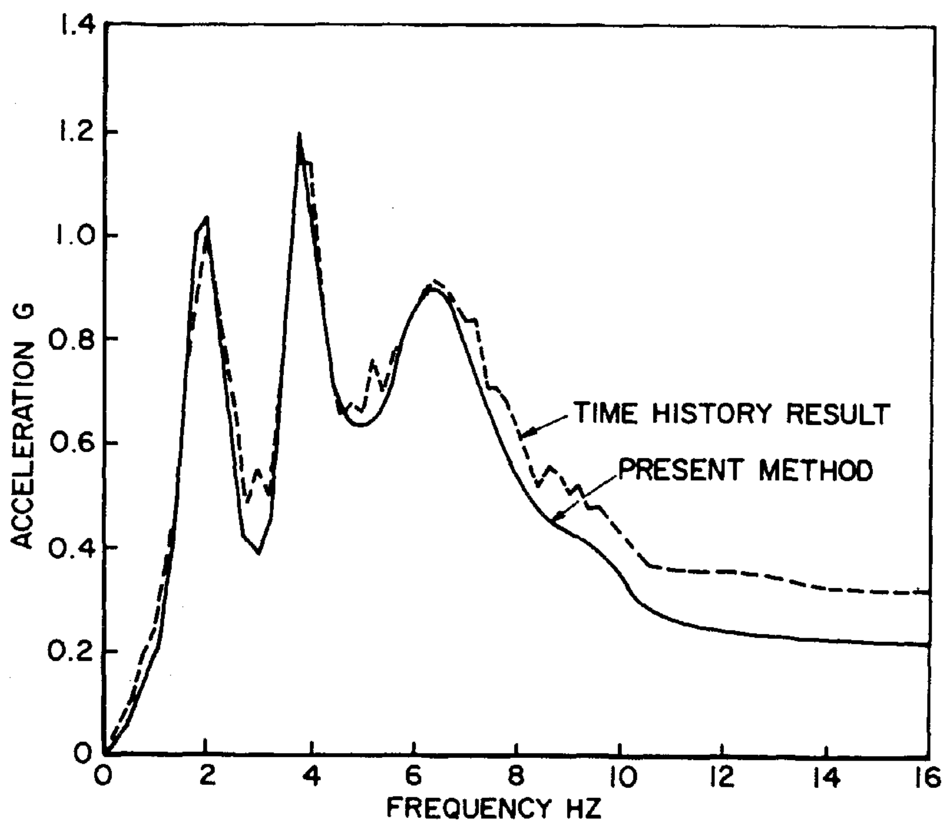

A REPRESENTIVE 3% SECONDARY SPECTRUM AT A POINT ON A COMPLEX STRUCTURE

FIGURE 1

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Purdue University and
University of Illinois at Chicago Circle

The purpose of this presentation is to describe a numerical method for integration of equations of motion. The method appears to be new, at least in some respects and details. The process is self-starting; step size may vary arbitrarily; properties of the system and characteristics of the forcing function may also vary. The method does not require more than one pass over each time-step as predictor-corrector and iterative processes require. Accuracy is high, computer costs are low, and the procedure is easily programmed.

The equation of motion for a damped one-degree-of-freedom system, with the usual definition of symbols, is

$$m\ddot{y} + c\dot{y} + ky = f(t)$$

This equation is transformed into a Volterra integral equation of the second kind by introducing the following substitution:

$$\ddot{y}(t) = Y(t)$$

so that the differential equation of motion is transformed to

$$mY + \int_0^t [c + k(t - \tau)]Y d\tau + (c + kt)C_1 + kC_2 = f \quad .$$

It can be easily shown that C_1 and C_2 are respectively, $\dot{y}(0)$ and $y(0)$.

The integral equation is solved numerically by representing Y over the time-step by a linear combination of appropriate functions:

$$Y(t) = Y_0 + A_1\theta_1(t) + A_2\theta_2(t) + \ldots + A_n\theta_n(t) \quad .$$

The A's are coefficients to be determined, the θ's are functions which may be as simple as powers of t, or may be polynomial functions, etc. When this representation of Y, together with consequent representations for $\dot{y}$ and y are substituted into the integral equation, this equation is transformed into an algebraic equation in which the A's are the unknowns. There are several methods for obtaining a solution to this algebraic form. Among these are collocation and variational methods. The values for $Y(= \ddot{y})$, $\dot{y}$ and y at the end of the time-step provide initial values for the following time-step.

An indication of accuracy is given by the fact that using a polynomial approximation of second power and a collocation algorithm produces results which have an accuracy approaching that which can be obtained by means of the Runge-Kutta fourth-order process. A cubic polynomial gives considerably greater accuracy and more rapid convergence with very little additional computational effort.

ANSHEL J. SCHIFF

Purdue University

Each of the following sections describes work associated with one of two projects which deal with the earthquake response or resistance of elements of electric power systems.

Earthquake Response of Electric Power Transmission and Distribution Systems

Electric power is one of the vital services of which the extended disruption can be a disaster in its own right. While utilities evaluate the response of their systems to first, second, and third contingencies, a methodology does not exist which can evaluate the response of a power system to the large number of failures which can be expected after a major earthquake. A methodology is being developed to evaluate utility systems. This methodology uses discrete event simulation (GASP IV) and Monte Carlo methods to simulate equipment failures and the post-earthquake recovery. The simulation is divided into several modules as follow. The Seismic Event Module uses knowledge of the geology, seismicity and history to postulate earthquake magnitudes with the major faults in the study area. The Local Seismic Environment Module (1) uses propagation attenuation and subsoil amplification laws to determine peak acceleration, velocity and displacements and surface spectra at each power system facility site. The Equipment Vulnerability Module determines the seismic exposure of each piece of equipment from knowledge of its method of mounting and the local seismic environment at the site. The Post-Earthquake Power Demand Module determines the initial reduction and subsequent change in power demand throughout the post-earthquake recovery period due to customer damage and recovery. The Equipment Damage Module (1) determines the operational status of each piece of equipment using equipment fragility, the seismic exposure and a random number generator. The Power System Reconfiguration Module (2) reconfigures the power system so as to maximize system performance. It also provides information on the effect of restoring various items of damaged equipment. The Recovery Module (3) simulates the recovery process through the allocation of repair crews, spare parts, and support equipment. The System Performance Statistics Module collects statistics for each Monte Carlo run which are then analyzed to evaluate system performance.

At the present time, the various parameters of the different modules are being adjusted to tune the simulation. Results of the simulation will be available at the end of the summer.

Field Testing of Power Transmission Facilities

While California utilities have adopted fairly stringent seismic requirements for their transmission facilities, equipment is only type tested. That is, a single production unit will be tested or analyzed to verify that it meets specifications. Large power transmission equipment are shipped in pieces and assembled in the field without further mechanical testing. This allows damaged equipment or improper installation to go without detection.

One purpose of the present effort is to develop a computer-based testing system which would facilitate acceptance/installation testing. A second goal of this effort was to do field testing to not only validate the system but to gather fragility data for use in the power system response study.

To date the system has been tested in the field and this work is continuing in conjunction with a local utility. An unanticipated benefit of this effort has been to raise the awareness of a large Midwest utility of the earthquake problem. Equipment which has been tested is also modeled using a specialized finite element program and the dynamic response is evaluated. Initial results indicate that the practice of minimizing slack in electrical cables between equipment can create reduced earthquake resistance. Construction standards are presently being reevaluated.

The system has been designed so that various methods of data analysis (4) are available and the system selects that which is best suited to the situation.

Evaluating Reliability of Structures With Ceramic Elements Subjected to Earthquakes

The electric power industry makes extensive use of ceramic structural members because of its desirable electrical properties. The brittle character of the material leaves much to be desired from the point of view of the structural designer. Present design practice for ceramic members is based on peak stress from static loads. A method is being developed using the flaw theory of failure in conjunction with the Weibull distribution function to assess ceramic member reliability when subjected to dynamic loads. The method incorporates effects of combined loads. The possibility of simplifying the design procedure using these methods is being evaluated and should be completed by the end of the year (5).

Seismic Reliability of Fossil Fuel Power Generating Facility

This project under the direction of Professors J. L. Bogdanoff and H. Lo deals with improving the earthquake response of fossil fuel power generating facilities. The main thrust is to develop simplified methods for doing dynamic analyses which are useful for design purposes. The systems being evaluated are: stacks, (self draft hyperbolic) cooling towers, coal handling equipment, piping systems, and the main power plant structure including the boiler.

The Paradise Power Plant, Unit #3 of the TVA, has been selected for study because of its location and the willingness of TVA to cooperate in the study. At the present time complex models using finite element methods with considerable detail have been completed. An experimental program to validate the complex models and determine estimates of system damping is well along. The power plant is located near a coal mine, blasting from which excites the power plant. Thus, this location holds the potential of obtaining the responses from blasting, winds (which can be quite severe) and earthquakes. Initial experimental results have confirmed the lower natural frequencies of the stack and power plant. Work has started on simplified models.

The experimental program has encountered many problems, several caused by power plant effluents. These included the chemical attack of instrumentation cables, causing 10% shrinkage, chemical attack on concrete structures causing instrumentation mounting problems, temperatures in excess of 120^{o}F and the need to occasionally wear gas masks because of the toxicity of the atmosphere.

It is anticipated that this work will continue for another two years, thereby allowing other plants to be analyzed and the work on simplified models to be completed.

Acknowledgements

The support of the National Science Foundation is gratefully acknowledged for work on power transmission facilities (GI 39428), as are the contributions of Professors James T. P. Yao and Ahmed H. El-Abiad, and for the work on power generation facilities (GI 41897) with contributions by Professors K. Kayser, A. Schiff, C. T. Sun, and H. Yang. Both of these projects have had significant support from the power industry. The work on the reliability of ceramics was initially supported by the National Science Foundation and is now supported by Purdue University.

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2. This work will be included in the Ph.D. thesis by Mr. Peter J. Feil.

3. This work will be included in the Ph.D. thesis by Mr. Donald E. Newsom.

4. This work has been carried out by Mr. James K. Sprandel.

5. This work will be included in the Ph.D. thesis by Mr. Rafael E. Torres-Cabrejos.

J. T. P. YAO

Purdue University

National Science Foundation sponsored research on active control of building structures for safety and/comfort. The literature on structural control was reviewed in 1971 [1]. Since then, the results of this research project at Purdue University are summarized herein.

Motion Control of Structures

Yao and Tang [2] suggested a two-stage active control system. The first-stage control can be used to maintain human comfort, and the second-stage control operates whenever the deformations of the structure are about to exceed corresponding limiting values for safety. In this phase of study, the problem of structural control is formulated. The control force in the form of series of impulse functions is studied and found to be effective. Solutions are obtained for certain cases of deterministic as well as random loads. As examples, the response control of one-story and two-story building structures subjected to wind loads and earthquake excitations are considered.

Yang et al [3,4] applied the stochastic control theory for the optimal control of the vibration of civil engineering structures. It is assumed that random excitations either stationary or non-stationary, can be represented by a filtered Gaussian shot noise. The structural system is described by a system of ordinary differential equations. It is further assumed that the measurements of all components of the response vector is possible. The effectiveness of the control system is measured with a performance index, which consists of (a) the covariance matrix of the response relating to the safety of the structure, and (b) the covariance matrix of the control force relating to the energy input requirement and thus representing a measure of economy. Under these conditions, the optimal control law which minimizes the performance index is a linear feedback control. The optimal control forces are obtained by solving a matrix Riccati equation. The same optimal control holds when the excitation is a shock of short duration. Moreover, the feasibility of implementing the optimal control by means of active dampers and servo-mechanisms are discussed.

Sae-Ung et al [5,6] studied structural control for human comfort. The criterion for human comfort is chosen on the basis of a literature review. A vibrational model of multistory building structures subjected to random excitation with comfort and/or safety control is formulated. Solutions were obtained with the use of the Monte Carol method. The mechanical principles for the safety and comfort control laws were obtained. The comfort control law was applied to a 40-story building structure. Results show that the comfort control law performed satisfactorily. In addition, statistical analyses indicate that it can be practical and feasible to use such an active control law in building structures.

System Identification in Structural Engineering

To control the dynamic motion of a structure, it is necessary to have a precise and current description of the system. Rodeman et al [7] studied and summarized some nine methods of system identification for structural applications. It was found that (a) most available methods deal with linear systems and (b) some techniques require noise-free test data. In reality, the structural response to dynamic load is frequently nonlinear, and the recorded test data are usually noise-polluted. Later, Rodeman [8] considered structures which can be represented with linear, time-invariant discrete parameter differential equations. A method was developed for the estimation of these parameters using noise-polluted transient reponse data. The frequency response function and its associated covariance matrix were estimated first, and then were used to estimate the abstract parameters of the assumed model using the method of maximum likelihood. Several numerical examples are given to demonstrate the efficiency and accuracy of this method. At present, an effort is being made to summarize current literature on system identification in structural engineering in tabular forms. The objective of this review is to re-examine the state-of-the-art in system identification from a broader perspective and the viewpoint of structural engineers.

Assessment of Structural Safety

Results of current research in system identification are certainly useful in giving more precise mathematical models of structures. Meanwhile a large body of knowledge has been accumlated concerning the behavior of structures. I have become interested in studying the possibility of formulating the problem of structural identification with the ultimate goal of assessing the reliability of structures in earthquake engineering, which requires the knowledge in both specialties. Figure 1 shows the current procedure of system identification and its application in structural engineering. It may be possible to assess the structural safety (or damage) in a more direct manner as indicated by the dash line in Figure 1.

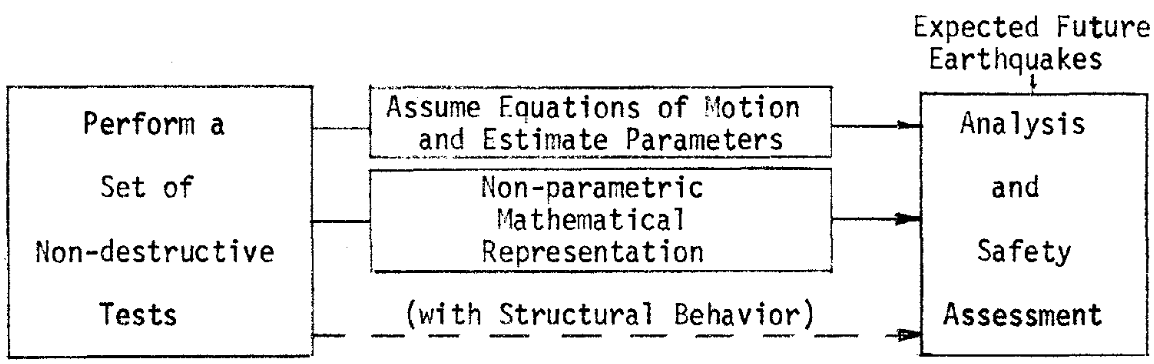

Figure 1

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A. S. VELETSOS

Rice University

Current research in earthquake engineering at Rice University is of an analytical nature and includes (a) studies of the dynamics of liquid storage tanks, (b) studies of selected problems of foundation dynamics and the dynamics of soil-structure interaction, and (c) studies of the coupled lateral-torsional response of structures.

The broad objectives of these studies are to assess the effects and relative importance of the numerous factors which influence the dynamic response of these systems; to develop information and concepts which may be used to anticipate the significant effects without the need for elaborate computations; and to develop improved methods of analysis and design. Since the characteristics of the ground motion and the physical properties of structures and soils are subject to considerable uncertainty, special attention is paid to assessing the sensitivity of the response to the uncertainties involved in defining the input motion and the physical properties of the structure-soil system.

Studies of Dynamics of Liquid Storage Tanks

These studies deal with the response of circular cylindrical, cantilever tanks which are filled with liquid and are subjected to a lateral component of ground shaking. The tanks are presumed to be of a uniform wall thickness and fixed at the base. Work todate has included the following four phases:

Phase 1 dealt with the hydrodynamic forces induced in rigid tanks. This effort has led to a clarification of the mathematical significance of the so-called impulsive and convective effects and to considerable new numerical data concerning the magnitude and distribution of the associated hydrodynamic forces.

Phase 2 involved the development of a simple approximate method for evaluating the effects of tank flexibility on the magnitude and distribution of the hydrodynamic forces. In this approach, the tank is treated as a single-degree-of-freedom system by assuming that it vibrates in a prescribed mode along its height with no distortion of its cross section. The method, which is an extension of that reported in Ref. 1, is clearly of limited applicability, but it provides valuable insight into the response of the system in many cases and a convenient frame of reference for the interpretation of the results of more precise analyses.

Phase 3 involved a comprehensive numerical study of the natural frequencies and modes of both empty and full tanks. This study was based on Flügge's shell theory and involved the use of the Rayleigh-Ritz procedure in combination with the characteristic functions for uniform cantilever beams. Special attention was given to modes of vibration for which there is a single sine wave in the circumferential direction.

It has been shown that the behavior of the tank depends primarily on its height-to-radius ratio, H/r. For large values of this ratio, the tank vibrates in a mode similar to that of a cantilever flexural beam, with practically no distortion of its cross section. For smaller values of H/r, the vibrational mode approaches that of a cantilever shear beam, and again involves little distortion of its cross section. For still smaller values of H/r, the vibrational mode corresponds to that of a series of independent rings undergoing extensional vibration, and for extremely small values, the wall of the tank vibrates essentially as a series of independent cantilever flexural beams. The transition between these four different types of behavior is naturally smooth rather than abrupt.

The fourth and final phase of this study involved the formulation of a general method for analyzing the forced vibration of the tank-fluid system, without any of the simplifying assumptions made in the Phase 2 study, except for the assumption of the anchored base. In this approach, the response is expressed as a linear combination of the natural modes evaluated in Phase 3.

Problems of Foundation Dynamics and Dynamics of Soil-Structure Interaction

In the area of foundation dynamics we have been studying the harmonic response of torsionally excited rigid, circular foundations which are supported at the surface of a two-layer elastic or viscoelastic medium. Such a medium consists of a stratum of uniform thickness overlying a halfspace. This study is complementary to those reported several years ago by Kashio (2) and Wei (3) for foundations in other modes of vibration. The response of the system is evaluated over wide ranges of the parameters involved, paying special attention to the influence of the relative rigidity of the two layers and to the effects of viscoelastic action in the medium.

In the study of foundations on an elastic medium, the system is analyzed exactly as a mixed boundary value problem, whereas in the study of the viscoelastic problem an approximate solution is used, based on an assumed distribution of the contact pressure at the foundation-soil interface.

Important objectives of this study are to elucidate the details of the mathematical solution, and to assess the sensitivity of the results to the numerical techniques employed in the solution. Those familiar with the literature on this subject will well appreciate the need for such a detailed study.

The aim of our current studies of the dynamics of foundation-structure interaction is to define the limits of applicability of the various approximate procedures that have been proposed in this area (4), and to develop improvements when necessary. The accuracy of these procedures is assessed by comparison with the results of "exact" analyses, the latter being obtained either in the frequency domain, by use of discrete Fourier transform techniques, or directly in the time domain, by use of the impulse response functions reported in (5).

Studies of Coupled Lateral-Torsional Response of Structures

The source of coupling between the lateral and torsional response of structures may be that the centers of mass and resistance of the structure do not coincide, or it may be a consequence of the fact that, because of the finite speed of propagation of the ground motion, all points of the base of the structure are not excited simultaneously. The effects of both factors are investigated for relatively simple structures responding in either the elastic or the inelastic ranges of behavior.

The work to date included studies of the response of symmetric linear structures to a horizontally propagating ground motion; studies of the response of eccentric linear structures; and studies of the response of both symmetric and eccentric yielding structures (6,7).

Acknowledgment

Part of this research was supported by the National Science Foundation under Grant GK-25917. The studies were carried out by Drs. M.O. Erdik and J.Y. Yang, and Messrs. A. Prodanovic and J.B. Valdivieso.

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BIJAN MOHRAZ

Southern Methodist University

The studies reported herein are a continuation of two statistical studies on horizontal and vertical earthquake response spectra which were carried out with Drs. Newmark and Hall at the University of Illinois. Currently the influences of site condition, duration of strong motion, magnitude of the earthquake, and distance of the recording station from the fault on ground motion, response spectra, and response amplifications are being studied.

The influence of geological conditions has been nearly completed. For investigating the effects of the geological conditions on ground motion, response spectra, and response amplifications a total of 54 complete records (three components each) from 46 recording stations in 16 seismic events are considered. The records are divided into 4 categories: those located on rock deposits; those located on approximately less than 30 ft. of alluvium underlain by rock; those located on approximately 30-200 ft. of alluvium underlain by rock; and those located on alluvium deposits. For each category statistical studies of peak ground motion and amplifications (ratios of the computed response to the peak ground motion for acceleration, velocity, and displacement) are carried out. The computations for amplifications are performed for five damping coefficients and at a large number of frequencies to include the applicable range of frequencies in the design spectra. The amplifications are then averaged within the acceleration, velocity, and displacement regions of the spectra to obtain design amplifications.

The results obtained to date indicate that the ratio of the peak ground velocity to peak ground acceleration for rock deposits is substantially lower than those for alluvium, with the ratio for alluvium layers underlain by rock being between those for rock and alluvium. The results also indicate that the average acceleration amplification for alluvium deposits extends over a larger frequency region than the amplifications for other site categories. The maximum acceleration amplification for the two alluvium layers underlain by rock is substantially greater than that for either rock or alluvium deposits.

Design spectra for each site category and each damping coefficient are computed from the product of ground motion and the corresponding amplifications. The desired degree of conservatism could be included in the design spectra by selecting higher percentiles for either or both ground motion and amplifications. As in the previous studies, the average ground motion and the median plus one standard deviation amplifications are used in computing the design spectra. Since the majority of current design spectra are based on records from stations on alluvium deposits, a set of coefficients are presented by which the ordinates of the design spectra for alluvium deposits could be multiplied to give the design spectra for other site categories. Comparisons of design spectra for different geological conditions indicate that the design spectra for rock and the two alluvium layers underlain by rock have substantially lower bounds in the velocity and the displacement regions, and a higher bound in the acceleration region than the spectra for alluvium. The study reveals that the current design spectra, which are based primarily on records from stations located on alluvium deposits are, in general, too conservative for other site categories.

Currently, similar studies are being carried out for the influence of the duration of strong motion.

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HARESH C. SHAH

Stanford University

Various research subjects that currently are under investigation at The John A. Blume Earthquake Engineering Center of Stanford University are the following: near-field seismology, dynamic scale modeling of structures, measurements and analysis of oil refinery structures, seismic risk analysis for various regions of the world, development of lateral load resisting criteria, lifeline earthquake engineering, analysis of past earthquake data, utilization of digitizing facilities, development of efficient digitizing and zero-correction routines, and public policy in earthquake effects mitigation. These projects are supported by the National Science Foundation, the State of California Department of Water Resources, Banco Central de Nicaragua, Ministries of Planning in Nicaragua and Costa Rica, the Institute of Engineers in Guatemala, and The John A. Blume Earthquake Engineering Center (JABEEC).

Descriptions and scope of several of the above projects will be presented in accompanying reports by Professors D. M. Boore, J. M. Gere, and T. C. Zsutty. Some of the research sponsored and supported by the JABEEC will be described in this report.

The John A. Blume Earthquake Engineering Center

The JABEEC was established recently at Stanford University to promote research and education in earthquake engineering. The Center conducts research, provides instruction, publishes reports and articles, conducts seminars and conferences, and provides financial support for students and faculty.

The major facilities of the Center are located in one of the engineering laboratory buildings on the Stanford Campus. The structural dynamics laboratory contains equipment for static and dynamic testing, including a shake table and test sled. The shake table is intended for model studies and can simulate any specified earthquake ground motion. The Fourier laboratory contains a complete Fourier analyzer system and computer, with associated equipment such as readers and plotters. A laser interferometer is used for dynamic measurements of structural motion either in the lab or at field locations. The computer and data processing laboratory contains equipment for digitizing and analyzing earthquake records. The geotechnical laboratory contains facilities to study behavior of soils under static and dynamic loading. Earthquake-related equipment includes a simple shear device, a liquefaction unit, and a self-boring pressure meter for in-situ testing.

Earthquake Digitizing and Data Acquisition System

The computer and data processing laboratory of the Center contains the following equipment:

Bendix Datagrid Digitizer
(Size 42 x 60 in.; resolution 0.002 in.; tracing speed 300 in./sec.)
HP 9864A Digitizer
(Resolution 0.01 in.; rate 50 points/sec.)
HP 9830A Calculator
(7904 16 bit word memory; BASIC language; external storage on HP cassettes)
HP 9866A Line Printer
(240 lines/min.)
HP 21MX Central Processing Unit
(32k memory; 16 bits/word; software includes FORTRAN IV, ALGOL, etc.)
Tektronix 4631 Hardcopy unit
Tektronix 4012 Graphics unit
HP 2748B Paper Tape Reader
HP 7970B Magnetic Tape Reader
CALCOMP 563 Plotter
HP 2313B Analog - Digital Subsystem
Data Products 2230 Line Printer
Terminals
(and auxiliary equipment)

Efficient routines are under development for digitizing data and achieving zero correction. All digitizing software is written in an interactive format so that the user and the machine can achieve desired results quickly and efficiently.

In another project of the Center a detailed study of all available (and digitized) strong motion data is being conducted. Parameters such as site conditions, magnitude of events, distance from epicenter, and duration of the record, are statistically studied to arrive at some characteristics of future events. In particular, it is observed that for all the available earthquake records, parameters other than the spectral accelerations, velocities, displacements, and peak ground accelerations should be investigated.

Geotechnical Engineering

In the geotechnical field, studies are underway into landslide phenomena in lightly cemented soils and deformation property determination for earthquake response analysis. The landslide work is oriented towards the type of slope failure which occurred in Guatemala in the February 1976 earthquake. The deformation property investigations are concerned with in-situ testing in soft clays; a new self boring pressure meter is being used to determine soil modulus values at high strain levels.

Publications

The following list of reports illustrates the results of research done by the Center in recent months:

"A Study of Seismic Risk for Nicaragua, Part 1", by H. C. Shah, C. P. Mortgat, A. Kiremidjian, and T. C. Zsutty, January 1975.

"A Study of Seismic Risk for Nicaragua, Part 2", by H. C. Shah, T. C. Zsutty, H. Krawinkler, C. P. Mortgat, A. Kiremidjian, and J. O. Dizon, Parts A and B, March 1976.

"Dynamic Analysis of Suspended-Floor Highrise Buildings Using Super-Elements", by B. J. Goodno, January 1975.

"Ambient Vibration Study of Six Similar High-Rise Apartment Buildings", by C. A. Kircher and H. C. Shah, January 1975.

"Probabilistic Seismic Exposure and Structural Risk Evaluation", by J. S. Dalal, January 1975.

"On Stochastic Load Combination", by W. Bosshard, July 1975.

"Earthquake Damage Prediction: A Technological Assessment", by J. A. Blume, E. C. W. Wang, R. E. Scholl, and H. C. Shah, October 1975.

"Analysis of Soil-Foundation-Structure Interaction During Earthquakes", by K. Ukaji, March 1975.

"Decisions of Optimum Structural Safety", by R. B. Kulkarni, May 1975.

"Determination of the Dynamic Characteristics of Full Scale Structures by the Application of Fourier Analysis", by C. A. Kircher, November 1975.

"Seismic Hazard Mapping of California", by A. Kiremidjian and H. C. Shah, November 1975.

"Seismic Risk Analysis for California State Water Project, Reach C", by H. C. Shah, M. Movassate, and T. C. Zsutty, March 1976.

DAVID M. BOORE

Stanford University

Several research projects concerned with the understanding and prediction of ground motions are being conducted with industry and National Science Foundation support: prediction of the surface wave contribution to ground motion at offshore drilling platform sites, study of ground motions from the 1906 San Francisco and 1952 Kern County earthquakes, and the development of a combined statistical-deterministic procedure to estimate ground motions close to faults.

Surface waves. Several factors make the specification of design motions for offshore drilling platforms a nonstandard problem: resonant periods of the structures are in the range of 2 to 6 sec, the nearest large fault may be 100 km or more from the site, and the ocean floor often has a thick (several tens of meters) cover of low rigidity sediments. No data are available for ground motions in this situation, and therefore we have used the computer to generate synthetic seismograms. Inspection of existing strong motion data suggests that surface waves dominate the motion in the period range of interest. This is borne out by the theoretical seismograms. The details of the motion are governed by a complicated interaction of several modes whose relative importance is controlled by frequency dependent resonance and attenuation. Although generalizations are difficult to make, we have attempted a few: phase differences across the horizontal extent of the structures (50-100 m across) should be small for periods greater than about 2 sec. The near-surface sediments have little effect on motions beyond 2-3 sec unless significant nonlinear response occurs, in which case motions with periods up to about 5 sec will be strongly influenced by the sediments. The surface waves and body waves have a similar dependence of motion with depth, suggesting that a body wave soil column analysis may adequately account for the influence of the near-surface sedimentary layers, provided that the input motion contains appropriate energy in the 2-6 sec period range.

Strong motion records. Strong motion studies are limited by the lack of data from large earthquakes, especially for recording sites close to faults. For this reason computer modeling can be a useful guide to the specification of design motions. It then becomes important to test these models against existing strong motion recordings. Here we discuss two sets of data which we are currently working on.

It is not generally recognized that the 1906 San Francisco earthquake was recorded at Mt. Hamilton, within 35 km of the fault (fig. 1). The record went offscale after the first half cycle of the S-wave arrivals and returned to scale after about 50 sec, but enough information exists both to constrain the epicenter of the event and to provide some data against which theoretical predictions of ground motion can be checked. The recordings are comparable to those from doubly integrated accelerograms: Fig. 2 shows the 1906 data (traces #1 and #2) compared with data from other strong motion recordings. Although no comparison of amplitudes can be made, the overall duration of the records is comparable. The theoretical body waves from a propagating rupture are shown in trace #3. Not shown are the theoretical surface waves, but these have amplitudes up to 9 times larger than the body waves and also give motions after 50 sec. which are comparable to the observed motions. Because of Doppler-like effects, the absolute amplitudes are sensitive to the speed of rupture propagation; reducing the rupture velocity from 3 km/sec to 2 km/sec reduces the peak surface wave motion by a factor of 5.

The 1952 Kern County earthquake is the largest (M = 7.7) California event for which a significant amount of data is available. As part of a comprehensive study of this data we have studied accelerograms recorded at Santa Barbara, Taft, and Pasadena. The velocity records all show a simple S pulse followed by a complex series of arrivals. Simple time considerations show that the first S pulse can only represent a small part of the overall rupture. Information on the rest of the rupture is contained in the jumble of arrivals following the first pulse. We are interested in separating the effects of geology from the complications due to erratic propagation and these records should provide important data for this. Figures 3 and 4 show a simple example of the effects of slightly noncoherent rupture. Fig. 3 is a model of the rupture surface. In one case smooth propagation outward from the focus was assumed and in the other, the smooth propagation was approximated by a series of fault segments properly lagged in time. The waves at the Pasadena station are remarkable different in the two cases, with the more complex fault giving a record which is more similar to the recorded motion (Fig. 4).

Statistical-deterministic predictions of motion. The example above demonstrated the importance of slightly incoherent rupture. Since it seems unlikely that extended ruptures propagate smoothly, the radiation produced by the "chatter" in propagation will be an important part of the near fault ground motion, especially at higher frequencies. (We expect the acceleration traces to be more sensitive to this effect than the displacement traces.) The study of this effect is in the initial stages. We have constructed various theoretical waveforms for equivalent point sources and compared them favorably with accelerograms from a small earthquake near Bear Valley, California. Our future work will involve the analysis of records from extended ruptures such as the Kern County earthquake.

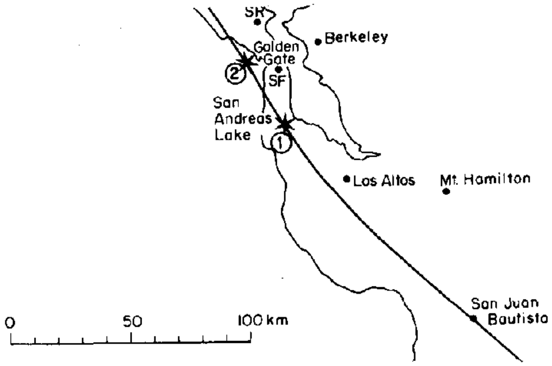


Fig.1.Dark line is the San Andreas fault.The 1906 epicenter was close to point 2.

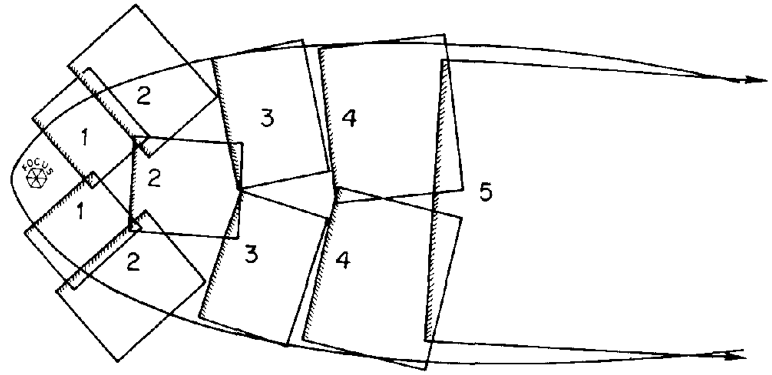


Fig.3.Schematic of 1952 Kern County earthquake rupture surface.Rupture started at the left side.

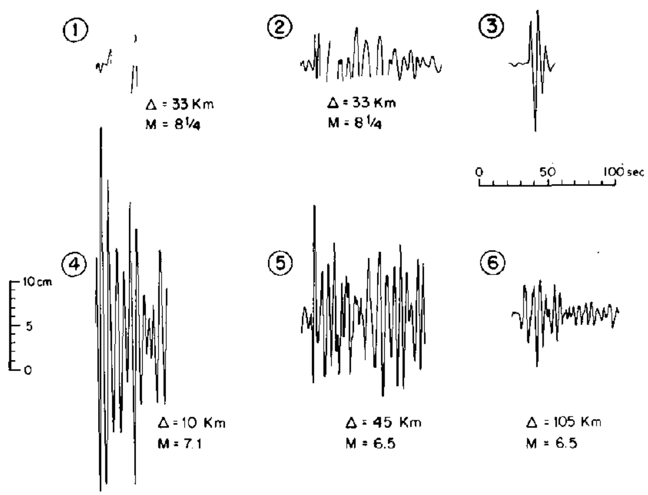


Fig.2.Comparison of 1906 and more recent data.

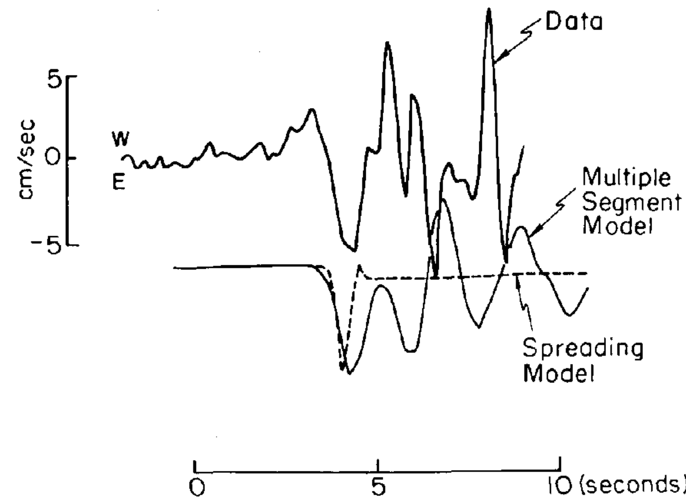


Fig.4.Comparison of waveforms for the Pasadena recording of the Kern County earthquake.

JAMES M. GERE

Stanford University

The behavior of oil refinery structures is being investigated through testing and analysis of several vertical vessels (or tall columns) located in a major California refinery. The objectives are to gain a knowledge of the dynamic properties of such structures and to improve the procedures used in designing them to resist seismic ground motions.

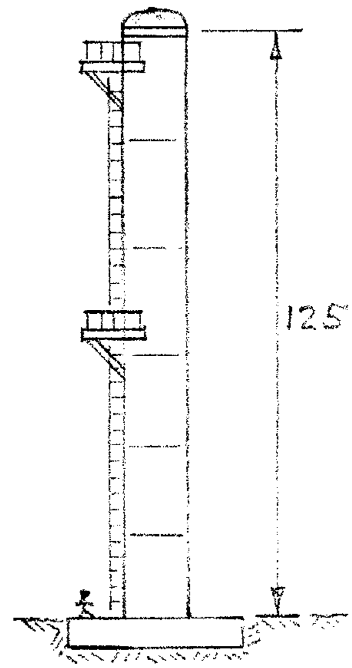
Model studies of building structures are being conducted with the long-range goal of reproducing on small-scale test facilities the response of large structures subjected to earthquake-induced motions. This research involves modeling theory, investigations of material properties, development of model construction techniques, instrumentation and data processing, and testing on a small shake table.

Both research projects are supported by the National Science Foundation, Research Applied to National Needs (RANN). Additional financial support for the refinery project is provided by the Standard Oil Company of California and for the model project by The John A. Blume Earthquake Engineering Center, Stanford University.

Testing of Oil Refinery Structures

Oil refinery structures can be severely damaged during earthquakes, resulting in waste of fuel, loss of refinery capacity, and the creation of a fire hazard from leaks and spills. Damage to refinery facilities was extensive during the earthquakes in Niigata (1964), Alaska (1964), and Kern County (1952). Present design practice for refinery structures essentially follows the concepts of the Uniform Building Code (UBC) and the recommendations of the Structural Engineers Association of California (SEAOC) for the design of buildings. Modifications of these provisions have been made to account for differences between buildings and refinery structures, but the basic concept remains that of equivalent static lateral forces. In order to improve on this method of design and make use of existing knowledge of ground motion properties and dynamic response of structures, it is necessary to know the dynamic characteristics of typical refinery structures.

