PROCEEDINGS

FIFTH NATIONAL MEETING

OF THE

UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

June 23-24, 1978

Massachusetts Institute of Technology

Sponsored by

National Science Foundation

Report No. UCEER-5

UCEER

Universities Council for
Earthquake Engineering Research

California Institute of Technology
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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. Ninety-five individuals gave reports. The written summaries of these reports as well as some summaries not presented orally are contained in this report. The summaries are organized under the following topics: ground motion; soils and soil structure interaction; structural elements; structural response, experimental; structural response, analytical; seismic risk, seismic design and codes.

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FOREWARD

This volume contains the Proceedings of the Fifth National Meeting of the Universities Council for Earthquake Engineering Research which was held on the campus of the Massachusetts Institute of Technology, June 23-24, 1978. 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 fifty individuals attended the meeting representing 67 universities, various government agencies and industries. Travel grants were awarded to 59 individuals.

There were six topically organized sessions consisting of brief seven minute research reports. Ninety-five individuals gave reports. The written summaries of these reports along with some summaries not presented orally are contained in this volume.

In addition to the research presentations, there was a special session on "Recent Developments in Federal Support for Earthquake Engineering Research." This session was conducted by personnel from the National Science Foundation, Division of Problem-Focused Research Applications.

Local arrangements for the meeting were ably handled by Professor James Becker and Maria Kitteridge of the Massachusetts Institute of Technology. The Banquet on Friday night at the MIT Faculty Club was attended by 115 individuals who enjoyed the excellent food and an interesting talk on photographing the Loch Ness monster.

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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UNIVERSITIES COUNCIL FOR EARTHQUAKE
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10:00 - 10:30	Coffee Break
10:30 - 12:00	Research Reports - Soils & Soil Structure Interaction, 1
12:00 - 1:00	Lunch
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10:00 - 10:30	Coffee Break
10:30 - 12:00	Research Reports - Structural Response, Analytical, 2
12:00 - 1:00	Lunch
1:00 - 3:15	Research Reports - Structural Response, Experimental
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M. Shinozuka, Columbia
C. B. Yun, Poly. Inst. NY
R. Dobry, Rensselaer
A. K. Mal, UCLA
C. M. Duke, UCLA
H. E. Lindberg, SRI Intl.
K. Wong, Berkeley

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B. C. Yen, Cal St., Long Beach
J. Ghaboussi, U. Ill.
I. Ishibashi, U. Washington
T. S. Vinson, Oregon St.
G. Ayala-Milian, UNAM
C. A. Miller, City Coll. of NY
S. K. Saxena, IIT
P. Christiano, Carnegie
G. Dasgupta, Columbia
O. M. El-Shafee, Wash. U.
J. M. Roesset, MIT
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M. Novak, U. West. Ontario
T. Ariman, Notre Dame
A. A. Huckelbridge, Case
G. R. Saragoni, U. Chile
A. Cella, U. of Genova

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W. K. Tso, McMaster
T. Huang, Lehigh
M. L. Porter, Iowa St.
D. Mitchell, McGill
C. W. Roeder, U. Washington
S. C. Goel, U. Michigan
S. Otani, U. Toronto
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R. L. Mayes, ATC
E. Popov, Berkeley

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J. M. Gere, Stanford
H. M. Krawinkler, Stanford
P. H. Gulkan, Berkeley
W. O. Keightley, Montana St.
D. Rea, UCLA
M. A. Sozen, U. Illinois
T. V. Galambos, Washington U.
H. G. Harris, Drexel
J. M. Plecnik, Cal St., Long Beach
R. W. Clough, Berkeley
A. M. Abdel-Ghaffar, Caltech
R. M. Zimmerman, New Mex. St.
T. Y. Yang, Purdue

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S. F. Masri, USC
R. K. Miller, UCSB
B. J. Goodno, Georgia Inst. Tech.
D. A. Foutch, U. Illinois
P-T. D. Spanos, U. Texas
W. K. Wen, U. Illinois
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D. T. Tang, SUNY
C. N. Kostem, Lehigh
D. G. Row, Berkeley
H. D. McNiven, Berkeley
G. H. Powell, Berkeley
J. M. Becker, MIT
A. J. Schiff, Purdue
I. J. Oppenheim, Carnegie
A. S. Veletsos, Rice
W. A. Nash, U. Mass.
G. W. Housner, CIT
S. A. Mahin, Berkeley

SESSION 6 - SEISMIC RISK, SEISMIC DESIGN & CODES

A. H. S. Ang, U. Illinois
S. Takada, Columbia
H. C. Shah, Stanford
R. L. Sharpe, ATC
G. Solomos, U. West. Ontario
S. Cherry, U. British Columbia
D. C. Holder, U. Colorado
C. J. Abend, Syracuse U.
R. V. Whitman, MIT
C. A. Cornell, MIT

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Zimmie, T. F.	Rensselaer

SESSION 1

GROUND MOTION

Chairman: W. D. Iwan

R. B. Matthiesen

Seismic Engineering Branch. USGS

The current strong-motion accelerograph networks in the United States are shown in Figure 1. The California Division of Mines and Geology (CDMG), which operates the largest network, has installed ground motion instruments throughout California and is instrumenting different types of structures and installing special ground motion arrays. The Army Corps of Engineers (ACOE) has completed about 2/3 of their planned program of dam instrumentation; the University of Southern California (USC) is developing an extensive array of ground stations throughout the Los Angeles Basin; and in the NSF program operated by the USGS, instruments are being transferred from California to other active areas. Other organizations are expanding their networks slowly. The numbers and types of installations by different organizations are summarized in Table 1.

The "typical" instrument in all networks is the self-contained analog accelerograph that records on film. Multichannel analog film recorders with remote transducers are currently being installed in most types of structures. Digital accelerographs have been developed commercially and are being introduced into many of the networks, particularly in special programs. The digital instruments will permit more rapid and less expensive data processing when they become widely used.

The records from the federal state and local agencies other than State of California agencies are archived by the USGS; those from State of California agencies are archived by CDMG with copies at the USGS; whereas those from university networks are archived by the universities or by the USGS. The records from "other" installations (such as nuclear power plants or buildings instrumented under local ordinances) may not be readily available.

The USGS routinely processes records as a part of the NSF sponsored program. Film records are digitized automatically by a commercial firm, whereas the paper records are digitized semi-automatically. The data processing programs originally developed at Caltech have been modified to accommodate the wide variety of records which are being processed. The difference in results obtained from the original programs and from the modified programs is illustrated in Figures 2 and 3. The CDMG is developing a capability for processing their own strong-motion records. The procedures used are the same as those of the USGS. Stanford has facilities for semiautomatic digitizing of records and processing them on a minicomputer, and is currently processing many of the older paper records in a cooperative program with the USGS. USC has completed the development of a facility for automatically digitizing and processing the records from the large array being installed in the Los Angeles Basin. Other universities digitize and process records from their own projects or on an ad hoc basis.

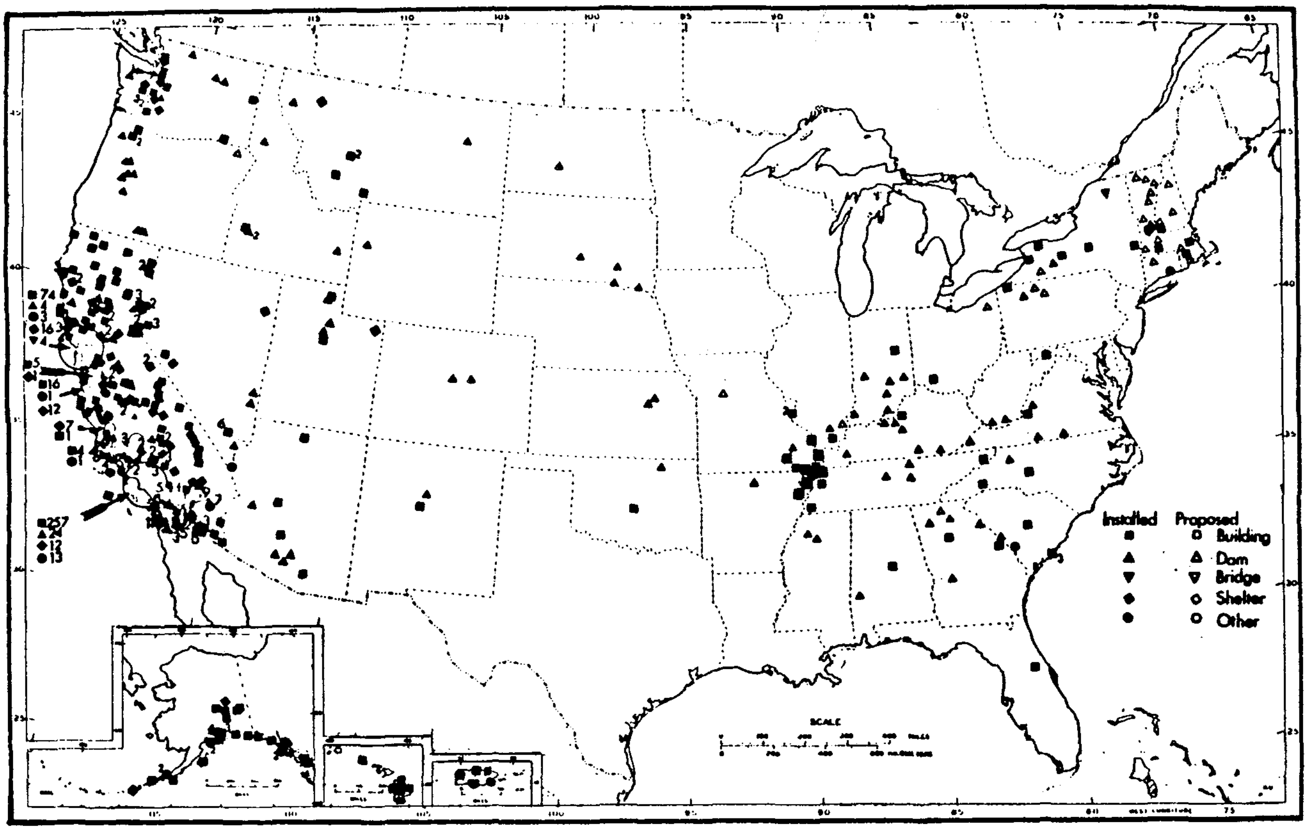

FIGURE 1. STRONG-MOTION ACCELEROGRAPH INSTALLATIONS - 1978

Table 1 - U. S. Strong-Motion Accelerograph Installations

Organization	Grnd	Bldg	Dams	Brdg	Other	Organization	Grnd	Bldg	Dams	Brdg	Other
ACOE	1		66		4	CIT	20	2			
FHWA				5		LDGO	10				
GSA		1				SLU	3				
LMEC	1				3	SNY	3				
NSF/USGS	200	4			2	UAK	10				
USBR	6		14			UCB	5				
VA	62	5				UCLA		4			
						UCSD/UNAM	15				
CDMG	300	30	10	4	3	UNV	6			1	
CDOT				3		USC	100				
CDWR	6		1		3	UWN	6				
CIAA(PR)	7	1									
MWD	18	1	1			Bldg Code		200			
WDOT				3		Other	20	6	3		20

Note: Abbreviations of the organizations are given in USGS Open File Report 77-374.

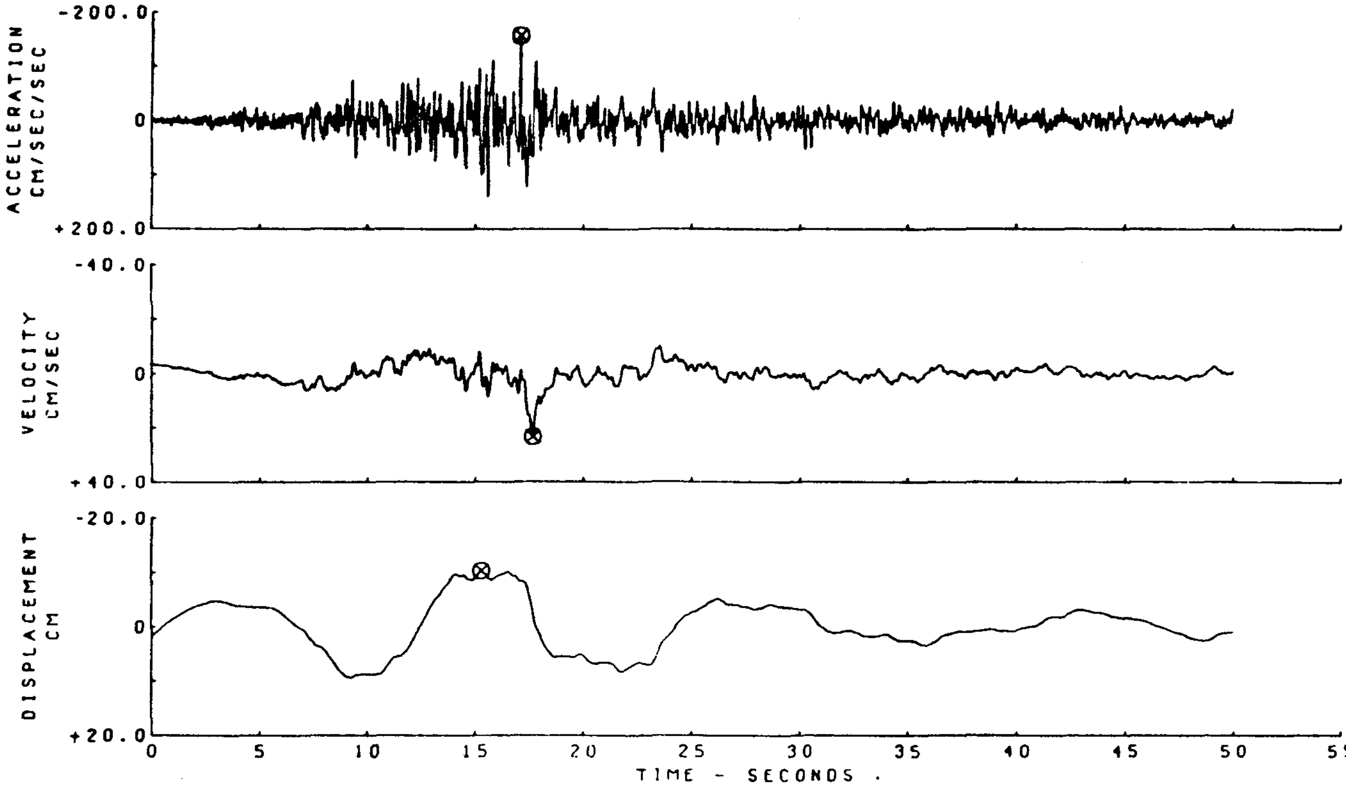

FIGURE 2. ACCELEROGRAM PROCESSED WITH ORIGINAL PROGRAMS.