Vibration measurements are being made on several tall columns sited on both rock and clay. Both ambient and forced vibration tests are being performed on each column in order to determine how the vibration properties (natural frequencies, mode shapes, and damping) vary with the amplitude of motion. The measurements are recorded on site by the Fourier Analyzer system utilizing accelerometers mounted on the columns at various locations from the ground to the top. The signals from the accelerometers are recorded and analyzed at the site in order that immediate decisions can be made as to what additional measurements are required.



The tall columns being investigated are typical of those used in many refineries for chemical processes such as distillation, cracking, and platforming. The main structure is a cylindrical shell (perhaps 0.5 inch thick) to which are attached various external piping connections as well as a climbing ladder with several landings. A typical column might be 125 ft. high with a diameter of 10 ft. and a shell thickness of 0.5 in. The principal internal parts are horizontal trays, spaced a short distance apart vertically, which fill the column from top to bottom. The columns currently being tested are not in operation, hence the vibration measurements are not affected by any moving liquid contents.

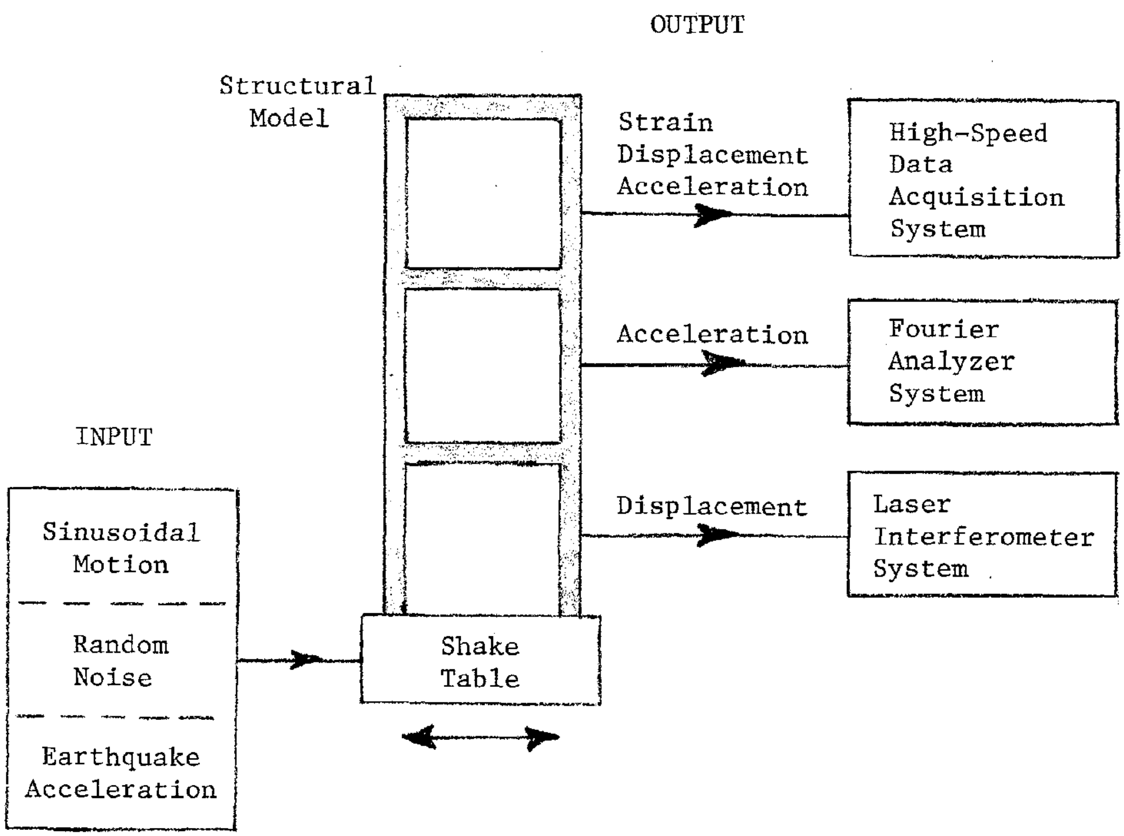
In addition to testing of the structures, it is planned to make mathematical models of them and then perform dynamic response analyses using existing computer programs. The measured and analytically-derived properties will be compared and correlated. Also planned are evaluations of soil-structure interaction effects. The final phase of the study consists of establishing design provisions for tall columns and recommending changes in current design practice.

Scale Modeling and Testing of Building Structures

The objective of this research project is to develop the capability for reproducing on laboratory test facilities the response of structures to specified earthquake excitations. The facilities used for this study include a small shake table (5 ft. by 5 ft.) with an input control system, a high-speed data acquisition system, Fourier analyzer system, laser interferometer system, high-speed cameras, electronic sensors, and auxiliary equipment. A schematic diagram of the overall testing set-up is shown on the next page.

As a preliminary matter, dynamic modeling theory is being investigated so as to provide a sound basis for the design of models. It appears that existing modeling theory can be extended to include the nonlinear, time-dependent behavior of materials. An investigation of mechanical properties of materials also is being conducted, with the goal of identifying special materials for constructing models that meet small-scale simulation requirements. A literature survey on the subject of damping in structures was completed as part of these preliminary investigations.

The development of model construction techniques will be an important phase of this project. Attempts will be made to model dynamically some simple types of structures including joints, supports, and nonstructural elements. The response of the models to various input ground motions will be determined by measuring strains, displacements, and accelerations at various locations. The necessary instrumentation and high-speed data handling has been under development for several months, and work is now beginning with actual models. Numerous subjects are of importance for future model studies: dynamic response in the post-elastic range, energy dissipation, effects of nonstructural elements on dynamic structural characteristics, effects of bracing, rocking and overturning effects, and soil-structure interaction.



THEODORE C. ZSUTTY
HARESH C. SHAH

Stanford University

Several research projects are being conducted in the general fields of planning and design. The specific projects are:

Seismic risk analysis and related design recommendations for the countries of Nicaragua, Costa Rica, and Guatemala

Lifeline hazard evaluation of the California Water System (supported by the Dept. of Water Resources, State of California)

Public policy for mitigation of earthquake effects through earthquake prediction and design regulations (supported by The John A. Blume Earthquake Engineering Center)

The following discussion is concerned with the first of these three projects.

Seismic Risk Analysis

For each of the three countries, iso-acceleration maps for regions and acceleration zone graphs for cities are being developed. These provide peak ground acceleration (PGA) values having a given probability of exceedence during a selected economic life time. The associated research tasks involved are:

Acquisition of historic and measured data for seismic events.
Location and description of earthquake sources.
Formulation of recurrence rates for individual sources.
Selection of attenuation equations based on regional characteristics.
Probabilistic modeling for exceedence.
Relation of PGA to the effective acceleration for scaling of response spectra.
Probabilistic description of response spectrum ordinates for given general site conditions.

The final maps and graphs are employed in the following manner. In a seismic region such as Central America, planners, building owners, and regulatory agencies must accept a moderate risk of damage and a small risk of condemnation during the economic life of any planned structure. These acceptable risks may be expressed numerically as probabilities P_D and P_C for damage and condemnation respectively, and their values depend upon the essential use or importance of the structure. The description of seismic hazard conditions in the form of an iso-contour map and acceleration zone graphs allows the relation of these acceptable risks to a descriptive parameter of the corresponding future seismic events. Specifically, the PGA value from the map or graph is converted to an effective acceleration value which is then used as a scaling factor for the formation of a representative response spectrum for future events.

Design Recommendations

Design rules must follow logically from the phases of seismic risk analysis. They must incorporate this information to provide the structures which can perform reliably at earthquake levels having the acceptable risks or chances of exceedence. The expressed needs of the regulatory agencies and the design profession of the contracting countries are for a response spectrum approach with levels based upon the seismic risk zoning. The primary requirement is a well defined procedure for dynamic analysis along with a simplified base shear version.

Since the complete design procedure is to be employed by review agencies and designers who are not particularly familiar with the state-of-the-art of seismic design, it is most important to provide a physical interpretation for all factors and parameters. This rationality is necessary in order to prevent inadequate system configurations and non-appropriate design load levels. In order to best achieve the close physical understanding of both earthquake effects and structure behavior, a dual spectrum criterion was selected:

Damage Threshold: for member strength design and damage drift analysis.

Condemnation Threshold: for evaluation of local ductility demands and verification of stability.

The damage threshold spectrum was selected for the strength design basis in order to avoid the assumption of the general ductility factor that would be required for an inelastic yield level spectrum. Designers can better visualize the damage state and its relation to the strength design level of the highest stressed members.

The level of the design force spectrum depends not only upon the classic K-factor type of the structural system, but also upon a quality grade assigned for any particular building. A grade of A, B, or C is given according to configuration regularity, stability, reliability, and quality control. Design loads are decreased about ten percent in order to benefit the good A grade systems and are increased to penalize the marginal C systems.

Work is continuing on:

Appropriate shapes and confidence levels for design spectra.
Classification and grading rules for structural systems.
Evaluation of local ductility demands and allowable values for various materials and systems.
Formulation of a simplified base shear version.

GEORGE C. LEE, DAVID T. TANG, and WILLIAM TOWNSEND

State University of New York at Buffalo

This report describes three current studies in earthquake engineering research at the State University of New York at Buffalo.

1. Seismic Response of Low Frames

This study involves the seismic behavior of low, large span buildings (industrial frames, schools, markets, etc.) attempting to bring into light several response patterns not included in the usual practice, and to assess their relative importance. One of the important items addressed to is the behavior of connections associated with warping torsion and their influence on the overall frame responses. The earthquake motion is introduced horizontally with different angles in relation to the building principal axis so that the relative importance of the different mode shapes can be assessed. Similarly, the vertical component of seismic motion is also introduced. The mathematical model comprises linear members having seven degrees of freedom per node (1); including warping torsion. The buildings are therefore modelled as three-dimensional structures. The mass properties or inertia effects are modelled by means of a consistent mass matrix, having equally seven degrees of freedom per node due to the reasoning that the type of structures under consideration do not have a clear physical point of mass concentration, as do high-rise buildings. The mode shapes of several typical structures have been determined and the influence of warping on the seismic performance of structures is being examined. An attempt is also made to correlate simple features such as stiffness and mass ratios to the expected behavior. It is hoped that a more clear understanding of the seismic behavior of low buildings can be gained by using this three-dimensional model.

2. Nonproportional Damping Mechanism

The objective of the research is to identify the role a nonproportional damping mechanism plays in the seismic response of structures. Such mechanism may be associated with, for instance, dynamic interaction between a stiff structure and its relatively flexible foundation.

The study is being made possible by making use of the experimental data available for a three-story steel frame structure tested at the Berkeley Earthquake Simulator Facility (2). It is motivated by realizing that the small-amplitude vibration damping ratios (0.1%) for this structure rigidly supported on the lab floor was observed to have much smaller values than the ones (0.5%) for the structure mounted on the shaking table. Although a mass-proportional damping model performs very well in data correlation (3), it is conceivable that a nonproportional damping model may also be adoptable for this shaking table-structure interaction system. The starting mathematical model comprising an assemblage of structural elements including those accounted for joint panel zone deformation and shaking table rocking is same as the one used in previous study. In the present study, however, the system equations are reduced initially by means of static condensation to have four degrees of freedom (three degrees for floor horizontal translation and one for table rocking). By admitting the normal mode decoupling for the fixed base structure, the final damping matrix can be defined by the modal damping ratios and the foundation damping coefficient. The direct step-by-step integration is then performed only for the four coupled equations of motion. The effect of the foundation damping on the response of the model can be identified since the modal damping ratios of 0.1%, say, is kept constant while the foundation damping coefficient becomes the sole model parameter to be adjusted throughout a series of response computation. In case that the data reconciliation is considered acceptable, it may be concluded that the relatively small damping ratios measured during small-amplitude vibration for field structures should directly be employed in the elastic dynamic response analysis provided that soil-structure interaction effect is also properly incorporated into the model.

In line of this work it is hoped that criteria and methods to interpret field damping data for each subsystem of a soil-foundation structure system can be developed so that damping matrices can more realistically be defined.

3. Ductile Design of Interior Reinforced Concrete Connections

An experimental study of full-scale interior reinforced concrete beam-column connections loaded to duplicate seismic conditions is being conducted. During a major earthquake an interior connection can be loaded with bending moments simultaneously on opposite column faces in the same sense that are large enough to yield the logitudinal beam steel. This loading condition produces high bond stresses around the longitudinal beam steel as it goes through the column which can produce complete bond failure during the first large inelastic loading cycle. In order to eliminate these high bond stresses the beam steel is bent 30° near each column face so that it goes diagonally through the joint core.

Full-scale reinforced concrete connections with a slab segment are being constructed using Grade 60 steel and 5 ksi concrete and tested for simulated earthquake loading. Of the five specimens being constructed, three are designed to meet the current recommendations of the ACI-ASCE Committee, 352. The other two are designed with longitudinal beam steel crossed in the connection to eliminate the effect of bond failure, thereby achieving a more ductile response.

Based on preliminary results, the standard connection was able to develop 66.5% of the calculated ultimate strength of the beam. The connection failure was very clearly a shear failure with shear cracks appearing at 50% ultimate.

The preliminary results also show that the diagonal steel specimen with no shear reinforcement in the joint core achieved about the same strength as the standard connection. The connection failure was tensile yielding of the longitudinal beam steel bent diagonally through the connection.

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PETER M. BYRNE

University of British Columbia

The geotechnical group are conducting a number of research projects in earthquake engineering, some of which have been described by Dr. W.D. Liam Finn. Two projects which the writer is currently most involved in are:

The Earthquake Hazard in the Fraser Delta

The first stage of this work was to make an estimate of the hazard based on available data. This has been completed and may be described as follows:

Empirical and analytical methods for predicting the occurrence of liquefaction of foundation soils during an earthquake are examined and applied to the Fraser Delta area of British Columbia. The area is underlain by deep deposits of loose sands and soft silts. It is diked and at present has a population of about 150,000 people who reside mainly in low-rise buildings. Liquefaction of the foundation soils would cause severe damage to buildings, services, highway and railway links, and the dikes.

Application of empirical methods based on blow count values indicate that liquefaction of the foundation soils could occur. Application of analytical methods indicate that liquefaction is likely to occur in the event of an earthquake having a maximum ground surface acceleration of .12g (the 100 year value).

The effects of various remedial measures are examined and it is shown that densification, drainage, fill loading, and the presence of a soft layer near the surface all serve to reduce the tendency for liquefaction to occur. The presence of a low permeability layer close to the surface may cause liquefaction to occur by impeding the drainage.

The second stage involves detailed studies of the dynamic resistance of the deposits. This requires recovery and testing of undisturbed representative samples of the material. However, since this is difficult and costly to carry out an attempt will be made to minimize the amount of recovery and testing of samples required by correlating the dynamic resistance with in situ measurements. Presently blow counts from standard penetration tests are used for this purpose. It is considered that static cone and compressibility measurements may lead to better correlations. A field testing vehicle is presently being equipped by Dr. R.G. Campanella with the purpose of: a) obtaining "undisturbed" samples and b) obtaining in situ values such as cone resistance and compressibility. The field testing is expected to commence in the spring of 1977.

Overturning of Tall Buildings on Soft Foundations During an Earthquake

This problem is analyzed by modelling the foundation soil by a set of elastic-plastic no tension springs. The building is modelled as a multi-degree of freedom viscoelastic system. A time step dynamic analysis using a variety of base input records is performed. Preliminary results indicate that if the static stresses on the foundation are such that a factor of safety of 3 exists, overturning is unlikely. However, residual tilt of the building still occurs.

W. D. LIAM FINN

University of British Columbia

Earthquake engineering research sponsored by the National Research Council of Canada is being conducted in the following areas:

the measurement of liquefaction potential, the development of constitutive equations for the static and dynamic response of saturated sands, dynamic effective stress analysis for saturated sands, seismic settlements of dry and saturated sands, soil-structure interaction, dynamic response of the coupled system of dam, reservoir and foundation, seismic stability of earth and tailings dams and anchored buttress concrete dams.

Liquefaction Potential:

A simple shear test has been developed for measuring the liquefaction potential of saturated sands which uses dry sand samples. The volume changes that occur during the test are so small that for all practical purposes the test may be considered a constant volume test. The test is based on the concept that the pressure reduction against the loading head during cyclic loading is equivalent to the increase in porewater pressure that would occur in the corresponding undrained test. Compliance in the constant volume test system is less than 1/20 that of the corresponding undrained test system and consequently the constant volume test gives more realistic estimates of liquefaction potential. In some comparative cases considered in the paper the undrained test overestimated the resistance to liquefaction in 10 cycles by at least 22%. The constant volume test is very quick and easy to carry out and has none of the difficulties associated with undrained cyclic tests.

Constitutive Equations:

Preliminary constitutive equations have been developed to describe the behaviour of dry or saturated sand under conditions of simple shear.

The constitutive equations take into account the variation of shear modulus with strain, the hardening that occurs during grain slip and volume compaction, hysteretic damping, and the different rates of contemporaneous generation and dissipation of porewater pressure. The equations were formulated on the basis of data from simple shear tests on dry and saturated sands and allow the computation of dynamic response in terms of fundamental soil constants.

They have been used successfully to predict the actual stress-strain loops in cyclic loading tests, the number of cycles of uniform stress to cause liquefaction in saturated undrained sand, and the variation of shear modulus with shear strain at various levels of volumetric strain. The computed hysteretic damping for various sands when converted to equivalent viscous damping compares well with published data.

Dynamic Effective Stress Analysis:

Methods of dynamic effective stress analysis have been developed based on the constitutive equations described above and also on the stress-strain laws used by H. B. Seed, University of California at Berkeley, and his co-workers. In both cases the method takes into account the contemporaneous generation and dissipation of porewater pressures. The dynamic properties of the sand are modified continually during the analysis for the effects of dynamic shear strains and the progressive changes in porewater pressures. The methods allow us to compute the distribution of accelerations, shear stresses, and shear strains in a saturated sand deposit during an earthquake, the development of porewater pressure with time, and the time of onset of liquefaction. Results are supported by laboratory and field data.

Settlements in Dry and Saturated Sands:

Using the constitutive relations and the dynamic effective stress method of analysis the settlements in horizontal sand deposits of dry and saturated sands are easily computed. Results show total settlements and the distribution of settlements with time at any level in the layer during an earthquake.

Stability of Dams:

Methods of non-linear analysis suitable for determining the static and dynamic response of earth and tailings dams have been developed and are now being improved upon. The performance of anchored buttress dams is being studied. Work continues on the general analysis of the response of the coupled system of concrete dam, rock foundation and reservoir during earthquakes considering the foundation to be a semi-infinite solid to include radiation damping.

Soil-Structure Interaction:

A general study of the dynamic response of interacting systems is being carried on to develop more efficient ways of coping with coupled systems of many degrees of freedom.

ARCHIL N. MOTSONELIDZE

Georgian Politechnical Institute and University of British Columbia

Static and Dynamic Analysis of the Buttress Dam Anchored in the Foundation

In massive gravity dams the basic use of concrete is to provide ballast for shift, tipping and other types of stability, but its ability to handle large compression stresses is only utilized to a small degree.

This inefficiency of construction was partly reduced with the appearance of gravity dams with broad seams and hollows.

In buttress dams the previously mentioned inefficiency is almost fully eliminated and maximum use is made of the strength qualities of concrete. However, in spite of the optimum cross-sectional shape of this type of dam, it is still possible to construct them much more economically by incorporating the anchoring method in their design. This has already been done for some gravity dams.

Idea of Anchoring

After the erection of the dam, but before the filling of the reservoir, the dam is prestressed by steel cables toward the upstream side. As the tension in the cables is increased the compression stresses in the dam rise at the upstream side and decrease at the downstream side. The anchor cable tension must be regulated so that the compression stresses do not exceed the allowable value for concrete, as well as the rock, at the upstream side, especially at the contact surface. Also, it is not advisable that the compression stresses change to tensile stresses at the downstream side.

After the dam is prestressed the reservoir is filled and a continual redistribution of stresses takes place in the dam.

This is a very simple, rational idea, but is not widely accepted because previous design theories did not provide a complete solution to the anchored buttress dam. The finite element method now gives us an opportunity to reach such a solution.

Static Analysis of Non-anchored Buttress Dam

We made a full static analysis of a non-anchored buttress dam under dead load and hydrostatic pressure assuming a plane stress condition. The cross-sectional shape of the central section of this dam is very close to that of real dams--upstream slope m=0.42, downstream slope n=0.5, thickness of cap B=14 m, thickness of buttress d=8 m.

Horizontal and vertical displacements u, v, the strains ε_x, ε_y, γ_{xy} and the stress components σ_x, σ_y, τ_{xy} at the nodal points of the finite element mesh were calculated.

Static Analysis of Anchored Buttress Dam

An attempt was made to find a more economical cross-sectional shape by anchoring the dam to the rock foundation. One such section is for a dam of the same height, with vertical upstream slope, a downstream slope n=0.5 and anchored in the foundation by N=1150 T tension. The three main forces acting on the dam are the hydrostatic head, dead weight, and the anchor tension.

Detailed static calculations show that both versions--anchored and non-anchored dams--are in almost the same plane stress state. But for the anchored version, the economy in cost of the structural material is ≈ 50%.

Seismic Analysis

Both dams were designed for seismic load as an acceleration equivalent to that produced by the El Centro earthquake with a maximum acceleration of 0.332 g.

Dynamic displacements and accelerations of nodal points, the components of dynamic stresses σ_x, σ_y and τ_{xy}, major and minor principal stresses and maximum shear stresses were calculated. A comparison of the results showed that the values of the maximum dynamic stresses for both dams were of the same order of magnitude.

N. D. NATHAN

University of British Columbia

Much of the local construction activity is devoted to medium height residential buildings for which the designer cannot afford to make detailed dynamic analyses. He must necessarily limit his efforts to a quasi-static analysis based on code seismic forces. For this reason, an effort is being made to clarify some of the code requirements which may leave the routine designer in a state of uncertainty.

As an example, the National Building Code of Canada (like the S.E.A.O.C. code) provides the designer with a set of lateral forces acting in each axis of the building, specifying that they should be applied non-simultaneously; but the Commentary warns that "particular attention" should be paid to external and reentrant corner columns. In an effort to enlarge upon that statement, a number of multi-storey buildings with rectangular and cruciform plan forms and varying degrees of eccentricity have been subjected to three dimensional time-step analysis under different earthquake inputs. The results are currently being interpreted and it is hoped to provide the designer with some more detailed guidelines. It is felt that a good deal of the damage suffered by corner columns is due to torsional ground motion, which may not be properly accounted for at all in typical codes.

Again, the Commentary on the NBC of Canada warns that, under certain circumstances, large torsional amplifications can occur. "It is, however, not yet feasible to identify such situations simply, without actually performing a detailed modal analysis". An effort is being made to give the designer more helpful advice on this point; it is hoped that simple tests can be provided for certain cases, to predict the susceptibility of the layout to this phenomenon.

At a more fundamental level, a project is being started which will attempt to rationalize the minimum percentages of steel to be used in load-bearing masonry. Use of this material in high-rise construction is now just beginning in local practice. The minimum percentages currently required by the code appear to be based on tradition rather than fact, and they do not distinguish between seismic zones or position in the building. Experimental and analytical studies are being started with respect to in-plane and out-of-plane forces; the depth to which this project will be carried depends upon funding arrangements which are not yet finalized.

The work described here is being carried out by Drs. Cherry and Anderson, with Mr. McKevitt and the author.

R. A. SPENCER

University of British Columbia

The behaviour of concrete buildings during strong earthquakes is being studied with the support of the Canadian National Research Council. Two areas of study are connections for precast structures and the non-linear response of coupled shear walls.

Connections for Precast Concrete Buildings

A simple connection that is commonly used to connect load-bearing wall panels in precast concrete buildings is being tested under large amplitude cyclic loading. This connection uses short lengths of angle, each with two headed studs fusion welded to it, embedded in the edges of each precast unit. A piece of plate, bar or road is welded between adjacent angles to make the connection. The connection is tested by applying a load to an angle in a panel so as to simulate the inter-panel shear force that would develop if connected concrete panels were used as a lateral load resisting system.

Tests made so far indicate that these connections can be suitable for buildings designed as box systems, or for precast buildings designed to be classed as continuously reinforced. Tests and analyses are now being made to investigate the action of the connections in more detail and to examine possible design improvements. The possibility of using connections to develop ductility is also being studied.

Nonlinear Response of Coupled Shear Walls

A computer analysis is being made of the nonlinear response of concrete shear walls coupled at each story by short deep beams with non-linear hysteretic load-deflection properties. A step-by-step integration technique is used, and the nonlinear behaviour is introduced by replacing the stiffness matrices for the elastic coupling beams with matrices derived for beams which have cracked and yielded, assuming piece-wise linear behaviour during each time increment.

The computer model will be used to study ductility demands in the coupling beams, and then modified to show the effects of yielding in the shear walls. The same program will also be adapted to study the nonlinear response of concrete panel buildings with connections similar to those described above.

AMIN GHALI and WALTER H. DILGER

University of Calgary

This research now in progress is intended to develop a type of reinforcement to increase the strength and improve the behaviour of flat-slab floors at their connection with columns when subjected to dynamic forces. Full scale specimens are subjected to constant axial force representing gravity loads, and a varying dynamic moment transferred between the column and the slab. A special kind of shear reinforcement, which proved to be effective in static tests(1), is used. Substantial improvement in strength, ductility and energy absorption capacity is achieved.

Introduction

Horizontal forces on flat-slab concrete structures produce bending moments of different values at the column sections just above and below the floor. For equilibrium, a transfer of moment must take place at the slab-column connection. During an earthquake, the lack of ductility of the connection, can result in brittle failure and progressive collapse or significant damage to the structure.

Figure 1a shows a typical test specimen, which is a full-scale representation of the region of an intermediate flat plate of a multi-storey structure at its connection with an interior column. The force V, intended to be held constant, represents the transfer of shear between the slab and column due to symmetrical gravity forces on the floor. The two horizontal forces P, introduced dynamically, are equivalent to a couple M=PL representing the moment transferred through the connection due to blast or earthquake loading. This was achieved by providing controlled displacement at each of the column ends. The rapid application of M causes some unavoidable variation in V particularly near failure (Fig. 2).

Top bending reinforcement of equal ultimate resisting moment is uniformly distributed in the x and y direction. The reinforcement ratio ρ_x is varying in various specimens. Bottom reinforcement one third the top steel is also provided.

The shear reinforcement used is in the form of single vertical bars anchored mechanically above and below the bending reinforcement meshes. Short segments (0.5 to 1 in. (1.27 to 2.54 cm)) are cut from a standard I-beam and arranged close to the column faces with their bottom flange nailed to the formwork (Fig. 1b). The same type of shear reinforcement used in static tests(1) increased significantly the strength and the ductility at failure. The amount and the arrangement of the shear reinforcement is varied in the test series.

Test Results

Figure 2 is a typical record of the time variation of the applied moment, M and vertical force, V and a nominal value of the connection rotation θ, calculated by dividing the sum of the two horizontal translations at the two ends by the distance L. Figure 3 compares the moment-rotation curves of four similar specimens with bending reinforcement $\rho_x = 1.0$ percent. The loading for two specimens were static and for the other two dynamic (specimens designated SM and DM, respectively). One of each pair was provided with shear reinforcement of area 2.0 in.^{2} (13 cm^2). The results of the experiments of a series of dynamic tests without shear reinforcement is reported in Ref. 2. The complete results of tests on slabs with shear reinforcement is the subject of a paper in preparation.

Main Conclusions

In slabs without shear reinforcement, the increase of M produces sudden punching failure following plastic rotation and the value of the plastic rotation is smaller with the higher reinforcement ratio.

The area below the M-θ diagram, considered representative of the energy absorption capacity, is much increased by the shear reinforcement in both the static and dynamic loading.

Further research is needed to determine the best arrangement and the amount of shear reinforcement to produce a fully ductile failure. This is expected to be possible, particularly when the bending top reinforcement ratio is not high (less than one percent), as is the case in practice.

Acknowledgement

This research is presently supported financially by a grant from the National Research Council of Canada.

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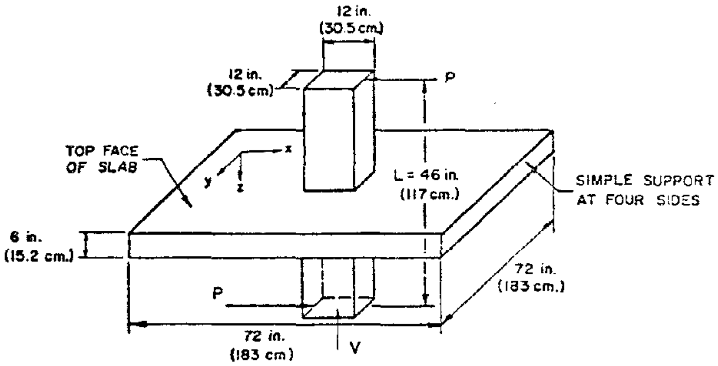
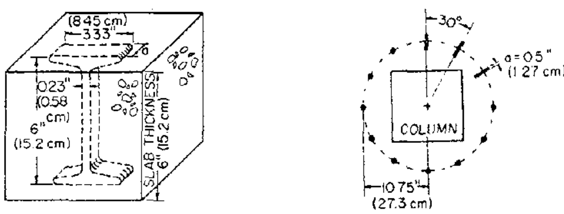


(a) Test set-up



(b) Typical shear reinforcement element and arrangement around column

FIGURE 1 - Test set-up and shear reinforcement

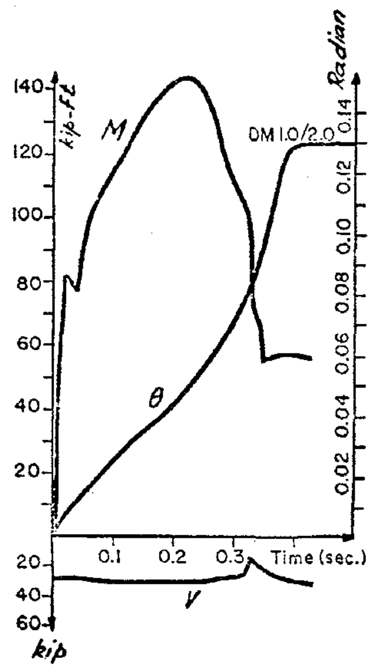
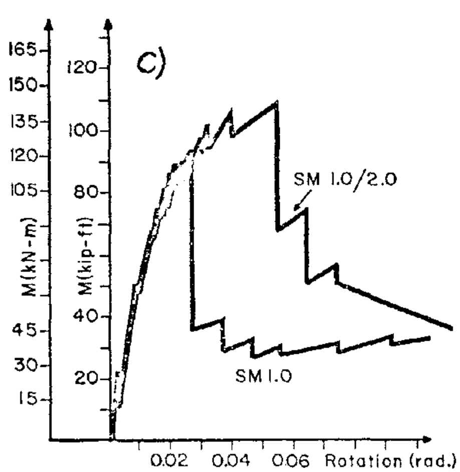
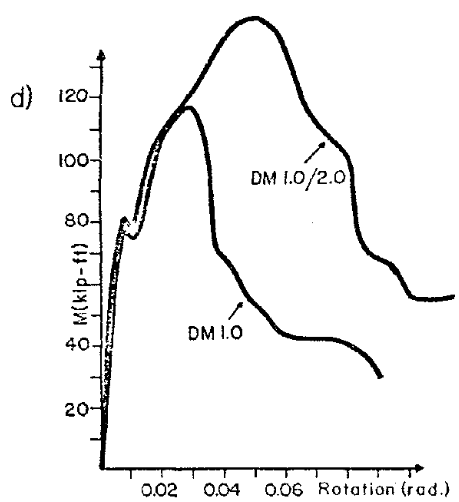


FIGURE 2 - Time variation of M, V and θ



(a) Static loading



(b) Dynamic loading

FIGURE 3 - Moment rotation curves of specimens with and without shear reinforcement subjected to static or dynamic loading

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National Science Foundation sponsored research is being conducted in the following two areas: Post-earthquake Damage Analysis and Aseismic Design Implications of Recent Research Results.

Post-earthquake Damage Analysis

Several major buildings that sustained different degrees of structural damage during the 1971 San Fernando, 1972 Managua and 1976 Guatemala earthquakes are being extensively studied to: (1) identify the structural and/or construction reasons for the observed damages and, thus, to assess the adequacy of aseismic design, analysis and construction practices; and (2) suggest improvements in current aseismic resistant design methods. These studies require the integration of pertinent research in the fields of engineering seismology, soil mechanics, and structural analysis with information related to professional design practices, construction techniques and the energy absorption and dissipation characteristics of structural components.

Conventional linear-elastic dynamic analysis techniques have been found to give generally unreliable predictions of structural response when substantial inelastic deformations occur. To assess the effectiveness of nonlinear dynamic analysis methods, studies are being conducted regarding problems in (1) defining, computing and interpreting ductility; (2) modeling flexural elements (lumped vs. spread plasticity models); and (3) accounting for stiffness degradation. An extensive investigation of the elastic and post-elastic stiffness characteristics of reinforced concrete slabs forming part of floor systems and their effect on overall structural response is underway.

A parametric study, suggested by the case study buildings, is being performed to optimize the nonlinear seismic behavior of coupled wall and frame-wall systems. This study includes the effect of stiffness degradation, foundation uplift, and neutral axis migration in structural walls.

The unusual damage observed in buildings located near the source of an earthquake has motivated studies to identify data needed to define design earthquakes and to evaluate the reliability of existing methods for prescribing design loads. The responses of single (in the form of nondimensionalized nonlinear response spectra) and multiple degree-of-freedom systems to various ground motion records are being studied.

The field observations of a four-member team that inspected damages resulting from the 1976 Guatemala earthquake are currently being analyzed. In addition to detailed information regarding the damage suffered by individual buildings, overall observations regarding the effect of the structural system, nonstructural elements and structural and nonstructural detailing on the seismic performance are being formulated.

Aseismic Design Implications of Recent Research Results

The ultimate objective of this work is to provide the engineering profession with a summary of recently acquired knowledge in specific areas of aseismic design in order to improve earthquake-resistant construction.

The specific areas of research being covered include: (1) selection of design earthquakes; (2) selection of structural material and structural systems (only steel and reinforced concrete structures will be considered with an emphasis on reinforced concrete); and (3) prediction of mechanical behavior of structures. The main effort will be devoted to the last area of research, in which present methods of analysis and design will be reviewed and their reliability in predicting actual behavior will be discussed in the light of available experimental data.

To achieve the above objective, it has been proposed to: (1) collect data obtained in research carried out in the areas specified above; (2) analyze, distill and integrate the results of these data with the results obtained in the investigations that the authors have been involved with; (3) synthesize and formulate the significance of the results in a manner that can be used by the engineering profession, particularly the aseismic structural designers, building officials, and code writers; and (4) convey the findings to the profession through a report and/or book.

The proposed work will be conducted in four phases. The first phase is nearing completion and consists of writing a brief state-of-the-art report regarding the "establishment of design earthquakes." Work on the second phase is presently underway to collect data for determining the most efficient structural systems that can be used for aseismic design in regions where severe ground shaking can be expected. After analyzing all the available data and results on the behavior of structural materials and structural systems, a brief report summarizing the significance of these results will be prepared.

In Phase 3, data available in the area of the prediction of the mechanical behavior of structures will be gathered and analyzed. Emphasis will be placed on the significance of the available data regarding preliminary design and final design (detailing) of reinforced concrete structures, especially on ductile moment-resisting frames and frame-wall systems.

The final phase will be devoted to the preparation of a final report or book.

VITELMO V. BERTERO, EGOR P. POPOV, RICHARD KLINGNER
TSAN-YUAN WANG, AND JOSE VALLENAS

University of California, Berkeley

National Science Foundation sponsored research in the area of seismic behavior of frame-wall and infill frame structural systems is being conducted by studying the seismic hysteretic behavior of R/C structural walls and the effects of engineered masonry infill panels on the seismic hysteretic behavior of ductile R/C frames.

Hysteretic Behavior of R/C Structural Walls

The ultimate objective of this investigation is to develop practical methods for the aseismic design of combined frame-wall structural systems. To achieve this objective, integrated analytical and experimental studies are being conducted.[1] The main objective of the analytical studies is to develop efficient computer programs for the analysis of multistory frame-wall structural systems. The main objective of the experimental studies is to obtain reliable data regarding the linear and nonlinear (particularly the hysteretic) behavior of frame-wall structural systems. The experimental program covers the testing of framed and frameless single and coupled wall systems. To conduct these experiments, a special loading facility has been developed. The principal feature of this facility is its ability to simulate pseudo-statically the dynamic loading conditions which could be induced in subassemblages of buildings during earthquake ground shaking.[1]

A series of tests has been conducted on four 1/3-scale wall component models of the bottom three stories of a ten-story frame-wall system which was designed according to 1973 UBC provisions. The four specimens consisted of a 4-in. thick wall framed by two 10-in. sq. columns and a portion of 3-in. thick floor slabs. The only difference between the four specimens was in the way that the concrete of the edge members was confined. While spirals were used in specimens 1 and 2, square ties were used in specimens 3 and 4. Rather than simulate the critical load combinations of gravity and seismic loads as specified by the 1973 UBC, it was decided to investigate the behavior of these walls under the most critical load combination which could be developed in the case of an extreme earthquake ground shaking. To estimate this critical load combination, the prototype building was subjected to a series of analyses using different methods for evaluating the seismic forces. Considerable discrepancies between the resulting shear span values for the wall component were obtained, which point out not only the difficulties involved in selecting the critical combination of inertial forces, but also, the need for carefully interpreting results obtained in experimental investigations in terms of the actual seismic behavior of structures.