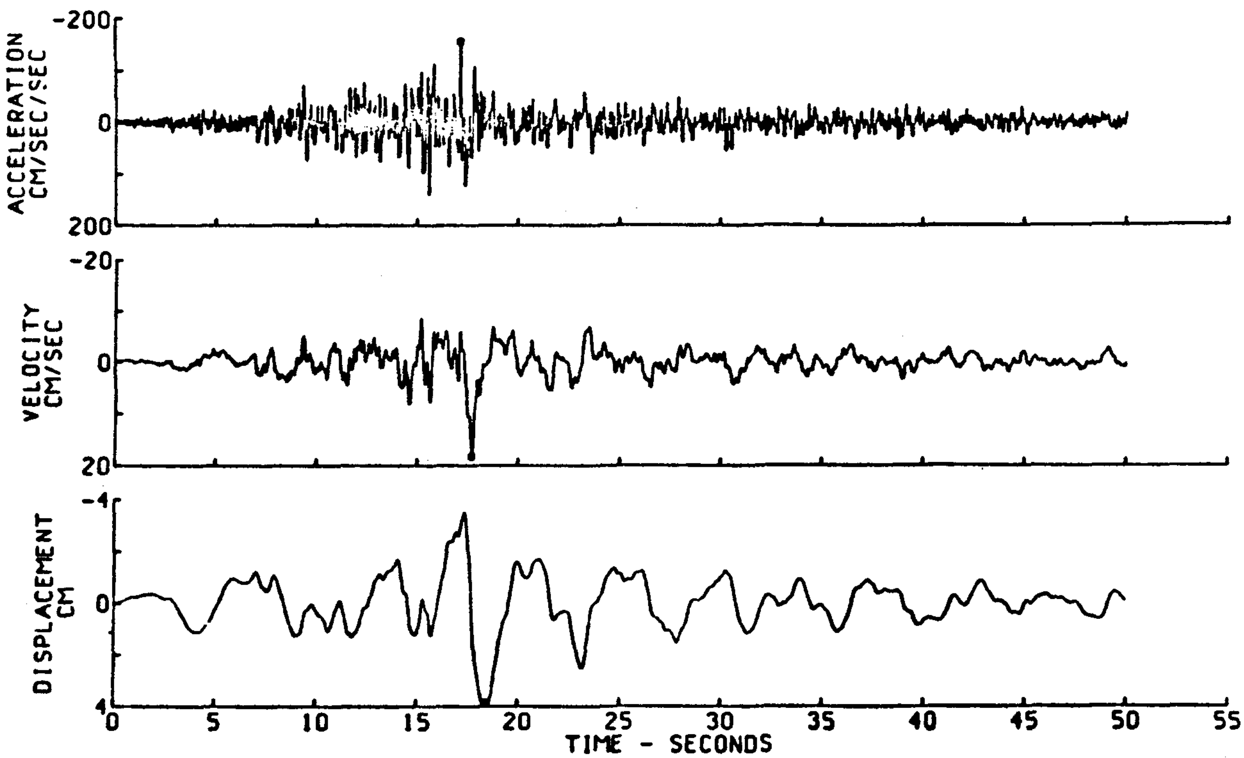

FIGURE 3. ACCELEROGRAM PROCESSED WITH MODIFIED PROGRAMS_

A. M. CONVERSE

Seismic Engineering Branch
U.S. Geological Survey

The National Strong-Motion Instrumentation Program is conducted through an interagency agreement between the National Science Foundation and the U.S. Geological Survey. The major objective of this program is to serve the needs of strong-motion data users who are involved in earthquake engineering research concerned with the improvement of structural design practices and the reduction of earthquake hazards. An important task defined for the program is the timely dissemination of information regarding strong-motion data records and the circumstances in which the records were taken. In order to make such information readily available, it is being entered into a computer data base management system. The system provides ready access to information about strong-motion records, recording sites, and recorded events. It should prove to be of considerable value in the aftermath of a major event by providing immediate information to persons in research, design, operations, and regulation.

Data Base Contents

The data base information of primary importance is that which describes strong-motion records and the level of processing and analysis that has been performed on them. Information about each event that triggered recorded motion and about the recording stations is also of major importance. Supplementary data sets include instructions and general information about the data base, additional information about the stations, recorders, and transducers, and identification of the organizations that own the instruments, that have additional information about the stations and sites, or that archive the original records. The specific information included in each dataset is indicated in Table 1.

At present, the information included in the data base is limited to that for which the USGS has a primary responsibility. The datasets may be expanded in the future to include information about all strong-motion programs in the U.S. In addition, the computer programs will be available to other organizations that operate strong-motion programs in other parts of the world so that information about strong-motion data can be exchanged in an efficient manner.

Data Base Access

The data base can be interrogated using an ordinary telephone and an interactive keyboard terminal that operates in full duplex mode and which uses ASCII character codes. Once accessed, the system will give the user a general introduction and will tell him how to retrieve and display more specific instructions and guidelines from the data base itself. Access the system as follows:

1) Set the switches, keys or buttons on the terminal that allow a choice of operating modes:
   - transmission speed = 30 cps
   - half duplex
   - on-line
   - lower case ASCII characters

2) Plug in and turn on the terminal. Turn on the acoustic coupler too, if it's a separate device.

3) Telephone the USGS computer at Menlo Park. Dial (415) 326-4350 and wait for a high-pitched tone.

4) Quickly place the telephone handset in the cradle on the acoustic coupler. Look for a label or diagram that will show you in which direction the telephone cord should go. Watch for the "carrier detect" light to turn on, indicating that the terminal is properly receiving the signal.

5) Type the line-feed key. The computer will respond with several lines that will tell you which computer system you've accessed, how many other users are connected, etc.

6) Type: enter <your_name> Sebdb <cr> <lf>
where <cr> is the carriage-return key,
<lf> is the line-feed key, and
<your_name> is your name typed without any embedded blanks.
Note that the "S" in "Sebdb" is in upper case.

7) From now on, the system will prompt you whenever it expects you to type something. Answer by typing the question-mark key if you don't know what is expected of you.

If you have a terminal that won't operate in the appropriate modes, or if other problems are encountered, contact April Converse (415-323-8111, ext. 2881 or FTS # 467-2881).

TABLE 1 - DATA SETS

EVENTS
- event identification
  (date & suffix)
- time (local or GMT)
- event name
- location: latitude
  longitude
- magnitude
- maximum intensity
- references

RECORDS
- event identification
- station number
- substation identification
- transducer level or location
- recorder identification(s)
- s-trigger interval, sec.
- epicentral distance, km.
- intensity at the site
- total length of record
- peak acceleration
- duration $\geq 0.1g$
- who has the original record
- references

DATA ANALYSES
- who digitized the data
- who has the digitized data
- length of record digitized
- highest stage of analysis
- stage 2 frequency band
- data processing type
- references

STATIONS
- station number
- station name
  (or street address)
- station location
  (or city)
- state (or country)
- nearby stations
- references

SUBSTATIONS
- substation identification
- date of installation
- date of removal
- location: latitude
  longitude
- geology: class code
- near surface shear wave vel.
- structure: class code
  size
  short description
- remarks

ARRAYS
- array name
- list of stations and their
  substations in the array
- remarks

NEARBY STATIONS
- station number
- list of nearby stations
- remarks

RECORDERS
- recorder identification
- owner agency
- date of installation
- date of removal
- remarks

TRANSDUCERS
- transducer serial number
- date of installation
- date of removal
- location: code
  short description
- direction of acceleration
- orientation
- trace location on record
- remarks

TRANSDUCER CALIBRATIONS
- calibration date
- sensitivity
- period
- damping
- remarks

RECORDER TYPES
- recorder type code
- descriptions

AGENCIES
- owner-agency code
- name, address, contact
  and other remarks

J. B. FLETCHER

U.S. Geological Survey

A set of 121 accelerograms for 14 aftershocks of the Oroville, California earthquake (1 Aug 1975, $M_L = 5.7$) comprise a data set unprecedented for the number of records for each event obtained at such close ($R \lesssim 15$ km) distances. Important characteristics of these records--short duration of the strong ground shaking (< 2 sec), short S-wave minus trigger times ($\lesssim 2$ sec), and enrichment in frequencies above 1 hz--are not unexpected from elementary seismological consideration of the magnitude of the earthquakes that were recorded ($2.8 \leq M_L \leq 5.2$) and the hypocentral distances of the accelerographs. Early work, which used data from the unprocessed film records such as peak acceleration and arrival times, has now been completed and emphasis has shifted to developing a rigorous understanding of the time histories of the corrected acceleration, velocity, and displacement traces. Methodologies which incorporate wave propagation, near-surface site effects, and the seismic source are being marshalled in analyzing these records.

The work done on analyzing data from the film accelerograms is presented in Seekins *et al.* (1978) and Seekins and Hanks (1978). In the first paper, arrival times of these S-waves were used to determine the shear-velocity structure at Oroville and they found the wedge of Great Valley sediments to have a low shear velocity of 1 km/sec compared to the much higher velocity of 3.7 km/sec for the basement rocks at depth. They also showed that earthquake locations computed using just S-wave arrival times from strong motion accelerograms are nearly as accurate as those computed using P waves from local arrays. In the second work, peak accelerations were shown to be lower on sedimentary rocks of several hundred meters thickness compared to other hard rock sites, other conditions being about equal. Peak accelerations increase with magnitude in the $3 \leq M_L \leq 5$ range, and this dependence appears to be stronger for sedimentary sites than bedrock sites.

Using this and other data on the shear velocity structure at Oroville, our work has now shifted toward using these records in various ways to study the seismic source. A first step is the calculation of corrected acceleration, velocity, and displacements. The displacements, in particular, are invaluable as most source models compute ground displacement. First attempts at processing these accelerograms were badly contaminated with long-period errors that simply could not be overlooked. This oscillation appears to be caused by errors in the actual response function of the high-pass filter (Ormsby, 1961), which is used to eliminate long-period distortions that arise fundamentally in the unknown initial conditions and are aggravated during the integration to displacement. The error was reduced by increasing the interval in frequency over which the filter response goes from unity gain to zero. In addition we have deleted a step to decimate the traces during high-pass filtering to reduce aliasing, and have removed a step to high-pass filter the displacement. In consequence, most of the errors were reduced with the added benefit of simplifying the program.

Ten accelerograms were recovered for the M_L = 4.7 0350 GMT 6 Aug 1975 aftershock yielding twenty horizontal displacement records (a sample of 14 records is shown in Fig. 1). Moment, source radius, and stress drop were computed for each station using Brune (1970) formulas, but the corner frequency was estimated from the S-wave duration and the long-period level from the S-pulse area. Averages of the individual measurements gave 4 x 10^{22} dyne-cm, .75 km, and 422 bars for seismic moment, source radius, and stress drop, respectively. The standard deviation of about 25% of the mean reflects the precision of each determination.

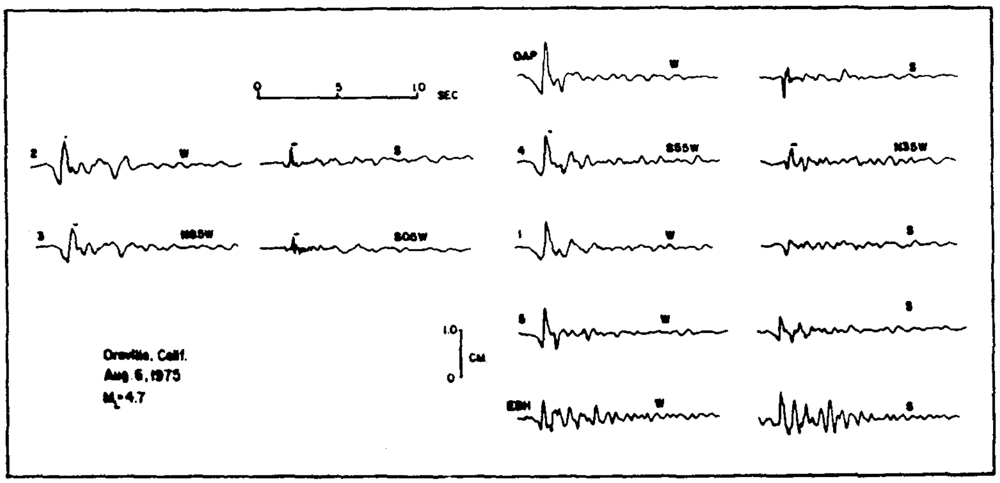

Figure 1: Horizontal displacement components for 7 of the 10 stations that recorded the 0350 August 6, 1975 Oroville, California aftershock--a normal faulting event along a NWW-striking fault plane. The hypocentral distances range from 11.4 km for station 5 to 15.2 km for station 3. The depth of the event is 9.3 km. The large pulse in all records (arriving about 1.5 sec after the start of the trace) is the direct S-wave. The ramp-like signature which precedes the S-wave, and the offset across the S-wave are near-field source effects. The smaller pulse which arrives about 0.8 sec after the S-wave on station 5 is an SH-wave multiply reflected within the Great Valley sediment wedge.

Eleven records for a M_L = 4.0 (0548, 16 Aug 1975) and 9 records for a M_L = 4.9 (0700, 8 Aug 1975) were compared to displacements computed from a theoretical point-source dislocation buried in a half-space by McGarr (personal communication). He showed that the near-field signature identified in the displacement traces can often be fitted quite closely with this model. Again, high stress drops of a few hundred bars were calculated for these events. The differences between the theoretical pulses and actual displacements proved invaluable in identifying propagation path and near-surface site effects.

In an effort to measure the directivity of the rupture, seismic energy was computed from velocity traces which had been squared (Boatwright, personal communication). He showed that for a M_L = 4.6 event, two stations to the east which are on bedrock have energies that are 4 to 5 times that of stations to the west. This suggests the rupture propagated up-dip. These calculations show that for structures that are susceptible to high frequencies, the direction of rupture propagation is an important consideration.

Work is now proceeding to bring to phase-II form all of the records in the set designated for further research. Although changes in the processing scheme appear to eliminate most of the long-period errors, other filters such as higher-order polynomial and Butterworth filters are being explored to reduce further any filtering errors. A synthesis of the source parameters for all of the earthquakes in this set should give confidence in estimating source parameters for other earthquakes in a similar tectonic environment as Oroville, a first step in estimating the strong ground shaking for any similar earthquake.

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KEIITI AKI

Massachusetts Institute of Technology

For the past several years, I have been searching for a method to calculate strong motion for a potential earthquake fault entirely based on the physical properties and conditions which can be measured at present. If we can find such a method, it will be a useful supplement to the statistical approach based on the past strong motion records and particularly helpful to assess seismic hazard when an important engineering structure is located near a potentially active fault.

Seismology has advanced sufficiently to compute seismograms for a realistic earth model and for a complex seismic source model which simulates rupture propagation along a fault. A major difficulty in this approach is how to translate the geologist's observations on a potentially active fault into a dynamic model of an earthquake rupture. I believe that we now begin to see some light on how to approach this problem. The new approach is based on the idea that an earthquake fault is not a single smooth rupture over the entire fault plane, but consists of multiple cracks joined by unbroken barriers distributed over the fault plane. The rupture propagates more or less with a uniform velocity over the entire fault plane but the slip function is quite irregular because of unbroken barriers.

I shall briefly explain this fault model, using the Parkfield earthquake as an example. The fault trace of this earthquake made a jump from one side of Cholame Valley to another. The aftershock zone determined by Eaton et al. (1970) clearly shows that this jump is not a superficial phenomenon, but actually the initial fault plane is terminated here and a new fault plane is started. This is a clear example of what we call an unbroken barrier. If we project the aftershock hypocenters of the fault plane, we find a cluster of aftershocks concentrated around this barrier. This is probably caused by the strong stress concentration around an unbroken barrier. There are other clusters of aftershocks which may correspond to other unbroken barriers unnoticed by the observations on the surface. The area without aftershocks, on the other hand, may correspond to a smooth section of fault where large stress drop occurred.

The accelerograph station no. 2 was located close to one of those smooth sections. Bouchon (1978) calculated displacement and velocity in the direction perpendicular to the fault using a model of right lateral strike-slip propagating in a layered half-space with parameters determined by various observations. An excellent agreement was obtained for a final slip of 35 cm and rise time of 0.3 seconds.

If we use this slip of 35 cm and the aftershock area to calculate the seismic moment, the result is about three times greater than the observed value determined accurately from the long-period records of world-wide stations. This discrepancy can be explained, if the slip observed near station no. 2 is about three times greater than the average slip over the entire fault plane. This is consistent with the presence of unbroken barriers inferred from aftershock distributions. From the aftershock distribution near station no. 2 we infer that the rupture responsible for the acceleration at station no. 2 was a crack with a diameter about 6 km. The strong motion record shows that the average slip on the crack was 35 cm. Such a crack is associated with stress drop of about 50 bars.