The testing procedure was as follows: The two axial forces necessary for simulating the effects of gravity forces were applied first. The effects of seismic forces were introduced following a different loading pattern in each of the specimens tested. The four specimens were subjected to cycles of full seismic force reversals in the working load range before being loaded in their inelastic range. In walls 1 and 3, the lateral force

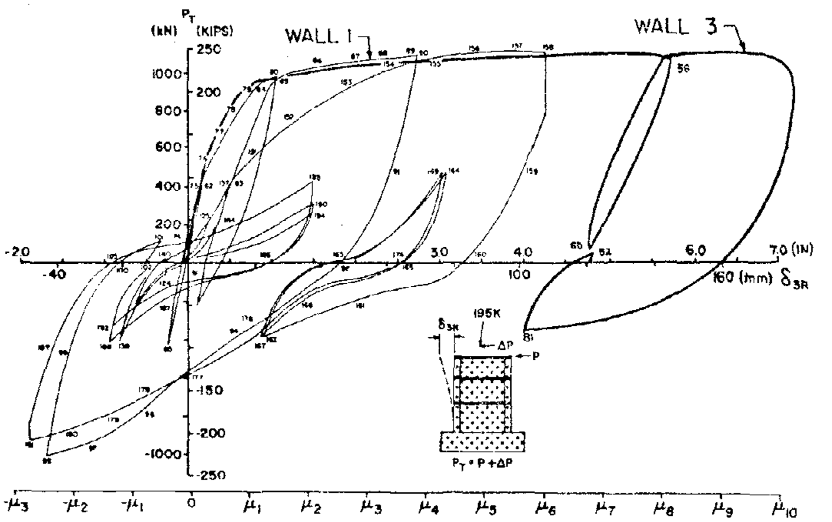

FIG. 1 P_T-δ_{3R} DIAGRAMS - WALLS 1 & 3

and change in column axial forces needed to reproduce the corresponding change in overturning moment were supposed to increase monotonically until a reduction in the lateral resistance could be observed. In the test of wall 1, however, a cycle with significant inelastic displacement reversal was introduced long before the drop in lateral resistance (Fig. 1). Walls 2 and 4 were subjected to a history of lateral shear and corresponding overturning moment that induced gradually increasing cycles of full reversal lateral displacement with at least three cycles at each displacement amplitude (Fig. 2).

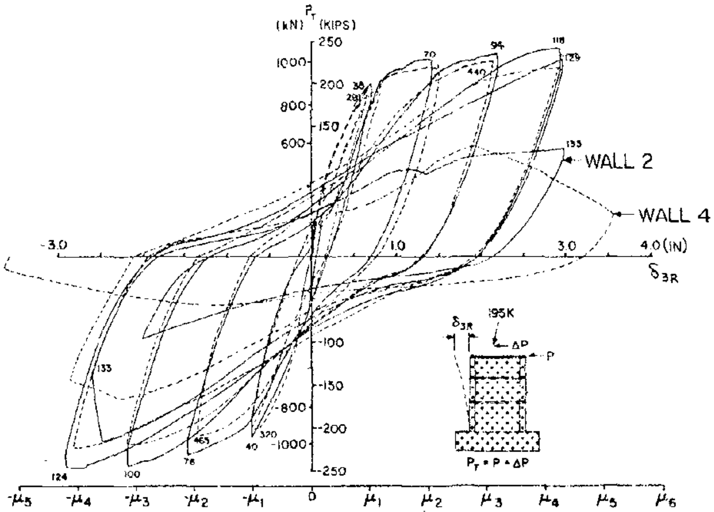

FIG. 2 P_T-δ_{3R} DIAGRAMS - WALLS 2 & 4

Figures 1 and 2 are composite graphs illustrating the overall response for the four specimens tested. These graphs facilitate evaluation of the two main variables of the tests already conducted, i.e., the effect of (1) cycling with reversal deformations versus monotonically increasing loads; and (2) different ways of confining concrete of edge members. Despite the limited amount of specimens tested, analysis of the data obtained enables the following observations to be formulated: (1) It is possible to design structural wall components capable of developing large ductilities even when subjected to full deformational reversals inducing nominal unit shear stresses up to $10\sqrt{f'_c}$. (2) Although the ductility was reduced significantly due to full reversals, this reduced ductility can be considered large enough to permit the development of energy absorption and energy dissipation capacities exceeding even those that would be demanded in the case of very severe earthquake shaking. (3) The closely spaced square ties were as effective as the spiral in confining the column concrete. (4) Present code specifications for design forces, load factors, and design and detailing of critical regions can lead to a wall design which considerably underestimates the amount of shear that can actually develop. In the next series of experiments, two specimens similar to those already tested, with the exception that no columns will be used as edge members, will be tested under monotonic and cyclic loading. A facility for testing coupling walls is presently being developed.

Hysteretic Behavior of Masonry Infilled Frames

Following an extensive literature survey, experimental and analytical studies were developed to determine the effect of engineered masonry infill panels on the seismic hysteretic behavior of R/C frames.[2] The experimental phase consists of pseudo-static cyclic load tests on a series of 1/3-scale model subassemblages of the lower three stories of an eleven-story, three-bay frame with infills in the two outer bays. Emphasis is placed on simulation of the proper force and displacement boundary conditions, and on the reinforcing details required to attain ductile frame action. The first series of tests just completed was conducted using the following models: (1) a bare frame (test #1); (2) this same bare frame, infilled with clay blocks after test #1; (3) a virgin frame, infilled with clay blocks; and (4) a virgin frame, infilled with concrete blocks. The infills were grouted in all cores.

In the design of these infilled frames, two basic design guidelines were adopted: (1) to maximize energy dissipation through distributed infill cracking, closely spaced horizontal and vertical reinforcement was used; and (2) to minimize the possibility of brittle frame failure which could result from panel falure, the frames were specially reinforced against shear, and the thickness of the infill was based on column shear resistance. Infilled frames designed and constructed according to these guidelines have several advantages over comparable bare frames, particularly if they may be subjected to severe ground motions: (1) Owing to the increased stiffness (500%) and strength (470%) provided by infills, behavior is greatly improved under service loads, moderate ground shaking, and even under the largest expected overload of standard live loads. (2) For severe ground motions demanding elastic base shears in excess of that corresponding to the bare frame collapse load, stiffness provided by infills significantly reduces the influence of P-Δ effects on seismic response. (3) For extreme ground motions demanding average story drifts in excess of 0.02, the engineered infilled frame is superior to the bare frame with respect to energy dissipation and resistance to incremental collapse.

The analytical phase of the investigation has two principal objectives: (1) to develop theoretically sound macroscopic mathematical models capable of describing essential aspects of the observed hysteretic behavior of engineered infilled frame subassemblages subjected to pseudo-static cyclic lateral loads; and (2) to use these mathematical models in analytical investigations of the effects of engineered infills on the overall seismic response of R/C structures. It is hoped that information gained from these experimental and analytical studies will be useful in the ongoing modification of pertinent design procedures and codes.

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Introduction

Cylindrical liquid-storage tanks have been damaged extensively in many recent earthquakes [1,2], hence the need for developing improved seismic design procedures is evident. To obtain data for this purpose, an experimental research program, making use of the 20 ft. square earthquake simulator of the University of California to study the earthquake behavior of model thin shell metal tanks, has been organized and funded by a group of interested organizations under the leadership of the Chevron Oil Field Research Company. The principal test parameters considered in the investigation are: size and geometry of the tank models, intensity and character of the seismic input, depth of liquid contained, and the top and base boundary conditions. The complete program involves four tank models, having diameter x height dimensions (in feet) of: 4 x 2, 12 x 3, 12 x 6, and 7.5 x 15. Top conditions are: open, fixed conical roof, and floating roof; base conditions are free to uplift at the edges, or fully clamped. Only the 12 x 6 ft. tank with open top will be discussed here; the significant influence of the base support condition will be emphasized.

Test Procedure

The University of California earthquake simulator [3] can generate the vertical and one horizontal component of any arbitrary earthquake motion, with peak accelerations of about 1/2 and 3/4g respectively. applied to a maximum test structure weight of 100,000 lbs. The 12 x 6 ft tank was welded from sheet aluminum using two 3 ft high courses, 0.080 and 0.050 in thick. It was designed as a scale model of a sheet steel tank with three times larger dimensions; using a time scaling factor of 1.73, both static and dynamic strains were simulated in the same proportion.

Instrumentation was provided to measure wave heights (6 locations across the excitation axis), shell strains (60 rosette channels) and radial and tangential displacements (26 channels), in addition to the table acceleration and displacement history. Four different horizontal earthquake histories were employed, each at three different intensities. Only results from the "standard" test conditions will be mentioned in the oral presentations: the El Centro earthquake speeded up by a time factor of 1.73 and with a peak acceleration of 0.5g, acting on the "full" tank (5 ft water depth). The base condition, fixed or free, is the only parametric variation discussed.

Test Results

The most important observation to be noted in the general response behavior is that there are two essentially independent causative mechanisms: the high frequency impulsive input resulting directly from the base accelerations, and the very low frequency convective pressure changes associated with the fundamental sloshing period of the liquid. These independent effects are quite apparent in the fluid pressure measurements and in the tank wall strains; as would be expected, the tank wall displacements are less responsive to the high frequency components of the base acceleration. It is noteworthy that the fluid pressures predicted by the Housner theory [4] (which recognizes both input mechanisms) agree well with the measured pressures for the case where the tank base is fixed. However, the Housner theory assumes a rigid tank, whereas significant tank wall displacements result when base uplift is permitted. Thus the tank fluid pressures are not well predicted by the Housner theory in the base uplift case.

Uplift of the tank base has an important effect on many aspects of the tank response and is reflected most directly in the observed tank wall displacements. The amount of uplift is a dramatically nonlinear function of the input intensity, increasing by a factor of about eight with a doubling of the input (0.25g to 0.5g). Radial tank wall displacements also changed dramatically with the condition of base fixity, being one to two orders of magnitude greater for the base-free condition. Moreover, the base-free displacement pattern is largely associated with the 3θ harmonic in the Fourier expansion; the amplification of this term seems to be related to the extent of the base along which uplift occurs during severe excitation.

Conclusions

The data obtained in testing the 12 x 6 ft tank is still being analyzed and interpreted, so final conclusions cannot be stated now. However, it is evident that the deflections which result when the tank base is free to uplift have a major influence on the hydrodynamic pressures and on the tank wall stresses. Thus it will be necessary to include this flexibility mechanism in the response analysis procedure before reliable predictions can be made for design purposes. Probably some modification of the Housner concept, which realistically accounts for the mode of deformation associated with uplift, will provide an adequate basis for design.

Acknowledgment

The financial support of the sponsor group, under the leadership of the Chevron Oil Field Research Company, is gratefully acknowledged.

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National Science Foundation sponsored earthquake engineering research is being conducted in the area of soil-structure interaction analysis.

Continuum-Discrete Synthesis in Foundation Modeling

The principal focus of this investigation has been the numerical modeling of foundations for soil-structure interaction problems. The rigid footing assumption is satisfactory for the analysis of certain class of structures, (for example heavy machine foundations, nuclear containments), however, the contribution of the deformation of the structure base becomes significant during earthquake excitation of dams, buildings and other important engineering installations with relatively flexible bases. The finite element method, through the introduction of the so-called absorbing boundaries, only very partially accounts for the radiation damping phenomenon inherent in an unbounded foundation. The continuum approach, on the other hand, accurately accommodates the effects of radiation damping but poses acute mathematical difficulties for the solution of any flexible base-foundation system. Thus, the motivation of the present investigation has been to integrate the discrete methods (which can handle arbitrary geometry, the effects of local inhomogeneity, etc.) and the analytical formulations of continuum mechanics (to reconcile with the mathematical non-uniqueness of solutions for unbounded foundations). In this study, the spatial aspect of synthesizing the discrete systems and the continua has been completed along with the general linear viscoelastic characterization for the constitutive models and the development for a synthesized temporal solution scheme is in progress. A comprehensive description of various stages of investigations is presented below.

Impedance coefficients, associated with the surface displacement Ritz's functions, were evaluated for a viscoelastic half plane by solving displacement potential equations for the continuum in the frequency domain (1). A detailed investigation (2) of the singular integrals, which represent the solutions of these potential problems, revealed severe computational inaccuracies whenever these expressions are evaluated according to a simple quadrature rule as recommended in Ref. 1. Infinite stress discontinuity, at the interface due to linear surface interpolations, were established in Ref. 2. Computational instability would be inevitable when such a foundation model is integrated with the finite element representation of the superstructure. Hence, the assumption of kinematic compatibility between the foundation continuum and the discretized superstructure was concluded to be an inappropriate numerical characterization of the interaction type mixed boundary value problems.

The above inference initiated the traction discretization where the stress continuity is maintained between the structure and the foundation

(3). Displacement compatibility was imposed only at the surface nodes. The displacement discrepancy distribution along the interface being of lower order compared to that for the stress profile this formulation leads to a satisfactory convergent solution. Numerically stable--smooth--responses were obtained for the solutions of the rigid footing compliances. The computational efficiency in this case, was 80 to 100 times that of the displacement discretization.

In order to check the reliability of the aforementioned traction approach developed to characterize viscoelastic foundations it was required to compare its solutions against some more rigorous analytical results. A direct comparison, however, was not possible since most of the theoretical solutions are available only for the elastic properties of the foundation medium. An efficient computational method was constructed to economically convert the available numerical elastic frequency responses to the viscoelastic ones. This was achieved by developing a numerical form of the elastic-viscoelastic analogy utilizing the analyticity property of the frequency response functions on the lower half of the complex plane (4). The analytical responses of a rigid footing supported by an elastic half plane were transformed accordingly to yield the viscoelastic foundation solutions, which showed excellent correspondence with those predicted by the traction formulation.

The traction discretization method thus established to be reliable, efficient and economic for surface interaction problems has been employed to analyze the dynamic interactions for embedded structure-foundation systems. A substructure deletion concept (5), representing the spatial synthesis of the continuum and the discrete systems, was developed to modify the responses on the flat surface of the homogeneous half space to generate the impedance matrices associated with the degrees of freedom located on the curved interface along the embedded periphery of the superstructure.

The synthesization of the time and frequency space solutions, pertaining to discrete (bounded) and continuum (unbounded) domains respectively, is now in progress. The discretized systems represented by mass, stiffness, and damping matrices encompasses the regions undergoing nonlinear deformations and is analyzed by forward march in time. The frequency dependent reduced impedance matrices for the remaining linear portion will be so transformed as to make it compatible with the above temporal integration scheme.

The concept to synthesize the discrete and the continuum approaches is intended to yield a unified solution technique which will preserve the outstanding features of both the methods leading to a numerically feasible, accurate and economic computational algorithm for the class of mixed boundary value problems of interaction type where an unbounded foundation medium undergoes deformation in conjunction with an arbitrary finite superstructure.

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Experimental Verification of the Use of Energy Absorbing Devices

The research to be reported is concerned with the experimental verification of the use of energy absorbing devices in earthquake resistant design. Over the past several years we have carried out extensive testing of several types of energy absorbing devices and have found that devices which absorb energy through the mechanism of large cyclic plastic torsion of mild steel have a number of advantages. They dissipate a large amount of energy per unit volume and are very resistant to low cycle fatigue. The response is predictable to a high degree and they exhibit a gradual as opposed to catastrophic deterioration during long term testing.

We have recently been able to carry out a series of tests in which a three story model steel frame was fitted with energy absorbing devices and subjected to several earthquake loadings on the shaking table at the Earthquake Simulator Laboratory. The column bases of the frame were fitted with a special type of footing which provided full horizontal constraint but allowed the bases to move freely vertically. Rolling bearings are incorporated to facilitate free vertical movement. The frame so fitted was tested by A. Huckelbridge (subjected to the N-S 1940 El Centro record with and without vertical motion and to the horizontal component of the Pacoima Dam record from the 1971 San Fernando earthquake, all run at a wide range of intensities). This work is being reported separately.

Following these tests the frame bases were modified to include torsion type energy absorbing devices with one device at each column base, and the frame tests were rerun with the devices in place.

The results of the El Centro test series were very positive. At each intensity (from 25% g max. to 100% g max.) the uplift of the frame footings was much less than when free and the frame displacements were smaller. The column tensions were also much less than those experienced when the frame feet are rigidly fixed to the table. For the Pacoima tests the results are less clear; when the feet were free to move vertically the maximum uplift was obtained on the run with the smallest intensity and the uplift decreased as the intensity increased up to the final case which was around 100% g max. When the devices were included, the maximum uplift was very small at the smallest intensity run and increased steadily with intensity up to the final run. However, the uplift when the devices were included was always less than when not although at 100% g the difference was not great. Why the trends were different is not clear and we are attempting to understand this result.

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University of California, Berkeley

In the research supported by the National Science Foundation, mathematical modeling is used to gain insight into the response of structures, both steel and reinforced concrete, to earthquake disturbances, with emphasis being placed on their ability to absorb energy. The research requires both mathematics and numerical analysis on the one hand, and physical experiments on the other. The long range goal is the ability to determine a realistic mathematical model of actual structures so that their response to earthquakes can be predicted. The program is divided into three areas. The first is the nonlinear model of a single story steel frame, the second linear models of one and three story steel frames and the third a hysteretic model of reinforced concrete members in flexure.

The Nonlinear Model of a Single Story Steel Frame

The problem of establishing a mathematical model of a single story steel frame began in August 1974 and has now been completed. The study involved both a method for constructing the model, for which we chose System Identification, and a series of experiments in which the earthquake simulator was used to impose earthquake motions on a large scale steel frame.

System Identification is a general method which leaves many of its details to the need of an individual modeling problem. We leave discussion of our treatment to the papers which have resulted from the research. We need say only that it consists of three parts. The differential equation we used accommodates linear viscous damping and Ramberg-Osgood energy absorption. The error function is the squared differences between the two responses, experimental and model, in terms of both acceleration and displacement, accumulated over a period of exposure of each to the same earthquake input. The optimization algorithm is a Gauss-Newton descent method with a cubic interpolation scheme for one-dimensional line searches.

The method is subjected to numerical experiments to debug the algorithm and to evaluate its efficiency. The parameters appropriate to a steel frame can only be ascertained, (short of an actual earthquake event), from physical experiments.

Two sets of tests were performed on the earthquake simulator with three tests per set. The tests were designed not only to provide data from which the parameters are established to complete the mathematical model, but also to gain insight into how a variety of conditions influence the parametric values.

Use was made of an existing steel frame which had been designed in such a way that yielding will occur in only one pair of columns. The pair that is used in all three tests in the first set was replaced by a new pair for the second set.

In the first test the frame was subjected to the horizontal component of an actual earthquake accelerogram with an intensity sufficient to produce considerable yielding in the columns. The second test was a repetition of the first. The purpose is to ascertain the influence of the previous yield history of the material on the parametric values. The present identification algorithm assumes virgin material. If the influence of previous yielding is significant, the algorithm will have to be modified to accommodate it. The third was a repetition of the first two and was done only to ascertain if continued nonlinear activity has a diminishing influence on the values of the parameters.

In the second set the frame was subjected to a different earthquake input. This enables us to establish whether the parameters obtained from one earthquake input will be substantually different from those obtained from a different earthquake.

The results of the modeling program have been very gratifying. When both the steel frame and the mathematical model are subjected to the El Centro earthquake, the acceleration responses, though extemely complicated, are almost indistinguishable from one another. The displacement responses while displaying the same phase and close to the same amplitudes, show a permanent set that needs explanation. The shortcoming of the model can be traced to a minor inadequacy of the Ramberg-Osgood equations. The equations (at least with one set of parameters) are unable to accommodate the difference in hysteretic behavior between virgin steel and subsequent excursions into the plastic zone. The response therefore, is, in a minor way, history dependent.

Study of the influence of the duration "T" in the cost function on the values of the parameters was carried out using three sets of data. Two sets of data from the El Centro earthquake, spans 900 and 700, and the Taft earthquake were used, the first and last acting upon virgin steel, the El Centro 700 upon steel that had been worked plastically. The values of the parameters varied significantly for short durations, especially where virgin steel had influence, but the significant finding was that when the full duration of the earthquake was used, the parameters were practically the same from each of the three sets of data.

Even though the model is in many ways satisfactory, the research itself suggested many ways in which both the Identification method and the model might be improved. Study will be made of introducing weighting factors into the cost function to increase the influence of displacement vis à vis acceleration.

Search will be made for a technique that will result in a series of sets of parameters to predict the frame behavior, one set derived from and appropriate to an individual segment of the earthquake input. This technique should be particularly valuable in the modeling of reinforced concrete when the parameters from segment to segment may change radically.

Linear Models of Steel Frames

The work is at an early stage and the study is beginning with the linear modeling of a single story steel frame. This simple problem is undertaken for two purposes. The first is to ascertain how well a linear model, formed using System Identification, can predict a nonlinear response. In formulating the model the parameters are found from a nonlinear response. The second purpose is to test optimization methods that could be useful for the more difficult problem of the three story steel frame.

Two algorithms will be explored. The first is extremely simple but may not work. In it the cost function is the square of the residue in the equation which results when response quantities and the table acceleration are introduced into it. The second uses for the cost function the squared differences in response quantities. Again, in anticipation of the three story frame, somewhat crude but simple methods will be studied for searching the cost function terrain for the global minimum. Experimental data for the single story frame are available for both of these studies. The two different formulations of the cost function reflect two different goals and it will be interesting to explore whether the parameters obtained from the first method (if it works) when treated as a first estimate for the second algorithm change significantly when the goal is changed.

Study of the three story steel frame will follow using data recorded by Clough and Tang from earlier shaking table experiments. The elastic response data will be used to gain insight into the damping and stiffness matrices when a three degree-of-freedom system is considered and subsequently a model will be attempted when the degrees of freedom are increased from three to six.

Hysteretic Model of Reinforced Concrete

The purpose of this study is to formulate a model that will predict the response of reinforced concrete members in flexure, not to dynamic loads, but to quasi-static. We anticipate using System Identification to estimate the parameters of the model by formulating a cost function involving response differences (using P or δ) at chosen time increments over the duration of the test.

The form of the model is very important. We are hoping to be able to use a model proposed elsewhere and are now searching the literature for a model which we think is appropriate for System Identification. The results of our study of segment-by-segment parameter estimation for the steel frame will be vital for the formulation of this model.

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A masonry program at the University of California, Berkeley was initiated in September 1972 as part of the broad research program on Energy Absorption Characteristics and has continued for the past four years. The program currently has two major parts. The first one is an experimental and analytical study of masonry tall buildings and the other is a study of masonry housing construction.

1. Masonry Tall Buildings

In late 1973 to early 1974, a sequence of three trial wall panels, of different types of masonry construction and window pier dimensions, were designed and a test system for applying in-plane earthquake type load to the panel was developed. Following these preliminary tests, a series of seventeen dimensionally similar concrete block double-pier panels, approximately 15ft. square, were fabricated and tested during 1974-1975.

Information obtained from these tests includes (1) The mechanism of failure; (2) The yield and/or ultimate strength; (3) Hysteresis characteristics; (4) Stiffness degradation; (5) Energy absorption characteristics; and (6) Equivalent elastic constants.

Because of the large number of parameters affecting the strength of masonry components and the time required for the double pier test, a single-pier test set up was designed to simulate the boundary conditions of a pier in the double-piered panel. The single pier test fixture was substantially modified after two preliminary tests were performed. The modified test system, which includes shear transfer keys at the top and bottom of the pier, simulated the behavior of the piers of the double-pier panel with reasonable accuracy.

Approximately 80 single-pier tests will be performed. The major parameters to be included in the study are (1) Geometry or Height-to-width ratio of the piers, (2) Materials and Material Strengths (concrete blocks, solid bricks and hollow clay bricks) (3) Quantity and Type of Reinforcement, (4) Rate and Type of Loading, and (5) Bearing Stress or Vertical Load.

Each set of single pier test specimen is associated with a small test program involving prism and square panel tests. The purpose of the prism tests is to evaluate the strength and deformation properties of masonry when subjected to uniform uniaxial compression stress. The purpose of the square panel tests is to evaluate the strength and deformation properties of masonry when subjected to a diagonal tension stress and to correlate the shear stress between these tests and the cyclic lateral loading tests of the single-pier.

Although the major part (85-90%) of the masonry research project has consisted of an extensive experimental project, concurrent theoretical studies have been pursued throughout the project. The main thrust of the theoretical investigations has been the formulation of procedures to evaluate equivalent elastic constants (Young's modulus, shear mudulus and Poisson's ratio) from experimental results. Obviously a linear elastic analysis of masonry structure requires knowledge of its equivalent elastic constants and as yet very little experimental data is available to define these properties.

As a continuation of studies on the determination of equivalent elastic constants, it is proposed to make use of the methods of wave propagation. Such methods have been used successfully in the study of other materials and could prove effective for masonry as well. This part of the program will be under the supervision of Professor H. D. McNiven.

2. Masonry Housing

The second test program is related to single story masonry dwellings. The overall objective of the program is to determine design and construction requirements for single story masonry dwellings under the earthquake loading. This objective will be accomplished, in part, by the performance of shaking table tests of recommended typical single story masonry dwellings to demonstrate structural adequacy for expected earthquakes.

Prior to the shaking table tests, the program consists of three major aspects,

1) To determine the reinforcement requirements for the in-the-plane resistance of typical masonry construction to seismic excitation.

2) To determine the reinforcement requirements for the out-of-plane resistance of typical masonry construction to seismic excitation.

3) To determine the adequacy of typical connection details of masonry housing construction to resist seismic excitation.

Before any extensive experimental work begins, a field survey was conducted in Utah, Arizona and California to determine the characteristics (types of materials, size and shape of shear panels, reinforcement details, connection details - both diaphragm and footings) of typical masonry housing construction. In addition, an extensive survey of all available information and test data will be conducted to determine the necessity of performing any further experimental work on aspects 2) and 3) of the program outlined above. Both surveys will conclude with presentation of a report which will incorporate conclusions and recommendations either for future research to be included in the program and/or for construction and reinforcement details to be included in the final report.

This masonry housing program is planned over a three-year period.

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This report outlines National Science Foundation sponsored research directed toward design of earthquake resistant structures.

Sensitivity Analysis - For analysis and design for dynamic loads, it is customary to idealize complex structures as spatially discrete dynamic systems whose degrees of freedom are associated with motion of a finite set of nodal points, at which are represented mass, damping and internal restoring force properties of the structural components. Spatial discretization is carried out by employing the finite element method, although in cases such as rigid frames, discretization into beam and column elements is an obvious choice. For a wide class of problems the resulting equations governing dynamic behavior of the structure can be put in the form

$$\mathcal{D}\,[\beta,z(\beta,\tau),t]=0\,;\ \tau\ \varepsilon\ [0,t],\ t\ \varepsilon\ [0,T] \qquad (1)$$

with initial conditions $z(\beta,0) = 0$, where $z(\beta,t)$ denotes the $\bar{N}$-dimensional state vector of the system at time t, $\mathcal{D}$ is a differential or integro-differential operator defining system dynamics and β is a P-dimensional parameter vector characterizing both the properties of the structure as well as those of the forcing function producing motion. For example, β may be partitioned into sub-vectors which respectively characterize distribution of mass, geometric properties of structural components, constitutive properties of materials and amplitude, frequency and stationarity characteristics of the exciting force system. The present value of the state vector may depend on the past history (path of evolution) of the dynamic process (such as may occur in inelastic systems); T denotes the extent of the time period of interest over which the system is observed.

In typical problems of prediction of structural response the vector β is completely prescribed; i.e., distribution of mass, length and area of members and their mechanical behavior as well as the dynamic excitation function are given and the problem is to obtain the state vector as a function of time (for the prescribed β) by direct numerical integration of (1). Here we are interested in an inverse problem found in mathematical modeling of mechanical behavior of structural components, optimal synthetic design or simply conducting trade-off studies in attempting to achieve an improved (not necessarily optimal) design of a structure. A common element in each is sensitivity analysis, the capability to compute change in structural response associated with changes in the parameter vector. In the present format, since both z and β are vectors, the resulting set of partial derivatives constitutes a sensitivity matrix of size $\bar{N}$xP whose elements are functions of time and the parameter vector β.

A format including both mathematical modeling (parameter identification) and optimal design is the following: Find

$$\min_{\beta} f[\beta,z(\beta,t)] \ , \ t \in [0,T] \tag{2}$$

subject to system dynamics (1) and a set of constraints

$$q[\beta,z(\beta,t)] \leq 0, \quad t \in [0,T], \tag{3}$$

where the dimension of the vector q is M.

The objective, or cost function (2) in the case of a parameter identification problem represents an error measure between a set (or sets) of observed data and the prediction of a hypothesized mathematical model whose parameter vector β is to be adjusted to minimize the error. Equation (1) defines the dynamic properties of the test configuration for which data are collected and constraints (3) reflect natural or imposed limitations on values of the parameter and state vectors. On the other hand, in design applications undetermined components of β are often taken to be member cross-sectional areas (or functions thereof), while the components of β associated with mass, member length and constitution, and input are prescribed. Here the objective function (2) is some measure of cost of the structure, (1) continues to govern dynamic response of the structure and (3) prescribes limits on structural response, e.g., maximum stresses or displacements in the structure. Whether dealing with the objective function or constraints, in either identification or design, to calculate changes in cost or constraints it is necessary (or at least helpful) to be able to calculate the sensitivity matrix $\frac{\partial z}{\partial \beta}$.

For example, in the method of feasible directions, computations of gradients of 'active' constraint functions are required, [1]. This requires evaluation of $\partial q_i/\partial \beta_j$ $(\beta,z(\beta,t))$ for each constraint q_i for which (3) is an equality. One method of evaluating these gradients is by first obtaining $\partial z/\partial \beta$ (β,t) as the solution of a system of <u>$(\bar{N}xP)$ matrix equations</u>, called perturbation equations, resulting from employing linear perturbation analysis on the dynamic equations of motion. Then, premultiplying this matrix by $\partial q/\partial z$ $(z(\beta,t))$ provides the required gradients. Since the dynamic equations of the system and the perturbation equations have the same form, substantial savings in computation time can be effected by carrying forward the solution of these equations simultaneously.

For maximum computational efficiency under certain circumstances it is preferable to employ a second method of evaluating the sensitivity matrix (and gradients of active constraints) in which use is made of the adjoint of the perturbation equation, a vector equation with dimensions $(\bar{N}x1)$.

For linear system dynamics it is possible to give explicit results for the calculation of sensitivity matrices. However, for nonlinear systems no such results are available.

The work reported in [1] presents theorems and details for numerical computation of sensitivity matrices for spatially discretized structural systems subjected to dynamic excitation. General results are presented for nonlinear (hysteretic) structures and explicit numerical examples illustrate the methodology applied to multi-story shear frames whose force-displacement relationship is bilinear hysteretic.

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Recent studies at Berkeley of the behavior of interior joints in moment-resisting reinforced concrete ductile frames developed in two different directions. Because of the observed severe cyclic bond degradation in the interior of beam-column subassemblages in earlier tests, one of the studies was directed toward cyclic bond degradation of individual bars with different embedment. In the other study, the design of the reinforcement was modified to avoid cyclic bond degradation in the joint. The National Science Foundation sponsored the work.

Introduction

Earlier tests on half-scale beam-column subassemblages representing the third floor of a typical 20-story ductile moment-resisting frame have clearly demonstrated the possibility of a severe cyclic bond degradation at the interior joints [1, 2]. The design of these subassemblages was based on the conventional approach of the strong column and weak girder. In that series of experiments the beam reinforcement was continuous, consisting of 4 #6 bars at the top and 3 #5 bars (50% of the negative steel) on the bottom of the beam. As to be expected, in these experiments the plastic hinges were formed in the beams at the faces of the column, corresponding to the locations of maximum moment. After repeated displacements into the inelastic range, the cracks in the beams at the column faces became very large and the bars extending through the column began to lose their bond. Eventually, at large ductility ratios the bars slipped completely through the column causing a large drop in stiffness and eventual failure.

It was to their problem of bar slippage in the column that subsequent experimental work addressed itself. Two different techniques for solving this problem were studied. One program was directed toward a study of the anchorage characteristics of bars of sizes frequently encountered in practice. The novel feature of these experiments was an arrangement where a bar was being simultaneously pulled from one side and pushed from the other. This condition corresponds to the one observed in the columns in the earlier tests. The other technique was to design the beam in such a manner that the plastic hinge forms away from the face of the column thereby increasing the anchorage length. In this manner the slippage of the bars in the column could be delayed until very large displacements or may be entirely eliminated.

Cyclic Bond Tests

The arrangement for determining the bond characteristic of bars is shown in Fig. 1. The specimens in the form of a rectangular block simulating a part of a column are tested in a horizontal position. The specimens are reinforced with longitudinal bars as well as stirrup-ties. The thickness of these blocks is uniformly maintained at 10 in.; their depths vary to provide different lengths of embedment for the bars. The bar sizes employed are #6, #8 and #10, and the depths of embedment used so far are 15 in., 20 in. and 25 in. The specimens are securely positioned with tie-down straps and rigid horizontal supporting arms. Hydraulic jack C is capable of applying an axial force simulating a column load.

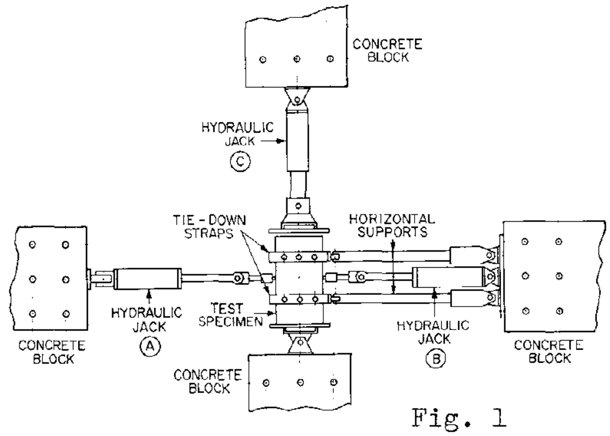

Fig. 1

Hydraulic jacks A and B are displacement controlled and can apply any prescribed ratio of the two forces; one being tensile, the other compressive. The direction of the two forces can be simultaneously reversed on command. Most of the test bars have a number of electronic gages along their length of embedment. These gages are placed into a machined groove and are carefully protected by a plastic material and a metal cap. The results of a monotonic experiment with a #6 bar in a 15 in. wide block are shown in Fig. 2. The bar was simultaneously pulled and pushed with forces of equal magnitude. The need for a longer embedment length of the bar for tension in comparison to that in compression is clearly brought out. Fig. 3 shows the bar stress vs. slip from the column face. Note particularly the decaying part of the curve, which defied measurement by previous investigators. The large loss of bond on the return stroke is noteworthy.

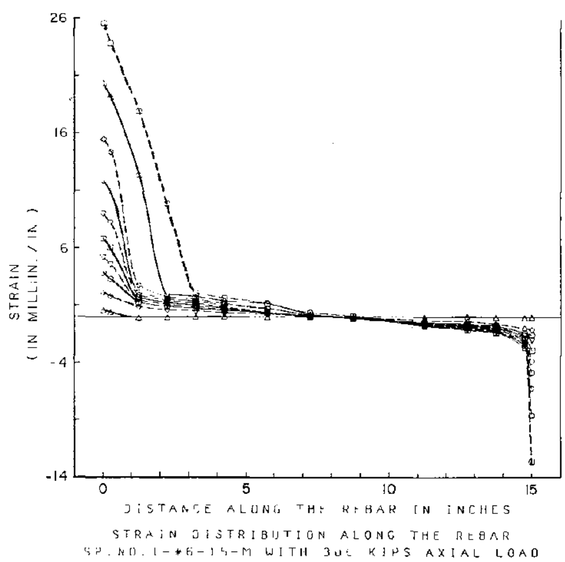

Fig. 2

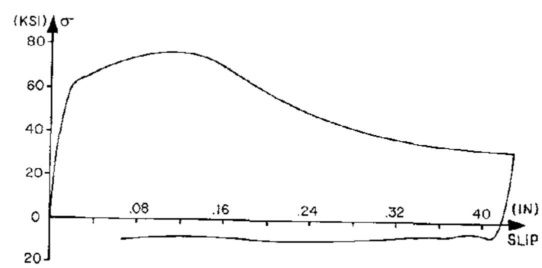

Fig. 3

Plastic Hinge Away From Column

In this series of experiments two beam-column subassemblages, BC5 and BC6, were designed to have the plastic hinges form away from the column faces. The details are shown in Fig. 4; in both designs 100% of negative steel was placed on the bottom of the beam. In BC5 the plas-

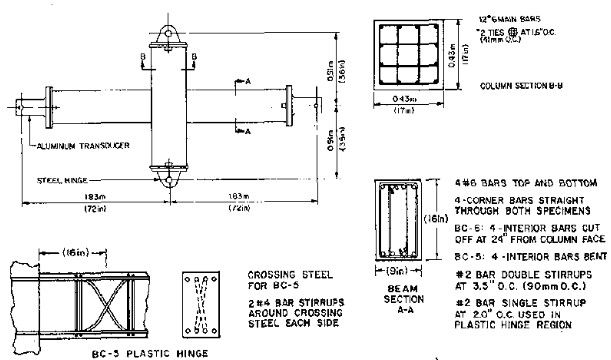

Fig. 4

tic hinge was located at 16 in. away from the column face by bending and crossing the middle bars of the top and bottom reinforcement. In BC6 the plastic hinge occurred at the cut-off points of the two middle bars 24 in. away from the column face. As in the earlier experiments, the top hinge of the specimen was held in position, the beam hinges were permitted to move only horizontally; the lower hinge was moved cyclically in the horizontal direction. A constant 470 kip axial force was maintained throughout each **experiment** giving rise to a large P-δ effect.