It is possible to use this barrier model for estimating peak acceleration near the fault of the great California earthquake of 1857 based on a geologist's observation of fault breaks. Wallace (1968) states that the 1857 earthquake fault might be a composite of many segmented cracks each about 15 km long with the maximum slip about 10 meters in the middle of each segment. This crack size is about 2 1/2 times larger than that for the Parkfield earthquake. Such a crack is associated with the stress drop of about 370 bars (7 1/2 times larger than that for the Parkfield). Since the acceleration is proportional to stress drop and inversely proportional to the length scale, we expect that the peak acceleration for the 1857 earthquake to be 3 times larger than that for the Parkfield, namely 1.5 g.

We are hoping that our barrier model may facilitate more interactions between geologists and seismologists, with the products useful for earthquake engineering.

CORNELIUS J. HIGGINS and GEORGE E. TRIANDAFILIDIS

University of New Mexico

The University of New Mexico, under NSF sponsorship, is investigating the technical and economic feasibility of simulating earthquake-like ground motions with high explosives. This form of simulation appears most applicable to evaluations of soil-structure interaction, where the structure response is coupled with the response of the media through which the ground motion waves propagate, and for large amplitude excitation of large structures.

Major tasks undertaken in the investigation include:

- Development of An Approach to Simulation Criteria
- Identification of Potential Simulation Methods
- Analysis of Existing Ground Motion Data
- Numerical Calculations to Supplement the Existing Data Base
- Development of Prediction Relations for the Design of Simulation Experiments
- Cost Estimates for Simulations of Various Size

Simulation criteria was considered a very important topic since no technique, explosive or otherwise, is capable of simulating every aspect of an earthquake. Accordingly, it is necessary to establish some basis for determining those characteristics of an earthquake which must be simulated for a credible test on a particular structure.

The identification and analysis tasks deal with the existing high explosive experimental data base. Although the objectives of the experiments which led to the data differed from those of interest in this research, there exists sufficient data for identification of potential simulation methods and a partial assessment of the technical feasibility of simulation with high explosives.

A high confidence assessment requires that detailed insight be obtained into data trends and that the data be extrapolated to motion regimes and time durations for which data does not exist. The calculation task was designed to provide the basis for this extrapolation. Finite difference calculations, viewed as numerical experiments, are being used to provide insight into important explosive ground motion phenomena and quantitative relationships between governing parameters which are not immediately evident from the experimental data alone.

A synthesis of the data and calculation results is being used to develop general relations which can be used for the design of simulation experiments. Cost estimates for the major elements of a simulation are being developed to enable evaluation of the economic aspects of high explosive simulation.

Results of the investigation to date indicate that explosive simulation of earthquake-like ground motions on engineering systems is technically feasible. Explosives in various arrays can produce motion amplitudes and frequency content which are in the range of those expected in large earthquakes. Further, the wave structure from planar explosive arrays contains a significant shear wave contribution to the horizontal motion. This is similar to what is thought to occur in natural earthquakes. Multiple cycles of motion and long time durations can be obtained from multiple, sequenced explosions. The use of trench barriers also appears to have significant potential for altering the ground motion field for enhancement purposes. Explosive ground motions in dry alluvial materials appear predictable with reasonable confidence using methods developed in the investigation.

Under a separate project sponsored by the Electric Power Research Institute (EPRI), the University of New Mexico is conducting explosive simulation experiments on model nuclear power plants at UNM's McCormick Ranch Test Site, south of Albuquerque. The objective of these experiments is to provide fundamental data on the rigid body rocking response of cylindrical structures when excited by ground motions having amplitudes and frequency content similar to those of a strong earthquake. Parameters varied in the experiments include model size, depth of embedment, backfill type and level of excitation.

Three experiments have been conducted to date. MINI-SIMQUAKE (ref. 1) was a small scale, double, planar array experiment designed to evaluate the use of closely spaced sequenced explosions for extending the time duration of explosive excitation. The experiment contained about 450 lbs of PETN explosive. A small structure (3.75 ft high x 2.5 ft diameter) and 30 dynamic measurements of free-field and structure response were included.

SIMQUAKE IA was a large scale, single, planar array experiment containing about 40 tons of ANFO explosive in an array 200 ft wide by 75 ft deep. The experiment contained five (5) model structures, the largest of which was 15 ft high by 10 ft diameter. About 125 channels of active instrumentation were measured. Measurements included free-field and structure motions, interface pressures on the structures and a few structure strains. The free-field motion amplitudes in the vicinity of the structures were 1 to 2 g, 30 to 40 ips and 4 to 6 inches. Major frequency content was in the range of 1 to 2 Hz.

SIMQUAKE IB was a retest of the same structures but at a higher amplitude of motion. The array contained about 30 tons of ANFO but the structures were 100 feet closer to the array. The motion amplitudes in the vicinity of the structures were 3 to 6 g, 50 to 65 ips and 8 to 14 inches. Frequency content was about the same as SIMQUAKE IA.

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A sequenced large scale experiment, designated SIMQUAKE II, is scheduled for later this summer. The experiment will contain a larger structure (22.5 ft high by 15 ft diameter) as well as amplitude variations on the other structures.

The results of the EPRI sponsored experiments support the feasibility conclusions of the NSF study. The experiments have provided a substantial amount of data on cylindrical structure response under highly nonlinear conditions. The data is undergoing analysis and will be used for the evaluation and improvement of soil-structure interaction analysis methods.

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"Development of A Data-Based Artificial Acceleration Model"

Introduction

One area in which an effort is being made under the National Science Foundation sponsored earthquake engineering research at Columbia University is the construction of nonstationary stochastic process models of ground acceleration and efficient generation of their sample functions for the purpose of Monte Carlo and other investigations relevant to earthquake engineering. We have indeed devised a nonstationary stochastic model that is primarily data-based and constructed on the Fourier transform information extracted from a record of ground acceleration (components). The model is simple to construct and has a convenient analytical form in generating its sample functions with the aid of FFT (Fast Fourier Transform) techniques, particularly as compared with other nonstationary stochastic process representations of the ground motions such as those associated with generalized power spectra, locally time averaged spectra, physical spectra and evolutionary spectra.

A Data-Based Artificial Earthquake Acceleration Model

Nonstationary characteristics of the earthquake ground accelerations are often conspicuous in the temporal variability not only in their intensities but also in their spectral contents. This is clearly demonstrated by Fig. 1a and Fig. 1c which exhibit the N-S and E-W components of the Niigata earthquake acceleration record (June 16, 1964). While it is undoubtedly of vital importance to examine the physical significance that such a record might suggest (for example, the effect of liquefaction), the present study develops a nonstationary stochastic process model dealing directly with the acceleration record.

(a) Simulation as a univariate process

Let $x_o(t)$ and $X_o(\omega)$ be a component of the acceleration record of duration T_o and its Fourier transform, respectively. Construct a nonstationary random process $x(t)$ so that

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |X_o(\omega)| \exp i\{\omega t + \xi_o(\omega) + \Psi(\omega)\} d\omega \tag{1}$$

where $\xi_o(\omega) = -\xi_o(-\omega)$ is the argument of $X_o(\omega)$ and

$$\Psi(\omega) = \Phi(\omega > 0), = 0 \ (\omega = 0) \text{ and } = -\Phi \ (\omega < 0) \tag{2}$$

The quantity Φ is a random variable and we can generate a sample function of $x(t)$ by assigning a sample value of Φ in Eq. 1 through the relationship given in Eq. 2. The most significant properties of sample functions of $x(t)$ thus constructed are that they all have identical duration T_o and Fourier amplitude $|X_o(\omega)|$ and that they can be generated with the aid of FFT techniques.

The following heuristic observation is of major interest; Since formally $d\omega = 2\pi/T_o$ and $|X_o(\omega)| = \sqrt{2\pi T_o G_o(\omega)}$ for stationary situations, Eq. 1 can be brought to the well-known form conveniently used for generating sample functions of a stationary Gaussian process with zero mean and spectral density $G_o(\omega)$ provided that $\Psi(\omega)$ represents a Gaussian white noise with respect to ω (with standard deviation approaching infinity). Indeed, this provision precisely indicates the difference between the nonstationary and stationary process models.

In the present study, we assume that Φ is a Gaussian random variable with zero mean and standard deviation σ. Because of the periodicity of $\exp i\Phi$, however, its distribution function under the assumption of Φ being Gaussian approaches the one under the assumption of Φ being uniform between zero and 2π as $\sigma \to \infty$. This fact is used conveniently throughout the paper.

We can then show that as $\sigma \to \infty$,

$$E[x(t)] = 0 \tag{3}$$

$$E[x(t_1)x(t_2)] = [C_o(t_1)C_o(t_2) + S_o(t_1)S_o(t_2)]/2 \tag{4}$$

$$E[x^2(t)] = [C_o^2(t) + S_o^2(t)]/2 \tag{5}$$

where $E[\cdot]$ indicates the expected value and

$$C_o(t) = \frac{1}{\pi}\int_o^\infty |X_o(\omega)| \cos\{\omega t + \xi_o(\omega)\}\, d\omega = x_o(t) \tag{6}$$

$$S_o(t) = \frac{1}{\pi}\int_o^\infty |X_o(\omega)| \sin\{\omega t + \xi_o(\omega)\}\, d\omega \tag{7}$$

We can also show under the same conditions that the generalized spectral density $S(\omega_1,\omega_2)$ for $x(t)$ is, with asterisk indicating complex conjugate,

$$S(\omega_1,\omega_2) = X_o(\omega_1)\, X_o^*(\omega_2) \qquad \omega_1\omega_2 \geqq 0$$
$$= 0 \qquad \omega_1\omega_2 \leqq 0 \tag{8}$$

and the density function of $x(t)$ is

$$f_{x(t)}(a) = 1/\{\pi\sqrt{A_o^2(t) - a^2}\} \qquad |a| < A_o(t) \tag{9}$$

where

$$A_o(t) = \{C_o^2(t) + S_o^2(t)\}^{1/2} \tag{10}$$

(b) Simulation as a multivariate process

Let $x_{ok}(t)$ be the k-th component of an n-component acceleration record ($n \leqq 3$) of duration T_o. Construct now a nonstationary component process $x_k(t)$ in the form of Eq. 1 with $X_o(\omega)$, $\xi_o(\omega)$ and $\Psi(\omega)$ respectively replaced by $X_{ok}(\omega)$, $\xi_{ok}(\omega)$ and $\Psi_k(\omega)$ with similar definitions. Important difference here is that we are now involved with n random variables Φ_k for $\Psi_k(\omega)$ $(k = 1,2,\ldots,n)$. Cross-correlations among $x_k(t)$ can also be introduced, for example, by assuming that Φ_k are correlated Gaussian random variables.

Dealing with a bivariate process and assuming a joint Gaussian density for Φ_1 and Φ_2 with an identical marginal density of mean zero, standard deviation σ and with correlation coefficient ρ, we can show that Eqs. 3-10 are valid, for both $x_1(t)$ and $x_2(t)$ individually, as $\sigma \to \infty$. Cross-correlation functions and cross-spectral densities $S_{12}(\omega_1,\omega_2)$ can also be derived easily. For example,

$$S_{12}(\omega_1,\omega_2) = X_{o1}(\omega_1)\; X^*_{o2}(\omega_2)\; \exp - (1 + h\rho)\,\sigma^2 \qquad (11)$$

where $h = -1$ for $\omega_1\omega_2 \geqq 0$ and $= 1$ for $\omega_1\omega_2 \leqq 0$.

Figures 1b and d respectively show a sample function each of $x_1(t)$ and $x_2(t)$ when $\sigma = 10\pi$ and $\rho = 0.999$ are used.

For the details of the process introduced above, see "Data-Based Nonstationary Random Processes," by the authors of this presentation, to be printed as NSF-ENV-76-09838, Tech. Rep. No. 5, Columbia University, June 1978.

Acknowledgment

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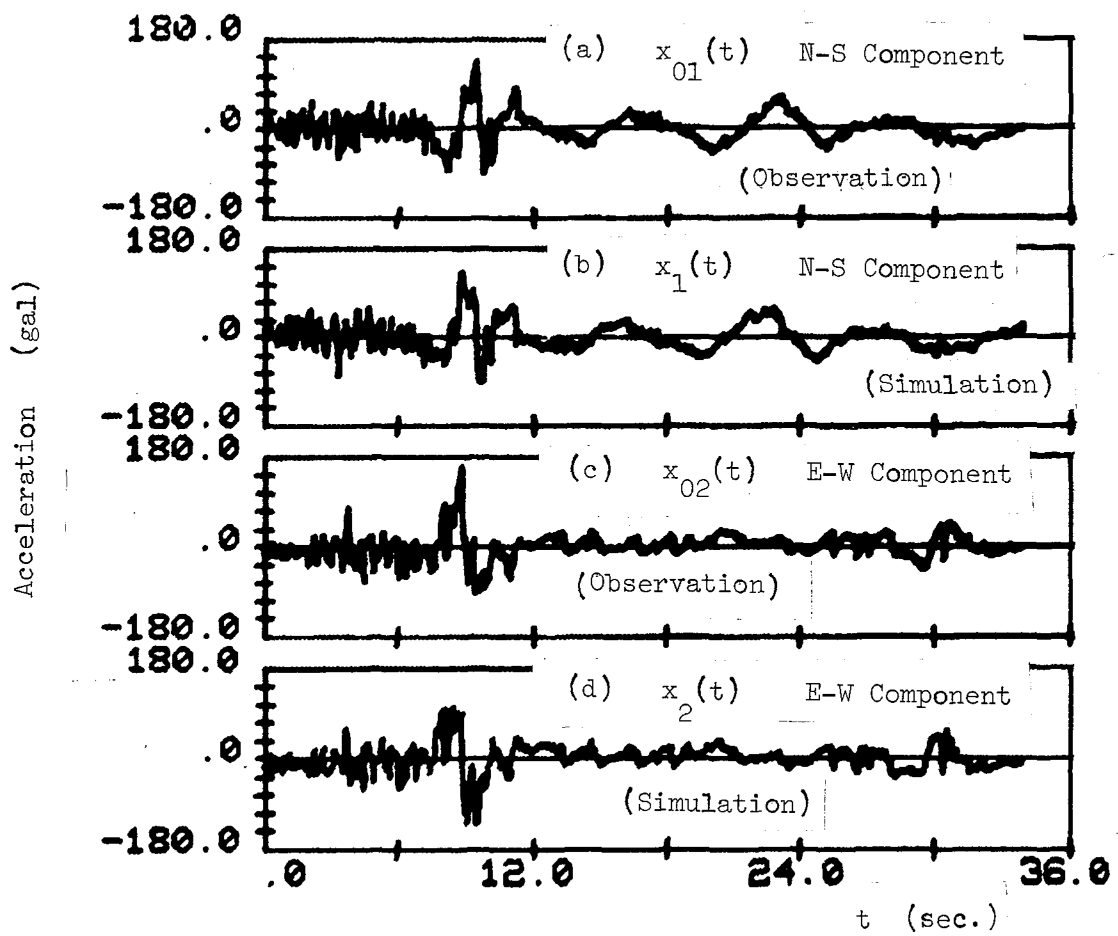

Fig. 1. Acceleration record of the 1964 Niigata earthquake and corresponding artificial acceleration components

P. C. Wang and C. B. Yun

Polytechnic Institute of New York

Our research project entitled "Predicition of Earthquake Resistance of Structure" is sponsored by the National Science Foundation. The main objective of the research is a development of a method to generate design earthquakes for reliable structural design. The approach is based on a minimum of assumptions especially regarding ground motion statistics. It leads to design comparable to those drawn up by design firms speciallizing in earthquake resistance of structures. Design response spectra with site specifics are obtained by using this method and reported here. It is found to be comparable with the one used in practice.