The most important results of these cyclic experiments are summarized in the plots of the equivalent horizontal force H_{eq} vs. δ, the horizontal movement of the bottom hinge. These are shown in Figs. 5 and 6. To obtain H_{eq}, the applied horizontal force H was increased by $P\delta/h$, where h is the height of the column.

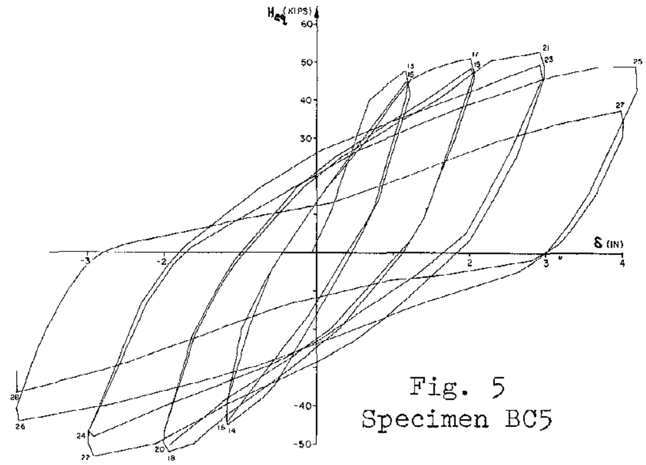

Fig. 5
Specimen BC5

Excellent results were obtained from the model BC5 in terms of overall member performance as well as in solving the problem of anchorage loss. Slippage of the bars through the column was completely eliminated, and also stable smooth hysteretic curves were recorded throughout the duration of the experiment. The steel at the face of the column yielded at approximately a ductility ratio of 4.5. Slippage of the bars through the column was also eliminated in BC6; however there was a large amount of shear deformation. The plastic hinge formed as expected at the cutoff point, but later began to move toward the face of the column as the bond at the end of the cutoff bars deteriorated and the moment capacity of that section decreased. Under repeated application of load reversal in the inelastic range the diagonal cracks at the top and bottom of the critical section of the beam increased until they crossed so that the concrete section became very weak in resisting the shear force, except for the frictional resistance between the two faces, and the dowel action of the steel.

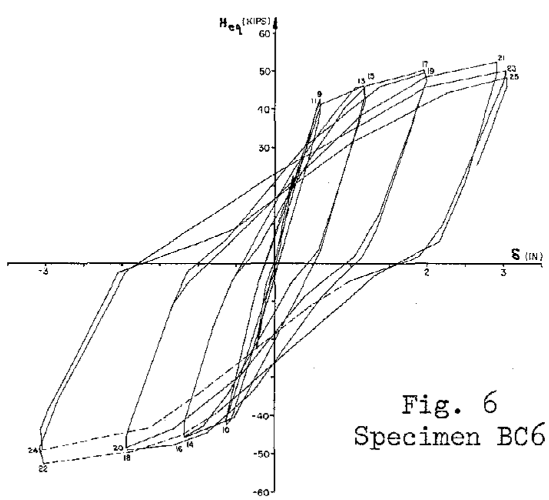

Fig. 6
Specimen BC6

References: [1] and [2] V.V. Bertero and E.P. Popov, EERC 75-16 and 5ECEE.

C.W. ROEDER, E.P. POPOV, and J.G. BOUWKAMP

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Investigations into the cyclic behavior of two structural steel bracing systems are in progress. In one study, sponsored by the National Science Foundation, the centerlines of beams, columns, and braces meet at each joint resulting in concentrically braced frames. In the other study sponsored by the American Iron and Steel Institute, the braces are deliberately made eccentric with respect to the intersection of the beam-column axes. Common to both studies, the development of more accurate cyclic constitutive relations for inelastic behavior of structural steel is also being pursued.

Concentrically Braced Frames

Three one-half scale identical braced frames have been constructed, two of which were tested; the third is being prepared for the next experiment. The overall width of each one of these frames is 17 ft which corresponds to one half of the building width. Three stories of braced panels, one above the other, are 14 ft wide. The braces in the lower two stories form an X-brace, whereas the braces in the third floor form an inverted K-brace. The overall height of the specimens is 18 ft 8 in. The columns and beams are made of small wide-flange sections, the braces are tubular.

In the first experiment an attempt to determine the static capacity of the frame was made; in the second, progressively increasing completely reversed cyclic displacements were applied; in the third test, cyclic displacements with a bias in one direction will be applied. During the experiments a hydraulically actuated gravity load simulator applies the required vertical forces. A horizontal hydraulic jack at the top of the frame applies the lateral loading in a quasi-static manner.

Characteristic of concentrically braced frames, their inelastic behavior during the application of large lateral loads is strongly influenced by the inelastic behavior of the individual braces. This strong influence is felt because the brace contributes the most to the lateral stiffness, and therefore, usually yields or buckles before the remainder of the structure. Several tests to determine the cyclic behavior of braces of the type used in the test frames are in preparation. A few experiments on full size braces are also a part of the program.

As an aid to the analytical prediction of the behavior of individual braces, experimental and analytical studies are in progress on the refinement of constitutive relations for cyclic plasticity. For this purpose tubular specimens of steel having approximately the same properties as that of rolled sections have been made. Some of these are being tested cyclically in the MTS tension-compression machine; the others, will be subjected to cyclic torsion. Some progress has been achieved in analytically describing this behavior [1]. Computer programs for material and geometric nonlinearities, which with some modifications may be applicable for this study, have been developed earlier [2].

Eccentric Bracing Systems

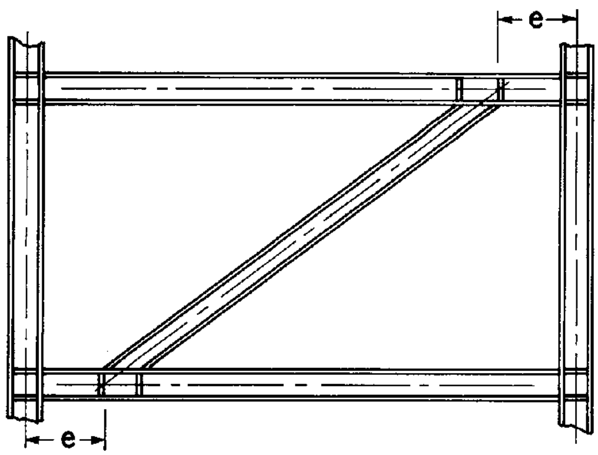

Fig. 1

There are strong indications that bracing systems with eccentric joints provide good energy dissipation characteristics. The results of experiments with symmetric K-braces in which large eccentricities were introduced at the panel centerline led to good results [3]. Inverted Y-braces offer another possibility [4]. In this investigation a detailed study of the eccentric bracing configuration shown in Fig. 1 is pursued as being of a type particularly well suited to American construction practice. However, since the inelastic activity occurs near the beam-column connection, this design requires careful scrutiny. No data on experimental investigations on this type of connection are available.

The bracing system selected for the study appears to offer excellent characteristics: it assures the frame of a high degree of stiffness, while at extreme loadings the energy is dissipated in the beams thereby obviating the undesirable buckling effects of the braces. The studies to-date show that the lateral stiffness of the frame is not significantly reduced from that of concentrically braced frames for moderately high values of eccentricity. It also appears that there may be an overall saving in the weight of steel. Although the braces, which are designed to prevent buckling, will be heavier, the columns will be lighter because of better control of the load transfer to the column. Moreover, an eccentrically braced frame is more highly redundant thereby tending to develop more regions of inelastic action for absorbing and dissipating energy.

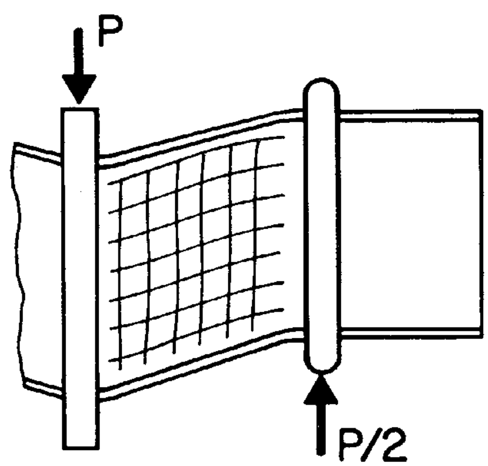

Fig. 2

The stresses in the eccentric zone are characterized by very high shear stresses in the web. Since the only tests of shear yield of the web reported in the literature [5] are monotonic tests, a series of simply supported beams in shear are being tested under cyclic loads. These specimens are designed to simulate one half of the eccentric zone. A schematic outline of a photograph of one of these specimens severely distorted in shear is shown in Fig. 2. Note the grid for photogrammetric measurements. The behavior of such members is very different from those in flexure. These experiments should provide information for the development of a simple analytical model for shear yield of beams, and show the effects of web buckling and diagonal tension formation on the hysteretic loops. It is also intended to study the nonlinear cyclic behavior of these eccentrically connected joints using finite elements, see Fig. 3. The design and tests of two one third-scale model steel frames with eccentric braces will follow to complete this program.

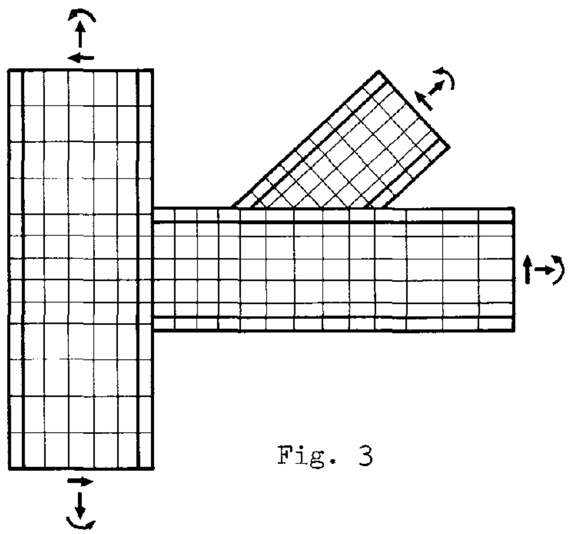

Fig. 3

Acknowledgements: Mr. Roy Stephen, Principal Development Engineer, is in charge of conducting the tests on concentrically braced frames. The cooperation of Professor V.V. Bertero on these projects is appreciated.

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Earthquake engineering research supported by the U.S. Nuclear Regulatory Commission, through the U.S. Energy Research and Development Administration, is being conducted on the "Sloshing of Water in Annular Circular Tanks under Earthquake Ground Motions".

Introduction

Sloshing response of water in annular circular tanks under arbitrary horizontal ground motions is predicted and the results are verified by tests. A linearized theory has been developed to derive the velocity potential for irrotational flow from which the water surface displacements, pressures, and velocities can be determined anywhere in the fluid. Comparisons with test results have shown that the linear solution has a sufficient range for practical problems such as encountered in annular tanks with outer and inner diameters of 120 ft. and 80 ft., respectively, and a depth of water of 20 feet. These structures are essentially rigid for this analysis.

Mathematical Model

Assumptions:

(1) Tank walls are rigid.
(2) Fluid displacements are small.
(3) Fluid is incompressible and non-viscous.
(4) Flow is irrotational.

Since the flow is irrotational, the velocity potential ϕ must satisfy the Laplace equation. Laplace's equation for ϕ was solved with appropriate boundary conditions, noting that the boundary conditions are time-dependent. A computer program was written to obtain numerical solutions for arbitrary ground motions applied to the tank.

Once the velocity potential is known, the displacement of the fluid, the pressure, and the velocity at any point in the fluid can be derived from the velocity potential. The computer program determines the sloshing frequencies, mode shapes, and water surface profile. Distribution of the pressure variation with depth along the inner and outer boundaries is also determined.

Comparison with Test Results

Tests to determine sloshing frequencies and water surface displacements were made on a small scale model (outer radius = 9 in., inner radius = 6 in., height of water = 3 in.). These tests were carried out under harmonic motions. The agreement between analytical and test results was within 10 percent for water surface displacement as high as 12 percent of the water depth, indicating a good range of the linear solution.

Test data for a 12-foot-diameter simple circular tank under actual earthquake ground accelerations were made available to us by Douglas Clough from his doctoral research project. Figure 1 shows the comparison between our theory and these test data for the El Centro (1940) earthquake. The analysis was carried out by letting the inner radius approach zero. The depth of water in the tank was 5 feet, and the maximum vertical displacement of the water surface was about 12.7 inches. It should be noted that for surface water displacements as high as 21 percent of the water depth, the agreement between the test and analytical results was remarkably good and the differences were within 10 percent. It should also be noted that the analytical model is good not only for the annular tanks, but also for the simple circular tanks.

The accuracy of dynamic pressure was checked against a known analytical solution for a simple circular tank and was found to agree within one percent.

Conclusions

The computer program based upon the irrotational flow theory can accurately predict the sloshing response of water in annular circular tanks (and also simple circular tanks) under arbitrary horizontal ground motions. The range of the linearized theory gives satisfactory results for water surface displacements of up to 20 percent of water depth.

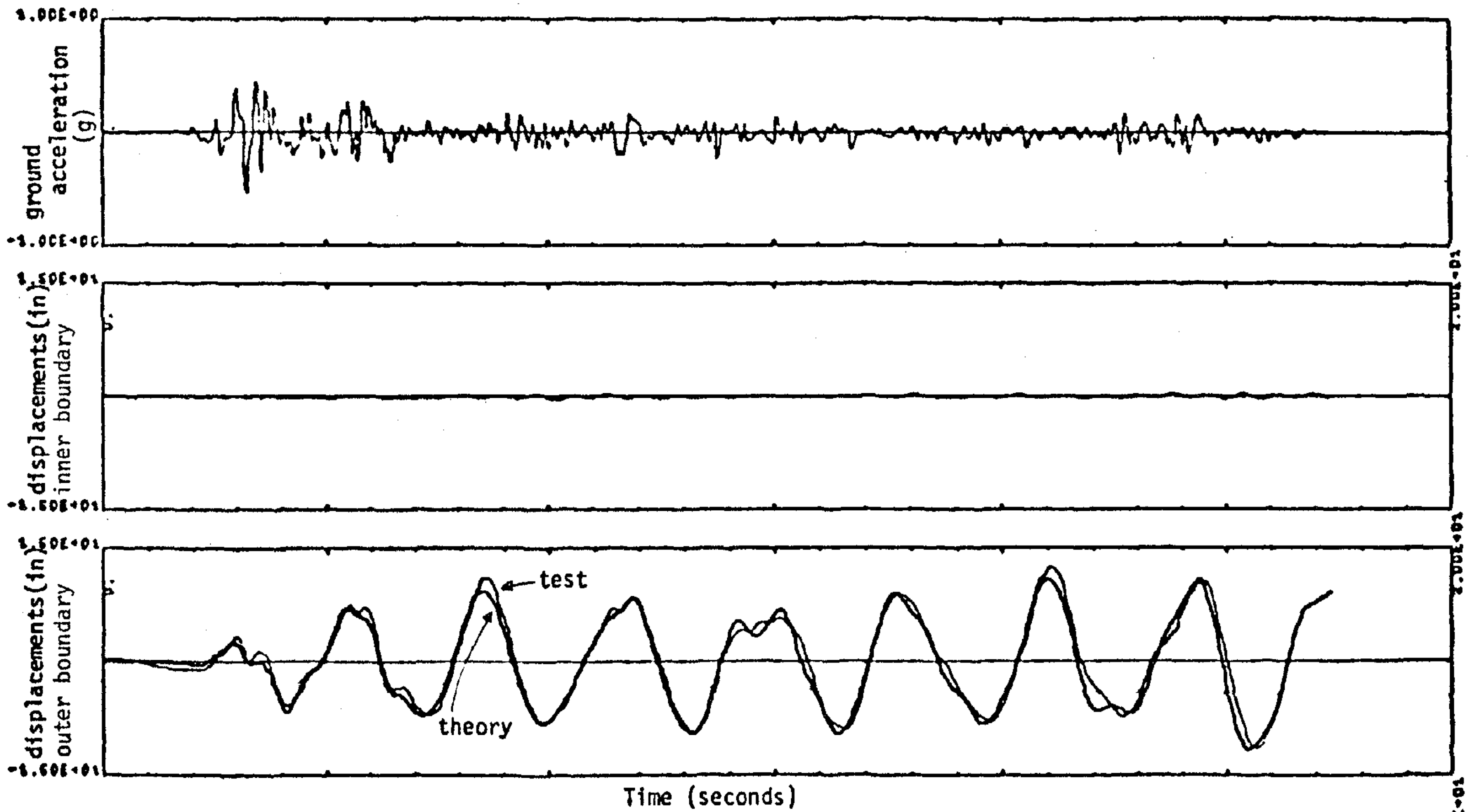

Fig. 1 SLOSHING RESPONSE OF WATER IN ANNULAR TANK(INNER RADIUS =0.1 IN, OUTER RAD=72.0IN, DEPTH OF WATER=60.0IN) UNDER ELCENTRO EARTHQUAKE(1940)TIME SCALE=1.73,MAX.ACCEL.=0.5G

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The concept of a National Information Service for Earthquake Engineering was a natural outgrowth of the increasing national awareness of the earthquake hazard, which resulted from the Anchorage earthquake of 1964, and of the subsequent research activity which was funded as a means of reducing that hazard. As the research activities increased in scope and complexity, it became apparent that the transfer of this expanding body of information to the engineering design profession should become a major phase of the total research effort.

The initial proposal for a five-year effort to develop a National Information Service for Earthquake Engineering (NISEE) was made in January, 1971. The program was planned as a joint University of California at Berkeley (UCB)-California Institute of Technology (CIT) project, taking advantage of the sizeable earthquake engineering resources of both institutions. The areas of principal research interest of each group were recognized in that initial proposal by the types of activities to be undertaken by each. The CIT activities are not to be discussed here, except to note that major efforts were directed to digitization and processing of strong-motion accelerograph records, to establish a comprehensive library, and support the Universities Council on Earthquake Engineering Research.

The principal components of the initial UCB-NISEE proposal were development of an earthquake engineering library, publication of an Abstract Journal in Earthquake Engineering, and organization of a service for collection and distribution of computer programs. Other activities included support of the International Journal of Earthquake Engineering and Structural Dynamics, and providing educational opportunities for practicing engineers in earthquake engineering.

The library has grown from nothing to a collection of over 10,000 items, well catalogued and publicized to the profession. The collection consists of research and technical reports, conference proceedings, periodicals, books, and other forms of materials. While the major emphasis is on earthquake engineering and relevant topics in structural dynamics and geotechnical engineering, the library also contains materials in the related areas of seismology, disaster planning, geophysics, geology, etc. The library maintains an active publication exchange program with domestic and foreign academic, professional and governmental institutions. As a result, the collection contains an extensive number of specialized publications in English and other languages which would not otherwise be available for study.

The library is open to the practicing professional and academic engineering community, as well as to the general public. Its services include loan privileges, reference assistance and photocopying. One of the unique aspects of the library is that it tries to reach out to users who are not able to visit it in person. In order to accommodate these distant users, mail-order photocopying and loan services are provided. Library users are informed about new titles through the library's acquisition lists which are issued periodically. In the future, these will be published in the EERC quarterly newsletter, the first issue of which is scheduled for distribution this summer. Access to the library's holdings is provided to visitors through its card catalog and to distant users through a printed catalog and the Abstract Journal in Earthquake Engineering.

The purpose of the Abstract Journal is to gather, organize and present an annual comprehensive collection of abstracts and citations of technical literature pertaining to the field of earthquake engineering. Each volume contains abstracts of research reports, technical papers, texts and reference books, codes and conference proceedings. The abstracts are identified and obtained by means of a survey conducted by the journal staff of domestic and international publications. Direct contributions also are received from authors and publishers. The journal is published in December each year; the first volume was published in 1972 and the latest, Volume 5, is planned for December. On the average, about 1,000 publications are covered in each volume.

At present, the abstracts contained in the journal are organized into nine sections corresponding to subject areas within the field. The journal also contains a listing of titles, an author index and a subject index. To enable users of the journal to obtain full texts of abstracted publications, information regarding their availability in the EERC Library and/or NTIS are included with each citation.

Substantial changes in production procedures were instituted with Volume 4. The journal is now compiled and produced with the aid of a computerized text and index processing system and photocomposition. These procedures have resulted in substantial savings in costs and staff time. Subscriptions to the journal have averaged 800 per year. The current price is $15.00.

The computer program distribution service currently has a total of 26 programs in its library, each fully developed and suitable for use in professional engineering offices. Codes included in the library have been supplied by Stanford, California Institute of Technology, University of Southern California, University of Michigan, University of Washington, University of California, Berkeley, and the firms of Dames and Moore and Sexton, Fitzgerald and Kaplan. Many of these programs are available in both CDC and IBM versions. During the past three years, an average of over 500 programs per year has been distributed.

In order to assist users in the application of some of the codes (SAP IV, NONSAP, TABS AND SPECTR) four extension courses have been conducted. Two of these were highly theoretical while the other two emphasized the practical aspects of program usage.

A survey of users of the codes available from NISEE indicated that they were being used by the profession for non-earthquake as well as earthquake engineering applications. Among the projects mentioned were analyses for: NASA HEAO-A3 Optimal Bench (orbiting X-ray telescope), clutch coupling assemblies for nuclear pumps, static and seismic studies of air handling equipment, combined thermal and pressure stress studies of high temperature heat exchangers, amplification studies of site soil structure, liquefaction and soil-structure interaction studies.

It has always been difficult to obtain contributions to the NISEE software library. Most researchers do not have sufficient funds to adequately develop or debug their programs for general use. One incentive for encouraging more contributions was the SHARE concept: three programs from the current NISEE library would be exchanged for one which was contributed for distribution by NISEE. Four programs were added to the library by this procedure. In another effort last year, Dr. Thiel wrote to NSF grantees requesting them to furnish NISEE information on computer codes which they had developed in earthquake engineering research. A total of six replies were received, four of which mentioned possible contributions to the NISEE software library. Documentation, however, was lacking for all of the programs offered and none have been completed or distributed to date.

Judging from the levels of usage and interest especially from the professional community, the NISEE program has performed a useful role in information transfer during its first five years. Insofar as the future for the UCB phase of NISEE is concerned, no major changes are planned. The existing services will be refined and geared for steady state operations as long as they are needed.

Acknowledgment

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This report outlines a National Science Foundation sponsored study to explore automated design of earthquake-resistant multistory buildings. Some background is given prior to presentation of recent results and future plans.

Design Automation - The subject discussed here is frequently labeled as "optimal design." This terminology, however, is not completely appropriate--a somewhat more descriptive term is "automated design." The distinction becomes apparent when it is realized that most optimal design methods in reality model standard design processes. What separates "standard" from "optimal" design techniques is that the latter are automated. While adherence to either design process could lead to formulation of an optimal design, use of automated procedures facilitates a more thorough search through potential design alternatives, yielding a greater probability that the optimal will be found. Note that optimal here does not mean some sort of grand supremum for the complete building (such a creation probably does not even exist) rather, a limited optimal for some specific portion of the design is intended. This will become clearer in subsequent discussion.

In order to automate a design process a specific description of the procedure is necessary. For the work described herein a somewhat philosophical but useful definition of design has been formulated. Design can be described as a complex collection of interrelated decision processes. This collection of decision processes has an entry point and an exit point, with the flow of decisions from entry to exit mobilized by a basic need, in this case the need for a multistory building. Each individual decision process is composed of three parts: (i) a collection of usable options, called the option set, (ii) a criterion by which various options can be assessed, called the decision motivator, and (iii) a procedure by which the set of usable options can be explored to satisfy the decision motivator, called the option search. Option sets can be divided into three categories: (i) sets composed of a continuous selection of usable choices, (ii) sets of discrete choices, and (iii) mixed sets of the preceding. Decision motivations are classifiable into two broad categories. The first category, labeled consignable motivators, consists of decision criteria which allow the assignment of numerical value, either scalar or vector, to each design possibility, thereby facilitating direct comparison of alternatives. The second category, referred to as subjective motivators, is composed of criteria for which no consistent, uniformly acceptable scale of value assignment can be devised. Subjective motivators might include such items as esthetic quality, environmental impact, open space needs, etc.

From the preceding discussion it is clear that to automate design is to model the various decision processes both individually and collectively. In building design there is an enormous number of decision processes reflecting a wide diversity of motivators and option sets. To completely model all of these decision processes is in all likelihood impossible. It is preferable to isolate individual decisions or small groups of interrelated decisions and study them a few at a time. This format will be followed here, i.e., attention will be restricted to decision processes which have consignable motivators and option sets which can be modeled using continuous functions. This latter restriction does not necessarily confine the effort to continuous option sets since many discrete option sets can also be modeled using continuous functions. In restricting the investigation to individual or small groups of decisions it is implicitly assumed that these decisions can be uncoupled from the remaining body of decision processes. Intuitively it would seem that this is not true in general but that groups of highly coupled decisions could possibly be isolated so that this assumption is approximately satisfied.

Some Results - The first in a series of studies to be conducted in this area explored the "member sizing" decision process, in particular column sizing in single bay shear buildings. This was followed by a second effort which incorporated sizing of beams as well as columns in single bay multistory flexible frames [1]. The decision motivator in both cases was weight minimization. Option sets were restricted to limited offerings from standard wide flange rolled steel sections. All connections were assumed rigid, with structural loading consisting of dead/live load plus earthquake type horizontal ground motion. Elastic analyses were employed utilizing mode superposition and the Housner response spectra scaled to reflect 25% of the El Centro, 1940, N-S component. Response constraints were stress limits and story drift limitations. The option search procedure employed was the mathematical programming technique called the method of feasible directions.

The main conclusions from the second of these two studies are:

1. The feasible directions algorithm has the very nice property that all designs generated during the search for the optimal are usable. Thus, the process can be stopped at any time, utilizing the last design generated. The algorithm does have some undesirable traits however. First, the feasible directions algorithm requires a fairly accurate determination of the location of each constraint encountered in the design search. This determination can prove to be a very time-consuming and expensive operation and may result in convergence problems if not handled correctly. Second, although it would be very useful if some degree of predictability or smoothness were inherent in the output of the algorithm, the feasible directions method is instead very erratic. Very small design changes are possible whether the option search is close to or far removed from the optimal. This raises difficulties in the very practical problem of trying to decide when to terminate the process.

2. Optimal column selection for an earthquake-resistant multistory building arrived at via a shear building model is substantially different from that obtained using a flexible frame model. Accordingly one must exercize caution in selecting a structural model for optimization purposes.

3. A considerable amount of member interdependence, i.e., decision coupling, was found to exist in multistory flexible frames. This is important because the extent of coupling determines to a considerable degree the efficiency which can be expected from any particular option search scheme.

4. A large number of constraints is necessary to define a usable system in multistory building design. It is imperative that these constraints be separated, as much as possible, into primary constraints, those which frequently govern the design process, and secondary constraints, those which infrequently govern the process. Design selection can then be made on the basis of the primary constraints, with a check of secondary constraints made upon final design selection.

Future Work - What has been covered in the first two phases is, of course, only the beginning as far as decisions to be made in the selection of a multistory building design. A third phase is presently underway in which an attempt to expand upon previous decision process modeling is being made. Exploration of additional decisions and more refined modeling is contemplated in the following areas:

1. Option sets for member sizing decisions will be expanded from the limited selections used previously to include all compact wide flange sections.

2. Beam - column connection flexibility will be added as a decision process, discarding the fully rigid connection assumption previously used.

3. Cost minimization including damage due to earthquake overload will be employed as a decision motivator rather than the weight minimization used to date.

4. Different option search procedures will be investigated.

Reference

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The experimental phase of an investigation concerned with the effectiveness of existing bridge design methodology in providing adequate structural resistance to seismic disturbance is summarized. It consisted of a model study and forms part of a multi-phased research project performed at the Earthquake Engineering Research Center under sponsorship of the U.S. Department of Transportation, Federal Highway Administration. Other completed phases included a literature survey of seismic effects on highway bridges and analytical studies. Linear and nonlinear analytical models suitable for modelling the dynamic characteristics of long multiple-span modern bridges were defined and analytical procedures and computer programs were developed for determing the seismic response of the three-dimensional system to given ground excitations. Procedures were also developed for linear and nonlinear two- and three-dimensional earthquake response analyses of short single or multiple-span highway bridges of the type where soil-structure interaction effects are important.

Model Design

A 1/30 true-scale microconcrete model of a simplified symmetrical version of a typical high curved bridge structure was constructed and subjected to appropriately scaled simulated seismic motions of varying intensity using the 20 ft x 20 ft shaking table at Berkeley. The model consisted of three deck segments, separated by expansion joints and supported at the abutments and on 3 ft high columns. The radius of curvature was 9 ft, the deviation angle was 135° and the total span approximately 22 ft. It was designed as an assemblage of replaceable components.

In relation to the prototype, the quantities scaled included all bending and torsional stiffnesses, self-weight effects and inelastic effects both in the expansion joint restrainers and in the columns.

The model was weight-distorted by adding deficiency weight equivalent to 30 times the self-weight of the model. The resulting time ratio was 1/5.5.

Model Response

Three types of simulated earthquake excitation were applied to the model, (1) horizontal excitation alone in the asymmetric longitudinal direction, (2) horizontal excitation alone in the symmetric transverse direction, and (3) horizontal excitation in the symmetric transverse direction with simultaneous vertical excitation. The response of the model, primarily the global relative displacements, was measured by means of LVDTs and recorded in digitized form by the data acquisition system. The response of the model was also recorded by a high speed movie camera.

Depending on whether the horizontal excitation was oriented in the longitudinal or transverse axis of the model, response was essentially oscillatory motion in the antisymmetric first mode or symmetric second mode. Both motions produce torsional discontinuity about the centerline of the bridge at the joints giving rise to torsional slamming during dynamic response. The structure was more susceptible to damage when responding in the prime symmetric mode. For curved bridge structures torsional deformations are typically more pronounced in this mode of response.

In all cases of high intensity excitation, severe damage occurred to the bridge deck at the zone of the expansion joints. The inclusion of ductile steel ties across the joints to prevent excessive separation of the girders and subsequent collapse of the structure did not prevent damage to the expansion joint region. The damage generally consisted of failure of the shear key and severe shear cracking across the hinge seat. Furthermore , the joint restrainers were subjected to large ductility demands. In the case of longitudinal excitation, spalling of the adjacent joint faces also occurred. It was caused by the large shear and impacting forces at the joints during the dynamic response of the structure and served to emphasize the undesirability of such discontinuities in this type of structure. For these particular test structures the column damage was insignificant.

The objective of these tests was to indicate trends of behavior, and also to provide test data on which to check the validity of computer analyses developed in Phase 2 of the project. The experimental studies clearly demonstrated the complexity of the 3-dimensional nonlinear response of curved bridges to earthquakes and some of the problems associated with the mathematical modelling of the phenomena.

Conclusions

On the basis of this study some comments pertaining to the feasibility of seismic studies with small scale structural models can be made:

i) Despite all the conflicting criteria to be satisfied, a model study of such a complex system as this high curved overcrossing has proved feasible. In general, for a nonlinear dynamic system where gravitational effects are important, the most suitable model will be weight-distorted and of true geometric scale in prototype material. Resulting time ratios should allow simulated seismic excitation to be applied by most modern shaking table facilities provided the scale is not too great.

   This particular study has emphasized the complex nature of the response of these structure to seismic disturbance, and has focussed attention on certain design problems. As such it has justified the approach adopted.

ii) The use of microconcrete and development of the simplified model design was apparently appropriate and satisfactory. Furthermore, the adopted component system proved very successful and allowed the replacement of isolated damaged components between tests.

The following recommendations concerning bridge design seem appropriate:

i) In designing expansion joints particular attention should be paid to the following factors: (a) the stiffness and ductility of axial restraint to prevent separation of the joint; (b) the length of the ledge necessary to accommodate the movement in 'a'; (c) the strength of the shear key to resist the large transverse forces; (d) the strength of the hinge seat in vertical shear and bending to resist the large local edge forces, caused by vertical reaction and torsion, combined with the axial tension due to joint opening; (e) the advisability of incorporating vertical restrainers to prevent torsional lifting.

ii) As the most difficult design problem in the structure is that of resisting the large dynamic forces and accommodating the movements at the joints, consideration should be given to reducing their number or eliminating them altogether where temperature and constructional factors permit. A curved bridge has an advantage over a straight bridge in that changes in center-line length can be accommodated by a slight change of curvature with consequent radial displacements. However, the potentially high stresses caused by out-of-phase effects of ground motion in a continuous long bridge structure should not be overlooked. The effect of non-rigid ground motion requires further study.

iii) The use of isolating devices and energy absorbers in the overall bridge system should be investigated.

C. M. DUKE

University of California, Los Angeles

National Science Foundation sponsored earthquake engineering research is being conducted on the effects of site and source on strong earthquake motion, a coordinated program of Messrs. Duke and Mal. The work on the source is under Mal and is described subsequently by him in this volume. The remainder of this report deals principally with site effects and is under Duke's supervision.

Spectral Analysis of Accelerograms

Data from the San Fernando earthquake and other earthquakes are being analyzed in an attempt to identify relationships between site conditions and ground motion, using as a model the so-called linear system theory. This has some deficiencies, such as being linear and not incorporating surface wave effects, but some useful results have been obtained from it.

Rigorous analytical models for strong earthquake motion require simplifying assumptions that limit their engineering applications. Such aspects as the effects of local site conditions, soil-structure interaction, the effects of the propagation mechanism from source to site and the source mechanism itself are difficult to incorporate in a rigorous analysis.

A linear system model can be developed which contains many of the essential ingredients. Such a model has been used with some previously reported success in analyses of local site effects in Kern County, San Fernando and Managua accelerograms. That model did not segregate the body and surface wave components of ground motion and assumed that the incident motion at a station is composed entirely of body waves. One objective of the present research is to evolve a new model which will remedy this deficiency.

A requirement of such a new model is that it incorporates transfer functions, based on exploration data, for surface waves as well as body waves. With these it is possible to compute the body wave and surface wave components of the motion recorded at one or more stations. The procedure can be extended to obtain improved representations of the transfer functions by making use of the body and surface wave parts of the instrumental data.

Correlation of Strong Motion Indices with Local Shear Velocities

One quantitative indicator of the dynamic character of a site is the profile of seismic shear wave velocity as a function of depth down to approximately 70 feet.

Shallow refraction surveys were made at or near to 47 stations which had recorded the San Fernando earthquake at or near to the ground surface.

The ground motion parameters used were the peak values of acceleration, velocity and displacement, and the value of Arias Intensity.

Briefly, as to results, speaking of soil sites, peak particle velocity and Arias intensity had significant correlations with the shear wave propagation velocity profiles. Peak acceleration and displacement showed much lower correlations, as did rock sites in general.

Recap

Both the spectral method and the strong motion index method have shown promise for correlation of dynamic site properties with measured ground motions.

GARY C. HART

University of California, Los Angeles

Research conducted by the above noted professor is in the following three areas: (1) Instrumentation of Full Scale High Rise Buildings, (2) System Idenfitication (3) Quantification of Damping.

The UCLA Full Scale Earthquake and Wind Laboratory has at its main element an integrated instrumentation program to measure full scale earthquake and wind response. The instrumentation is intended to measure low, medium and severe wind response of high rise buildings approximately thirty days per year. The response will be used to study human comfort response levels as well as building period variations with amplitude.

System Identification studies for buildings are a continuing research project. The progress to date as well as a literature search has been summarized in a paper presented at the ASCE/EMD specialty conference held at UCLA in March, 1976.

Damping variation with amplitude is an area under study. Full scale and shaker table studies underway are intended to study energy dissipation with response amplitudes.

KENNETH L. LEE

University of California at Los Angeles

My recent past and expected near future earthquake engineering research deals with three major topics: (1) Reinforced earth, (2) Cyclic Strength of Soil and (3) Seismic Stability Analyses of Embankments.

Most of the oral presentation will be devoted to a 4-minute sound movie produced by the UCLA public relations office which describes some of our work on the seismic stability of a 20 ft high reinforced earth test wall. This wall was constructed and tested in a period of 8 weeks during the summer of 1974 by 3 graduate students, which in itself attests to the ease with which reinforced earth walls can be built. It was subjected to forced vibration shaking tests and to dynamite blast tests which gave a total of 11 peak accelerations in excess of 0.5g for a total duration of strong shaking of 13 seconds. Although the wall was designed by conventional methods for only static loading, it was not significantly damaged by the dynamite blast testing. The research has led to an empirically based method for seismic design of reinforced earth walls. Currently ongoing research is aimed at improving the design method and giving it a more rigorous basis than at present through the use of additional models on the Berkeley 2-D shaking table and the use of the Berkeley finite element program FLUSH.

Studies in the area of soil strength during cyclic loading have involved the following topics: The effect of end restraint in cyclic triaxial tests (0 to 30% strength increase depending on soil type and density); Experimental justification of the equivalent uniform cycle concept; Results of simple shear vs triaxial cyclic tests; 3-D cubic vs triaxial cyclic tests, static strength remaining after cyclic loading; The effect of partial saturation on the cyclic strength of soil; and The response of different types of soil to cyclic loading including decomposed granite, sands of various particle shapes, and various clays including extremely sensitive marine clays. The work has also included a brief inquiry into the effect of some low-level shaking before the major seismic disturbance and the effect of drainage during cyclic loading.

Seismic stability analyses techniques have included an assessment of the relative influence of various parameters which pertain to the stability of embankments, including: embankment height, slope, soil density, seepage conditions, and earthquake characteristics. In addition, methods have been studied to improve on existing techniques for analyzing the stability of embankments under seismic loading conditions, including the effect of the non-saturated zone above the phreatic line, the possibility of failure along one curved surface through the embankment rather than along assumed horizontal surfaces through every element and a method of estimating non-failure permanent deformations resulting from an earthquake.

A. K. MAL

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National Science Foundation (RANN) sponsored research is being conducted on strong ground motion produced in shallow earthquakes. A major effort is made to develop models which would be able to predict displacement, velocity and acceleration at a given site due to a given earthquake. As a prerequisite, two aspects of the problem are being examined. One involves the nature of the earthquake source and the other, the development and subsequent transmission of surface waves through the alluvial or other layers near the surface of the earth. Summaries of the directions of our current research, together with the significant results obtained so far are described below.

Investigation of the Earthquake Source

An accurate knowledge of the source is an essential ingredient in the construction of reliable predictive models. Unfortunately, the mechanics of the earthquake source is not very well understood at the present time. It has been well established, however, that almost all shallow focus earthquakes are caused by propagating ruptures along preexisting fault surfaces. Accordingly, the current state of knowledge in the theories of brittle fracture is being utilized to develop a parametric model of the source. A major objective of our research has been to identify the parameters which play significant roles in producing strong ground motion in the vicinity of the source. To this end, we constructed simple kinematic models (in 2 and 3-D) of the source based on fracture theory and calculated near field ground motions by placing the source in a simplified model of the earth (usually, a uniform half space). The results were compared with the available near field data from two earthquakes (1966 Parkfield, 1971 San Fernando). In both cases, the agreement between the predicted and recorded motions was good for displacements, fair for velocities and poor for accelerations. A more accurate model of the source is clearly needed for calculations which are relevant in earthquake engineering. One major difficulty in the currently used source models is that the rupture is assumed to have the same properties as those in the fracture of brittle, homogeneous solids while, in an earthquake, the failure propagates along a preexisting weak zone on a fault surface. There may be significant differences in the two processes which in turn may cause a great deal of difference in the calculated velocities and accelerations. Two separate approaches are being pursued in an attempt to remove this difficulty.

In one approach, we are attempting to construct more realistic theoretical models of faulting by introducing a weak transitional zone of small thickness across the fault surface. The initiation of failure in this weak zone due to tectonic prestresses and the subsequent propagation of the failure is being investigated.

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Table 1

Available Accelerograms for Seventeen Aftershocks
Between August 3 and August 16

Date	HrMn	M_L	DJR	OMC	OAP	DWR	EBH	1	2	3	4	5	6	7	8
Aug 3	0103	4.6		AS	AS	AS	AS	AS		A	AS	AS			
3	0247	4.1		AS	AS	AS	AS	AS		A	AS	AS			
4	0947	3.5	AS				AS			A	A	AS			
5	0228	3.3	AS				A				AS	AS			
5	2044	3.2	A				A	AS		A	AS	AS			
6	0350	4.7	AS	AS	AS	AS	AS	AS	AS	AS	AS	AS			
6	0351[1]		AS	AS	AS	AS	AS	AS	AS	AS	AS	AS			
6	0351[1]		AS	AS	AS	AS	AS	AS	AS	AS	AS	AS			
6	1625	3.1	A				A					A			
6	1641	3.6	AS		AS	AS	AS	A		AS		AS			
8	0700	4.9	AS		AS	AS	AS	AS			AS	AS	AS	AS	
8	1337	3.2	A			AS	A	A				A	AS	AS	
8	1903	3.1					A	AS				AS	AS	A	
11	1611	4.3	AS	A		A	A	A			A	A	AS	AS	AS
11	1559	3.6	A	AS	AS	AS	AS	AS			AS	AS	A	AS	A
16	0548	4.0	AS	AS	AS	AS	AS	AS			AS	AS	AS	AS	AS
16	1223	2.8	A		A	AS	A	AS			AS	AS	A	AS	AS

Vertical solid line: Instrument not installed
Vertical dashed line: WWVB time not identifiable

[1]Two small aftershocks of 0350, magnitudes unknown, recorded within run time of 0350.

located on substantial thicknesses (several hundred meters) of alluvium than at hard rock sites and 2) for aftershocks of comparable magnitude, peak accelerations decrease more rapidly with R for the shallower events. The latter observation suggests that the upper 3 to 5 km of the Earth's crust, in which the entire transmission paths for the shallow events lie, is considerably more effective in attenuating and/or scattering high-frequency seismic radiation than is the crustal material at greater depth. The first observation implies that unconsolidated alluvium has a stronger effect in this regard than near-surface crystalline rock.

The S-wave arrival data have been used to estimate the gross shear-wave velocity structure of the epicentral region, indeed a novel use of data obtained from strong-motion accelerographs. The section of recent alluvium in the western half of the epicentral region manifests itself not only in reduced high-frequency amplitudes of the S-wave, but also in a significant delay of the S-wave arrival time. Well-recorded aftershocks occurring within the closure of the array have been located with a fair precision with the S-wave arrival times taken only from the strong-motion accelerograms.

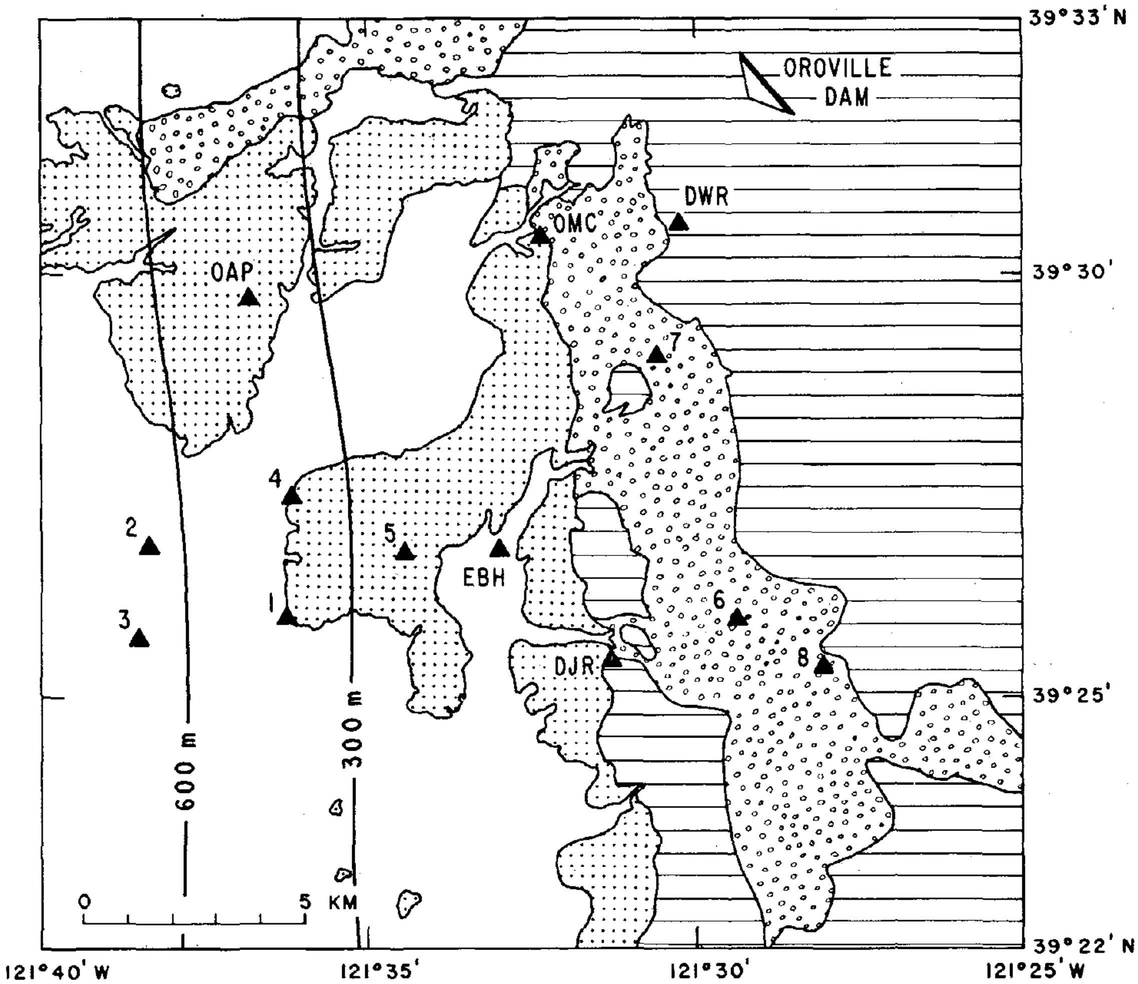

Figure 1. Epicentral region of the Oroville, California, earthquake. Generalized surface geology: blank areas, recent alluvium; dotted areas, Pleistocene gravels and alluvium; open circled areas, mainly Tertiary gravels and conglomerates, with occasional Tertiary volcanic rocks and sandstones; lined areas, pre-Tertiary crystalline rocks. Depth to basement shown by contours in western part of the area.

were as great, and often greater, than those known prior to this earthquake sequence. The following values are the largest recorded at Oroville for the magnitudes given in parentheses: 70% g (M_L = 4.7, R = 13 km), 58% g (M_L = 4.6, R = 13 km), 42% g (M_L = 4.3, R = 5 km), 24% g (M_L = 4.0, R = 12 km), 19% g (M_L = 3.3, R = 8 km), 19% g (M_L = 3.2, R = 9 km), 10% g (M_L = 2.5, R = 6 km), and 5% g (M_L = 1.8, R unknown). Peak accelerations of 10% g or greater were a common occurrence for all well-recorded $M_L \geqslant 3$ aftershocks.

An examination of the raw peak acceleration data has revealed that 1) peak accelerations for the same shock at comparable distances are generally lower, and often by a considerable margin, at sites

THOMAS C. HANKS

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STRONG-MOTION ACCELEROGRAMS OF THE OROVILLE AFTERSHOCKS

Within 48 hours of the Oroville, California, earthquake (Aug. 1, 1975; $M_L = 5.7$) 10 strong-motion accelerographs, each with the capability of writing the WWVB time code directly on the recording film, were installed in the epicentral region by personnel of the California Division of Mines and Geology (CDMG), the California Institute of Technology (CIT) and the U.S. Geological Survey (USGS). Although the array changed configuration several times due to redeployed and additional CDMG instrumentation, at least 10 accelerographs were operational in the epicentral region through the end of October. Figure 1 displays these accelerograph locations as triangles, the solid symbols denoting instruments operational for most or all of the time interval August 3 to October 31.

Positively identified strong-motion accelerograms have been obtained for intermediate-magnitude earthquakes, precisely located by the network of USGS high-gain stations, in virtually staggering proportions. Through the end of October, 313 positively identified strong-motion accelerograms had been obtained for 86 different aftershocks, with magnitude (M_L) as large as 5.2 and as small as 1.8. Almost all of these accelerograms were written at hypocentral distances (R) of 5 to 15 km, a distance range in which very few strong-motion accelerograms had previously been available.

Especially significant are the number of accelerograms available for individual aftershocks of $M_L \geqslant 3$ for a wide range of site conditions (Figure 1). Table 1 lists 17 of the larger aftershocks, including all events of $M_L \gtrsim 3.2$, in a 14-day interval defined by the field operation of four continuously recording, long-period seismographic systems operated in the epicentral region by the Seismological Laboratory of CIT. The entry A denotes a positively identified accelerogram for the appropriate source-station pair, and the entry AS denotes that the accelerogram began prior to the S-wave arrival. With respect to the number of strong-motion accelerograms and completeness of coverage at such close distances, these data are without precedent in strong-motion seismology. Even so, Table 1 is hardly a complete listing of all the aftershocks that have been well-recorded. Generally, aftershocks located within the closure of the array wrote three or more accelerograms down to $M_L = 3.0$, with the exception of several shallow aftershocks of $M_L \simeq 3$ for which only the closest one or two accelerographs triggered. Forty-three aftershocks with $M_L < 3$ were recorded, but only seven of these wrote three or more accelerograms.

Through the entire magnitude range for which any accelerograms are available ($1.8 \leqslant M_L \leqslant 5.2$), acceleration amplitudes at $R \simeq 10$ km

A major observation which was made is that for a wide range of values of structural and ground motion parameters, the number of "fully reversed inelastic cycles" of response (or loading) is not likely to exceed 5 or 6, under a 10-second duration of strong ground motion. Of significant interest is the fact that in many cases the maximum amplitude of response occurs rather early with no significant inelastic cycles preceding it.

EXPERIMENTAL INVESTIGATION

The experimental program is divided into three parts. In Part I, reversing loads are applied to isolated walls. In Part II, reversing loads are applied to wall systems. In Part III, elements of systems are to be tested. Part III is primarily an investigation of the behavior of confined concrete and of coupling beams.

Highlights of the program to date

Part I - Isolated Walls. The isolated walls represent an element of a structural wall system. They are being tested to determine their strength, ductility, and energy dissipation capacity.

The test specimens are approximately 1/3-scale models of actual walls. The model walls are 15-ft. high and have a horizontal length of 6 ft.3 in. The web thicknesses are 4 in. All test specimens are subjected to in-plane horizontal reversing loads.

Controlled variables covered in the program to date (9 walls have been tested) include the shape of the wall cross section, the amount of main flexural reinforcement, and the amount of hoop reinforcement around the main flexural reinforcement.

Part II - Systems. Systems containing connecting elements with various proportions will be constructed and tested at approximately 1/3-scale. The systems specimens are being designed with the intent of providing proof tests of structures having proportions and details representative of typical structures. Three coupled structural walls and a wall-frame structural system are planned.

Part III - Elements. Tests have been performed on specimens representing the compression zones of structural walls. These tests are being performed to evaluate the effect of confinement reinforcement and to determine the effective stress-strain curve of confined concrete. The controlled variables in the test program include spacing and size of the confinement reinforcement, concrete strength, amount of longitudinal reinforcement, and size of test specimen.

In addition, a series of tests of coupling beam elements for coupled walls is being carried out. To date, three specimens having a cross section of 4 x 6-2/3 in. and an overall length of 16-2/3 in. (giving an aspect ratio of 2.5) have been tested to failure under slow load reversals.

will serve as the basis for the design procedure to be developed as the ultimate result of the project; (2) synthesizing a "representative" loading history which can be used in the laboratory testing of isolated wall specimens on the basis of the results of the dynamic analysis; and (3) studying the measured force-deformation curves from the experimental program to determine the influence of shear and examine the range of moment and shear when the primary (monotonic) curve can be adequately predicted on the basis of flexural considerations alone.

A brief discussion of the work carried out to date and some of the results obtained is given below:

(A) Force levels and deformation demands corresponding to various ranges of major structural and ground motion parameters

To determine the range of moments and shears and deformation requirements which can be reasonably expected for practical cases, a number of building configurations using isolated structural walls were studied. Two types of wall sections were considered, i.e., the rectangular section and a flanged section.

Particular attention was given to the levels of shear stresses which can be expected in practical cases. The variation of the maximum shear stress as well as the corresponding rotational ductility requirements and interstory displacements was determined for different plan configurations. This information, with the results of the evaluation of the critical shear/moment ratios expected in isolated walls, will provide the basis for recommendations of force levels and deformation requirements to guide the design of structural walls. When considered together with the experimental data on strength and deformation capacity of walls of typical sections, this information will form the basis for the rational design of isolated structural walls for earthquake resistance.

In the second phase, coupled walls and wall-frame interactive systems will be studied.

(B) Loading history study

The major aim in undertaking this study is to determine a representative range of earthquake induced deformations in terms of the amplitude of the maximum response and the number of cycles of significant amplitude which can be expected in isolated walls under a range of structure and ground motion parameter combinations. The study was motivated by the belief that the behavior of laboratory specimens, or actual structures for that matter, can be influenced significantly by the type of loading (magnitude, number of cycles and sequence) imposed on the structure.

Quasi-static reversed loading tests conducted to date have used more or less arbitrary loading sequences characterized by progressively increasing amplitudes of deformation until failure.

MARK FINTEL

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In July of 1974, PCA started (with NSF-RANN sponsorship) a comprehensive 5-year analytical and experimental program to investigate the response to earthquake excitation of reinforced concrete structures containing structural (shear) walls. The aim of the study is to develop design procedures and reinforcing details for earthquake resistant multistory reinforced concrete structures containing structural walls.

ANALYTICAL INVESTIGATION

The objective of the analytical study is to investigate (through inelastic dynamic response) the effects of the following parameters:

1. Fundamental period of vibration
2. Yield level
3. Post-yield stiffness
4. Viscous damping
5. Character of moment-rotation hysteretic loop
6. Stiffness taper
7. Strength taper
8. Degree of fixity at base
9. Number of stories or height of building
10. Ground motion intensity
11. Ground motion frequency characteristics
12. Duration of ground motion

In addition to the major effort of undertaking the dynamic analysis associated with the parametric studies, preliminary studies of input motion data were undertaken to determine a suitable basis for normalizing accelerograms with respect to intensity, and also to characterize accelerograms approximately in terms of their frequency content. Also, an initial effort was made to carry out a parametric study of typical structural wall sections under combined flexure and axial load.

The analytical work of the first two years has been concentrated on the evaluation of the results of the dynamic analysis of isolated walls, with the aim of (1) arriving at guidelines for the design of earthquake-resistant structural walls, with particular reference to force (moment and shear) levels and deformation demands (ductility and energy dissipation) which may be expected under particular ranges of values of both structural and ground motion parameters. This information, together with data obtained from laboratory tests, energy peak is of the order of 2 percent. These relationships remain under study and are most complex owing to the dependency between consecutive response peaks.

Other statistical and probabilistic modeling studies are in progress and the results will be reported as the work is completed.

JACK R. BENJAMIN

Engineering Decision Analysis Company

The purpose of the research reported is fundamentally to improve the assessment of seismic design criteria in the form of response spectra by improving the understanding of the response characteristics of engineered systems to earthquake records. The analytical techniques are probabilistic and statistical in nature. The general assumption is made that the instrumental record is probabilistic so that the entire process is probabilistic and that probabilistic models can satisfactorily summarize the properties of seismic response that are of engineering interest.

The approach has been to select six different earthquakes having differing characteristics and with different apparent records and site conditions. Preliminary studies have focused on elastic response and 5 percent damping. Analyses have begun with response time histories at 22 periods 0.08 to 3 seconds considering that the response time history is a realization of a complex random process.

The statistical properties of the response time histories were first determined and compared. Although the realizations of the process at 0.02 second increments and peaks are not independent, the numerical summaries of the response time histories are of major interest. First, the ratio of mean of peaks to mean of increments is a constant for all periods, all earthquakes, and all sites. The same is true for RMS of peaks and increments. The coefficient of variation of peaks is equal to the square root of two for all earthquakes, periods, and sites.

Extensive studies of response spectra from the standpoint of probabilistic modeling discloses that the mean value function for all earthquakes, sites, and damping is of the form:

$$S_A = C_1 e^{C_3 T} + C_2 T e^{C_4 T}$$

in which C_3 and C_4 appear to be constants relatively independent of earthquake and site while C_1 and C_2 have a near constant ratio to each other for a given earthquake. Interestingly enough, C_1 appears to be non-linear with peak ground acceleration and this is the only parameter that appears to be correlated in any way with peak ground acceleration.

Using the statistical properties of the peaks of response, it appears as though the probability of exceeding the mean value function for S_A with an earthquake containing a single or dominant

- Design requirements related to life safety for architectural elements, and mechanical and electrical systems and equipment. Special requirements are also listed for essential facilities with the aim of maintaining facility functionability and protecting life safety during and after an earthquake.

- Provisions for evaluation and repair of potentially hazardous existing buildings. Three appendices are being prepared covering evaluation of post-earthquake hazards of existing buildings, evaluation of earthquake hazards in existing buildings, and repair and strengthening of existing buildings.

- A detailed commentary covering the reasoning and justification for the recommended provisions.

It is planned to make a number of trial analyses and designs for conditions in various areas of the United States when the final recommended provisions are completed.

In conclusion, this has been a very ambitious effort and the final documents should be of considerable assistance in designing buildings to mitigate earthquake hazards. The final documents will represent a consensus on state-of-the-art design provisions for use by professional practitioners. It should be realized, however, that the provisions will need continued work and updating as further advances are made in the science and art of earthquake engineering.

I would like to thank the many participants for their unstinting efforts.

- Building occupancy factors based on essential (emergency) use or occupancy density. Special requirements for construction, such as type of framing, connections, ductility, etc., will be specified as appropriate.

- Design coefficients based on stressing of structural materials or seismic force resisting structural systems to near-yield conditions.

- Three analysis procedures which are specified depending on seismic hazard zone and seismic hazard exposure of the building. Procedure 1 does not require an earthquake analysis but special design requirements are mandatory. Procedure 2 uses equivalent lateral force procedures somewhat similar to those specified in SEAOC Lateral Force Requirements and the Uniform Building Code. Procedure 3 is a two-dimensional modal analysis.

- Distribution of lateral forces in buildings considering the dynamic characteristics of the structure. This requirement will apply to buildings with highly irregular shapes, large differences in lateral resistance, or stiffness between adjacent stories or other unusual features and can be satisfied by using Procedure 3.

- Base shear for Procedure 2 calculated by $V = C_s W$ (effective weight of building)

  where $C_s = \frac{1.2\ AG}{RT^{2/3}}$

  A = normalizing factor based on EPA or EPV.
  G = soil profile factor ranging from 1.0 for rock and stiff soil to 1.5 for soft soils.
  R = response modification coefficient depending on type of structural system (ductile, semi-ductile, shear wall, etc.) including vertical and horizontal lateral force distribution systems.
  T = structural response coefficient based on framing method and geometry of building and is used for defining minimum base shears.

- Base and story shears, and overturning moments may be reduced for the effects of soil-structure interaction. Specific procedures are given.

- Draft limitations considering occupancy.

- General and special design requirements which provide for interconnection of building elements, interaction effects of flexible and rigid elements, limitations on materials, and deformational compatibility between lateral force resisting and non-lateral force resisting structural elements.

ROLAND L. SHARPE

Applied Technology Council

The Applied Technology Council (ATC) has been working for over two years on the development of nationally applicable seismic design provisions. The work is being done under a contract with the National Bureau of Standards (NBS) with funding by NSF RANN and NBS. The project is part of the Cooperative Federal Program in Building Practices for Disaster Mitigation initiated in 1972 under the leadership of NBS. A total of 85 participants from many parts of the United States is involved, representing practicing engineers and architects, academicians, and code promulgating and enforcing groups. The project goal is to transform many of the research results of the past decade or so into design provisions that can be understood and used by practitioners.

The project organization is essentially the same as presented at the UCEER meeting in May 1974. The five task groups comprised of fourteen task committees have invested a lot of effort to date. Two draft reports were prepared and reviewed intra-project in 1975. More recently, a 400-page Working Draft was submitted in February 1976 to some 500 reviewers representing practice, academicians, industry, professional organizations, and government. The many pages of constructive comments received are being considered by the task committees who are now preparing modified design provisions and detailed commentaries. Another draft will be completed this fall and will be submitted for limited review. A final draft is scheduled for April 1977.

The design provisions are unique in that they cover many items not now in building codes, including non-structural elements (architectural, mechanical, and electrical systems), and evaluation and repair of potentially hazardous buildings. The underlying philosophy is to minimize hazards to life safety and to maintain post-earthquake functionability of certain essential or emergency facilities such as hospitals, communication and control centers.

Briefly, the provisions include:

- Design regionalization maps of the United States which take into account earthquake history, distance from anticipated epicenters, frequency of occurrence, and geologic-tectonic structure. The goal is to have roughly the same probability of exceedance of the design ground motion in all sections of the United States. Two maps are involved--one for effective peak acceleration and one for effective peak velocity. A prime reference for preparation of the EPA map is the work being done by Algermissen and Perkins of USGS.

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Finite Element Model

A high-precision finite element procedure originally developed for the static analysis of arbitrarily loaded, thin elastic shells of revolution[1] has been generalized to include dynamic effects based on Hamilton's variational principle[2]. The efficiency of the formulation is greatly expedited through the use of a kinematic condensation technique which permits only the nodal variables to be retained without appreciable loss in accuracy. In order to model the system of supporting columns, an equivalent discrete elastic support element which is compatible with the rotational shell element was developed[3]. For this element, the axial and bending stiffness properties of the closely spaced columns are expressed in terms of the shell coordinates and then assumed to be uniformly distributed around the circumference. The elastic support element is then combined with regular shell elements to model the hyperboloidal geometry for the vibration analysis. Upon the completion of the dynamic analysis, the stress free condition between columns is enforced with a self-equilibrated edge loading. The ring beam which is generally present as a transition between the columns and the shell proper, as shown on the figure, is modeled using tapered rotational shell elements.

Results

Response spectrum results which show the influence of the base flexibility on the spectral velocity for a typical case were presented at the UCEER meeting at the University of Michigan in 1974 and are given in Reference 4. Some further results have been obtained with respect to the computation of stress resultants and couples in the course of a response spectrum analysis.[5] Two alternative computational methods were compared: (1) The associated inertial forces are computed and applied to the shell as a set of static loads. Then, a standard stiffness analysis is carried out and the ensuing forces and moments are calculated by applying the kinematic and constitutive equations to the computed static displacements; and (2) The strains and changes in curvature are found directly by applying the kinematic and constitutive laws to the dynamic displacements. It was found that serious errors may occur with the first method and that the second method is far more reliable, especially with a sparsely spaced finite element grid which is advantageous with high-precision elements.

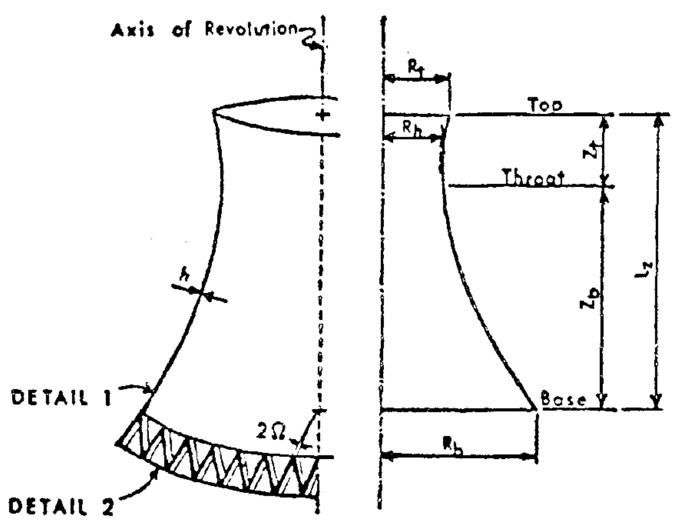
It has also been found that direct integration solutions for the dynamic response of rotational shells are quite efficient with the high-precision element.[6]

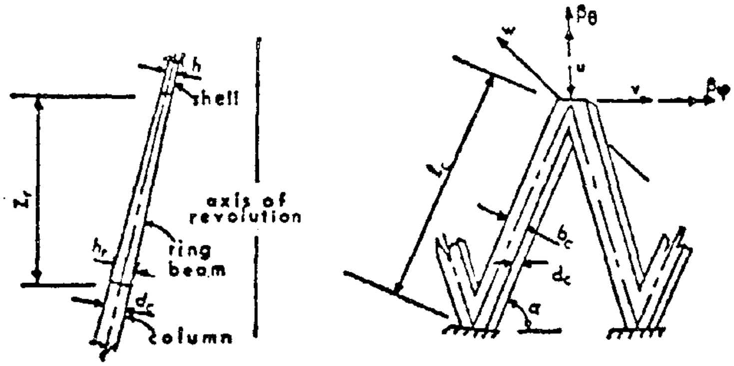
P. L. GOULD

Washington University

General

National Science Foundation sponsored earthquake engineering research dealing with the seismic analysis of hyperbolic cooling towers is in progress. The response spectrum method is generally accepted as a realistic basis for the seismic analysis of cooling towers. From a structural engineering standpoint, the information required to perform such an analysis is obtained chiefly from an undamped, free vibration analysis. For doubly curved shells such as cooling towers, a dynamic analysis is best approached with a variationally based method which produces a consistent mass matrix and a consistent loading vector. The principal reason for requiring this degree of sophistication is that purely physical lumping of the masses and loads is difficult and often inacurrate with curvilinear coordinates. Also the presence of the column system at the base of the shell obviously influences the natural frequencies and mode shapes, particularly those due to a horizontal seismic excitation where the shell may translate with respect to the base of the columns.





DETAIL 1 DETAIL 2

accelerator facilities have maintenance programs of their own. All possible solutions are studied on the Hybrid Computer where the actuators control system can be optimized. The feasibility of active isolation will be investigated for sensitive buildings such as hospitals or communication centers.

C. Computerized Structural Dynamics: The last area of current research concerns numerical algorithms to determine the dynamic response of large structural systems. We are upgrading the ANSWER System (Analysis of Structures, Wisconsin Engineering Research System) to include specialized features such as automatic formation of consistent mass matrices and automatic reduction of the size of the dynamic model by appropriate condensation of the mass and stiffness matrices. In connection with the above, studies are conducted on computation time, error, convergence, accuracy, and number of eigenvalues which must be calculated to obtain sufficient accuracy.

Equations of motion for generalized discrete systems in 3 dimensions, including rotation of the base as well as nonlinear terms, are studied. Rigid body base movement in 3 dimensions results in complex motion, especially if the rotational components are large. We are also interested in motions of structures relative to base (movable structures, antennae, cranes, etc.). These problems result in stiffnesses which are a function of displacement in a nonlinear sense, and we are investigating the possibility of substructuring for obtaining eigenvalues by parts.

A.H. PEYROT and W.E. SAUL

University of Wisconsin - Madison

Earthquake Engineering Research at the University of Wisconsin falls into 3 major areas: Parametric Studies of Complex Nonlinear Earthquake Responses on the Hybrid Computer, Performance Studies of Earthquake Protection Systems, and Improvements in Computerized Dynamics of Linear and Nonlinear Structures.

A. Hybrid Computer Simulation: We are using the Hybrid Computer (combination of Analog and Digital) extensively in Monte Carlo studies of the earthquake response of highly nonlinear support systems for structures and equipment. These Monte Carlo studies are done in two steps: artificial earthquakes generation and response simulation.

An hybrid scheme has been devised to generate ensembles of artificial earthquakes of given average response spectrum. The generation process involves sequences of random numbers in the digital computer, transformation into analog signals and passage through electronic filters. The filters' characteristics are iteratively improved until the response spectrum matches the target spectrum. Since filtering and response calculations are done on the analog computer, the fitting process is extremely fast. Once a desirable earthquake has been generated, it is automatically digitized and stored for later use.

The nonlinear structures which we are studying are entirely modeled on the analog portion of the equipment. This permits modelling of extremely complex configurations where the dynamic characteristics are nonlinear and functions of the past and present states of the system. Once the model is established, a complete earthquake response to a given artificial earthquake can be obtained in no more than 5 seconds, regardless of the complexity of the model. Statistical properties of response collections are used to evaluate a given design.

B. Earthquake Protection Devices: We are studying possible passive (or active) support devices to protect equipment (and eventually buildings).

An active protection device has been developed for nuclear particle accelerators where a slender ceramic or glass column must be used to support equipment electrostatically charged at several million volts. The device consists of battery operated telescopic arms which can provide additional support to the column within one second of the onset of an earthquake. One such device is being installed by a Wisconsin manufacturer on the Tsukuba University (Japan) accelerator.

Other passive (or active) isolation systems are being investigated for the accelerator industry. One such device involves a controlled system of actuators and springs which minimize the acceleration response of the equipment in the event of an earthquake. The maintenance necessity of such devices is not considered a problem because such

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M. NOVAK

University of Western Ontario

Theoretical and experimental research into interaction between an elastic pile and the soil is being conducted. The objective of the research is to define impedance functions of the soil-pile system, obtain fundamental insight into the problem and verify the potential for theoretical prediction of pile-supported footings and structures.

Theory for dynamic soil-pile interaction

Two theoretical approaches to dynamic soil-pile interaction were developed. Both assume vertical piles of circular cross-section and linear elasticity or visco-elasticity. Despite this idealization, the approaches appear to be useful for small displacements and may be extended for large displacements by means of equivalent linearization.

The first approach is relatively simple. It is based on the assumption that the soil can be represented by a set of infinitesimally thin independent horizontal layers that extend to infinity. This assumption is equivalent to the assumption of plane strain or taking into account only horizontally propagating waves. The solution of all vibration modes can be obtained in closed forms. Horizontal, vertical and torsional responses were analyzed and the behavior of floating piles was also examined. The results are described in Refs. 1 to 3.

The second theory is more rigorous. It assumes a visco-elastic layer overlying rigid bedrock. This theory is particularly illustrative in clarifying the effects of material damping, Poisson's ratio and resonances with the natural frequencies of the soil layer. The agreement of this theory with the simpler one is generally quite good and increases with frequency. The more rigorous theory is or will be available in Refs. 4 to 6.

Field experiments with vibrating piles

The theory developed was compared with field experiments conducted with pile-supported rigid footings subject to harmonic excitation. The pile foundations used were small enough to be inexpensive and large enough to be reasonably representative of real foundations. The excitation applied was vertical, horizontal and torsional. The results of the experiments and their comparison with theoretical predictions are described in Ref. 7.

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tion spectra are more stationary than the power spectral ratios and that the natural ground frequencies determined by the amplification spectral ratio method agree very well with those determined from shear velocity measurements in the field.

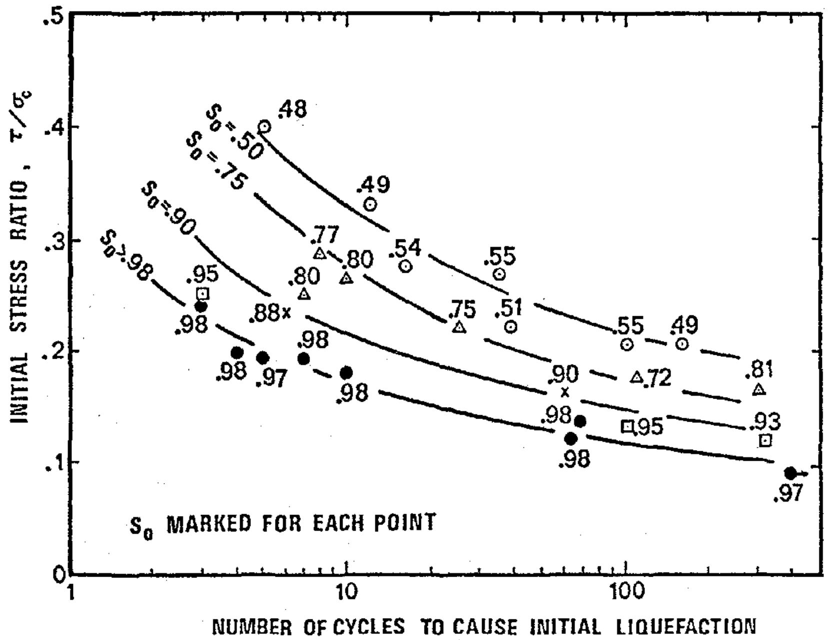

Fig. 3 Effect of initial degree of saturation on liquefaction potential

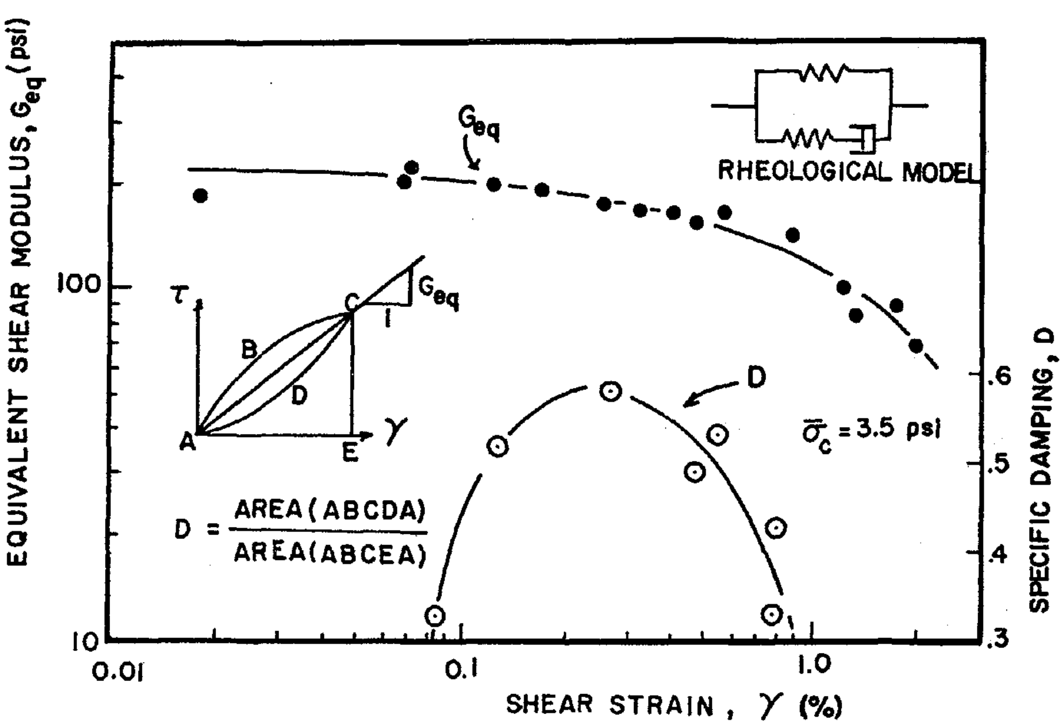

Fig. 4 Shear moduli and damping for marine sediment

relationship is established as shown in Eq. 2. This equation predicts the pore-pressure buildup in a saturated sand under either uniform or non-uniform dynamic shear stresses as a function of stress history and the number of stress cycles.

$$\Delta U_N = \left\{1-U_{N-1}\right\} \left\{\frac{C_1}{N_{eq}^{C_2} - C_3}\right\} \left\{\left(\frac{\tau_N}{\sigma'_{N-1}}\right)^{\alpha}\right\} \text{ and } N_{eq} = \sum_{i=1}^{N} \left(\frac{\tau_i}{\tau_N}\right)^{\alpha} \qquad (2)$$

where ΔU_N = normalized pore-pressure increment per cycle (pore-pressure rise divided by the total confining pressure u_N/σ_c); U_{N-1} = normalized residual pore pressure at the end of $(N-1)^{th}$ cycle; N_{eq} = equivalent number of cycles; τ_N = cyclic shear stress at Nth cycle; σ'_{N-1} = effective confining pressure at the end of $(N-1)^{th}$ cycle; and C_1, C_2, C_3 and α = parameters (vary with density and soil type). Fig. 2 shows a relationship between the theoretical predictions by Eq. 2 and the laboratory data.