The method relies on the concept of the critical excitation. The critical excitation used here is defined as an excitation among a certain class of excitations which will produce the largest response peak for a structural variable of interest. The class in which critical one is determined should be chosen in such a way that it includes all ground motions that are credible to the location of consideration (as few others as possible). In this study, it was required to include, to start with, all those which have been already recorded at locations with similar geological properties. In addition, all of the linear combinations of those ground excitations were included in it.

Three such classes were constructed, based on ground accelerations which were recorded on rock, stiff soil and deep cohesionless soil sites. The critical excitations were, then, computed for each class. An example of the critical excitation is shown in Figure 1. At least on inspection, it has no conspicuous traits which disqualify it and others similar to it as possible ground motions. The critical response peaks are computed for various natural periods and plotted in the form of response spectra in Figure 2. For the purpose of comparison, they are displayed along with one which has been proposed by the Applied Technology Council (ATC) and which is now often relied on in practice. It is noteworthy that the ATC spectrum agrees fairly closely with the critical one for rock sites. However, for stiff soil and deep cohesionless soil sites, the critical response peaks are consistently larger than the ATC spectrum by approximately a factor of 2. The results indicate that there are realistic ground excitations which produce response peaks twice as large as those predicted by ATC spectrum.

From these results, it may be concluded that the structures whose survival and integrity are of considerable importance, may be some what under designed, if they are based on currently used response spectra.

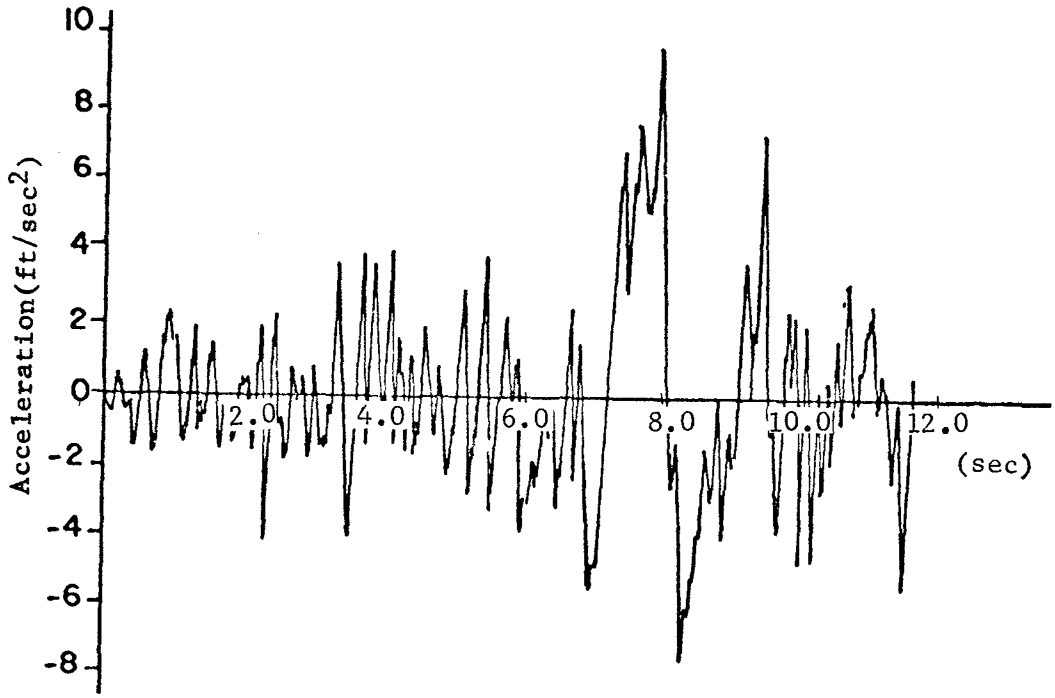

Fig. 1 Example of a Critical Ground Excitation (.35g)

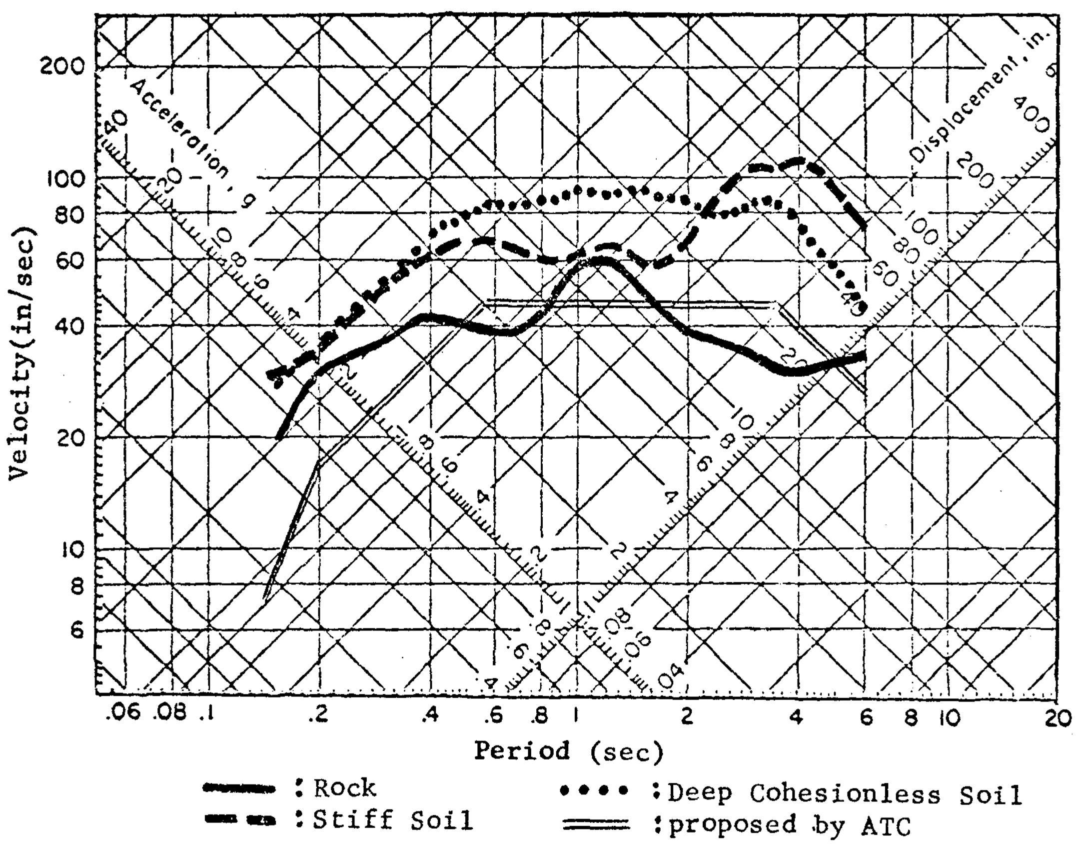

Fig. 2 Response Spectra (.5g, 5% Damping Ratio)

R. DOBRY and M. O'ROURKE

Rensselaer Polytechnic Institute

The main objective of this research is to produce improved methods for characterizing and predicting earthquake strong ground motions for engineering applications. A growing body of evidence, obtained from analysis of horizontal accelerograms from shallow earthquakes in the Western U.S., shows that near field accelerograms may be broken into three parts: a first part corresponding to P-wave arrivals, a second strong part corresponding mainly to S-wave arrivals, and a third part. In rock records the third part is relatively weak. However in some soil records, this third part contains long period components, due to reflected, indirect wave arrivals and surface wave effects. This long period part in these soil records is of great engineering importance.

In this study, rock accelerograms are studied first, and the parameters characterizing the strong second part are correlated with relevant seismological parameters. The improved understanding thus obtained is then applied to a study of the more complicated soil records. The specific research objectives are the following:

<u>Rock Records</u>

1) Determination of the duration Δ (duration of the direct S-wave arrivals) and the average RMS horizontal vector acceleration $\bar{a}_{xy}$ of the strong part for approximately 60 earthquake acceleration time histories recorded on rock in the western United States. It is believed that the combination of $\bar{a}_{xy}$ and Δ provides an acceptable two-parameter engineering definition of intensity of motion on rock.

2) Correlate the 2-parameter intensity thus defined $(\bar{a}_{xy}, \Delta)$, with other definitions of intensity, such as Modified Mercalli Intensity. Also, determine correlation and attenuation relationships between $\bar{a}_{xy}$, Δ and seismological factors such as earthquake size, distance to source, stress drop, etc.

3) Investigation in more detail of these characteristics of the strong part of the shaking for the same rock accelerograms. In particular, the frequency content, RMS accelerations and the principal directions of the ground motion will be studied including the variation of these characteristics with time. Also, the relation of these characteristics to the source mechanism and to different seismic wave arrivals at the site will be studied. Finally, a probabilistic description of the values and times of occurrence of the largest pulses of the horizontal acceleration components will be investigated as well as their relation to the peak acceleration.

Soil Records

4) Investigation of the influence of site and geologic conditions on $\bar{a}_{xy}$, Δ and other characteristics of the strong part of soil records. Study of the existence and characteristics of the subsequent long period part in soil records as well as possible development of analytical methods for predicting this long period part. For these purposes, soil accelerograms obtained in the Western U.S. will be studied and correlated with the results of the study on rock records mentioned in objectives 1-3 above.

5) Investigation of the validity of simple, widely used models, such as the shear beam model to determine how successfully the main characteristics of soil accelerograms including the long period part, are predicted by these models.

6) Development of criteria which could be used to determine when a site can be considered to be "rock". For this, site and geologic conditions at and around the stations used in the study are studied and correlated with the existence or non-existence of the long period part in the records.

Present Status of the Research

This is a cooperative research effort undertaken by investigators at both the Civil Engineering Department of Rensselaer Polytechnic Institute and the seismological group of Woodward-Clyde Consultants in San Francisco. This cooperation between engineers and seismologists is believed to be critical for the success of a project of this type. This joint research started in 1977, with internal support at both RPI (Program BUILD) and Woodward-Clyde Consultants (Professional Development Committee), and presently a proposal is being submitted to NSF-ASRA for a continuation and expansion of the effort.

A. K. MAL

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Research is being carried out on strong ground motion produced by earthquakes. This is a continuing effort that originated about three years ago under a grant from the National Science Foundation (No. GI-44056). Some of the work, reported below, is done jointly with my colleague at UCLA, Professor C. M. Duke.

The most commonly used current tool in the estimation of ground motion levels to be employed in designing against future quakes has been the creation of response spectra as generalized by averaging, smoothing, enveloping and other reasoned manipulations. While this procedure has obvious advantages for the design of linear single degree of freedom structures, a number of difficulties have been encountered with the use of conventional response spectra for the design of complex structures.

It will be highly advantageous for the dynamic design of important structures, if reliable artificial earthquake motion time histories or other fuller description of the ground motion in the next event can be specified in advance. A major difficulty in developing a procedure for generating such time histories has been the practical unknowability of many essential aspects of the next quake. It is nevertheless felt that it is worthwhile to develop a systematic general procedure under the present level of understanding of the earthquake phenomenon, which would enable the professional engineer to obtain the maximum possible reliable information regarding the relevant properties of the ground shaking that may occur at a given site in a future event.

As a prerequisite to the development of such a procedure, we have been involved, during the past few years, in studying the nature of the ground motion produced in the vicinity of moderate to large earthquakes. The studies have been carried out from three different angles, as described below.

1. Data Analysis. We have studied the major features of most of the available free field accelerograms recorded within 50 km of the source (epicenter). Unfortunately, not many such records are available at the present time. A common feature of all the records is the rapid decay of the ground displacements with increasing frequency, a decay that is difficult to explain on the basis of the damping properties of the soil. The decay appears to be related to some dissipation mechanism at the source. Some common features also exist in the velocity and accelerations. However, due to the sparsity of the records it is difficult to make any general conclusions. It is hoped that the extensive strong motion network currently employed in various geographical locations in the U.S. will provide valuable data in the near future so that a systematic statistical analysis of the records can be performed.

2. Theoretical Modelling. In order to examine the feasibility of

creating a purely theoretical model of real earthquakes, a number of highly idealized models were constructed and the influence of the various parameters of the system on the resulting ground motion in each model was studied. In the idealized models, the earth was replaced by a uniform half space and the earthquake source by a propagating brittle fracture on a prescribed fault plane. Both strike slip and dip slip models of the earthquake were considered. Simple theoretical models of the 1966 Parkfield earthquake (in 3D) and the 1971 San Fernando earthquake (in 2D) were constructed based on the available information. Most of the analysis was performed in the frequency domain. The main results and conclusions derived from these studies are as follows.

(a) Surface waves play a significant role in producing ground motion in shallow earthquakes. For earthquakes accompanied by surface breaks, the surface wave spectral amplitudes are on the same order of magnitude as those of the body waves even at epicentral distances on the order of fault dimensions. Surface waves become more dominant with increasing epicentral distance.

(b) Dip slip faults are more efficient in producing surface waves than strike slip faults.

(c) Simple attenuation laws of the type $e^{-\omega r/2cQ}/r^n$, (where r is the epicentral distance, ω the frequency, c a phase velocity, Q the attenuation coefficient, and n a positive number) holds only for points several faults lengths away from the source. No such simple law appears to hold for any of the characteristic properties of the ground motion in the near field.

(d) Most of the high frequency components of the ground motion is generated by discontinuous changes in the velocity of the rupture (e.g., start, stop, changes in the direction of propagation, etc.).

(e) Many important features of the ground displacements in a real event can be reproduced on the basis of simple theoretical models. Two-dimensional models can be very useful in yielding qualitative results and deeper understanding of the earthquake phenomenon. More detailed models of the earthquake source as well as the earth are needed to calculate ground accelerations.

3. Linear System Analysis. In another approach we have pursued an approximate, semiempirical linear system technique to create the ground motion at a given site by modifying an existing record in a nearby site. The underlying assumptions in the method, as used in the past, are that (a) the acceleration spectra at a given site can be decomposed as the product of a source dependent term and site dependent transfer function, and (b) all of the motion at the site is produced by body waves travelling vertically between a semi-infinite basement complex and the intervening soil layers between the basement complex and the free surface. While these assumptions are reasonably appropriate for deep sources of small dimensions, they cannot be valid for shallow and/or extended sources. The attractiveness of the technique lies in its inherent simplicity.

In order to extend the applicability of the technique to shallow earthquakes, we have modified it so that the surface waves can be incorporated in the analysis. To accomplish this, it has been necessary to introduce horizontally propagating multimode guided waves in the system, in addition to the vertically propagating body waves. The source function as well as the transfer functions were then modified to include the appropriate surface wave terms. Application of the modified technique to appropriate field data will be made in the future.

As a consequence of our experience with these preliminary researches as well as the results obtained therefrom, we have concluded that it is possible to develop a reasonably accurate technique that will yield a number of limited but useful qualitative and quantitative information regarding the nature of the ground motion expected to occur at a given site in a future event. At the present time, we are in the process of developing more accurate models of the earthquake source which would be useful for high frequency strong ground motion calculations. We are also in the process of developing more efficient programs for calculations in layered systems.

C. MARTIN DUKE

University of California, Los Angeles

Three topics in earthquake engineering research are being pursued under sponsorship of the National Science Foundation. The work falls under the general title of the effects of local site conditions on earthquake ground motion, which is one of the main elements involved in establishing a design earthquake at a site.

The three research topics are:

(1) the development of an approximate linear system theory to provide a method of incorporating site effects in design earthquakes;

(2) the representation of site effects in terms of dynamic field measurements of site properties; and

(3) the incorporation of site effects on seismic risk.

Most work is being done jointly with Professor Ajit Mal and in collaboration with several students. The title of the project is "Effects of Site and Source on Earthquake Ground Motions."

Linear System Theory

A. Research was conducted to test linear system theory against Managua ground motion and geologic data, using Fourier transforms and a realistic source representation as to the adequacy of this theory for explaining near field ground motion. Body wave subsurface transfer functions were considered appropriate for use because of Managua's relatively simple near surface geology, the proximity of the accelerograph sites to the causative faults, and the lack of surface faulting for most of the events studied.

In order to quantify various parameters of the system model it was necessary to develop procedures to determine (a) the general frequency characteristics of the source, including corner frequency, (b) the predominant period of the recording sites, as a function of strain level and (c) the thickness of the near surface geologic materials.

In addition, two different methods were used to calculate ground motion without a source function, using recorded data and transfer functions at a site in downtown Managua. One method required the use of geologic data and recorded mainshock data at one site. The other method relied heavily on small ground motion data simultaneously recorded at the two sites. The first of these proved to be the more useful, computational problems limiting the use of the second.

B. A method was developed to separate body and surface waves in strong motion accelerograms. This method incorporates a linear system model which accounts for the behavior of both body and surface waves. To demonstrate the method, Fourier spectra of the mainshock records from the 1971 San Fernando earthquake were used. Spurious peaks occurred in many calculations due to divisions of Fourier spectra. A multi-station scheme which eliminates the spurious peak problem is presented.

C. An approximate technique was developed to calculate the surface wave transfer functions for propagation between two stations with different site conditions. The technique is applied to Love waves propagating in a two dimensional single-layered model of the soil containing a discontinuous change in the layer thickness. The displacement spectra produced by sudden dislocation near the free surface at two stations located on either side of the transitional zone are calculated and compared. The influence of the higher modes is shown to be highly significant, especially at higher frequencies.

Subsurface Modeling Using Shear Velocity

D. Correlations among seismic velocity, Poisson's ratio, depth, and a geotechnical classification scheme were developed from 109 in-situ velocity measurements in the greater Los Angeles area. Average shear-wave velocities at the surface for 11 soil and geologic materials were found to vary from about 500 ft/sec for unconsolidated soils to about 3900 ft/sec for fractured basement complex. The functional relationship between shear-wave velocity and depth was found to be adequately given by $v_s = Kd^n$ between depths of 10 and 100 feet, approximately, where the constants K and n are dependent upon the geotechnical classification.

E. Basement and free field accelerograph station records from the San Fernando, California earthquake of February 9, 1971 were compared with the above geological and geophysical site data, particularly shear wave velocity profiles. Geophysical surveys were made at 109 accelerograph sites to determine the velocity profiles to about 70 feet in depth.

Both peak particle velocity and Arias instrumental intensity were found to have statistically significant dependence upon the mean shear wave velcity and the rate at which it increased with depth. See the attached figure, which uses the K factor.

Bayesian Seismic Risk

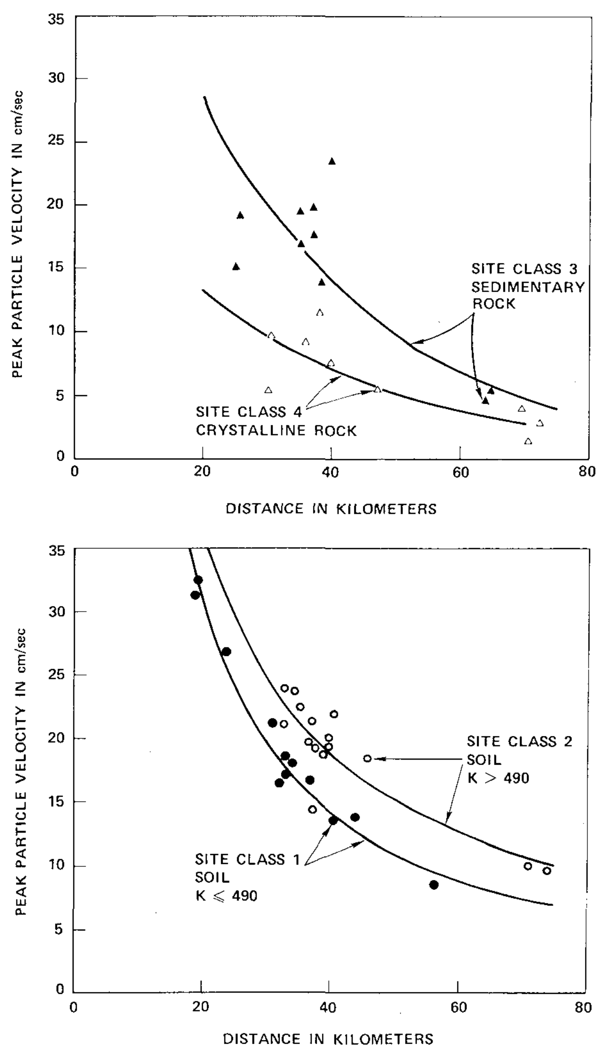
F. An earthquake risk model that incorporates a bayesian estimate of seismicity and an amplification factor for local site conditions is developed and applied to the Los Angeles, California area. Recency of faulting is used as a criterion for assigning activity rates to faults with no "historic" record of earthquake epicenters. Shear wave velocity profiles are used to characterize local site conditions. 100-year expected peak velocities are computed by combining the above models with probability and statistical models of earthquake occurrence.

G. Bayesian probability theory provides a rigorous mathematical basis for including diverse types of information in the estimation of seismic risk, defined as the probability that the largest earthquake magnitude occurring in a given period of time will exceed a specified value.

The Bayesian distribution of seismic risk is developed based on the extreme value distribution of seismic risk and posterior Bayesian distributions of the mean rate of occurrence and the magnitude distribution parameter.

Seismotectonic data, that is data relating to the process of ground deformation and earthquake generation, together with theoretical and empirical expressions relating seismic moment, magnitude and rate of strain release is used in the development of an expression for the prior estimate of the mean rate of occurrence.

To evaluate the procedure, the Bayesian distribution of seismic risk was applied to three Southern California faults for which sufficient seismotectonic data were available to compute prior estimates of the mean rate. The Bayesian estimates of the 50-year, 100-year, 250-year and 500-year events on these faults are similar to geologically-based estimates for these same faults.



Attenuation of Peak Particle Velocity for Soil and Rock Site Classifications

BIJAN MOHRAZ

Southern Methodist University

The past and current research activities in earthquake engineering at Southern Methodist University include the influences of the duration of strong motion and the magnitude of earthquake on ground motion and response spectra as well as the study of the shape and the magnitude of response spectra for flexible structures.

Influence of the Duration of Strong Motion

The study of the influence of the duration was limited to the horizontal components of the records from stations located on alluvium deposits with a peak horizontal ground acceleration greater than 0.10g. Similar studies on vertical components and on records from other geological conditions were not carried out because of the lack of an adequate number of records. A "bracketed duration", i.e. the time interval between the first and the last acceleration peaks greater than a specified value (0.10g for this study) was used as a measure of the duration. The earthquake records were classified into two categories: one with durations less than 10 seconds and the other with durations of 10 seconds and greater. A statistical analysis was employed to obtain the summaries of ground motion, the three spectral amplifications (displacement, velocity, and acceleration), and the spectral bounds defined as the product of ground motion and spectral amplifications.

The results indicate that although the average displacement and velocity for a unit horizontal ground acceleration for the two categories are nearly the same, records with durations of less than 10 seconds give slightly higher displacement amplifications and lower velocity amplifications than records with durations of 10 seconds and greater.

Influence of the Magnitude of the Earthquake

Horizontal components of the records from stations located on alluvium deposits with a peak horizontal ground acceleration greater than 0.10g were also used to study the influence of the magnitude. The records were divided into two categories: those having magnitudes between 5 and 6, and those having magnitudes between 6 and 7. A third category with magnitudes between 7 and 8 was not included because of the lack of an adequate number of records from stations on alluvium deposits which had a peak horizontal ground acceleration greater than 0.10g.

The statistical summaries of ground motion and spectral amplifications indicate that for a unit horizontal ground acceleration, the mean velocity and displacement for records with magnitudes between 5 and 6 are substantially lower than those with magnitudes between 6 and 7. In addition, the three spectral amplifications for records with magnitudes between 6 and 7 are greater than the amplifications for records with magnitudes between 5 and 6.

Response Spectra for Flexible Structures

Most of the statistical studies on response spectra in the past have used records selected on the basis that the horizontal peak acceleration is greater than 0.05g or 0.10g in order to include strong motion records. While the use of such a limit is justified, there is a general belief that peak ground accelerations relate primarily to high frequency components in the motion, and therefore, statistical summaries computed from such records, for the low-and even the intermediate-frequency regions of the spectrum, may not be as reliable as those for the high-frequency regions. Although a design spectrum based on such statistical summaries would be satisfactory for stiff structures, it would not necessarily be appropriate for flexible structures.

Studies are being carried out to determine the shape and the magnitude of earthquake spectra for flexible structures by selecting earthquake records with both the strong motion and the long period oscillation characteristics which are desirable for flexible structures. The long period oscillation characteristics of the record are included in the selection process by normalizing the Fourier amplitude spectral ordinates of the record, squaring the normalized ordinates, and then computing the area under the squared normalized Fourier amplitude-frequency curve in the frequency range of interest. The areas provide a pseudo measure of the power spectral density of the record in the specified frequency range. Preliminary results show that, as expected, the records with long period oscillations have generally higher average ground motion and higher displacement and velocity spectral amplifications.

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H. E. LINDBERG, G. R. ABRAHAMSON, AND J. R. BRUCE

SRI International

The need for an in-situ test technique to guide the design of earthquake-resistant structures has long been recognized. This need has become more acute with the development of nuclear reactors, greater population concentrations, and the more efficient designs that are made possible by computer technology. SRI International is conducting an investigation sponsored by the National Science Foundation on the feasibility of simulating earthquakes by contained explosions in line source arrays.

The simulation technique consists of detonating a plane array of vertical line sources placed in the soil near the structure to be tested. Each line source produces ground motion through an expandable rubber bladder rugged enough to withstand repeated tests with expansions of as much as twice the initial bladder diameter. The explosive is detonated inside a steel canister within the bladder, and the explosion products flow out of the canister through vent holes to pressurize the bladder at a controlled rate. In this way, both amplitude and frequency content are controlled at levels suitable for testing with the source arrays close to the test structure. This opens the possibility of in-situ testing at strong shock levels with little disturbance to nearby structures. In a full-scale test the array might measure 100 by 30 feet, consist of 10 to 20 vertical boreholes 30-feet deep, spaced on 5- to 10-foot centers, and be placed about 30 feet from the structure to be tested.

The key features of the line sources are (1) a minimum amount of explosive is required because containing the explosion products eliminates the high ground shocks associated with freely expanding explosions, and therefore, the line source array can be located close to the structure; (2) the line sources are reusable and give repeatable results; (3) the duration of the simulated earthquake motion can be controlled by delayed multiple detonations, within each line source and between groups of line sources, and (4) no surface eruptions are produced by the detonation.

During the first year of this study, reusable hardware was developed for producing contained explosions in single 1/3-scale sources, and instrumentation was incorporated for hardware diagnostics and output measurements. Tests with single sources gave reasonable accelerations (up to 1 g) and frequencies (near 15 Hz) at the 1/3-scale factor. Corresponding full-scale values are 0.3 g and 5 Hz. Repeated use of sources was demonstrated with repeatable results. Measured soil wave energies were about 0.5% of the explosive chemical energy in the cylindrical geometry of a single source.

To estimate the increased energy conversion resulting from nonlinear interaction between sources in a complete array, we performed calculations for an array of sources using a nonlinear finite element computer code (NONSAP). Measured single-source performance and ground response were used to obtain soil properties for the mathematical model. Further calculations with these properties gave reasonable agreement between measured and calculated soil response for other single source experiments. With this consistency demonstrated, the model and soil properties were used in an array calculation that showed that, for a complete array, 1.5% of the explosive chemical energy would be converted to plane wave soil energy.

With a conservative assumption of 1% energy conversion, a one-dimensional elastic wave theory was used to estimate the amount of explosive required to give representative strong earthquake motion. For a 100 by 30 foot array, a 5-Hz pulse with a 0.5-g peak acceleration can be produced with about 100 lb of explosive. A complete train of oscillations typical of strong earthquake motion lasting 10 s with peak accelerations reaching 1 g was estimated to require about 500 lb of explosive, fired in 10 detonations.

During the coming year we will perform array tests with about 10 line sources at 1/3-scale and will design and test a single full-scale line source. This work will be accompanied by further developmental investigations to improve line source performance, to achieve multiple pulses, and to vary the frequency content. Theoretical analyses will be performed to interpret simulation performance and to examine requirements for test arrays for various structures and construction sites.

R C DENTON, A DONOVAN, K K WONG

Earthquake Engineering Research Center
University of California, Berkeley

The National Science Foundation recognizes that an effective transfer of NSF-sponsored research information to the engineering profession and to other researchers is an essential part of the total research effort in earthquake engineering. In 1971 the National Information Service in Earthquake Engineering (NISEE) was established, and since then has become the national focus for information on earthquake and other natural hazards mitigation. Specific functions of NISEE are: to develop a library of technical data, reports and publications; to publish an Abstact Journal; to duplicate, verify and disseminate computer programs; and to provide educational opportunities for professional engineers.

EERC LIBRARY The EERC library collection has grown from nothing to over 12,000 items, consisting of research reports, technical journals, conference proceedings, monographs, periodicals, books, slides and maps. The scope of the subject matter has been broadened to include all aspects of earthquake hazard mitigation: earthquake engineering, structural dynamics, geotechnical engineering, seismology, disaster planning, geophysics and geology. Nontechnical publications on all aspects of earthquakes have also been included.

An active publications exchange program with academic and governmental institutions brings to the library collection much U.S. and foreign research literature that is not available elsewhere.

Circulating materials are mailed without charge to individuals and organizations within the U.S. Noncirculating materials which are difficult to obtain from other sources may be photocopied for a nominal fee.

Library users are informed of additions to the collection through the following publications: a monthly Library Acquisitions Alert, the quar-EERC News and the annual Abstract Journal in Earthquake Engineering.

ABSTRACT JOURNAL The Abstract Journal in Earthquake Engineering provides the only comprehensive annual collection of abstracts and citations of world literature in earthquake engineering. Each volume contains approximately 1,000 abstracts of research reports, technical papers, books, codes and conference proceedings. The abstracts are obtained by the staff from a survey of 81 technical journals and publications of 23 countries and international organizations. Direct contributions are also received from authors and publishers.

Abstracts are organized into nine subject areas within the field. In the broader area of hazard mitigation, abstracts for architecture, public planning and socioeconomic literature are included. The Journal contains a list of titles, an author index and subject index. Materials which are available from the EERC Library or from NTIS are indicated.

The first volume of this annual journal was published in 1972. Volume 6 was just recently published. Journal circulation if approximately 900.

Subscriptions are available on either a one- or a two-year basis. Back issues of Volumes 2,3,4 and 5 can be ordered. Complimentary copies of Volume 1 are still available.

COMPUTER APPLICATIONS The Computer Applications software library currently contains 40 programs. Each of these programs is a result of earthquake engineering related research. The programs are usable by professional engineers and by other researchers. Over the past four years an average of 500 copies of programs and over 2,000 computer program manuals have been distributed annually.

Duplicate decks or tapes which have been compiled and executed with sample data are supplied to requestors. Many programs are available in either an IBM or a CDC version.

Extension courses through the University are being planned to introduce engineers to the use of programs available. Previous courses have been both practical as well as highly theoretical. The possibility of holding seminars in cities other than Berkeley is being explored.

Researchers are encouragedto contribute software to NISEE for public distribution. In return for one program accepted by NISEE, three programs from the current library are sent to the contributor. Several universities have participated in this exchange.

FUTURE PLANS Activity in information transfer through NISEE has steadily increased during the past five years. Future plans are to refine and maintain the current level of services while publicizing NISEE more widely.

ACKNOWLEDGMENT The UCB phase of the NISEE program has been supported by NSF grants ENV76-20744 and ENV77-20667.