4. Liquefaction Potential of Partially Saturated Sands. - Research on the liquefaction of partially saturated sands reveals that liquefaction is sensitive to the degree of soil saturation. The data in Fig. 3 shows that the liquefaction potential for a given soil decreases with decreasing saturation.

5. Dynamic Shear Moduli and Damping of Submarine Clays. - Studies conducted on Pacific Ocean clays show that the equivalent shear moduli decrease with increasing dynamic strains, while damping in these clays increases with increasing strain up to a certain level and decreases thereafter as indicated in Fig. 4. The above behavior can be described by the rheological model shown in Fig. 4.

6. Strength Degradation of Submarine Soils due to Dynamic Loading. - Dynamic experiments conducted on the above submarine clays reveal that these soils lose strength when subjected to dynamic loading as a function of applied strain amplitudes γ; excitation frequencies f; and time t.

7. Microzonation Studies. - Microzonation for land use planning studies is being conducted employing the ratio technique. The results to date indicate that the averages of the ratios of amplifica-

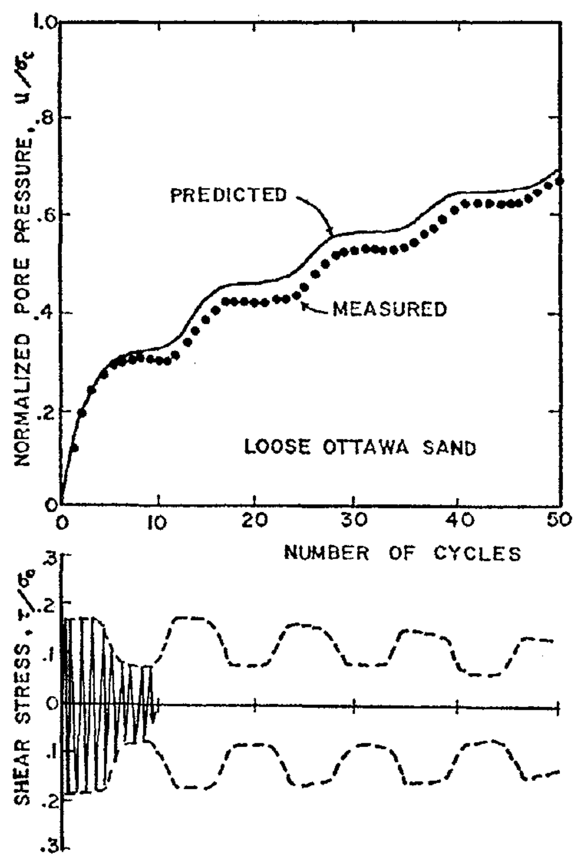

Fig. 2 Measured vs. predicted pore-pressure rise

MEHMET A. SHERIF AND ISAO ISHIBASHI

University of Washington

Geotechnical earthquake engineering research at the University of Washington involves the areas outlined below.

1. Dynamic Shear Moduli and Damping of Dry Sands. - Experiments conducted in the Torsional Simple Shear Device on five dry sands at various densities have resulted in Eqs. 1a and 1b, defining the variation of equivalent shear moduli G_{eq} in terms of shear strains γ, confining pressure $\bar{\sigma}_c$, and angle of friction ϕ as shown below:

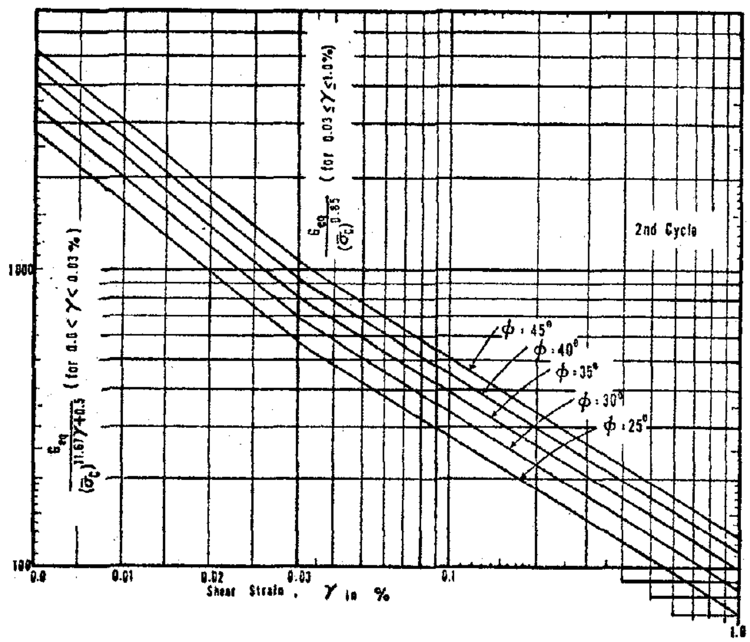

Fig. 1 Nomograph for determining G_{eq}

$$\text{For} \quad 0\% < \gamma < 0.03\%: \quad \frac{G_{eq}}{2.8\phi(\bar{\sigma}_c)^{11.67\gamma+0.5}} = 40(0.205)^{\frac{\gamma}{0.05}} \tag{1a}$$

$$\text{For } 0.03\% < \gamma < 1.0\% : \quad \frac{G_{eq}}{2.8\phi(\bar{\sigma}_c)^{0.85}} = \gamma^{-0.6} \tag{1b}$$

A nomograph based on the above equations is shown in Fig. 1. The coefficients of damping for the above sands as determined from hysteresis loops increase with increasing dynamic shear strain.

2. Liquefaction Potential of Saturated Sands. - The results of the data obtained from soil liquefaction research on fully saturated sands show that when the data is plotted in the form $\Delta\tau_{max}/\sigma_{oct}$ versus the number of cycles to liquefaction N_L, the initial value of K_0 (coefficient of earth pressure) does not influence the liquefaction potential.

3. Dynamic Pore-Pressure Variation in Saturated Sands. - From studies aimed at understanding pore-pressure variations in saturated sands of different densities under dynamic loading, a theoretical

gress on composite specimens, the interface between the precast and cast-in-place concrete lying in the shear plane. This work is funded by the National Science Foundation.

5. Headed Stud Shear Connections Subject to Reversed Cyclic Loading (Mitchell, Hawkins)

Tests have been conducted on 15 pushout specimens consisting of a steel beam connected by headed studs to a concrete slab(7). Variables have been the use of solid slabs or ribbed metal deck slabs, the stud layout, the orientation of the metal deck, the geometry of the deck, and the load history. Details were chosen so that specimens simulated connections likely for seismic drag struts. For reversed cyclic loadings of increasing magnitude, the capacity was 20 percent less than that for monotonic loading for specimens failing by shearing of the studs. For failures initiated by pullout of the studs, there was a 30 percent decrease in capacity. In general, connections proportioned according to AISC 1974, showed good hysteretic behavior and failure in a ductile mode for solid slabs or slabs with metal deck ribs parallel to the direction of motion. For decks with ribs transverse to the direction of motion, the hysteretic behavior was poor and the failure brittle. Future tests will examine in more detail the effects of load history and rib geometry.

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the Reinforced Concrete Research Council and the International Lift Slab Companies.

3. Reversed Cyclic Loading Bond Deterioration Studies (Hawkins, Kobayashi, Fourney)

High intensity reversed cyclic loading tests have been conducted on twelve reinforced concrete specimens simulating conditions at exterior beam to column connections(4,5). The alternating loads have been applied directly to the beam bar. Measurements have been made of strains along the bar, relative motions at the "attack" and "tail" ends of the bar, acoustic emissions from the bar and the holographic interferometry patterns for the specimens' surfaces. Variables have included the load history applied to the bar, the yield strength for the bar, the concrete strength, the amount of stirrup reinforcement in the joint, the beam bar size and the use of a straight bar or a bar terminated in a 90 degree standard hook. All measurements have indicated a fundamental difference in the bond transfer mechanism for straight and bent bars. While a hook was beneficial for tensile loadings it reduced the capacity for compressive loadings. For bent bars large movements occurred once yielding penetrated to the end of the lead-in zone for the hook. The hook then provided additional strengths for tensile loadings but the capacity decreased for compressive loadings and hysteresis loops became characteristically S-shaped. The location and the load level at which bond deterioration between the bar and the concrete initiated and the spread of that deterioration with further loading were readily detectable from the acoustic emission and holographic data. The contribution of hooks should be neglected in anchorage assessments if the reversed cyclic loading stresses a bar in compression to greater than 75% of the loading in tension. Further, in that case, anchorage lengths should be double those required by ACI Code 318-71 if joints are to develop ductilities of five or greater. Future work will study load history, bar size, and end anchorage effects. This work has been funded by the National Science Foundation - RANN.

4. Shear Transfer Across a Crack Under Cyclically Reversing Load (Mattock)

This experimental study is concerned with the shear transfer behavior of reinforced concrete initially cracked in the shear plane, when subjected to cyclically reversing shears. Such conditions are likely for precast concrete connections(6). The initially cracked specimen is gripped by friction on opposite sides of the crack and shear applied along the crack. Twenty-eight specimens were included in this study. Variables were the loading history, the initial crack width, the amount of reinforcement crossing the shear plane and the type of aggregate. The shear transfer strength under cyclically reversing loads of progressively increasing magnitude was about 80 percent of the shear strength for monotonic loading for both normal and lightweight aggregate concretes. Shear transfer across a crack is not a good absorber of energy for reversed cyclic loading. Except for very low shears and the initial loading cycle hysteresis loops are markedly S-shaped with extreme pinching effects in the low shear stress region. Tests are currently in pro-

NEIL M. HAWKINS and A. H. MATTOCK

University of Washington

This paper outlines the scope and the findings of the five earthquake engineering investigations being conducted by the structural engineering group at the University of Washington.

1. Seismic Resistance of Reinforced Concrete Slab-Column Connections (Hawkins, Elias, Mitchell)

This project is examining the effects of reversed cyclic loadings on the strength, energy absorption and stiffness characteristics of connections between reinforced concrete slabs and columns or walls. Tests have been made on 26 specimens modeling connections in a flat plate structure designed for gravity loadings according to ACI Code 318-71 and having 20 ft. square panels(1-3). Variables have included the intensity of the reversing moments and shears transferred to the column, the extent and amount of flexural and stirrup reinforcement in the slab and the column proportions. Even for reinforcement ratios as low as 0.6% all connections without shear reinforcement have failed suddenly by punching. In contrast, connections with properly designed stirrups have been able to develop rotations eight times those for first yield of the slab reinforcement without significant loss in energy absorption. In the elastic range, edge deflections have been more than double those predicted using the equivalent frame method of ACI Code 318-71 and a cracked section for the slab. Testing of interior column connections is now completed and recommendations(3) developed for porportioning the connection, its flexural and shear reinforcement, and for assessment of its strength and stiffness. In current tests the characteristics of edge column connections are being examined. This work is sponsored by the National Science Foundation - RANN.

2. Moment Transfer to Columns for Post-Tensioned Prestressed Concrete Slabs (Hawkins, Mitchell)

This project is concerned with the factors dictating the strength, stiffness, and reversed cyclic loading behavior of slab-column connections in unbonded prestressed concrete slabs. Specimens duplicate the type of prestressed concrete construction likely as an alternate to the reinforced concrete construction modeled in the preceding project. To date tests have been completed on three specimens, two modeling conditions for an interior connection and one for an exterior connection. Banded construction has been used for all specimens. In future tests the effects of tendon distribution, the intensity of the reversing moments and the use of lift slab construction will be examined. While all connections tested to date have been very tough, the energy dissipated for reversed cyclic moment or shear transfer has been small. Behavior has been essentially elastic until punching failures have occurred at the loading combinations predicted by ACI-ASCE Committee 423's recommendations. This work is sponsored by the Post-Tensioning Institute,

identical column with 2.4% lateral reinforcement (4C6-5). Observing that at high strains cover concrete is not effective, increase in the load carrying capacity of the concrete core is about 50%.

Behaviour of Beam Column Joints

There has been a significant difference of opinion on the effect of axial compressive force on the behaviour of joints. Major differences in behaviour observed among some of the tests have been attributed to the difference in the axial compressive force present. This resulted in difference of opinion on the evaluation of the contribution of concrete to carry the shear across the joint.

A research program has been underway at the University of Toronto for some time, to study the behaviour of beam-column joints under load reversals. To date, nine "full size" specimens have been tested. Four of the specimens were "corner joints" with two 12" x 20" beams framing into a 15" x 15" column, while five specimens had only one beam.

To study the effect of the magnitude of column axial compression, two identical specimens were tested with the column axial force being the only variable (1.1 P_b and 0.2 P_b). The experimental evidence shows that high axial compressive force helps to delay the initial cracking of the joint region, but after cracking of the joint core, the behaviour of the two sub-assemblies are very similar. The significance of this observation is to indicate that it is valid to apply the result of tests in which large axial compressive force was present, to design of joints with low axial compression.

The experimental data obtained from the sub-assembly tests include bond deterioration of beam steel in the joint region, energy dissipation characteristics of reinforced concrete sections subjected to full inelastic reversals. Analytical studies are also being carried out to assess the effect of bond deterioration, joint distortion and slip on the overall behaviour of sub-assemblies and frame structures.

S. M. UZUMERI

University of Toronto

Following are the research projects currently underway on earthquake engineering. The funding for these studies is provided, in part, by the National Research Council of Canada.

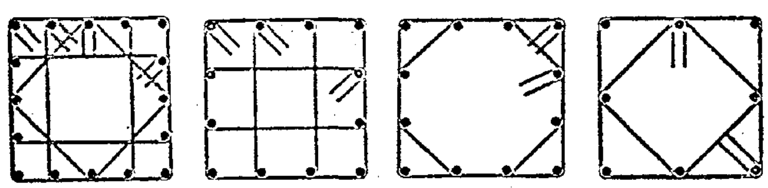
Strength and Ductility of Reinforced Concrete Columns with Rectangular Ties

While most of the researchers agree that the rectangular ties improve the ductility of the confined concrete, there is a considerable difference of opinion about the increase in the load carrying capacity of the confined concrete core.

A research program is currently underway at the University of Toronto, to examine the behaviour of reinforced concrete columns with rectangular ties. Experimental work is carried out using 12" x 12" x 6'-6" reinforced concrete columns. Core dimensions are 10.5" x 10.5" (measured from centre of the perimeter tie), columns are cast in vertical position and, at this stage, are subjected to monotonic axial compression.

The test parameters are:

1. Amount of column longitudinal steel (2 or 4%)
2. Distribution of longitudinal column steel around the perimeter (8 or 12 or 16 bars)
3. Volumetric ratio of tie steel (0.8 or 1.6 or 2.4% of column core)
4. Size of tie reinforcement and their spacing
5. Stress vs. strain characteristics of the tie steel (flat yield plateau or "round house" curve)
6. Tie configurations as shown below



Test region, column and tie steel are instrumented to determine deformations and strains at various load stages.

Results to date indicate that the appropriately placed longitudinal and lateral steel increases the ultimate strength as well as the ductility of columns. For example, while the maximum axial compressive force carried by the column with 0.8% lateral reinforcement (4C1-3) is about 0.95 $(\frac{P_o}{\phi})$ the capacity increases to 1.2 $(\frac{P_o}{\phi})$ in the case of otherwise

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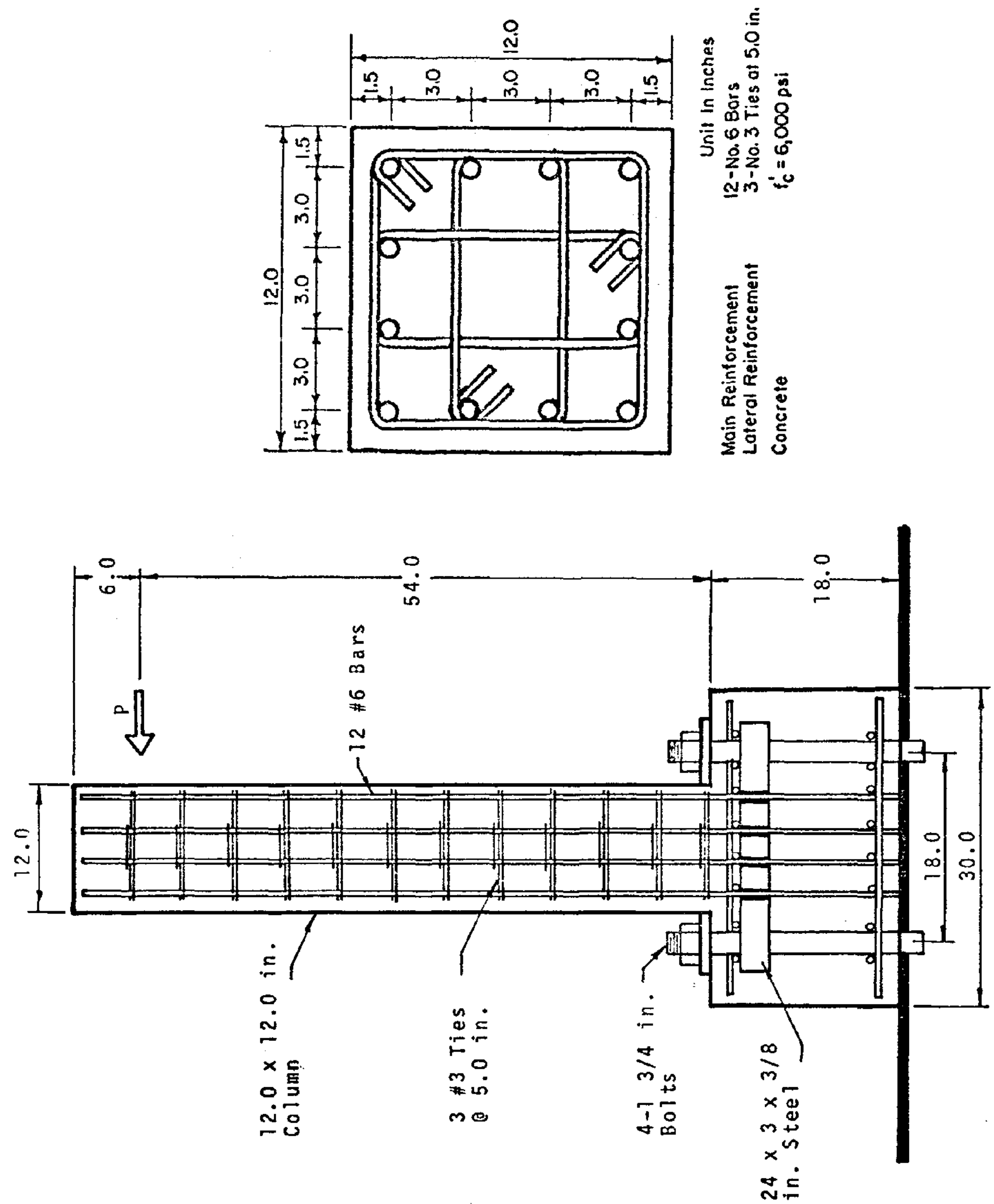

FIG.1 TEST STRUCTURE

data of reinforced concrete members subjected to uniaxial lateral loads. The design procedure should be critically examined under more realistic biaxial earthquake load conditions.

The test structure is a reinforced concrete cantilever column (Fig.1). Two identically designed columns are casted simultaneously. One column is tested under uniaxial lateral load reversals. The other column is subjected to biaxial lateral load reversals. The behavior of biaxially loaded columns is discussed in relation to that of corresponding uniaxially loaded columns, since the information about the behavior of uniaxially loaded columns has been accumulated in the past.

The first pair of columns are designed in accordance with ACI 318-71 Code, and now being prepared in the Structures Laboratory. The spacing of the ties is variable in the current test series.

Comparison of Design Procedures

The National Building Code (1975) of Canada permits the use of dynamic analysis procedure as a tool to determine earthquake forces in a structure. The procedure is based on a linearly elastic response spectrum analysis method with nonlinear response spectra. The conventional equivalent static load procedure (similar to the one used in the Uniform Building Code) specifies smaller design forces than the dynamic procedure in structures with fundamental periods less than approximately 1.0 sec. On the other hand, the dynamic analysis procedure specifies much smaller earthquake forces in a long period structure; for a structure with a period of 4.0 sec, the dynamic analysis procedure specifies earthquake forces almost one-third to one-half of the values determined by the equivalent static load procedure.

A work is now in progress to study the effect of this large discrepancy between the earthquake forces from the two procedures on the determination of design member strength including the effect of gravity loads and their load factors. The work will be extended to include various earthquake resistant building codes.

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SHUNSUKE OTANI

University of Toronto

Introduction

This brief paper describes two research projects currently in progress at the University of Toronto: (1) Experimental investigation about the behavior of reinforced concrete columns under biaxial earthquake motion in the horizontal plane, and (2) Analytical study about the behavior of frame structures designed in accordance with different earthquake resistant design codes. Both projects are relatively new, and no results have been obtained for discussion. The Connaught Fund of the University of Toronto and the National Research Council of Canada support the projects.

Biaxial Earthquake Test

The major objective of the experimental work is to study if a reinforced concrete column designed by current code provisions can behave in a sufficiently ductile manner under static biaxial lateral load reversals.

The motion at the base of a structure during an earthquake is obviously not limited in one horizontal direction, nor is the response of a structure confined in one vertical plane, although structures have been routinely analyzed in longitudinal and transverse directions, separately and independently. Recent nonlinear dynamic analyses (1,2) of simple structures indicated that structures subjected to biaxial earthquake motions deformed much more than those subjected to uniaxial earthquake motions.

Columns of a framed structure must resist lateral forces in two horizontal directions, simultaneously. Methods to estimate the strength of reinforced concrete sections under axial compression and biaxial bendings have been studied in the past on the assumption that a bending moment increased monotonically in a specific direction with components along the two major axes. Or innumerable reinforced concrete columns have been tested to failure under axial compression and lateral load reversals in only one direction. Although these studies are valuable, the information obtained from these studies may not be directly applicable in the earthquake resistant building design if the column is to be subjected to biaxial lateral load reversals.

One of the essential means to acquire and ensure the ductile flexural behavior from reinforced concrete columns is to prevent a premature shear failure before the flexural strength could be developed. The loss of shell concrete due to combined biaxial bending reversals as described in Ref.3, may cause a premature shear failure because the design formula used in the code is based on the experimental

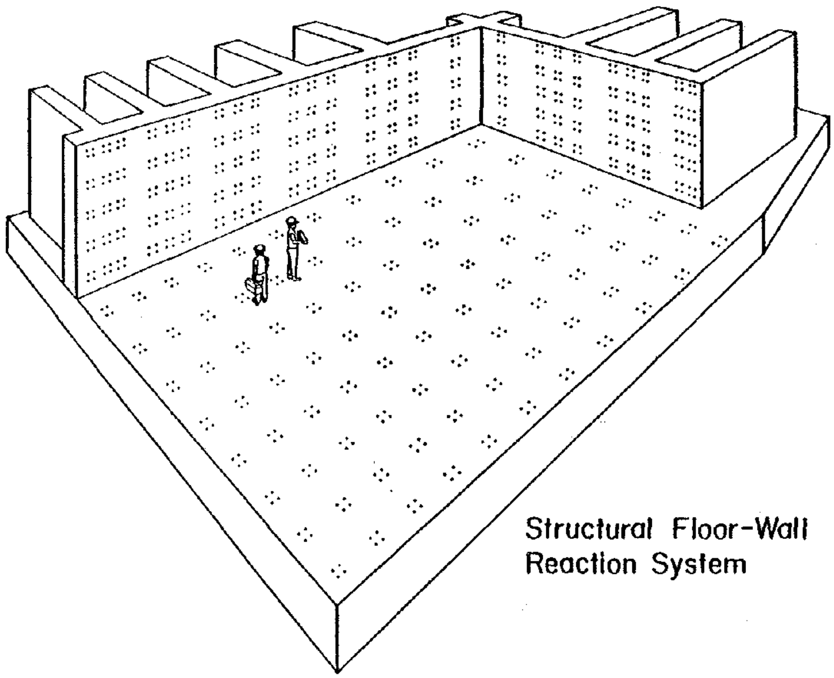


Fig. 2. Test facility to be constructed

Research Plan

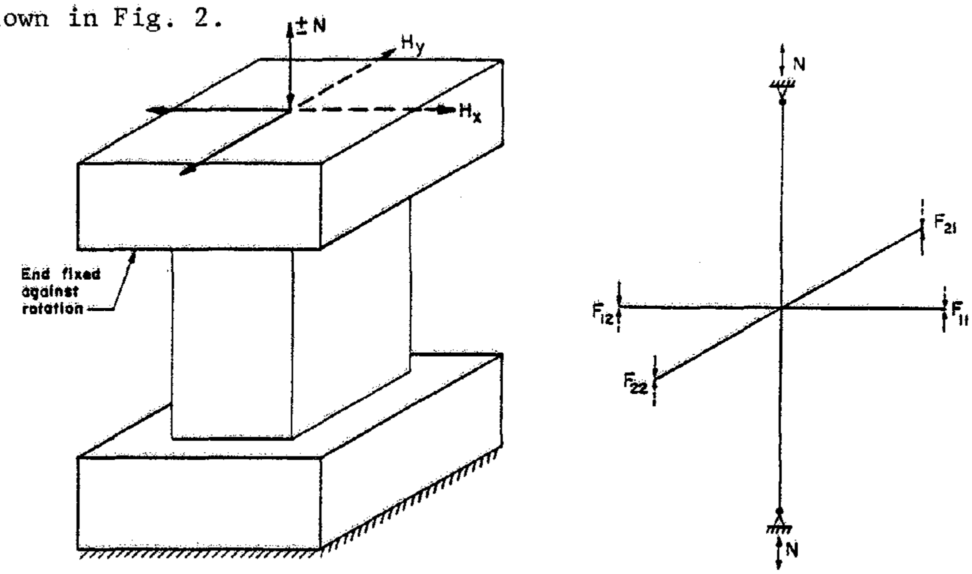
Since the object of the research is to evaluate the importance of bidirectional lateral loading histories and variable axial loads on the response of frame elements, the variation in specimen geometry will be kept to a minimum and the sequence of bidirectional and axial forces will be systematically varied. All loads will be applied slowly--effect of strain rate will not be considered.

Column shear tests. The first phase of the research program involves tests of short column specimens subjected to bidirectional lateral deformations and variable axial loads. A sketch of the test specimen is shown in Fig. 1a.

Beam-column joint tests. In structures where columns are flexible, it is likely that shear distress in the columns will not be critical; however, shear degradation in the beam-column joints may become an important consideration. Tests will be conducted to evaluate the performance of beam-column joints under the effects of racking moments (in both directions) applied to the joint through the beams. A sketch of the test arrangement is shown in Fig. 1b.

Test Facilities

In order to carry out the studies described, a floor-wall reaction system will be constructed. The facility will permit the application of loads in both horizontal directions, as well as in the vertical direction. The floor-wall system will be served by a computer controlled data acquisition and closed-loop hydraulic loading system currently being acquired by the laboratory. The facility planned is shown in Fig. 2.



a) Column Shear Tests

b) Beam Column Joint Tests

Fig. 1. Test specimens

J. O. JIRSA

The University of Texas at Austin

A major research effort at The University of Texas at Austin in earthquake engineering concerns the behavior of reinforced concrete frame elements under biaxial lateral loadings. The research is being sponsored by the National Science Foundation and will be primarily experimental in nature.

Background Information

During the past decade, extensive research into the behavior of structural elements subjected to simulated seismic loading has been carried out. The experimental studies have concentrated almost exclusively on behavior under unidirectional lateral loading and compressive axial loads. The direction of lateral load coincided with a principal axis of the structure or structural element. Some very limited recent studies indicate the seismic response of structures may be quite severely influenced by biaxial lateral motions, as compared with uniaxial motions. In order to realistically assess the significance of biaxial lateral forces or movements on structural response, experimental studies are needed. Such studies can be used to evaluate the importance of lateral and axial load history on behavior. If such variations are shown to be important, the results can be used to develop design recommendations for dealing with the effects of complex load histories. The results will also be used to develop behavioral models of structures or structural elements under varying load histories for use in extending the results to additional parameters and for use in seismic analysis of structural systems.

Objectives

The objectives of the proposed research program are threefold.

(1) To evaluate the importance of load history (bidirectional lateral loads and varying axial load levels) on the response of columns and beam-column joints of reinforced concrete structures. The prime variable to be considered is the sequence of application of lateral movements and axial forces.

(2) To develop design recommendations for the shear strength of columns and beam-column joints under skewed lateral loads or deformations and various levels of axial load.

(3) To develop models which can be used to predict the behavior of columns and beam-column joints subjected to large shear forces.

following three hysteritic models are being evaluated. (1) Bilinear, (2) Degrading Bilinear, and (3) Degrading Trilinear. The reduction in the initial stiffness depends upon the maximum ductility requirement of the member during yield. The degrading trilinear model is thought to be more representative of test results. The reduction in joint stiffness in the girden Column Connection is also being considered.

The degrading trilinear model is being used to evaluate the seismic response of other reinforced concrete structural systems. Included in these is an optimized reinforced concrete frame and a framed tube.

V. I. WEINGARTEN

University of Southern California

Earthquake engineering research is being conducted in three areas: the effect of geometric imperfections on the dynamic response of cooling towers, transient response of cooling towers to propagating boundary excitation, and seismic response of reinforced concrete frames with degrading stiffness.

Effect of Geometric Imperfections on the Dynamic Response of Cooling Towers

The objective of the research was to use linear theory to evaluate the effects certain imperfections might have in contributing to the unexpected response of the higher circumferential wave numbers of a cooling tower.

The research was carried out in three phases. First the analytic verification of the effect of imperfections was examined and a simple study of the forced response of perfect and imperfect rings.

Second the effect of seismic excitation on the response of a cantilever cylinder was studied. Various types of locations of the imperfections were examined. The effect of dead weight loading with and without imperfections was determined.

Finally several hyperboloidal shells with seismic excitation were studied. Various types and locations were examined and the effect of dead weight loading was considered.

Results of the analysis showed that asymmetric geometric imperfections will cause significant response of modes other than the beam bending mode when the cooling tower is excited by earthquake excitation.

Transient Response of Cooling Towers to Propagating Boundary Excitation

The response of axisymmetric shell structures such as cooling towers are subjected to propagating boundary excitation. The cooling tower is analyzed as a shell of revolution by using the finite element method. The boundary excitation is decomposed into Fourier components for each time interval. The normal mode method was used in conjunction with the linear acceleration technique to determine the response of the cooling tower. Preliminary results indicate that the cooling tower dynamic response to a traveling wave is quite different than the response to a standing wave excitation.

Seismic Response of Reinforced Concrete Frames with Degrading Stiffness

The inelastic seismic response of a ten story, single bay, reinforced concrete frame is being investigated with regard to the idealized hysteresis behavior which is assumed for the ends of a member. The

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stiffness using the information contained in the measured roof response is developed.

A commonly used procedure for such iterative techniques is to determine the "sensitivity-coefficients" which give the rate of change of the model response at the measurement point with respect to the parameters estimated. These coefficients determine the manner in which the parameter estimates need to be changed to successively improve the history match between the measured and the calculated responses. However a determination of these coefficients involves the integration of the system equations (n+1) times (where n is the number of parameters to be estimated) at each iternation making the computation extremely inefficient. For a 50 story structure (n=50) considering that one may need 50 to 100 iternations to converge at a set of estimates, the computation times involved may become prohibitive. The algorithm provided in [5] utilizes an optimal control formulation for the problem thus reducing the computation time by a factor of (n+1)/2. Application of the technique to the response of an 18 story structure has been carried out. Currently, problems related to the resolving power of the identification scheme are being investigated so that inferences about the extent to which structures are left weakened after earthquakes, can be scientifically based.

2) Strong Ground Motion Studies

Analyses of the peak amplitudes and the spectra of strong earthquake ground motion are being carried out with emphasis on their dependence on earthquake magnitude, epicentral distance and the geologic conditions at the recording site [6]. Approximate scaling functions are being developed which for a selected confidence level will yield estimates of the peak as well as the spectral amplitudes of ground acceleration. Data available for a range of epicentral distances (between about 20 to 200 kilometers) obtained from records collected over the past forty year period is being utilized. Peaks of strong ground motion have been found to depend in a linear manner on earthquake magnitude, only for small shocks. For larger magnitudes, this dependence appears to no longer exist.

Studies on the influence of local geology, topography and the angle of incidence of seismic waves on the nature of strong ground shaking are also being carried out.

3) Automatic Optical Digitization of Accelerograms

Hardware for the automatic optical digitization of accelerograph records is being installed for the purpose of accurate and quick digitization of available strong motion records. Various aspects of graphics - assisted operator solutions of specific digitization problems, such as manual data insertion, are being currently worked on.

F. E. UDWADIA

University of Southern California

The following report summarizes the research effort at the University of Southern California in the areas of Building Response and Strong Ground Motion Studies.

1) Building Response Characterization and Identification Studies

Studies of the response of structures to strong ground shaking are continuing with special emphasis on trying to determine suitable structural models from such high level testing. Both parametric and nonparametric identification methods are being investigated.

a) Nonparametric Identification: The Weiner technique of nonparametric identification has been investigated and its applicability to building structural systems studied. The sources of error have been looked into and several new results have been presented on accuracy calculations stemming from the various assumptions in the Weiner theory. The technique has been applied to study the response of one reinforced concrete and one steel structure to a recorded earthquake. The linear and nonlinear contributions to the total roof response in each case have been identified and it is shown that during the large amplitude excitation of the structure the nonlinear contribution to the response is almost as large as the linear contribution [1,2]. Further work in this area is presently continuing.

b) Parametric Identification

1) Uniqueness problems in the parametric identification of multidegree of freedom systems from "input-output" type data has been investigated. Through the analysis of a structure modeled as a shear beam, it is shown that though uniqueness in identification may be obtained by proper instrumental location, the roof and basement records, which are often used in identification studies, do not have sufficient information in them to determine the estimates of structural stiffness and damping uniquely. At sensor locations where nonunique solutions are present, an upper bound on the number of such solutions has been presented. The degree of nonuniqueness is found to monotonically increase with increasing height of sensor in the building system from at most one, for a sensor located at the first floor level, to almost N! for a sensor located at the Nth floor of an N story structure [3,4].

2) The general problem of estimating a space dependent coefficient in a forced linear hyperbolic differential equation from the knowledge of the solution at one or more isolated points has been dealt with. The technique has been used to estimate the height dependent stiffness and damping properties of a building structure, modeled as a shear beam, from records obtained during strong ground shaking. Starting with an initial "guess", a systematic method of iteratively improving the estimates of the structural

a) Developing theoretical and numerical models on the propagation of a tsunami wave train in a slowly varying water depth. Recent research efforts at USC have produced a viscous model for propagation of nonlinear, dispersive waves in a variable depth media. The results compared very well with the published laboratory experimental data. Thus the discrepancy between the inviscid solution and the laboratory data can now be accounted for. It has also demonstrated that due to the dissipative effect the nonlinear effect is gradually reduced as these waves propagate further away from the initial position and into a region of shallower depth. Because of this development, a more realistic prediction of the propagation characteristics of a tsunami can now be obtained thereby improving the prediction of the eventual run up of tsunamis in the coastline region.

b) Developing methods for calculating the response of bays, harbors and coastlines to the linearized ocean waves. Research efforts in this area have contributed quite extensively to the understanding of the response characteristics of a bay or harbor to a linear ocean wave system. A number of programs have been developed which can be used for engineering analysis and design. The computation method includes finite-difference technique, integral equation technique as well as finite element technique. The problems attacked include arbitrary shape harbor with variable depth, arbitrary shape harbor with permeable breakwaters, arbitrary shape harbor containing islands, etc.

S. F. MASRI

University of Southern California

Summary of some of the Research Activities in the Civil Engineering Department

<u>Response of Structures to Correlated Random Boundary Excitation</u>
Investigators: S. Masri, F. Udwadia

Investigations of the response of structures to progressing waves indicate that the characteristic times defining the passage of the wave front across the structure may have a significant effect on the response of such structures.

Analytical studies currently underway are concerned with determining the transient mean-square response of various types of structures to boundary excitation that is characterized by a random input, having an earthquake-like spectrum, which propagates across the structure foundation in a finite time.

<u>Analysis of the Response of Critical Equipment to Strong Ground Shaking</u>
Investigators: J. Anderson, S. Masri, F. Udwadia

The major objectives of this comprehensive analytical and experimental study of nonlinear system modeling and scaling are to:

a) Determine the correlation between analytical and experimental results when considering material nonlinearities and geometric nonlinearities.
b) Investigate nonlinear scale effects.
c) Evaluate the reliability of various excitation techniques for simulating the effects of arbitrary dynamic environments.
d) Develop design curves for preliminary design of dynamically loaded structures.

<u>Seismic Risk Analyses</u>
Investigator: A. Der-Kiureghian

The probabilistic basis for earthquake-resistant design of structures is being studied. In this respect, a comprehensive model for the analysis of risk associated with various levels of ground motion has been developed. Methods for reliability-based design are being studied; in particular, development of risk-consistent earthquake response spectra, and their relevance to earthquake-resistant design, is of interest. Results from such studies are being directed toward development of methodology for cost-effective design or upgrading of structures.

<u>Tsunami Propagation and its Coastal Effects</u>
Investigator: Jiin Jen Lee

Research activities in this area at USC have been directed in two major areas:

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a. Stresses caused by prescribed external dynamical loads in a similar shell of finite length without a crack (nominal solution).
b. Stresses in the shell caused by applied edge loads along the crack otherwise free of any other loads (residual solution). These loads are equal in magnitude but opposite in sign to those present in the uncracked shell at the crack location.

The total stress field is the sum of the residual and the nominal stresses. It is shown that the residual solution leads to singular stresses at the crack tip (or high stress concentration) represented by the stress intensity factor. The nominal solution affects the magnitude of this singularity, but the existence of the singularity is a result of the residual solution above. For a particular time-dependent internal pressure loading extensive numerical results are obtained for dynamic stress intensity factors in aluminum and steel pressure vessels. It is shown that the dynamical stresses exhibit a square root singularity is also characteristic of elastostatic crack problems. All the stress intensity factors (bending and membrane), except one exhibit the same general trend. They first decrease from their corresponding static value, and then begin to increase. It is also concluded that the solutions presented in the paper are valid for crack lengths satisfying the inequality $2c/L < 0.2$.

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T. ARIMAN AND R. F. HEGARTY

University of Notre Dame and Rockhurst College

The study of the dynamical behavior of plate and shell structures has received increasing attention in recent years. Presently there is a great need to solve practical problems in this area. Earthquakes or explosions could severely damage underground oil, gas, water and nuclear reactor pipelines if they were not designed to withstand such dynamic loading conditions. In fact, any such installation, because of its extremely difficult accessibility, must be designed with such factors in mind.

In recent years the linear fracture mechanics has established itself as a reasonably satisfactory tool in the investigation of the phenomena of the fracture and the fatigue crack propagation in structures. The initial flaw in pressure vessels and pipes is usually subcritical and may be in the form of a weld defect or other defects due to manufacturing. For a subcritical flaw to propagate and reach a critical proportion, one or more growth mechanisms must be active over a sufficiently long period of time. Crack propagation due to dynamic loads, fatigue or stress corrosion are the most common mechanisms. Generally, fracture problems in pressure vessels and pipes may be considered in two broad categories [1,2]. In the first, it is assumed that the flaw is a part-through surface crack, the dimensions of which are small compared to the wall thickness of the vessel. In the second group of problems, the wall thickness h is relatively "small" so that the crack is either a through crack or the entire section of the wall under the part-through crack is plastically deformed. If the crack is only part-through but the net section under the crack is yielded, one may replace this section by tensile tractions and still use the basic through crack analysis [1,2].

While quite a few papers on the elastostatic stress analysis of pressurized cylindrical and spherical shells with cracks have appeared recently in the literature [3-13], there is only one recent publication by Ariman and Hegarty [14] to the best of the author's knowledge, on the investigation of dynamic analysis of finite cylindrical shells with circumferential and longitudinal cracks.

This paper further investigates the area of the authors' previous article [14] and deals with the dynamic response of a thin, elastic circular cylindrical shell of length L, representing a pressure vessel, due to time-dependent loadings symmetric with respect to the axis of the cylinder. The shell contains an axial through crack of length $2c$. The dynamic counterpart of Donnell's thin shell equations are employed in the study. The linear analysis of the problem is based on the method of superposition. The actual dynamical stresses in the shell are considered as the sum of the following two parts [15-18].

Most current building codes require design for only two orthogonal horizontal translational components, acting one at the time. Two aspects of the problem of design for multicomponent earthquakes are under study: response of tall buildings on a rigid base to components other than horizontal traslation, and criteria for designing for simultaneous actions of any number of components.

An investigation that aims for recommendations for design and construction of concrete walls taking into account ductility requirements, deterioration and energy absorption under alternate loading is in action. The project uses microconcrete models with the following variables under study: effect of floor system in strength and stiffness of the wall, structural lay out of the wall, total height to wall length ratio, distribution and amount of vertical and horizontal reinforcement and axial loading. Also different ways of reinforcing masonry walls are being studied to improve their strength and/or ductility. An experimental programme has been performed and the results are now being interpreted.

Rural Housing in Earthquake Areas. The project aims to establish criteria to reinforce existing rural housing and to define methods for future constructions. The criteria are based on the use of local materials with a minimum of industrial products and technical supervision. The project includes: evaluation of rural housing in earthquake areas; static and dynamic tests; and recommendations for design andconstruction followed by their technical and economical evaluation.

Optimization. Aspects of optimization under study are: optimum research allocation to research: optimum design of single-degree structures,constrained optimum design of buildings for specified design spectrum and optimization criteria which include devising alternative structural solutions, analyzing, designing, evaluating, and comparing them, checking computations, drawings and specifications and supervising construction.

The prediction of earthquake intensity in terms of source parameters and local conditions is under study. The project is developing semiempirical expressions which include local soil effects. The results Are based on data of magnitudes and intensities recorded in Mexico, United States and Japan, and on the statigraphic information of the sites.

On empirical grounds it is known that over a large range of magnitudes a plot of **ln** λ vs **M** is a straight line, where λ = exceedance rate of magnitude **M**.Theoretically this relation cannot hold for indefinitely large magnitudes, and empirically it is found indeed that **ln** λ dips sharply beyond some magnitude. Design of important structures is based on the premise that a physical upper bound magnitude, $\mathbf{M_1}$,exists. Several **ln** λ vs **M** models are being considered, with particular attention to Bayesian estimation of $\mathbf{M_1}$. Information used to find the distribution of $\mathbf{M_1}$ includes historical data and geological evidence from the region of interest and from regions with similar seismological characteristics.

Seismology. The problem of base line correction has been attacked along two lines. First, an improvised version of a procedure introduced by Berg and Housner which uses orthogonal polynomials to represent the zero base line. Second a revised version of the procedure followed in CALTECH whose main difference lies in the choice of characteristic function of the filter.

An earthquake model for predicting near-field ground motion is being developed in which a stress pulse is applied over a circular area. At early times the displacement is similar to one predicted by Brunes modelo. Effect of half-space, finite rupture velocity and couple sources are being incorporated.

Theoretical expressions for stress drop associated with certain slip distributions on a circular fault have been obtained. Stress drop on a fault may not be constant although it is usually so assumed. In such a case the relation between the seismic moment and the dimension of the fault would be modified and the estimates of stress drop would change.

Analysis and Design of Structures under Earthquake Loading. Approximate methods of earthquake analysis of buildings with load bearing walls are being investigated. The methods include effect of horizontal displacements, torsion and flexural stiffness of the floor system. Its application is feasable in a minicomputer and permits the evaluation of horizontal displacements, rotations and internal forces.

It is intended to find approximate criteria for the prediction of the dynamic response of multistorey buildings considering torsion. The analysis considers different combinations of stiffnesses and strengths for structural elements with bilinear hysteretic behaviour.

An equivalent linearization criterión suitable for seismic analysis of nonlinear systems is being studied. Results of an equivalent modal analysis are calibrated by comparison with those of a nonlinear step by step method. Cases studied include multistorey systems with different laws of variation of yield levels. Preliminary results suggest an improved alternative to conventional modal analysis based on tangential initial stiffness and strengths. The methodology is being further used to study the seismic response of structures considering soil-structure interaction. Results obtained from the step by step analyses will be used to obtain reliable criteria to assess the effect of interaction in the seismic response of buildings.

Current approach for analysis of equipment and components subjected to distinct earthquake inputs is to use the envelope of all spectra inputs in a standard one-input response spectra analysis. In some cases this technique gives unconservative results so a simple response spectrum approach has been developed. The basic diference from the standard method is the participation factors which are computed using the influence matrix of the multiply-supported dynamic theory.

G. A. AYALA

Institute of Engineering, UNAM

The Mexican Government and the National Autonomous University of Mexico are jointly financing a research programme in earthquake engineering. The fields under study are soil dynamics, seismicity, seismology, seismic analysis and design of structures, rural housing in earthquake areas, and optimisation.

Soil Dynamics. Experimental research has been focused on the design and construction of apparatus to study liquefaction of saturated sands under cyclic loading, and dynamic properties of clays. Under construction is a simple shear apparatus which, in conjunction with our shaking table, will be used for the dynamic testing of large samples of saturated sands.

Effort is being devoted to the development of new analytical and numerical techniques to determine the seismic response of earth masses. Earthquake effects in dams and reservoirs are being studied with the purpose of evaluating and putting into operative shape different available treatments of special features. Points of particular interest are the treatment of interfaces, effects of gravity on the liquid in the reservoir, time integration, effects of nonlinear material behaviour and large displacements and different methods of drastically reducing spurious reflections of seismic waves at artificial boundaries. New boundary conditions which allow the free passage of waves have been derived. The formulation has been implemented in a finite element programme and applications are currently being made.

An approximate method of modal analysis including soil-structure interaction has been proposed. It allows the study of the effect of soil properties and of the individual contribution of the different modes of the structure in the global response of the system. In a new research project soil-structure interaction under earthquake loading has been formulated as a diffraction problem. It has been shown that the minimal information in solving the problem is the motion time history at the base of the foundation as if the excavation were absent.

Mathematical models for assessing seismic risk on local soil sediments are under study. Deterministic approach research includes evaluating existent analytical methods, defining variables which influence the phenomenon and obtaining algorithms to determine the characteristics of the motion at a given site. In the probabilistic approach probability distributions of earthquake parameters of local soil deposits are being derived from those for hard ground conditions. The method is intended for cases where site amplification effects dominate the soil response spectrum.

The controversy over the definition of soil liquefaction under earthquake loading suggested an analytical project to study recently derived constitutive equations for saturated sand. Preliminary results give a new outlook for more ambitious research.

Seismicity. The Institute of Engineering continues to compile historical and instrumental data on earthquakes in Mexico. This information is incorporated and classified in a computer programme. Concerning seismic instrumentation, the project of installing 25 accelerographs in addition to the 55 already present is in action.

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required optimum stiffness of systems for various ground motions to produce minimum interstory distortion. The project will be extended to study optimum design of elastic and inelastic systems subject to coupling earthquake motions.

INVESTIGATION OF THE EFFECT OF THREE DIMENSIONAL PARAMETRIC EARTHQUAKE MOTIONS ON STABILITY OF INELASTIC BUILDING SYSTEMS

It has been shown by analytical studies of plane structural systems, the interaction of horizontal and vertical earthquake components can cause a structure to be dynamically unstable under certain conditions. Recent experimental work on reinforced concrete members also indicated that a biaxial ground motion can significantly reduce the energy dissipation capacity and that an increase of ductility requirements is expected. Because an earthquake motion and a building system are three-dimensional in character, it is important to study the instability and ultimate capacity of building systems subjected to three-dimensional motions.

This project undertakes the instability studies on the overturning effect of vertical static and inertial forces which act through side-sway displacements from the elastic range to the condition of collapse. The ultimate capacity of a system will be examined in terms of the damping, geometric nonlinearity, and the elastic and inelastic material utilizing a bilinear model.

An analytical procedure and a general computer program will be developed to study the following specific objectives: 1) to identify the structural parameters that cause a system to be sensitive to three-dimensional ground motion, 2) to observe the response history of different structures to various motions, 3) to study the ductility demands at critical sections of the constituent structural members, 4) to observe the energy absorption characteristics, and 5) to make an engineering evaluation and recommendation by comparing the observed ductility requirements with the current Code requirements.

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This paper summarizes three research projects currently in progress at the University of Missouri-Rolla. The continuing research efforts in earthquake structural engineering at UMR have received their supports from the National Science Foundation, the University, and others.

DYNAMIC INSTABILITY AND ULTIMATE CAPACITY OF INELASTIC SYSTEMS PARAMETRICALLY EXCITED BY EARTHQUAKES

The first phase of this project includes the procedure of analysis for determining the dynamic instability and response of framed structures subject to pulsating axial loads, time-dependent lateral excitations, or foundation movements. Included in the analytical work are the instability criterion, the consistent mass formulation, and the computer solution methods. Dynamic instability is defined by a region in relation to transverse natural frequency, longitudinal forcing frequency, and the magnitude of axial dynamic force. The general considerations are bending deformations, P-Δ effect, girder shears transmitted to columns, and the effect of axial force on plastic moment capacity. It has been observed that the deflection response of a system corresponding to the instability region grows exponentially with time.

The second phase of the project has been emphasized on the behavior of structural systems subject to coupling earthquake motions of vertical and one horizontal component. Studies are extended to bilinear material, damping formulation, and lumped mass model of various types of structures. Response behavior has been studied for different lumping parameters, energy absorption characteristics, and ductility and excursion requirements. The significant influence of vertical earthquake motion on the above comparison studies has been observed.

EARTHQUAKE STRUCTURAL DESIGN BASED ON ENERGY AND OPTIMALITY CRITERION

This project is for optimum design of framed structures subject to earthquake motions. The objective of the design procedure is to obtain a minimum weight for a structure without exceeding strength limits that are determined by the stiffness requirement and optimality criteria. The design loads are based on the lateral forces recommended by the U.S. Uniformed Building Code, Housner's response spectrum, and the earthquake record of El Centro of 1940. Included in the study are: (1) consistent mass formulation with bending and axial deformations, (2) P-Δ effect, (3) combined stresses of bending, axial, and shearing, (4) structural and non-structural masses, and (5) optimization algorithm. The computer program has sophistically been developed for large structural systems requiring a minimum effort for input data and computation and can be used by researchers and practitioners for determining the bridge. The shaker system used was designed to produce a maximum dynamic force of 20,000 lb. in the 0 to 10 Hertz range.

The model tests showed that deterioration of the concrete deck would reduce the bending stiffness of the composite cross section. The full-scale tests therefore incorporated a dead load ballast of 40 kips in each span so as to minimize the maximum tensile strain in the deck slabs due to the $\pm$ 2.5-inch deflections induced by the shaker about the static equilibrium position.

The model tests showed that extraneously induced vibration introduces distortion in the structural response modes. In addition to the fatigue life tests, tests were therefore included to determine if the dynamic properties can be determined from the transient response of the structure. Random vibration theory and time-series analysis techniques are being used to analyze this data. The objective of these tests is to determine if ambient vibration data may be used to detect structural damage as reflected by changes in stiffness and damping.

effective hinge axis is located on the neutral axis of the supported member. Horizontal extensional deformations due to load rotation about the hinge axis can therefore be eliminated or at least reduced. By stacking two sway frames, a linkage or rocker bearing can be constructed to accommodate temperature expansions or contractions. Fatigue life has been a concern, however pilot studies conducted in the laboratory on a 30-foot composite girder model have given satisfactory performance. Even though the plates were welded in the zone of maximum stress, reversal, failure has not occurred after about 200,000 cycles of load application.

The design concept is not limited to simple sway frames; "fanned" plate arrays can be used to increase flexibility or load capacity. Conical arrays of pins can be used to effectively produce a pivot bearing. "Potting" with an elastomer appears to be a feasible method of increasing buckling resistance and internal damping. Application of flexible bearings is not limited to bridges. Such devices should prove useful in supporting heavy machinery to provide shock and vibration isolation.

The principal advantage offered by this bearing concept, however, is that the bearing can provide a positive tie to resist vertical and transverse force components. Funds are currently being sought for further research.

"An Investigation of the Behavior of a Three-Span Composite Highway Bridge" (J.W. Baldwin, R.C. Duffield, and H.J. Salane)

As a result of flood control work on the St. Francis River, a relatively new (1963), two-lane, three-span (72' - 93' - 72') continuous composite (concrete deck on steel girders) highway bridge in south-eastern Missouri was scheduled for demolition, thus providing a rare opportunity for full-scale destructive testing of a modern structure. Following an initial contract by the Missouri State Highway Commission and the Federal Highway Administration for a feasibility study of a field investigation, a contract was awarded for a field study of the fatigue behavior and dynamic properties of this structure. The field study was completed in October 1975 and the data collected is currently being analyzed.

The primary ofjectives of the field study were: 1) To determine the fatigue life of the bridge at girder design live-load and impact levels; 2) To discover whether bridge properties are significantly altered by cumulative damage during the service life of the structure and whether a forced vibration test can be used to detect and assess this damage.

From the point of view of earthquake engineering, the most relevant part of this study was the development of a dynamic loading system required to achieve the above objectives. Based on the results of tests on a single span, two-beam, composite slab laboratory model, a "moving mass" electro-hydraulic actuator system, operating under closed loop control was developed for inducing resonant vibrations in the

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This summary includes research work, directly or indirectly related to earthquake engineering, currently in progress. The name of the principal investigator(s) is shown in brackets following each title.

"Precast Concrete Panel Joints and Connections" (A. Pauw, John Salmons)

The design and analysis of industrialized large concrete panel structures has been an important area of research for the past decade. The structural response and strength of these structures is governed primarily by the characteristics of the joints and connections between panels. Early investigations were almost exclusively concerned with the bearing strength of wall-floor connections and gave little or no insight on the stiffness and flexural response characteristics of these connections.

The progressive collapse failure following an explosion in the Ronan Point Tower, focused attention on the need for providing general structural integrity against accidental or low probability overloads, even in zones of low seismic risk. From risk evaluation studies a new design philosophy has evolved to develop designs for general structural integrity that will confine and localize structural damage and minimize loss of life for rare and accidental overloads. Small scale model studies have been performed under the direction of Professor Salmons to qualitatively evaluate the three-dimensional effect of floor diaphragms to help in redistribution of loads by wall cantilever action.

The author's research efforts have been concentrated on studies of wall-floor joint stiffness, tensile strength and rotational and extensional capacity under normal compressive wall load forces. Under a collaborative research program with the Technical University in Delft, the Netherlands, twenty eight 1/3-scale model tests were performed during the author's sabbaticaly year 1974-75. The test specimens included three connection types and they were subjected to programmed sequences of compressive wall force, horizontal (floor) tensile force and applied bending moments. The main objective of this pilot test program was to obtain a better insight about joint behavior and at least a qualitative evaluation of the effect of load and other design parameters on joint strength and deformation performance.

"Flexible Plate Bearings" (A. Pauw)

The recent failures due to freezing of the rocker bearings on the east approach spans to the Poplar Street bridge in St. Louis as well as the dropping of a number of highway girders during the San Fernando earthquake has stimulated research on improved bridge bearings. Initial experiments conducted on an inclined-leg "sway-frame" configuration have demonstrated the feasibility of this novel bearing concept. With this configuration, a fixed-hinge bearing can be so detailed that the

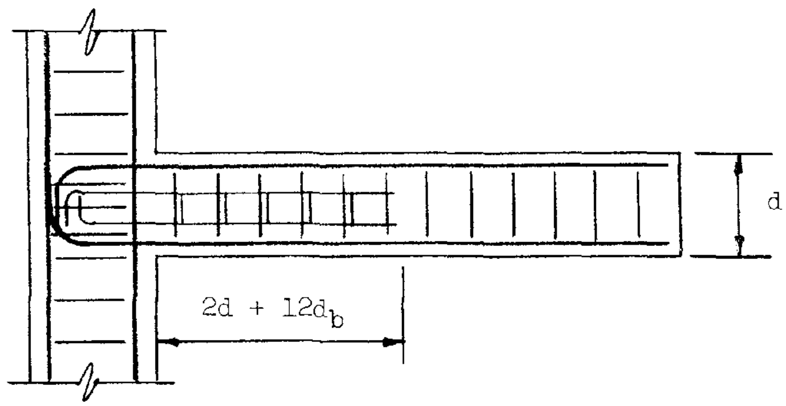

Fig. 1(a) Typical Reinforcement Pattern

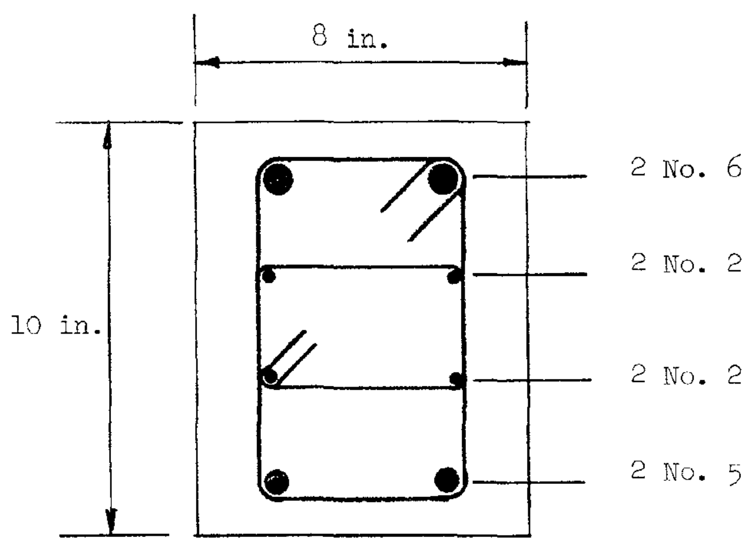

Fig. 1(b) Typical Beam Cross Section

II. Use of Intermediate Longitudinal Bars as Supplimentary Shear Reinforcement (Principal Investigator: James K. Wight)

The purpose of a research program now in progress at the University of Michigan is to study the use of intermediate longitudinal bars as a means of preventing or at least delaying the deterioration in shear strength of a reinforced concrete member when it is subjected to large load reversals. A typical reinforcing pattern is shown in Figs. 1(a) and 1(b). The intermediate longitudinal bars are intended to serve two purposes. First, they should provide an additional tensile component across the steep inclined cracks which form in the hinging zone.[2-5] Second, the dispersion of longitudinal bars throughout the cross section and the use of extra ties around the intermediate bars should provide much better confinement of the beam core and therefore effectively delay the deterioration of the beam core. Major variables of the testing program will be the percentage and arrangement of intermediate reinforcement and the shear span to depth ratios. It is expected that this type of reinforcement will be most useful for beams with moderate (2.5 - 4.5) shear span to depth ratios.

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W. S. RUMMAN

University of Michigan

This report summarizes two areas of research in Earthquake Engineering now in progress in the Department of Civil Engineering at the University of Michigan.

I. Inelastic Behavior of R. C. Structures With Hollow Circular Sections

The research is being conducted in two main areas: Experimental studies relative to the reversed cyclic behavior of reinforced concrete members of hollow circular sections, and the response of structures with such members to severe earthquake motions. Hollow circular sections are encountered in reinforced concrete chimneys, bridge piers, intake-outlet towers, offshore platforms and other similar structures.

The experimental studies

Specimens 128" long, 16" outside diameter, two inches in thickness and reinforced by both longitudinal and circumferential steel are now in the initial stages of construction. Steel forms for building the specimens have been obtained on loan from the Civil Engineering Laboratory of the Naval Construction Batallion Center at Port Hueneme, California.

The members will be subjected to reversed and cyclic bending with the presence of an axial force. Moment-curvature relationships will be obtained by testing many members so that the variations in both the axial load and the amount of reinforcement are considered. Previous theoretical studies at the University of Michigan[1] have shown that the cyclic behavior of these members is primarily a function of two non-dimensional parameters: W/rtf'_c and $\rho(fsy/f'_c)$ where W is the axial force, r is the mean radius, t is the wall thickness, f'_c is the strength of the concrete, ρ is the steel ratio of the longitudinal reinforcement and fsy is the yield stress of the steel.

Earthquake Response

The moment-curvature hysteresis loops as obtained from the experimental results and also from the theoretical work already done will be used to develop a model that describes the large inelastic deformations and the deterioration of the structure. The model which will be a function of the two non-dimensional parameters will be used to determine the behavior of tall concrete chimneys or other similar structures when subjected to severe earthquake motions.

one containing only the initial properties and the other containing only nonlinear terms. The changes in the material properties are reflected only in the stiffness matrix that contains the nonlinear terms. These subdomains are divided into elastic deformation elements and zero thickness joint elements which provide for the nonlinear deformations. The joint elements have only shearing and normal stress components and are assumed to exhibit the total nonlinear behavior of reinforced concrete including cracking and crushing. The element stiffnesses are derived for a composite material and the hysteretic material models will be based upon the experimental and analytical studies of previous investigators.

Repair of Damaged Reinforced Concrete Frame Structures.

An experimental investigation on the repair and retest of reinforced concrete exterior beam-column subassemblages was made by Duane L. N. Lee and James K. Wight. Eight half-size T-shaped specimens were designed using the 1971 American Concrete Institute Building Code either for seismic or non-seismic areas in order to represent both types of existing structures.

During original testing, the specimens were subjected to loading which represented either a moderate or severe earthquake in order to obtain different degrees of damage. Either removal of damaged material and replacement with various high early strength materials or pressure injection of epoxy was used to repair the specimens depending upon the degree of damage. The specimens were retested in the same manner as the original test to study the repaired behavior and to compare this behavior with the original behavior.

The stiffness, strength, and energy dissipation capability of the specimens were selected as the primary response characteristics for comparing the original and repaired behavior to determine the effectiveness of repair. It was concluded that the epoxy injection, and removal and replacement techniques of repair can restore structural integrity to the members damaged by flexural action. The beam-to-column joints should be evaluated before repairs are made to determine if the joint is adequate to resist a future earthquake. Severe damage in the joint can result in the structure behaving poorly during an earthquake.

This research was supported by NSF Grant GI39123 and the final report is completed.

Method To Analyze The Cyclic Behavior of Slender Shear Walls

A finite element technique to analyze the cyclic behavior of reinforced concrete slender shear walls to be used in conjunction with the cyclic material models for concrete and reinforcing steel is being developed by Haluk Aktan in this study. The analysis technique differentiates the elastic and nonlinear deformations and uses different finite elements to represent these respective deformations. The analytical results will be compared with experimental results of other investigators to check the accuracy and usefullness of the proposed method.

The shear wall is divided into subdomains for the analysis. The deformations of each of these subdomains are separated into linear and nonlinear deformations. Two separate stiffness matrices are computed for each subdomain,

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Reinforced Concrete Shear Walls for Aseismic Strengthening.

Five half-size reinforced concrete frames were constructed and tested by Lawrence F. Kahn to experimentally determine the effectiveness of infilled walls in strengthening existing framed structures against earthquake loads. The one-story, one-bay frames which measured 1.68 m. by 2.74 m. were tested under static, reversed cycle loads. One specimen was the unstrengthened open frame; the second used a wall cast monolithically with the frame; the third used a wall cast-in-place after the frame was constructed; the fourth used a single precast wall fitted within the frame and mechanically connected to top and bottom beams; and the fifth used a wall made of six small precast panels which were mechanically connected within the frame and then joined together.

Response of the open frame and the frame with monolithically cast wall provided reference limits for the remaining specimens. The cast-in-place wall behaved as a typical shear wall, like the monolithic cast model, until the wall-frame connection failed just below the beam. Models with precast infilled walls behaved in a combined frame and shear action. The maximum strength of the multiple precast wall was about half of that of the other walls, although it maintained its load capacity over larger deflection levels. Energy dissipation capacity of the two precast and one cast-in-place models were similar, yet they were half the capacity of the monolithic wall structure.

These test results were used to empirically modify simple theoretical equations so that cyclic response of various infilled, shear wall systems may be predicted. Three general conclusions were that cast-in-place walls can provide the same maximum strength as an equivalent, new monolithic wall but with less ductility, that multiple precast panels provide a strong, ductile and easy-to-construct strengthening technique, and that the cyclically degraded load capacity of shear walls should be used in the structure design rather than the virgin, monotonic capacity.

This portion of the research which was supported by NSF Grant GI39123 has been completed and a report published. Additional specimens which will use pneumatically placed concrete and stronger infilled precast panels are being planned.

factors as hysteresis behavior and different arrangements of bracing members, and vertical component of ground motion on the total response of these structures(2,3,4,5). Bracing patterns that have been considered are K, V, X and split-K types. The responses are being studied with a view to identify structural parameters which will produce controlled inelastic activity in braced frame structures when subjected to severe earthquake motions.

The results obtained, thusfar, have shown that a realistic representation of post-buckling behavior of bracing members is important and must be included for an accurate prediction of the response of braced frames(2,3). Results also indicate areas of concern such as large permanent deformations in the floor girders of K-braced frames and that overall displacement response may not indicate the inelastic deformation in certain members and locations(2,4). Efforts are being made to incorporate these aspects of structural behavior in formulating design recommendations and analytical procedures for earthquake-resistant design of braced frame structures.

Torsion in 3-Dimensional Structures

This study deals with developing simpler 2-dimensional models to represent moment frames and coupled shear walls or bracings with respect to their linear and non-linear stiffness characteristics and eccentricities. The effects of torsion-translation frequency ratio and the eccentricity-polar radius of gyration ratio, and orthogonal-strength interactions in conjunction with torsion will be studied with respect to ductility requirements. The "house of cards" phenomenon i.e., progressively increasing eccentricity with nonlinearity, will also be studied.

RELATED PUBLICATIONS

1. Prathuangsit, D., "Inelastic Hysteresis Behavior of Axially Loaded Steel Members with Rotational End Restraints," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, April, 1976.

2. Goel, S. C., "Inelastic Response of Multistory K-Braced Frames Subjected to Strong Earthquakes," Proceedings, Fourth Japan Earthquake Engineering Symposium, Tokyo, Japan, November, 1975.

3. Singh, P., and Goel, S. C., "Hysteresis Models of Bracing Members for Earthquake Response of Braced Frames," Accepted for VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

4. Goel, S. C., "Seismic Behavior of Multistory K-Braced Frames Under Combined Horizontal and Vertical Ground Motion," Accepted for VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

5. Kaldjian, M. J., "Inelastic Cyclic Response of Split K-Braced Frames," Accepted for VI World Conference on Earthquake Engineering, New Delhi, India, January, 1977.

SUBHASH C. GOEL

The University of Michigan

This paper summarizes a current research program concerning the hysteresis behavior of axially loaded bracing members and response of braced frame structures of steel. Principal investigators are Professors Glen V. Berg, Robert D. Hanson, Movses J. Kaldjian and Subhash C. Goel. The research project is sponsored by the National Science Foundation.

Hysteresis Behavior of Bracing Members

Past theoretical and experimental studies have generally treated the bracing members as either pin-connected or fully-fixed against rotation at the ends. The hysteresis curves are obtained by varying either the axial force or the axial displacement. In a just completed theoretical study(1) Prathuangsit used a model with rotational springs at the ends and a prescribed initial out-of-straightness in order to simulate, respectively, the effects of restrained rotation due to end-connections and transitional yield-buckling in compression. Elastic-plastic behavior was assumed for the member and end-connections. The variables included connection strength and stiffness, and length, size and shape of the member. The study concluded that the optimum post-buckling behavior of the member is obtained when yielding occurs simultaneously in the connections and at mid-length of the member. Further, for such a member (called the balanced connection strength member) the hysteresis behavior can be predicted by using a pin-connected member of equivalent slenderness ratio.

Experimental work is now in progress in which small size rectangular tube members with welded gusset plates for end connections are used. Cyclic axial displacements are applied both statically and dynamically. This work will serve either to verify the theoretical results or to provide a basis for suitable modifications. Particular attention is being paid to such effects as local buckling and its influence on hysteresis behavior and fatigue life of the specimens. Failure mechanisms are being studied to determine the ductility and energy dissipation capacities.

Response of Braced Frame Structures

Based on member studies a simple mathematical model and a physical model (consisting of two rigid links and a plastic hinge) have been derived for the hysteresis behavior of axially loaded bracing members for use in computing the response of braced frame structures when subjected to severe earthquake motion. These two models have been programmed for use with DRAIN-2D program which was originally developed at the University of California, Berkeley. Response of braced frame structures is being studied to learn more about the effects of such

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The University of Michigan

A numerical model to investigate soil liquefaction potential has been developed, and is undergoing further study and refinement. The model includes a means of coupling the non-linear shearing stress-shearing strain behavior of saturated granular material with inelastic vertical deformation. The one-dimensional analysis provides a time history of pore-water pressure changes concurrent with shearing deformation. A random horizontal velocity or displacement input is used to excite the system.

The liquefaction model incorporates the following features:

a. Excitation of the one-dimensional model is by transient shear waves.

b. The shearing stress-strain deformation law is strain-softening as described by a modified Ramberg-Osgood relation.

c. The constrained modulus is coupled to the nonlinear behavior of the shear modulus.

d. The effective stress and pore pressure combine to support the overburden only; i.e., there is no external vertical excitation, and the total vertical force at any elevation does not change with time.

e. The soil skeleton may settle or expand in response to changes in effective stress and constrained modulus.

f. Consolidation of loose granular materials causes an increase in pore pressure with a concurrent reduction in effective stress, which alters the shearing stiffness and strength of the soil. The process of soil liquefaction is monitored through observations of pore pressure build up and shearing strains.

g. Leakage or drainage occurs in response to new pressure gradients generated during the transient motions. The resistance to water movement in the porous media is modeled by Darcy's Law.

The model provides an intuitively correct response in parametric studies involving such quantities as overburden forces, permeability, soil density, etc. The model will benefit from refinements in the handling of material properties, particularly in the relationship between the reduction in constrained modulus and the change in shear modulus. Alternative relationships may be used, since the currently imposed assumptions are not basic requirements of the model.

This research has been supported by a National Science Foundation Grant No. GI-34771 to The University of Michigan.

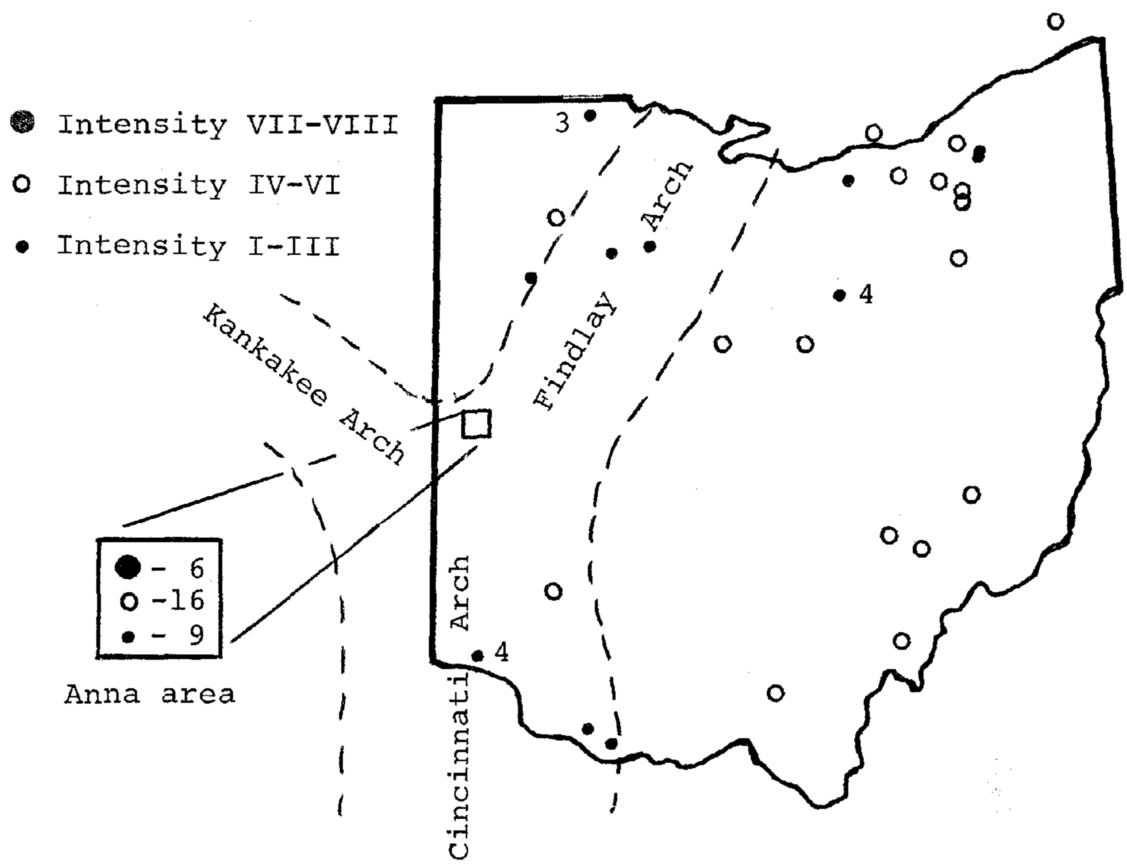
JAMES T. WILSON

The University of Michigan

Under the direction of Henry N. Pollack, Professor of Geology and Mineralogy at the University of Michigan, the Department is installing a network of stations in the Anna area to investigate the regional seismicity.

A number of moderate earthquakes have occurred in the Anna, Ohio region in historic times -- most recent damaging shocks occurred in 1937. One station has been in operation for several months and several more will be installed within the next few weeks. The data is telemetered to Ann Arbor. Other related studies are underway involving stress measurements and a high precision gravity survey.

The work is being carried on under the sponsorship of the Nuclear Regulatory Commission.



Historic Seismicity of Ohio

F.E. RICHART, JR., R.D. WOODS, AND C.S. CHON

University of Michigan

National Science sponsored earthquake engineering research is being conducted on the effects of earthquakes and vibrations on the behavior of friction piles. Model piles are subjected to horizontal static and dynamic loads to study (a) the changes in effective fixity, (b) the changes in natural frequency and damping, (c) and the changes in vertical pull-out resistance, all as functions of the amplitude of horizontal pile motions and number of load repetitions.