SESSION 2

SOILS & SOIL STRUCTURE INTERACTION

Chairmen: J. Roesset
J. Biggs

A. ASKAR AND A.S. CAKMAK

Princeton University

National Science Foundation sponsored earthquake engineering research is being carried out in two areas: Earthquake waves in soils with stochastic properties and soils with nonlinear properties described by the Romberg-Osgood model.

Waves in Soils with Stochastic Properties

An elastic model with stochastic moduli and density is used to represent a soil layer. Each modulus consists of an average value plus a stochastic component with zero statistical average.

Assuming certain correlations to be stronger than others and assuming these functions to be exponentially decaying one can obtain field equations for the averaged surface displacements by following the procedure introduced by Karal and Keller [1]. The resulting equations are of the integro-differential form and are similar to those in non-local continuum theories introduced by Edelen and Eringen [2].

The resulting equations are put into an initial value problem form, which lends itself to solution by the Laplace transform method.

Solutions are obtained for the one dimensional problem subject to periodic loadings at the bottom [3], and are extended to the multilayer case by means of transfer matrices. The results for the shear wave case show that resonance singularities are removed and there are shifts in the resonance frequencies with respect to the homogeneous case. The removal of the resonance singularities allows one to assume values for the stochastic properties, by comparing these reductions to those obtained by the introduction of viscous damping. It is clear that the stochastic nature of the medium introduces dispersion into the system.

It is planned to obtain results for a given earthquake history and to extend the results to two dimensions. The results for a given earthquake history are currently being obtained, however the extension to two dimensions depends on finding ways of determining the values to be used for the correlation functions.

Waves in Soils with Nonlinear Properties

In this nonlinear study soil behavior in one dimension is modeled by the Romberg-Osgood model [4]. The resulting nonlinear partial differential equation is solved by means of a modified Poincare procedure. The modified Poincare procedure allows one to eliminate the secular terms introduced in the neighborhood of the resonance frequencies.

The general solution for shear waves in a single layer is obtained. Based on this, transfer matrices for the various harmonics are constructed by relating the displacement and the stress at one face to those at the other. By means of these transfer matrices the solution for a multilayer system is obtained for an arbitrary periodic input. The results indicate shifts in frequencies as compared to the linear case and the elimination of resonance singularities.

Currently results are being obtained for arbitrary forcing functions, representative of actual earthquake histories for coupled shear and pressure waves for both the single and multi-layer cases. A deconvolution procedure is being developed to translate surface motions into bedrock displacements for use in this nonlinear model.

Computer packages for both the stochastic and nonlinear problems for the one dimensional coupled equations are being prepared and will be available by the end of this year. However, extensions of the procedures to two dimensions, though formally completed, lack realistic and useful data for soil properties in two dimensions to allow practical applications.

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THOMAS F. ZIMMIE and CARSTEN H. L. FLOESS

Rensselaer Polytechnic Institute

Fundamental Research in the area of the behavior of fine grained soils subjected to earthquake and other repeated loading is presently being conducted. This earthquake engineering research is sponsored by the National Science Foundation.

Specific objectives of the study include the development of a theoretical model for the soil behavior based on effective stress principles, both for normally and over-consolidated soils. Stress-strain-strength characteristics are being investigated, including degradation of strength and stiffness during earthquake excitation. Comparison of static stress-strain-strength relationships before and after cyclic loading are also being investigated. An extensive literature search has also been undertaken.

The strength and deformation characteristics of clay soils are being evaluated using a Norwegian Geotechnical Institute (NGI) Direct Simple Shear Device (commercially available through Geonor). The NGI device has been modified for stress controlled cyclic loading. Plans are presently being formulated for obtaining a loading system capable of either stress or strain controlled cyclic tests with a large range of loading shapes and frequencies.

Because the in situ structure of cohesive soils is an important parameter in determining their behavior, only natural undisturbed samples are being tested. Undisturbed block samples of Concord Blue Clay from the Buffalo, New York area have been tested. Undisturbed 4 and 5 inch diameter core samples from the Gulf of Alaska and the Gulf of New Mexico are presently being tested.

Constant volume direct simple shear tests are being conducted on both the standard 50 square centimeter size sample and a smaller 1.875 inch diameter sample. The effect of sample size is being studied. This is especially important, since many offshore core samples are too small for the standard sample size.

An important aspect of this investigation is the cooperative effort with research being conducted at Cornell University. Both research programs are investigating the behavior of the same fine grained soils subjected to cyclic loading conditions. However, Cornell University is using a triaxial testing program. This will allow a comparison of direct simple shear and triaxial testing results.

Lateral stress measurements are being made on the samples during static and cyclic tests. This is done using calibrated membranes and a strain gauge indicator. This extra information greatly adds to the knowledge of the state of stress in the sample and facilitates drawing stress plots and the comparison of results with triaxial tests.

The importance of this investigation is directly related to the increase of major construction projects founded on fine grained soils. Especially notable in this area is the construction of offshore oil platforms.

D. ATHANASIOU-GRIVAS

Rensselaer Polytechnic Institute

General

The main objective of this NSF(ASRA) sponsored research is to determine the safety of naturally formed or man-built soil slopes during earthquakes. Because of the randomness associated with the earthquake threat, any rational approach to evaluating the safety of slopes during earthquakes must, of necessity, be based upon probabilistic analysis. Thus, in this study the safety of a slope is measured through its probability of failure rather than the customary factor of safety. Three kinds of uncertainty are taken into account: (a) uncertainty with regard to the loading conditions that exist inside a slope during an earthquake, (b) uncertainty in the numerical values of the material parameters, and (c) uncertainty associated with the exact location and shape of the failure surface. Both the resistance of the slope against failure (its capacity) and the applied loading (the demand) are introduced as random variables reflecting the above three uncertainties. Failure of the slope is then defined as the event whereby the calculated available strength is exceeded by the applied loading. Therefore, the probability of the occurrence of this event is equal to the probability of failure.

In this study it is assumed that the resistance of the slope against failure is constant during the earthquake loading. This is considered to be a reasonable assumption for a wide variety of soils, particularly cohesive ones. It is not directly applicable when the resistance of the soil material decreases during the cyclic loading (as is the case, for example, of liquefaction of saturated sands or sensitive clays).

Specific Research Objectives

The specific objectives of this research are the following:

1. To describe what additional forces are imposed upon a slope during an earthquake.

These forces are random in nature and depend on the level of the acceleration the soil mass experiences during an earthquake. It is assumed that the maximum acceleration of the soil mass is equal to the peak ground acceleration which is introduced through its probability density function. The latter is derived with the aid of available attenuation relations and therefore, it depends on the type of earthquake source considered (i.e., point, area or line), on the earthquake magnitude, on the distance between the site of the slope and the earthquake source and on a number of regional parameters.

2. To develop a model for the failure of the slope.

It is assumed that the rupture surface, created in the interior of a soil slope because of an earthquake, tends to propagate towards the boundary along a logarithmic spiral. Thus, its location inside the slope depends on the ϕ-parameter of soil strength (introduced through its density function) and on the coordinates of its center (taken also as random variables). The statistical characteristics of the most probable failure surface are then obtained through a simulation scheme.

3. To assess the reliability of the slope.

The probability of failure of a slope with given boundary conditions is obtained through an application of the Monte Carlo simulation technique.

4. To examine the influence each significant (seismic or material) parameter has as the reliability of the slope.

The parameters examined are:(a) the geometry of the slope, (b) the statistical values of the soil properties and indices, (c) the magnitude of the earthquake, (d) the mean earthquake occurrence rate, and (e) regional parameters (appearing in the expression for the attenuation of the peak ground acceleration). Design details which could decrease the probability of failure of a slope are also investigated.

5. To apply the developed analysis to a number of case studies which reflect the seismic characteristics of the State of New York.

New York is an earthquake State of a relatively long seismological history. The possibility of an earthquake should be an important factor in geotechnical engineering design. It is expected that the results of an application of the developed model to slopes located in New York will lead to discussions and conclusions that will provide benefits to other parts of the country as well.

6. To examine the applicability and limitations of the present analysis and to provide recommendations for future research on the subject.

Present Status of the Research

A computer program is being developed which will be capable in providing the probability of failure of a soil slope during an earthquake. This is a modification and extension of a previous program which analyzed the safety of slopes under static conditions. The new program will provide a quasi-static treatment of the problem. The occurrence of earthquakes is assumed to follow the Poisson model and thus, the process is characterized by the mean occurrence rate. The probability distribution of the earthquake magnitude is obtained with the aid of a log-linear magnitude-recurrence relation. Upper and lower values for the magnitude have been considered for engineering purposes. For known earthquake history of a particular region, the program can find the best magnitude-recurrence relation by performing a regression analysis on the data available. The maximum acceleration at the site of the slope is introduced as a random variable the distribution of which is obtained with the aid of a known attenuation relation. Finally, the numerical value of the probability of failure is found through a Monte Carlo simulation.

Data available on the seismic characteristics of New York and neighboring States are being collected, and an analysis of these data is currently underway.

BING C. YEN

California State University, Long Beach

Under the sponsorship of the USGS Earthquake Hazard Reduction Program, research is being conducted on shallow slides induced by the 1971 San Fernando earthquake. Interpretation of aerial photographs by the USGS personnel indicated that the earthquake triggered more than one thousand landslides in a 250 km^2 area in the hilly terrain north of the San Fernando Valley. Of the several modes of slope failure, shallow slides are by far the most common. Shallow slides are characterized by a shallow depth relative to the slide length and occur most frequently within the weathered soil mantle overlying parent rocks or older colluvial slopes. The toe of the slides most frequently emerge from a constant slope within long hillsides or occur where the slope has been steepened by cutting or erosion.

The objectives of this research are to provide an engineering understanding of the slide mechanisms and to define the common characteristics of this type of slope failure. Based on this understanding, the goal of this research is to develop a simple but practical way to identify the potential location and estimate the size of slope failures in seismically active foothill areas. The research is essentially using the San Fernando event induced slides as a field laboratory to develop an analytical model. From this model, preliminary guidelines may be developed for planners and engineers to use when determining building setbacks, lifeline or utility corridors, and route selections in seismically active foothill regions.

Summary of Work Accomplished

A unique area of about 6.5 km^2 has been chosen for this study (Lopez Canyon). This area was selected because it contains three different geologic formations (Saugus, Modelo and Towsley-Pico) generally found in the area. Twenty-one slides were mapped, sampled and laboratory tested. These slides were surprisingly well preserved, probably because of the extended dry years of 1971-1977. However, the January and March 1978 heavy storms in California obliterated nearly all traces of the original earthquake induced slides. The 21 mapped slides and soil samples appear to be all that are left from the slides triggered by the 1971 event. On the other hand, hundreds of mudflows have occurred in the seismically weakened slopes and in the scarp areas of the earlier slides. Preliminary work is in progress to map and sample these mudflows. In this summary, only the work related to the 21 slides is presented.

Field observations suggest that all slides have a translational mode of failure and a large length-to-depth ratio. The average ratio is 31, and the maximum is 80. The depth is generally on the order of 1 meter. Regionally, the slides are underlain by bedrock forming a homoclinal structure dipping northerly to northeasterly. The dips of individual beds are mostly between 45 and 65 degrees from horizontal, generally too steep relative to slopes to create sliding planes. Natural slopes which produce shallow slides range between 33 and 46 degrees, roughly 1-1/2:1 to 1:1, horizontal to vertical. It appears that if a slope is too steep, the residual soil mantle is not thick enough to produce an inertia force to cause failure. If a slope is too flat, there are not sufficient downslope forces to initiate sliding. Field measurements included slide geometry, orientation and relative location with respect to ridge top and foothill. No consistent trends were found between the occurence of the slide with any of these parameters for the slides studied.

Because of the low ratio of depth to length of the slides and their planar mode of failure, a one-dimensional mathematical model with an equivalent inertia term is used to account for the accumulative shaking effect causing failure. The model assumes an elastic soil layer bonded to a rigid plastic base. As all the cases studied failed during the 1971 earthquake, back calculations from surveyed and tested conditions are used to check the validity and applicability of the theoretical model for evaluating seismically-induced, shallow slope failures. To enable a rational comparison of field measurements with results of theoretical approach, it is necessary to know properties of soils involved in the slides. A laboratory program to evaluate soil properties was initiated. Laboratory tests indicated that the slide materials are generally clayey or silty-sands of little or no plasticity (SC or SM) regardless of the parent geologic formation. This observation negates the earlier postulation that the distribution of slope failures is lithologically controlled, instead, areas where bedrock is likely to weather into SM or SC soil, more shallow slides may be anticipated. Considering the shallow depth of the slides, the shear stress-strain relationships under low normal load appear to be significant in choosing strength parameters for analyzing slope stability. The results of comparison between the field and the theoretical model suggest that the methodology developed and applied to the Lopez Canyon area shows promise for estimating the likely size of shallow slides. The estimated slide length could serve as a rational guide for decision makers and planners for use in a seismically active foothill region. The analysis also showed that conventional pseudo-static slope stability analysis, using 0.1 or 0.2 constant acceleration, could be risky in assessing the potential of shallow seismic slides in Lopez Canyon.

There are physical and mathematical limitations of the proposed one-dimensional model. It is inevitable that some of the slides have been altered more than others since the 1971 earthquake. To broaden the data base and to improve the present technique, additional field mapping should be conducted immediately following future seismic events.

Future Plans

The hundreds of mudflows that recently occurred in the study area are either located in the slopes originally weakened by the 1971 event, or located in the slide scarp areas remaining from the 1971 earthquake. The loss of life and property, and the interruption of major highways this year in Southern California (the first wet year since 1971), epitomizes the mudflow hazards experienced in many other seismically active foothill regions around the world. Our observations of the Lopez Canyon mudflows and review of recent case histories* suggest that mudflows either initiated in slopes weakened by previous seismic events, or in saturated slopes triggered by earthquakes, are greatest overall hazard in the seismically active foothill regions. These mudflows are characterized by swift movement, high momentum and generally large slide length to depth ratio.

Our future plan consists of two facets: (1) use the Lopez Canyon area as a unique field laboratory to study mudflows in seismically weakened slopes, and (2) expand on the mathematical model developed under the on-going USGS project to investigate the mechanism of mudflows triggered during earthquakes.

Detail of certain parts of the research reported herein has been published in the Proceedings of the Earthquake Engineering and Soil Dynamics Conference, ASCE, Vol. II, June 19-21, 1978. The paper is entitled "Shallow Slides Due to 1971 San Fernando Earthquake," pp. 1076-1096.

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*For example: In the 1973 Costa Rica earthquake, M=6.5, 23 lives were lost to the seismically induced mudflows during the rainy season; 27 persons died in Japan as one mudflow, after the rainy season, was induced by the Nagaki earthquake of 1974.

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Research in the area of seismic response and liquefaction of saturated sands is being conducted under the sponsorship of National Science Foundation.

General Approach

Saturated sands are treated as two-phase media with consistuent materials being the granular solid skeleton and pore water. The separate phases of solid granular skeleton and pore water are modeled individually and the coupling between these two phases is taken into account. The two phases are coupled through the volumetric strains. The pore fluid is allowed to flow with respect to the granular solid and this process is assumed to be governed by Darcy flow law with the coefficient of permeability as the material constant. A nonlinear material model is developed for the solid granular medium in terms of effective stresses. Finite element method is used to discretize the system. The independent variables in the resulting discrete system of equations of motion are the displacements of solid phase and the relative displacements of the pore water with respect to the solid phase. The nonlinear discrete system of equations are solved by using direct integration methods. The results of the dynamic analysis are the time histories of the response, the effective stresses and the pore water pressure. The earlier development of this approach is reported in References 1, 2, 3.