Testing Equipment and Procedures

Model piles 3 in. to 5 in. diameter, or rectangular cross sections, were embedded from 3 to 7 ft. into a saturated or drained bed of fine dune sand. The sand was contained within a 7.5 ft. diameter x 10 ft. high "quicksand" tank. Thus reconstituting the desired sand bed conditions for each new test was accomplished by creating the loose condition with upward water flow, then compacting the sand bed with a concrete "spud " vibrator.

Static horizontal load tests, displacement controlled low frequency tests, steady state dynamic load tests, and free vibration tests developed by the "plucking" procedure were applied to the model piles.

Preliminary Results

The static and dynamic load-displacement behavior is nonlinear with stiffness of the system decreasing and damping increasing with amplitude of motion, as might be expected. The decrease in pull out resistance after horizontal loadings was found to be greater when the sand was in the submerged dense condition than when the sand was in the drained dense conditions. Evaluation of test results and correlations with theories for nonlinear horizontal response of piles will continue during the summer of 1976 and it is anticipated that a report on these studies will be available in the fall.

WILLIAM A. NASH

University of Massachusetts

The program in the Department of Civil Engineering of the University of Massachusetts is concerned with the behavior of slab-supported liquid storage tanks subject to seismic excitation. The work is under the sponsorship of the Earthquake Engineering Program, Division of Advanced Environmental Research and Technology, (RANN), of the National Science Foundation.

Two approaches have been developed for this problem area. The first is analytical and employs the Flugge equations governing small elastic deformations of circular cylindrical shells. The slab-supported tank is assumed to be filled to an arbitrary depth with a perfect liquid. Several realistic boundary conditions are considered at the tank top. Natural frequencies of the coupled liquid-elastic wall system are determined and a computer program rapidly yields frequencies and mode shapes for an arbitrary depth of liquid. Then modal superposition techniques are employed to determine the response of this coupled system to horizontal base excitation. Again, a computer program permits specified ground pulses to be employed as base driving functions. Several examples of simple pulses applied to a realistic tank geometry have been investigated. Also, the response of a tank to an artificial earthquake record has been determined.

The second approach is based upon finite elements. The problems treated are identical. Thus, first finite elements are employed to determine the natural frequencies of the coupled liquid-elastic wall system, with the tank being represented by ring-shaped elements. Then, the response of this same system to horizontal base excitation is determined through modal superposition. Response results obtained for several typical tank geometries through both the analytical and also the finite element approaches are in excellent agreement.

It is planned to investigate the effect of a ring-shaped baffle on natural frequencies and response of such a liquid storage tank.

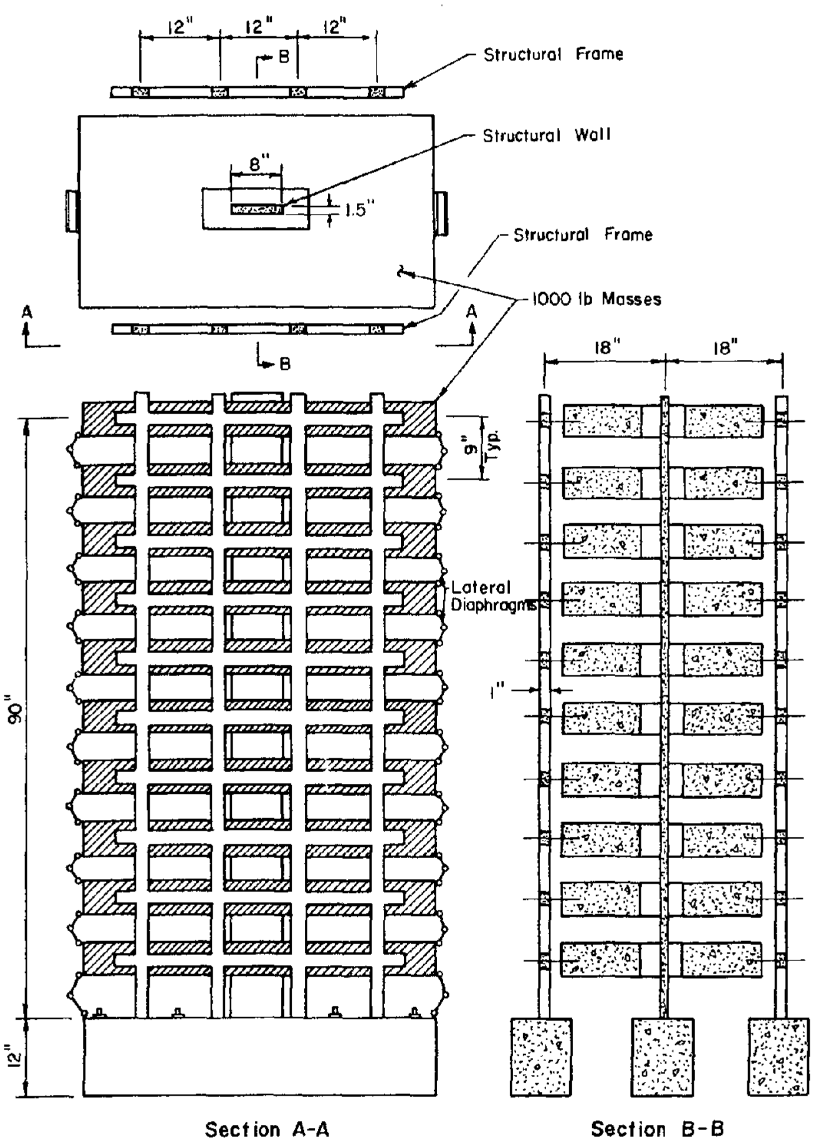


Fig. 2 Test Structure with Two Frames and a Wall (Columns 2x1.5x1, Beams 1.5x1.5x1)

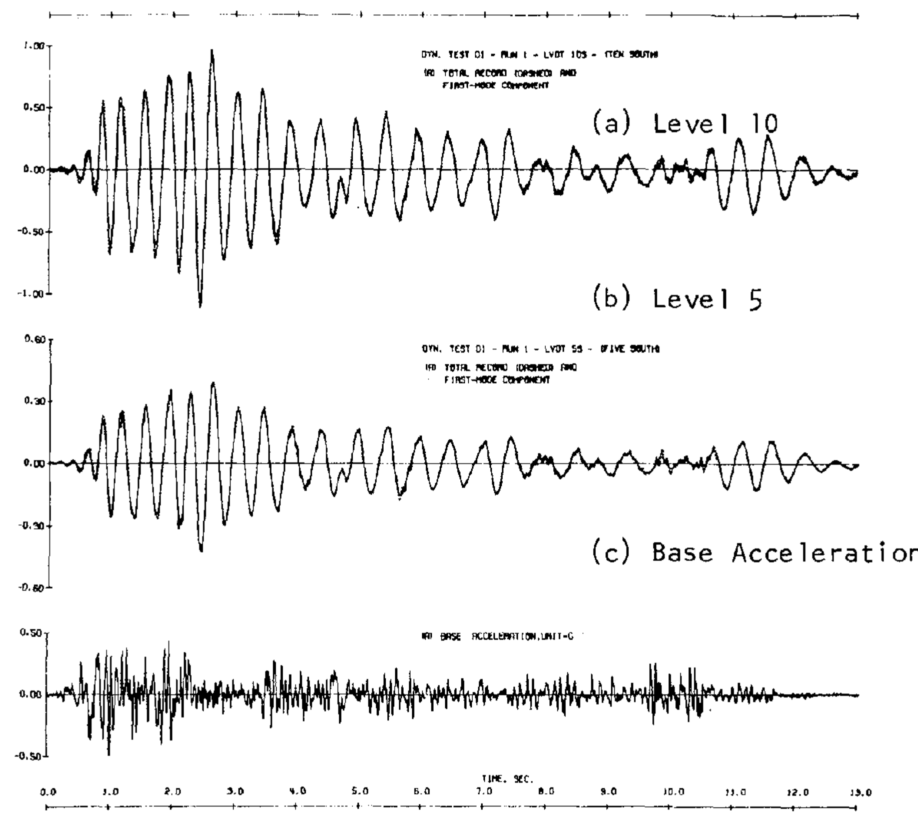


Fig. 3 Displacement Response, Ten-Story Coupled-Wall Model

of the reinforcement. Reduction in the measured fundamental frequency was proportional to the square root of the maximum displacement. As in preceding dynamic experiments of columns, one- and three-story walls and three-story frames, a linear relationship was observed between the level of damage (indicated by maximum displacement) and Housner's Spectrum Intensity.

The investigation is conducted by D.P. Abrams, D. Aristizabal, H. Cecen, L. Ebers, and J. Lybas under the direction of W.C. Schnobrich and M.A. Sozen.

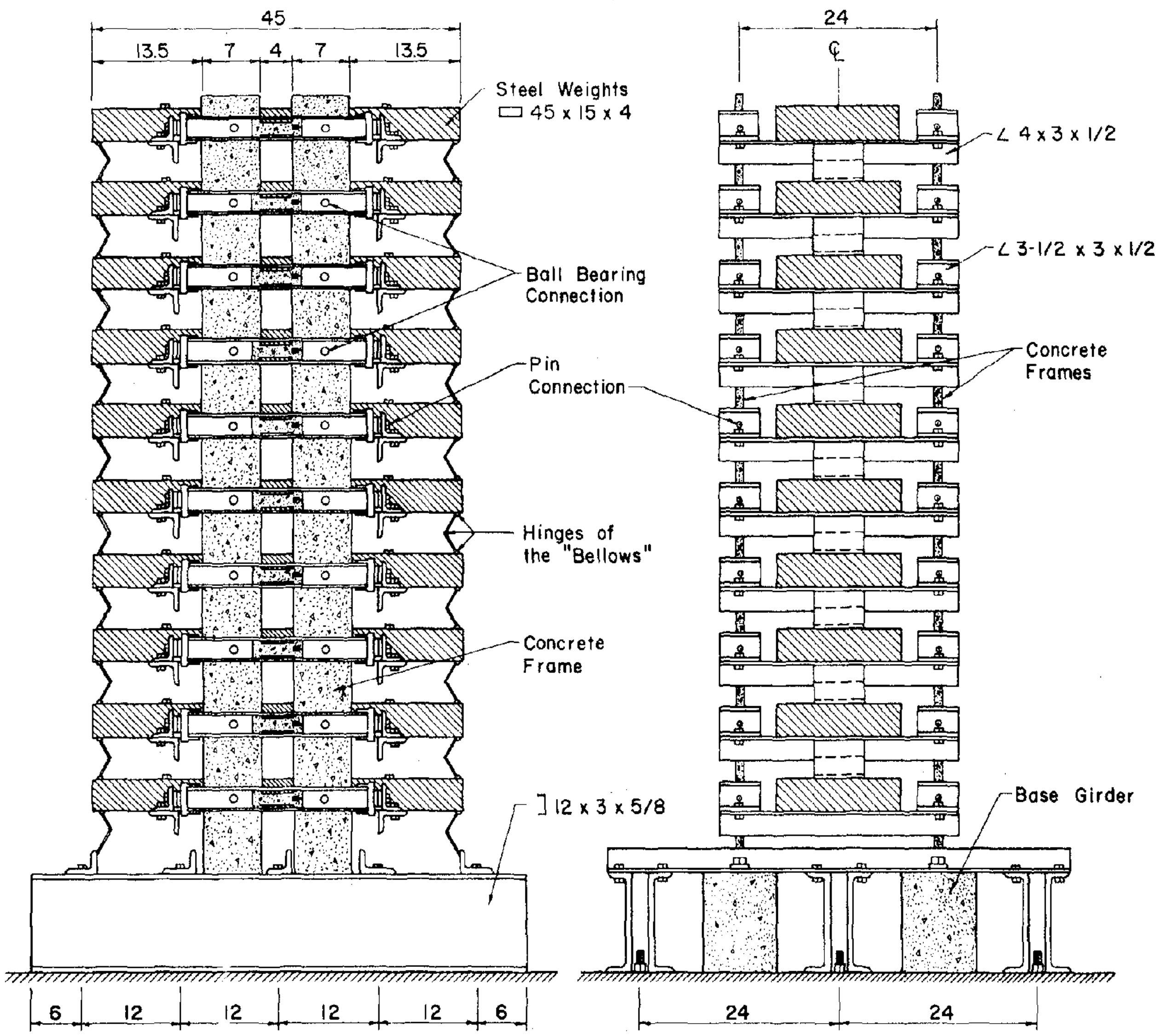


Fig. 1 Ten-Story Coupled Wall Model

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A series of tests of ten-story structural models of reinforced concrete walls and frames are in progress at the University of Illinois supported by NSF Grant ATA74 22962. The objectives of the investigation are (a) to study the nonlinear dynamic response of multi-story reinforced concrete structural systems, (b) to check experimentally the feasibility of a design procedure for determining the relative strengths of members and (c) to provide data for testing the results of analytical models for nonlinear response of multi-story structures.

The experimental program includes three series of tests. The test structures of the first series were coupled structural walls as shown in Fig. 1. The 7x1 in. walls were connected at each level by 1.5x1 in. beams spanning 4 in. The story height was 9 in. A steel weight of 1000 lb was attached to each story level. Each model comprised two sets of coupled walls (Fig. 1) working in parallel. Transverse stiffness was provided by a steel "bellows" which resulted in negligible resistance in the direction of the planes of the walls. Four structures were built and tested with the main variables being the strength of the beams with respect to the walls and the base motion.

Each test structure of this series was subjected to a number of increasingly stronger base motions, simulating one horizontal component of El Centro 1940 or Taft 1952. Measurements included accelerations and displacements at all levels as well as the crack patterns after each test.

The second series, which is currently in progress, comprises four ten-story frames, each test structure being made up of two frames working in parallel. The overall geometry of the frames is shown in Fig. 2 (Section A-A). The main experimental parameters are the relative strengths of the beams and the columns and the type of base motion.

The third series of test structures will incorporate a slender wall with two frames as described in Fig. 2. The relative strength of the wall will be the main experimental parameter.

Although the supporting data can not be included, some of the overall observations from the first series (coupled walls) are recorded below.

The displacement and base-moment responses were typically governed by the lowest mode (Fig. 3). The maximum force and displacement responses could be reconciled with the results of a linear model having a reduced stiffness and increased equivalent viscous damping. Increasing the beam-to-wall strength ratio naturally resulted in a structure with improved behavior for the "design" earthquake but also with a vulnerability to total collapse when subjected to higher intensities of motion. The stiffnesses of the connecting beams were influenced strongly by slip of the reinforcement because of the low ratio of span length to development length

T. Takayanagi and W.C. Schnobrich
University of Illinois

It is not possible to thoroughly investigate thru model tests the influence of the many possible variations in the various parameters that control the response of reinforced concrete shear walls either as isolated walls, coupled walls or walls in association with frames. The models are too expensive in terms of both time and money. Furthermore, it is not always possible to record when all the events of interest take place. Therefore, from the beginning of the project an analytical phase was programmed to run parallel to the experimental effort.

This presentation reports on the development of a nonlinear analysis of coupled shear walls being conducted by Mr. T. Takayanagi. The basic model used in the study is composed of flexural line elements, both for walls and the coupling beams, Fig. 1. Even for the isolated walls, the aspect ratio was high enough that to model the wall by plane stress finite elements was considered to be unnecessary, even inaccurate, in comparison with the flexural line element. Rigid links connect the coupling beams to the line elements modeling the walls. Line elements for the walls were further subdivided between stories in order to allow the nonlinear effects to propagate thru a story, rather than happen abruptly. The degree of subdivision decreases with story level. The stress resultants at the centroid of the segments or subdivisions are used as the control points for the determination of the nonlinear properties of the segments. All interior or segment nodal points are condensed out of the stiffness matrix before it is used so that only story level translations remain in the final equations.

The coupling beams, on the other hand, are treated as two component members. Rotational springs at the ends of the member handle all the nonlinear action, including any bond slip, etc. A linear elastic element spans between the springs. Since the couple moment from the axial forces in the walls is an important contribution to the overall overturning moment for the system, the entire structure consisting of both walls, as well as complete coupling beams, had to be considered.

A step by step time history of response was performed using a linear acceleration ($\beta=1/6$) variation. For the ten story specimen the time step used was 0.00035 sec. However, in the interest of economy, the stiffness matrix was updated every fifth time step if necessary.

The crossectional properties of the wall elements take into account the nonlinear effects of both flexural and axial contributions. The moment curvature of the basic wall section has a primary (backbone) curve which is approximated by a trilinear form, control points for the curve being the cracking and yielding moments. Takeda based hysteresis rules govern the cyclic behavior of the section Fig. 2. The presence of axial force in the wall is assumed to modify the moment capability as shown.

of attachment where only one frequency of the secondary system is allowed to match one of the frequencies of the primary system. Multiple-connected and simple non-linear systems will be investigated also.

6. *Torsional and Coupled Motions*

The effects of structural eccentricity and base rotation are being studied as they affect the torsional response of low-rise buildings. (J. R. Whitley -- W. J. Hall). The effects are being studied first independently and then in a combined form. The purpose of the study is to arrive at a basis for evaluating the adequacy of present code recommendations which vary widely, and to arrive at new simple procedures for estimating torsional effects in low-rise buildings.

Another study dealing with coupled motions is underway. The initial portions of the study will deal with the effect of vertical accelerations in decreasing or enhancing gravity effects accompanying lateral motion. The long range goal is to arrive at simple design procedures for handling coupled motion. (A. C. Stepneski -- A. R. Robinson -- W. J. Hall).

Acknowledgment

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Another study involves development and evaluation of approximate methods for handling non-linear multi-degree-of-freedom systems, the objective being to utilize, as much as possible, techniques already familiar from linear analysis. (V. Tansirikongkol -- D. A. W. Pecknold). The approach consists of using an equivalent linear system, taking into account frequency shifts, change of mode shapes and increased effective damping as a function of the level of inelastic behavior.

3. Seismic Shears and Overturning Moment in Buildings

Studies of the effects of shear and overturning moment arising from earthquake motion is being made with the response spectrum approach (R. Smilowitz -- N. M. Newmark). Among the parameters studied is the type of building (shear wall, shear beam, or combination) spacing of the lower modal frequencies, the relationship of the fundamental frequencies to the spectrum "knees" and the effects of foundation compliance.

4. Effect of Damping and Inelasticy

A study is underway to evaluate the influence of damping and inelastic behavior on the response of single-degree-of-freedom systems subjected to base motion (R. Riddell -- N. M. Newmark). One objective of this study is to develop an empirical amplification factor versus damping relationship valid over a wide range of damping, for example from about 0 to 100 percent of critical. Another aspect of the study involves consideration of non-linear single-degree-of-freedom systems to review the concepts of equivalent damping.

Another study involves the review of the damping of reinforced structures stressed within the elastic range under earthquake type excitation (G. M. Portillo -- D. A. W. Pecknold). The purpose is to evaluate the current recommended damping values for concrete structures and to develop a model for estimating the total damping of structures based on energy absorption characteristics of the components.

5. Dynamics of Building Subsystems

The response of building subsystems to earthquake excitation and the effect of the presence of such a subsystem on dynamic response of the structure is under study (G. Ruzicka -- A. R. Robinson). One part of the present study has dealt with methods of handling accurately systems having widely diverse masses and stiffnesses. One of the important applications of the procedures relates to modifications which may be necessary in the usual spectral analysis of a multi-degre-of-freedom structure when frequencies exist which are very close to one another.

Another study in this area involves an expansion of earlier studies carried out by N. M. Newmark for estimating the earthquake response of light secondary systems attached to primary structures (R. Villaverde -- N. M. Newmark). The first part of the study is intended to improve on the bounds to the response of lightweight equipment (secondary systems) supported in or on a structure (primary system). In the initial studies the analysis is limited to simple elastic secondary systems with a single point

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This research program is aimed at the development of simplified and improved methods of design to resist dynamic hazards with emphasis on earthquakes. The four general areas in which work is going forward are as follows: (1) response of subsystems to dynamic forces and motions; (2) simplified general methods of analysis and design for earthquakes and wind; (3) inelastic behavior of multi-degree-of-freedom systems subjected to dynamic loads and motions; (4) simplified approaches to dynamic soil structure interaction. In addition to the two principal investigators the other senior investigators are Professors A. R. Robinson, D. A. W. Pecknold and W. H. Walker. The names of the Graduate Research Assistants and Professors associated with each of the topics under study is identified in the text.

1. Close-In Earthquake Effects and Attenuation of Ground Motion with Distance

The close-in effects study involves analysis of earthquake records in a manner to account for wave dimensions and building size as they affect lateral, vertical, rocking and torsional effects. (J. R. Morgan -- N. M. Newmark -- W. J. Hall). Substantial differences can arise between free field records and those recorded at the basement level of buildings in the same area and these studies are directed towards identifying these differences and providing a basis for estimating the variation in effects.

The study concerned with the attenuation of ground motion involves reexamining the proposed relationship of the attenuation of acceleration with earthquake magnitude and distance using expressions derived from dimensional analysis. (N. Qureshi -- N. M. Newmark -- W. J. Hall). It is envisioned that the approach will be extended to include attenuation relationships for ground velocity as well.

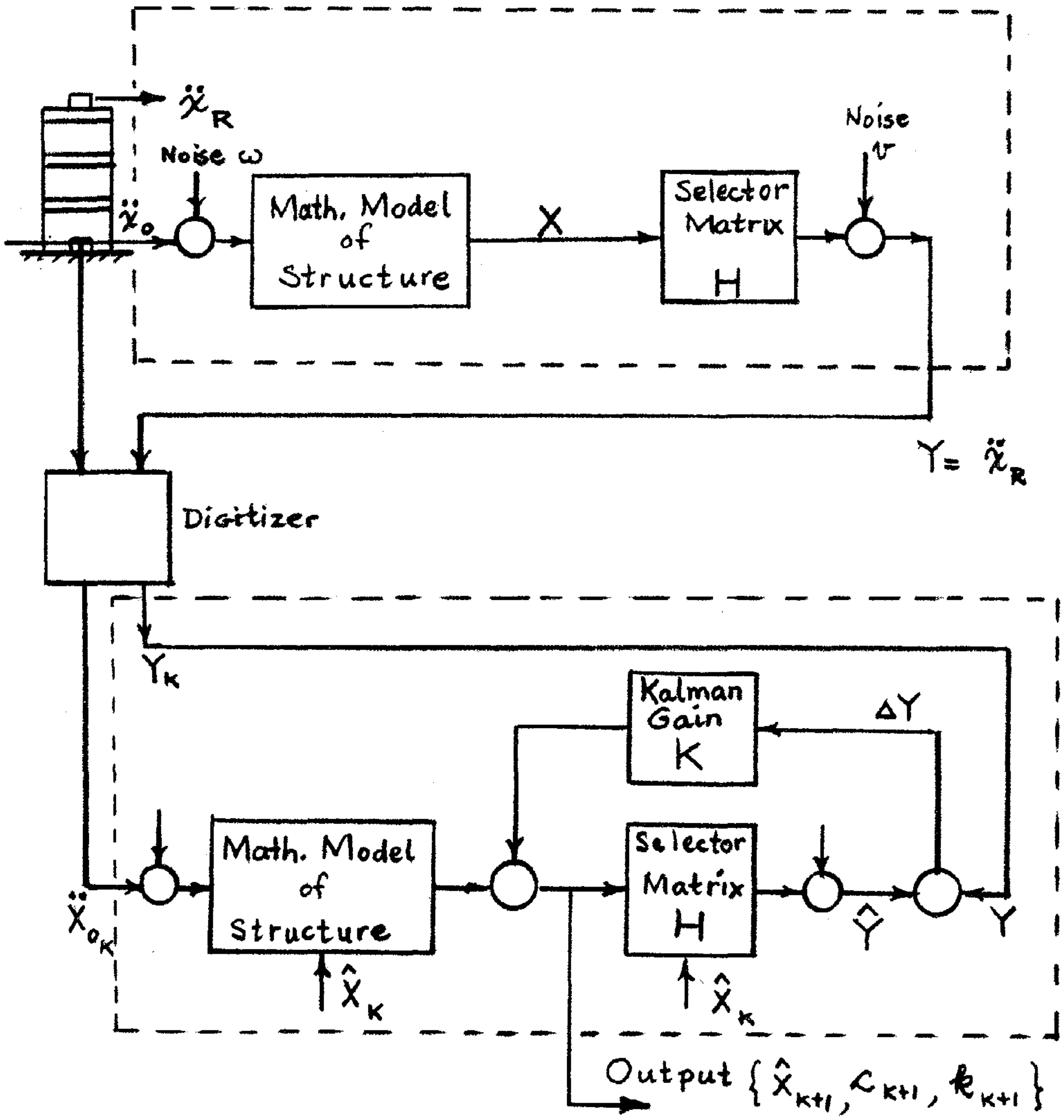
2. Inelastic Dynamic Response

The study of the inelastic dynamic response of low-rise steel buildings involves investigation of recently developed methods for handling nonlinear behavior and the development of approximate design procedures. (C. J. Montgomery -- W. J. Hall). An attempt is being made to assess the margin of safety inherent in the given earthquake resistant design.

Another part of the inelastic behavior studies involves development of simplified computer models for biaxial bending of reinforced concrete columns under variable amplitude cyclic loading. (M. Suharwardy -- D. A. W. Pecknold). The models incorporate moment-axial load interaction and the effects of stiffness and strength degradation under cyclic loading.

interstory parameters. The parameters at each time step are considered to be constant, but they may vary with time as in the actual earthquake.

The filter equations in the recursive form have been derived and are now being programmed for the computer. It will first be tried out on a two-story building with accelerometers at the roof and ground floor using actual earthquake data.



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Over the past few years we have developed a least-squares parameter identification procedure for determining the interstory damping and interstory stiffness of any building from earthquake excited response.[1] Although the procedure has been successful even in the case of noisy response, one of its serious drawbacks is that it requires measured response at every floor. For a high-rise building the cost of instrumenting every floor is impractical, and hence it is desirable to develop a new procedure which will identify all interstory parameters from a limited number of measurements, say the roof, mid-height and basement. This has been one of our goals for the UCLA-UCSB earthquake research project.

In studying the literature on parameter identification, it appears that the Extended Kalman Filter offers a possible procedure to solve this problem. It will give estimates of the interstory response as well as the parameters to be identified.

It would be impossible to go into the details of the Extended Kalman Filter in any summary paper. To obtain some kind of a physical feeling for the workings of the filter, the following oversimplified block diagram is offered.

Assume that we have a three story building with accelerometers at the ground floor and the roof. Measurements are not made at the first and second floors. We will assume that the measurements $\ddot{x}_o$ and $\ddot{x}_R$ are generated by a mathematical model of the building expressed in terms of the state variables X. The actual measurement $Y = \ddot{x}_R$ of the roof is selected from X by the H matrix and is digitized together with the ground acceleration $\ddot{x}_o$. Thus, the upper dotted block indicates how the actual measurements might be generated, and it also includes state noise w and measurement noise v.

The lower dotted block represents the Kalman filter. The digitized measurements of the roof and ground accelerations represent inputs to the filter which contains a similar mathematical model and selector matrix of the upper block diagram. The difference here is that the model and selector are both updated by the previous best estimates of the state $\hat{X}_k$. The new updated state $\hat{X}_{k+1}$ is computed from the difference ΔY of the actual measurement Y and the computed value of the measurements $\hat{Y}$ at each time interval from recursive equations which orthogonalizes ΔY from all past measurements. The result is the least minimum variance unbiased estimates of all the states including the uninstrumented floors and their corresponding

(1) Hart, Thomson, Caravani, Watson, Nakamoto, "Parameter Studies and Interpretation of Building Earthquake Response Records 1975," UCLA-TR-No 7614.

Since the attachment between equipment and building is often nonlinear, the interaction can be nonlinear. The objective of the investigation is to develop a simple analytical model for predicting the effect of nonlinearly mounted equipment on such building characteristics as effective mode shapes, frequencies, and damping ratios.

The Attenuation of Seismic Waves Across a Slipping Interface

Energy is dissipated as seismic waves propagate through a fault surface. The details of the resulting attenuation are of geological interest and are useful for the prediction of ground motion amplitudes. The goal of present investigations is to determine the effect of various frictional models for fault slippage on the effective transmission and reflection coefficients.

The Identification of Optimal Passive Vibration Isolation Systems

There have been several recent proposals to mount an entire building on an intentionally flexible and nonlinear foundation in order to achieve a reduction in seismic forces. Assuming such a system may be modeled as having localized nonlinearity, one obtains a single functional relation between the response and the foundation characteristics. By applying optimization techniques, it is the goal of this investigation to identify the optimal passive foundation restoring force which minimizes the steady-state response of a given structure.

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Research is being conducted on the dynamic response of multidegree-of-freedom structures whose nonlinear behavior is confined to a single location. This localization of nonlinear behavior may occur either by intentional design or prevailing circumstances. Examples of such systems might include certain models for buildings with a flexible first story, or equipment mounted on nonlinear vibration isolators. In other examples the nonlinearity may be sandwiched between two separate linear systems, such as a weak structural attachment between adjacent structures, or a frictional fault surface between elastic soil layers.

By isolating and analyzing the nonlinear element separately from the remaining linear system, an approximate analytical technique may be used to calculate the dynamic response. One advantage of using such a technique is that it provides a single functional relation between the observed response characteristics and the system properties which cause them. This aids in the identification of the important parameters and the interpretation of the response in terms of simplified behavior for use in design. Another advantage is that it provides a considerable savings in computational effort over direct numerical integration schemes.

Studies were recently completed [1,2] on the steady-state response of such systems to harmonic excitation. The goal of these studies was to predict the essential features of the response without the need for extensive numerical simulation. The method of equivalent linearization was used to linearize the single nonlinear force, which resulted from hysteretic, elastic, and viscous elements. Transfer function techniques were used to characterize the linear system. The functional form of the resulting amplitude-frequency response equation was used to develop several theorems concerning the qualitative nature of the response. The dependence of the effective natural frequencies, location of response peaks, boundedness of response, and other response characteristics on the properties of the nonlinear constraint were emphasized.

Studies are currently in progress on the steady-state response of several special cases of locally nonlinear systems, including (1) the interaction of buildings with nonlinearly suspended equipment, (2) the attenuation of seismic waves across a slipping interface, and (3) the identification of optimal passive vibration isolation systems. Studies of the response of each of these systems to random and earthquake excitation are planned.

The Interaction of Buildings with Nonlinearly Suspended Equipment

The earthquake failure of electrical and mechanical equipment is of continuing concern at such facilities as hospitals and nuclear power plants. Often the equipment is sufficiently massive that the response of the building itself is affected by interaction with the equipment.

Some results obtained from the computer models include synthesized seismograms and their Fourier and response spectra for several points on and around the rupture surface. The finite element three-dimensional computations proceed at a rate of 0.8 m-sec. of CDC 7600 computer time per element per numerical time step.

Future research will be directed towards the improvement of the numerical modeling of the rupture mechanism and the detailed study of the geology effects. Special study is being given to the format of display of information in the neighborhood of the fault in order to clearly characterize the earthquake hazard in that region.

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structures such as those on a densely built area, and the evaluation of the dynamic response of structures caused by elastic waves generated by a nearby explosion.

Several of the studies on soil-structure interaction have been conducted in collaboration with Dr. H. L. Wong from Caltech.

Installation of an Array of Strong Motion Seismographs in Northern Baja California—Northwestern Sonora, Mexico.

This program is being conducted by Professor Brune of UCSD in collaboration with Professors Rosenblueth, Prince, Esteva and Lomnitz from the Universidad Nacional Autónoma de Mexico (UNAM). The program involves the installation and maintenance of a timed strong motion array in Northwest Mexico. The array consists of 17 instruments deployed along the Cerro Prieto, Imperial, Agua Blanca and San Miguel Faults. Given the very high seismicity of the area there is a good chance of recording a large earthquake within a few years. It is expected that these records will provide important information on earthquake source mechanism, stresses, and maximum accelerations and velocities in the near field.

Laboratory and Numerical Simulation of Near Field Earthquake Ground Motion.

Research in this area is being conducted by Professors Brune and Frazier. The major goal of this study is to obtain a deterministic characterization of earthquake ground motion in terms of fault proximity, fault type, and intervening earth structure.

Two complementary methods are being employed: controlled laboratory experiments and numerical computer models. Earthquake-like behavior is produced in the laboratory using large blocks of foam rubber. When critical levels of stress are reached, spontaneous slip occurs along a precut surface in the foam rubber. Surface motions, observed using high-speed photography and Fotofet transducers, contain information on both instantaneous and final stress drop, focusing of seismic waves and wave form at various distances from the fault.

Three-dimensional finite element computer models have been developed and have been verified by reproducing a variety of analytical solutions as well as the surface motions observed in the laboratory experiments.

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The following is a summary of research work at the University of California—San Diego in the areas of soil-structure interaction, near field earthquake ground motion and strong motion instrumentation. These studies are funded by grants from the National Science Foundation.

Soil-structure Interaction

As a preliminary step in the study of the interaction between structures and the soil, analyses of the dynamic response of foundations to both external forces and nonvertically incident seismic waves have been made. Analytic methods to obtain the dynamic response of arbitrarily shaped flat rigid foundations have been presented. Also, analytical solutions have been obtained for the problem of the torsional vibrations of rigid embedded foundations. In particular, the case of hemispherical and semi-ellipsoidal foundations has been considered in detail. The results of these studies give a clear picture of the effects of plan geometry and embedment on the foundation response. In addition, the effects of the nature and angle of incidence of the seismic waves are also clearly defined. It has been found that nonvertically incident SH or Love waves generate a marked torsional component of response in addition to translational components. Similarly, nonvertically incident P, SV or Rayleigh waves generate a large rocking response component.

Work has already started on the formulation of an approximate analytical method to obtain the dynamic response of rigid foundations of arbitrary shape embedded in a layered viscoelastic medium. The study of embedded foundations will be complemented by the use of a novel three-dimensional finite element approach that eliminates the need for energy absorbing boundaries.

In regards to the complete soil-structure interaction problem, several studies have been conducted on the torsional response of axisymmetric structures for nonvertically incident SH waves. It has been found that in many cases the torsional response associated with nonvertically incident waves is of the same order of magnitude as the translational and rocking response. Studies on the complete dynamic response for other types of nonvertically incident waves are presently under way.

Other topics currently being investigated in this area include the interaction through the soil among a large number of closely spaced

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Earthquake hazard mitigation through improved design and analysis of masonry structures is the subject of a large-scale experimental, analytical, and numerical research program at the University of California, San Diego. Of primary interest is the development of a basis for a rational earthquake response and damage analysis of load-bearing reinforced concrete masonry multistory buildings. The experimental effort is intended to define material and connection behavior, including the highly nonlinear domain; the analytical phase involves the translation of observed experimental data into viable mathematical models; the numerical effort concerns the conversion of mathematical models into numerical form and the construction of digital computer programs to simulate response and damage accumulation resulting from earthquake ground motion.

The approach selected to achieve the project objectives involves a sequence of increasingly complex levels of concurrent experimentation, analysis, and numerical simulation. This sequence begins with elementary experiments on the basic constituents of reinforced concrete masonry and their interactions. It proceeds to biaxial tests of panels (the first such tests) under both quasistatic and dynamic cyclic load histories. The above is complemented by dynamic tests of typical floor-to-wall and wall-to-wall connections. The sequence culminates with experiments and case studies on major structural elements. The ability to extrapolate from conceptually simple laboratory-scale experiments to a wide variety of structural configurations, including simulation of full-scale buildings under seismic ground motion, is regarded as one of the most significant aspects of the project.

The above research effort is sponsored by the National Science Foundation (RANN). The research team is an integrated university-industrial consortium with unusual capability and facilities. Participants include the University of California, San Diego (host institution); San Diego State University; Agbabian Associates; Weidlinger Associates; Convair Division/General Dynamics Corporation; and a panel of practicing structural engineers.

In the second approach, we are using a crude form of system identification technique to invert the existing data and thus determine the source parameters considered significant in earthquake engineering studies. At present, we are working with the Pacoima Dam accelerogram recorded during the 1971 San Fernando earthquake. The fault is assumed to consist of several straight line segments. Each segment is assigned a set of trial parameters consisting of the length, orientation, rupture speed, maximum offset and an additional parameter which describes the space and time dependence of the slip across the segment. An attempt is being made to fit the discretized recorded velocity and displacement time histories with the calculated motions by varying these parameters. The initial results are encouraging enough to warrant a more careful investigation of the technique.

Investigation of Surface Waves

It has been demonstrated in a number of recent papers that surface waves play a significant role in producing strong ground motion even in the near field in shallow earthquakes. It is also well known that these waves are strongly affected by local layer thicknesses as they propagate away from the source. The existence of these waves has largely been ignored in earthquake engineering studies. Their dispersive properties and more recently amplitudes have been extensively studied by the seismologists in the determination of the internal constitution of the earth. Although the techniques developed by the seismologists are powerful and highly efficient, they cannot be directly used in earthquake engineering research. This is due to the fact that while the interest of the seismologists is in the long periods (> 10 sec.) and large distances (> 100 km.), exactly the reverse is true in earthquake engineering. We are in the process of developing a systematic procedure for studying the amplitude of surface waves in relatively short periods (.1-10 sec.) and small distances (10-100 km.). Close contact is maintained with the seismology group at UCLA, headed by L. Knopoff, in order to avoid any duplication of efforts. At the present time, we have developed a computer program which calculates the Love wave phase velocities and near field spectral amplitudes produced by an arbitrary point dislocation located near the surface in a single layered half space. The results obtained so far indicate that the ground motion is a strong function of the epicentral distance as well as the depth of the source within the layer. The interference between the different modes may produce entirely different ground motion spectra at two stations with identical site parameters. We have also developed an approximate technique, valid at short periods, to calculate the transfer functions of Love waves across layers of varying thickness. These transfer functions will be utilized in a generalized linear system model including body and surface waves to determine site effects. We plan to extend these techniques to multilayered media and Rayleigh waves.