Effective Stress Material Model for Sands

An effective stress material model has been developed to simulate the drained behavior of saturated sand under arbitrary stress condition (References 4 and 5). This material model is used to describe the behavior of the solid granular portion in the previously described two phase model. An important consideration in the development of this material model was to simulate two aspects of the behavior of sand as closely as possible; the hysteretic loops under cyclic stresses and the volumetric strains, specially those resulting from shear deformations (dilatancy). These two characteristics of the material behavior are very important in the dynamic analysis of saturated soils. The first property is to model a major part of the energy dissipation (damping) in soils which occurs through the hysteretic behavior. The second property controls the magnitude of the pore pressure build-up. In development of this material model a new type of kinematic hardening was introduced and in order to simulate the volumetric strains correctly it was necessary to use a non-associated flow rule. A liquefaction criterion defined in terms of effective stresses was introduced in the analysis. However, prior to liquefaction the material undergoes a significant change in its response to cyclic stresses. This material behavior change which occurs in undrained or partially drained condition takes place when the stress state reaches close to the failure condition. This condition of near failure is defined as initial-liquefaction. A post initial-liquefaction material model has been developed and used in the dynamic analysis.

Seismic Response and Liquefaction of Level Ground

The level ground is idealized as a horizontally layered system. A one dimensional model has been developed and the response of the system to base acceleration is computed (Ref. 6). A computer program, LASS-II, has been developed (Ref. 7) for analysis of seismic response and liquefaction of horizontally layered sands. A number of analyses have been performed including the analysis of Niigata like soil profile.

Another computer program, LASS-III, has been developed for analysis of seismic response and liquefaction of layered sands under multi-directional shaking. The analyses performed so far indicate that the vertical component of earthquake does not have much influence on possible liquefaction of level ground. The vertical acceleration only causes oscillations in the pore pressures and only slightly influences the effective pressures. However, including two horizontal directions of shaking significantly increase the liquefaction potential as compared to one direction of horizontal shaking.

Seismic Response and Liquefaction of Soil Structures

Two dimensional finite elements are used to model systems of saturated sand whose behavior is moded with the previously described material model. The resulting coupled system of equations are solved to compute the seismic response of the system. It is intended to use the developed computer program in the study of seismic behavior of two types of systems; earth dams and embankments, and; soil-structure interaction of heavy structures such as nuclear reactors and off-shore platforms. Because of the type of the material model used in this approach, it is expected that more realistic strain time histories can be computed, than is possible with the other available material models. This will enable more realistic assessment of the stability such systems during earthquakes. Also, the major part of the energy absorption characteristic of the system is represented in the material model, therefore, eliminating the need to indirectly incorporate the damping in the analysis as is often down by using proportional or modal damping. Another energy absorption mechanism present in the proposed method of analysis is provided by the resistance of granular solid to dissipation of pore pressures.

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Geotechnical earthquake engineering research at the University of Washington involves the following studies:

1. Pore-Pressure Prediction of Saturated Sands during Earthquake Loadings (Refs. 1 and 2)

From studies aimed at understanding pore-pressure generation, hence liquefaction potential, in saturated sands of different densities under dynamic loading, Equation 1 is presented:

$$\Delta U_N = F(N, U_{N-1}, \tau_N, \sigma'_{N-1}, \alpha, C_1, C_2, C_3) \qquad (1)$$

where U_N is the pore-pressure increment at the Nth cycle, U_{N-1} is the residual pore pressure at the end of the (N-1)th cycle, τ_N is the applied cyclic shear stress during the Nth cycle, σ'_{N-1} is the effective confining pressure at the end of the (N-1)th cycle and α, C_1, C_2 and C_3 are the material constants. This equation can predict pore-pressure generation under actual earthquake loading, as well as under uniform cyclic loading. The material parameters α, C_1, C_2 and C_3 are given in Fig. 1 for Ottawa sand as a function of void ratio and are under investigation for different types of soils.

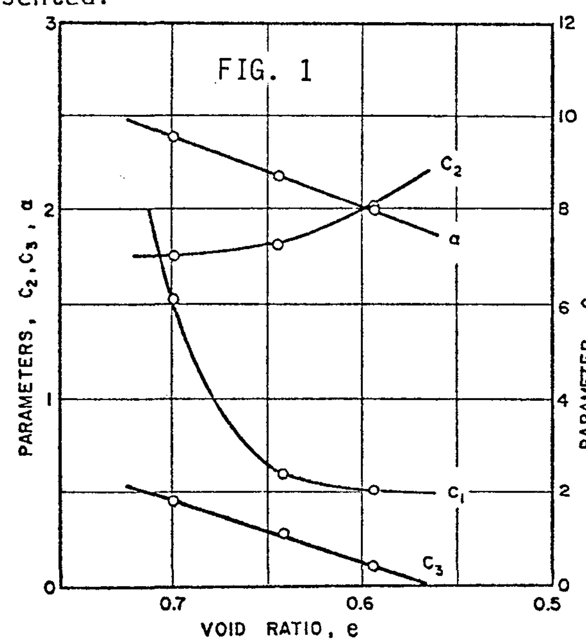

FIG. 1

Fig. 2 demonstrates a comparison between predicted (Eq. 1) and measured pore-pressure variations in the laboratory torsional simple shear test.

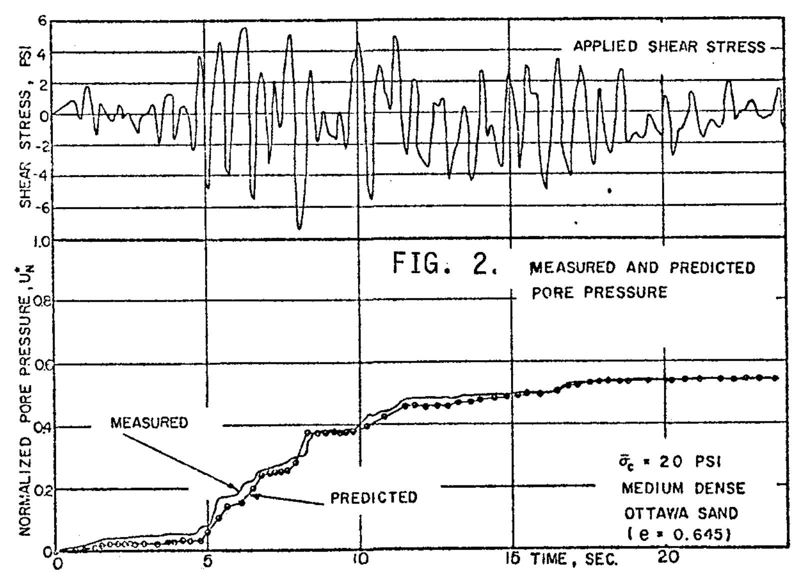

FIG. 2. MEASURED AND PREDICTED PORE PRESSURE

2. Dynamic Shear Moduli and Damping of Dry Sands (Refs. 3 and 4)

Based on experiments conducted in the Torsional Simple Shear Device on four different types of dry sands, equations for dynamic shear moduli (Eq. 2) and damping (Eq. 3) are presented, in which G_{eq} is dynamic shear modulus, λ is damping ratio, γ is shear strain, $\bar{\sigma}_c$ is effective confining pressure, ϕ is angle of internal friction, F is soil gradation and sphericity factor, ψ is soil sphericity and $C_g = D_{30}^2/(D_{10} \times D_{60})$ is the coefficient of gradation.

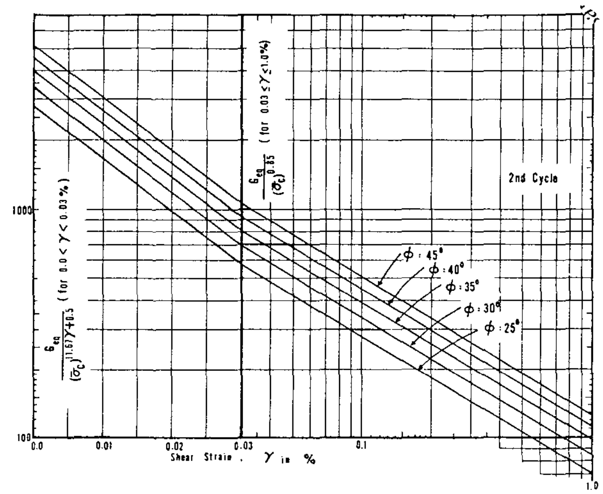

FIG. 3.—Nomograph for G_{eq} Determination for Dry Sands

Dynamic shear moduli:

$$G_{eq} = 40(0.205)^{\frac{\gamma}{0.05}} \cdot 2.8\phi(\bar{\sigma}_c)^{11.67\gamma + 0.5} \quad \text{for } 0\% < \gamma \leq 0.03\% \tag{2}$$

$$G_{eq} = 2.8\phi(\bar{\sigma}_c)^{0.85} \cdot \gamma^{-0.6} \quad \text{for } 0.03\% < \gamma < 1\%$$

Damping ratio:

$$\lambda = \frac{50 - 0.6\bar{\sigma}_c}{38}(73.3F - 53.3)\gamma^{0.3} \qquad F = \frac{1}{\psi^2 C_g} \tag{3}$$

In Figs. 3 and 4, nomographs are shown for the determination of shear moduli G_{eq} and damping ratio λ.

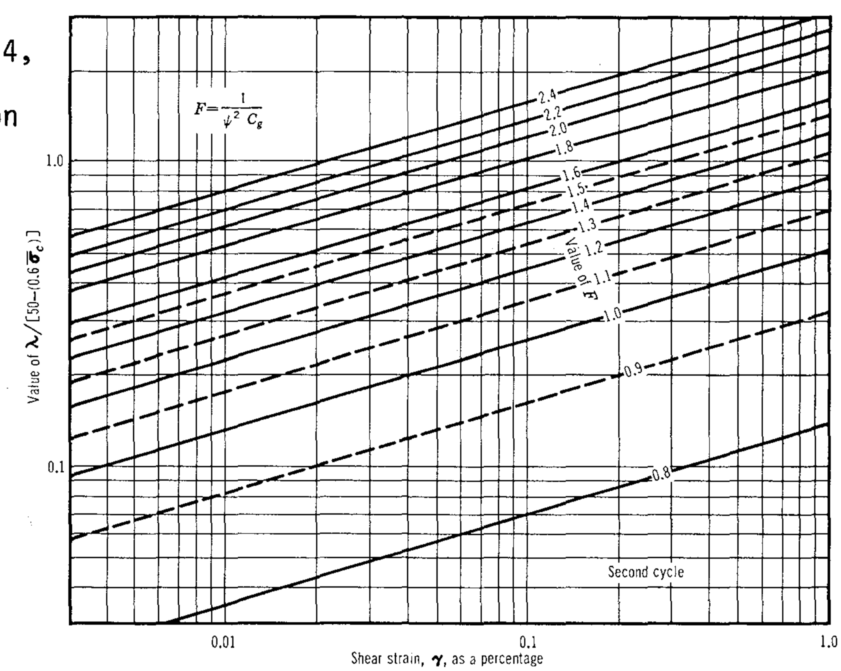

FIG. 4 - Nomograph for λ Determination for Dry Sands

3. Soil Properties and Loss of Strength of Submarine Clays due to Dynamic Loading (Ref. 5)

Dynamic shear moduli and damping ratios for two different types of submarine clays (red clay and yellowish-brown clay) are investigated in the Torsional Simple Shear Device, which was modified to successfully accommodate testing of very soft clays. Results revealed that the yellowish-brown clay lost strength after dynamic excitation, but the red clay did not. Currently, research is underway to study the effects of soil type, dynamic strain level and number of applied cycles on loss of strength.

4. Dynamic Lateral Earth Pressure in Shaking Table

In order to evaluate the neutral, active and passive dynamic earth pressures on the retaining structure, a movable retaining wall is designed inside the University of Washington shaking table (8' x 6' x 4' in dimensions). This wall has the following features:

a. The movable wall is separated into three parts in order to eliminate or minimize side-wall friction effects. In this way, only the center wall measures the actual horizontal and vertical earth pressure exerted on the wall.
b. A counterweight is installed to cancel the torque caused by the inertia force of the center wall.
c. Resultant earth pressure, wall friction angle and point of application of the resultant force are obtained. Also, soil pressure distribution is measured by soil pressure cells.
d. As the shaking table vibrates, two worm-gear systems slowly move the wall in different ways: either rotation from the top or the bottom or pure translation.

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Introduction

Several analytic techniques are presently available to predict ground surface motions during earthquakes. These techniques require values of dynamic properties of soils determined under simulated earthquake loading conditions. National Science Foundation sponsored research is being conducted to evaluate dynamic properties of frozen soils over a range of test conditions associated with dynamic loading of frozen soil deposits. The dynamic properties of frozen soils determined from this work may be used, with reasonable judgment, in existing analytic techniques to predict surface motions of frozen ground deposits during earthquakes.

Dynamic Properties of Artificially Frozen/Reconstituted Test Specimens

Under NSF Grant ENG74-13506 values of dynamic Young's modulus, E_d, and damping ratio, λ, were determined for six frozen soil types and ice at two densities using cyclic triaxial test equipment. Specifically, artificially frozen/reconstituted test specimens of Ontonagon clay (OC), a mixture of Ontonagon and Montmorillonite clay (MOC), Hanover silt (HS), Alaskan silt (AS), Ottawa sand (OS), gravel (G) and ice at densities of 0.77 g/cm^3 (LDI) and 0.90 g/cm^3 (HDI) were tested at temperatures of -1, -4, and -10°C, confining pressures of 0, 350, 700 and 1400 kN/m^2, axial strain amplitudes from 3.2×10^{-3} to 10^{-1}%, and frequencies of 0.05, 0.3, 1.0 and 5.0 Hz.

The results from the research program indicate there is a decrease in E_d with (1) ascending temperature, (2) increasing axial strain amplitude, and (3) decreasing frequency. In general, the rate of decrease in E_d for the respective changes in the variables is greatest for the cohesionless soils (OS, G, HS, AS), lower for the cohesive soils (OC, MOC) and least for ice (LDI, HDI). The cohesionless soils have the highest values of E_d and the cohesive soils have the lowest values of E_d. The values for ice are intermediate. The values of E_d for the soil specimens in the frozen state are approximately two orders of magnitude greater than the values of E_d for the materials in the unfrozen state.

There is an increase in λ with (1) ascending temperature and, in general, with (2) increasing axial strain amplitude and (3) decreasing frequency. The rate of decrease is greatest for the fine-grained cohesionless soils (HS, AS) and least for the cohesive soils and ice. The values of λ for the materials in the frozen state are close to the values of λ for the materials in the unfrozen state.

E_d for the coarse-grained cohesionless soils tested (OS, G) and ice increases with increasing confining pressure, whereas E_d for the fine-grained (HS, AS, OC, MOC) does not change with confining pressure. λ does not change with confining pressure for all the soil and ice specimens tested.

Dynamic Properties of Naturally Frozen/Undisturbed Test Specimens

It is generally recognized that the structure of frozen soil, in situ, can differ markedly from the structure of artificially frozen/reconstituted test specimens. While the results of studies such as those mentioned in the previous section can contribute to a phenomenological understanding of the behavior of frozen soils, the specific applicability of the test results to predict surface motions of frozen ground deposits during earthquake loadings is questionable. In recognition of this fact, research is presently being conducted under NSF Grant ENG77-04437 to:

1. evaluate the dynamic properties of naturally frozen/undisturbed soils over the range of test conditions associated with wave propagation problems of frozen soil deposits (e.g., foundation vibrations, geophysical exploration, blasting, ground response analyses during strong motion earthquakes);

2. investigate parameters that might influence the dynamic properties of naturally frozen/undisturbed soils such as soil type, soil density, nature of the ice phase, anisotropy, temperature, confining pressure, and amplitude, frequency and duration of dynamic loading.

To conduct the research approximately 100 naturally frozen soil samples taken in situ from Alaska will be shipped to the Cold Room Test Facility at Oregon State University. Specimens obtained from these samples will be tested with both resonant column and cyclic triaxial equipment. The specimens will be cored from the large diameter undisturbed samples with an industrial drill press (using a diamond or tungsten carbide bit) kept in the cold room. Depending on the in situ core sample diameter, as many as four 70 mm diameter test specimens may be obtained from a single sample. At a minimum, those samples with distinct layering will be cored in both a vertical and horizontal direction (and possibly an intermediate direction) to evaluate anisotropy.

To evaluate the dynamic properties of the specimens over the range of strain amplitudes and frequencies associated with all wave propagation problems, resonant column and cyclic triaxial test systems will be employed. Both of these test systems will be used in the cold room. With the resonant column system it should be possible to test the frozen specimens at high frequencies and low strain amplitudes in both the longitudinal and torsional mode. With a knowledge of the complex shear and Young's modulus, Poisson's ratio can be evaluated. The range of frequencies for the resonant column test is between 100 and

10 kHz and range of strain amplitudes is between 10^{-5} to 10^{-4} percent for frozen soils. The range of frequencies for the cyclic triaxial test system is between 0 and 100 Hz (or greater, depending on strain amplitude and capacity of the hydraulic power supply) and the range of strain amplitude is between 10^{-3} to 10^{-1} percent. The tests with both systems will be conducted over a range of temperatures from -1 to -10°C and a range of confining pressures from 0 to 1400 kN/m^2. A given test specimen will be tested with both the resonant column and cyclic triaxial test system. Resonant column testing is nondestructive. Consequently, the specimen will first be tested with this equipment and immediately following, it will be tested with the cyclic triaxial equipment. This procedure has two advantages. First, a considerable amount of data can be obtained from one specimen. Second, when comparing and combining the results from the two test systems, there will be no variations in test results associated with differences in material properties.

Publications

The following publications are related to the NSF sponsored research described herein:

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This report summarizes three research projects currently in progress at the Institute of Engineering of the National Autonomous University of Mexico. The projects are jointly sponsored by the Mexican Government and UNAM.

Finite element modelling for dynamic soil amplification and soil-structure interaction studies.

The aim of this project is to define a general methodology for the numerical solution of seismic wave propagation in soil deposits using the finite element method. Topics under study are:

1) Boundary conditions at artificial boundaries. The recently developed idea of efficient active boundaries (see ref 1) is being exploited. Assuming that the waves at the fictitious boundaries are plane, nearly perfect absorption is obtained if the solution there is considered to be the sum of the free field solution without irregularities and/or structure, and the perturbation-due to the irregularities, and only for this last part the absorption condition is applied. With these boundaries the restrictions of rigid bedrock and body waves propagating upwards are removed. The applications under consideration are seismic response of retaining walls and soil amplification in alluvial valleys.

2) Step by step time integration. A new family of step by step methods is being investigated. The scheme is obtained by assuming within the interval a linear variation for the acceleration with slope defined by a parameter α- related to Newmark's β. The error of the approximation is minimized using two different alternatives for Galerkin's method. The method is currently being tested in order to find the value of α which gives the best accuracy for the least strict stability limit.

3) Optimum element size. By defining a mass element matrix as a linear combination of the consistent and the lumped mass matrices an optimum size for different element geometries is being investigated. The benefit of this study well be a minimum computation time for a required wave length representation.

Seismic design of flexible retaining walls.

In the early stages of this project the application of the Mononobe-Okabe method was critically reviewed. It was found that the method only works for retaining walls with a plastic state fully developed in the backfill. For flexible walls the problem has been formulated as a soil-structure interaction problem. The computational tool is the programme FLUSH modified to include new approximated conditions at artificial boundaries which reduce drastically the computation time. From a simplified dimensional analysis three different parameters are being investigated: a) ratio of wall height to dominant wave length of the considered earthquake, b) ratio of the flexural stiffness of the wall to the shear stiffness of the backfill, and c) maximum shear deformation in the backfill for vertically incident shear waves. Earthquakes records are being simulated from design spectra consistent with local soil conditions.

Preliminary results show that the magnitude of the bending moments in flexible walls is smaller than that obtained from the Mononobe-Okabe method, and is strongly dependent on the walls preliminary static design i.e. as the stiffness of the wall increases the soil-structure interaction effect decreases. For rigid retaining walls for which no failure surface is developed the pressure distribution resembles that predicted by the Mononobe-Okabe method but with higher intensity.

The method of characteristics in nonlinear two dimensional soil amplification studies.

In the search for an efficient numerical procedure to study nonlinear wave propagation in soil deposits the numerical method of characteristics was rediscovered (see ref 2). The method is being applied by idealizing the problem as piecewise linear elastic and two dimensional. The governing equations are written as a set of three and of five partial differential equations for SH and for P and SV waves respectively. The formulation results in a procedure of three (for SH) or five (for Pand SV) explicit equations with velocities and stress components as unknowns for each of the points for which the solution needs to be computed.

Using the paraxial approximation of the wave equation, differential relationships at artificial boundaries are being derived.

At the present moment the treatment of singular points such as corners is being examined. Preliminary results show that the best way of dealing with corners is to use a finite element analogue for such points. As described in the first project of this report the free field's solution of use at fictitious boundaries is being calculated also using the method of characteristics.

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The response of a structure to a seismic disturbance is often evaluated with a finite element model of the soil "immediately" around the structure. A seismic motion is input at bedrock (or a suitable stiff layer) and allowed to propogate up through the soil and interact with the structure. The major uncertainty in this approach lies in the selection of an adequate mesh and material properties to model the soil. This research program has the objective of relating finite element mesh characteristics to accuracy of the calculated structural response.

This has been approached by comparing finite element with exact solutions for the transfer matrix of a rigid foundation resting on an elastic half space. Variations considered in the finite element mesh are:

transmitting versus conventional boundaries
hysteretic damping value of the soil
depth of mesh
width of mesh
element size

Using combinations of these mesh characteristics about 150 solutions were obtained in the form of transfer matrix coefficients as a function of frequency. A comparison of these data with the exact solution leads to the following conclusions:

(1) Large oscilations in the coefficients occur when the conventional boundaries are used.
(2) The addition of hysteretic damping in the soil (with conventional boundary conditions) tends to reduce the magnitude of the oscillations but the finite element solution converges to a different solution than the exact solution.
(3) The mesh geometry does not alter the above two conclusions but merely moves the peaks in the oscillation.
(4) The use of transmitting boundaries greatly reduces the oscillations and good accuracy may be achieved with reasonable mesh sizes.

This work is continuing in the following areas:

(1) Structural response parameters will be used as the measure of error rather than interaction transfer matrix coefficients. Typical structures will be considered and errors in peak acceleration and frequency of the peak at several locations in the structure used as the measure of error.
(2) The effects of embedment depth for the structure will be considered. Unfortunately exact analytical solutions are not available for this case. Comparisons will be made with several approximate analytical solutions and between the finite element solutions themselves.
(3) The effect soil layering may have upon the above conclusions will be considered.

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This research deals with effects on foundation response produced by stress waves propagating from the underlying soils.

In this study a 3 ft. diameter vessel was used in which a 24 in. thick layer of 20-40 Ottawa sand was used as a soil mass beneath the footing. Two circular footings, 6 in. and 3 in. diameter, and a square footing of 3 in. size, having different contact pressures, were used. Vertical loads were transmitted to the foundation from mechanically-induced ground motions by means of three hydro-line cylinders.

The behavior of surface footings as well as buried footings was investigated in this study. Measurements were made of stress, strain-time histories using embedded gages. These records were correlated with acceleration-time records of the input load and foundation response to provide a comprehensive picture of stresses and strains in a soil mass subjected to an earthquake type loading. It was noticed that the influence of mass of the footing on the vertical stress distribution is negligible at a depth more than two footing diameters below the footing. The data also indicated that at a distance equal to 1.5 times the diameter of the footing from the axis of symmetry, the effect of footing on the vertical stress distribution is negligible. The stress intensities in the vicinity of the footing increases as the distance from the transient load source decreases.

Experiments were also conducted using a thin layer of compressible material buried at a depth of one radius below the footing. Four sponge materials and a rubber material, having different compressible characteristics, were used in the investigation. These compressible materials were used as damping materials which absorbed some of the compressional waves travelling towards the bottom of the footing. This technique of screening the waves (generated at a distance away from the footing) has been defined by previous workers as Passive Isolation. A series of five tests were conducted, each time using one of the different compressible materials. The foundation response (acceleration-time), and the vertical stress in the vicinity of the footing were recorded under dynamic load conditions.

The above test series was repeated for static load conditions where static loads were applied to the soil through the footing to estimate the bearing capacity of the footing (surface footing only). The test data has been analyzed to: obtain a relationship between the percentage reduction in deceleration of the footing, percentage reduction of the vertical stress in the vicinity of the footing and the subgrade modulus of the compressible material. A relationship between the percentage reduction in deceleration of the footing and percentage reduction in the factor of safety against the bearing capacity failure based on allowable settlement was established.

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Research in the area of soil-structure interaction, sponsored in part by the National Science Foundation, is briefly summarized.

Dynamic Response of Flexible Foundations

This project (being conducted in collaboration with Professor W.L. Whittaker) considers flexible mat foundations, bearing on an elastic or viscoelastic halfspace, to be subjected to either externally applied dynamic loads or seismic excitation. Except for limited previous analytical treatment under plane strain conditions (1), accommodation of the deformability of the mat represents a departure from established procedures. The present research relies on the previous work by Chopra and Vaish (2) and by Wong and Luco (3) in representing soil-structure interaction through a substructure analysis, in which impedance coefficients are developed for the subgrade independently of the geometry or material properties of the mat. The impedance coefficients presented by Chopra et al. (4) for a viscoelastic subgrade are used in the modelling of plane strain strip foundations; for three-dimensional mats, impedance coefficients are derived in the manner described by Wong and Luco (3).

The mat foundation is represented by a finite element assemblage whose mass and stiffness matrices are combined with the subgrade impedance matrix to form the governing equations of motion. The analytical model permits inclusion of shear deformation and rotatory inertia of the plate; the computer program that has been developed accommodates arbitrary loading, stiffness and mass distributions, and either a perfectly rough or perfectly smooth plate-subgrade interface. Computation is performed in the frequency domain.

As the method of analysis is well established, the present work emphasizes the particular behavior of plates bearing on a halfspace. Currently numerical results for strips and rectangular plates are being compiled to assess the effect of flexibility on overall impedance, contact stress and internal bending stress under the action of various external load distributions and incident seismic waves. Results for strip foundations subjected to harmonic seismic waves are in good agreement with those presented by Oien (1). We have also noticed that for strips which might normally be considered rigid (eg., 200-ft wide and 20-ft thick concrete mats bearing on alluvium), the deformation and contact stress is highly dependent on the distribution of externally applied loads. Results for rectangular footings are in good agreement with those presented by Thomson and Kobori (5) dealing with uniform normal stress applied to the surface and by Wong and Luco (3) dealing with rigid footings. We expect reports on this research to be available by January 1, 1979.

Soil-Structure Interaction Associated with a Poroelastic Halfspace

Previous research directed toward evaluating foundation impedance has treated the subgrade as an elastic or viscoelastic solid. No consideration has been given to the effect on impedance functions due to the presence of the pore fluid (except for including its mass in an approximate manner). Work has begun on representing the subgrade as a liquid-filled poroelastic solid whose motion may be described by equations established by Biot (6); impedance functions are being evaluated, and will be compared with those based on an elastic or viscoelastic solid. Preliminary analysis indicates that the difference between these two treatments may be substantial for coarse-grained soils subjected to loading in the frequency range normally associated with strong seismic motion. In addition to the direct significance as regards structural response, treating the subgrade as a porous medium may have importance implications in establishing methods for assessing soil liquefaction under other than free-field conditions.

The present research (being conducted in collaboration with graduate student Marc Halpern) has the following objectives:

1) Within the context of Biot's formulation, solve the counterpart of Lamb's problems; i.e., describe the motion of a semi-infinite, liquid-filled porous solid subjected to harmonically excited normal and tangential concentrated forces applied to the surface.

2) Use the solutions to these problems as Green's functions and, through numerical integration, determine the impedances for strip and rectangular footings founded on a poroelastic halfspace.

3) Using these impedance functions along with free-field motion at the surface of a poroelastic halfspace due to arbitrarily incident seismic waves (as described by Deresiewicz et al. (7,8)), compare the soil-structure response to that computed on the basis of an elastic solid.

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Methods to compute foundation impedance matrices for embedded structures is the subject of this presentation. The general area of the research project is to investigate algorithms which synthesize the continuum and finite element approaches leading to foundation impedance matrices. In order to economize computational efforts for viscoelastic foundation models, development of numerical forms of elastic - viscoelastic analogies have also been undertaken. During the first six months of research efforts the following three topics have been investigated.

Substructure Deletion for Embedment Problems

A numerical technique for evaluating the force-displacement relationships for linear viscoelastic homogeneous foundations supporting embedded structures has been developed. Available procedures for embedment problems resort to computationally expensive finite element methods to model soil regions with so-called absorbing boundaries [1]. Such formulations only partially account for the energy loss due to outgoing waves propagating into the semi-infinite soil regions. A substructure deletion method [2] has been employed in order to evaluate the frequency dependent "stiffness" (impedance) matrices of soil regions supporting arbitrarily shaped deformable embedments. Continuum and discrete solutions are synthesized to obtain a general model; the former [3], accounts for radiation damping, while the latter represents the geometric irregularities in the structure-foundation interface. Numerical results have been obtained for embedments in viscoelastic half planes. It is expected that the proposed technique would be computationally economical in analyzing dynamic responses for foundations containing geometrical irregularities, zonal inhomogeneities, local non-linearities, etc., as encountered in a large number of earthquake engineering problems. The existence and uniqueness of solutions of the substructure deletion equation have been investigated as reported below.

Nonclassical Boundary Value Problem

In the context of the substructure deletion method [2] in finite element formulations one comes across the following problem. The reduced stiffness matrix $\{K^o\}$ for B refers to Fig. 1, associated with degrees of freedom on $\partial B_1 \cup \partial B_2$ is given. For the portion B_1, the reduced stiffness matrix, $\{K_1\}$, corresponding to nodes on $\partial B' \cup \partial B_1$ is also available. The problem is to determine the reduced stiffness matrix, $\{K_2\}$ for B_2 associated with nodes on $\partial B' \cup \partial B_2$. The solution poses a situation when forces and displacements are simultaneously prescribed on $\partial B'$. This has led to the analysis of the following continuum problem.

The existence and uniqueness of solutions for problems in elasto-dynamics for a displacement, traction or a mixed boundary condition are well established. Numerical solutions for such problems can also be guaranteed for approximate methods, e.g., finite difference or finite element schemes. In studying the development of the continuum analog of substructure deletion methods [2] one comes across the following unconventional boundary value problem which does not belong to the domain of the classical ones.

Consider a linear elasto-static system in three dimensions as described in Fig. 1. The boundary ∂B of the domain B is subdivided into two nonzero proper subsets, ∂B_1 and ∂B_2, i.e., $\partial B_1 \cup \partial B_2 = \partial B$. It is also assumed that they are mutually exclusive, i.e., $\partial B_1 \cap \partial B_2 = \Phi$, the empty set in $\mathbb{R}^2$. On ∂B_1 the traction and displacement vectors, $\underset{\sim}{T}$ and $\underset{\sim}{u}$ respectively, are prescribed, whereas on ∂B_2 neither $\underset{\sim}{T}$ nor $\underset{\sim}{u}$ is assigned. For this nonclassical boundary value problem it has been proved that the stress or displacement solution for B may not exist for arbitrary specification of $\underset{\sim}{T}$ and $\underset{\sim}{u}$ on ∂B_1. It has been further resolved that whenever such an elasticity solution exists it is also unique. These conclusions can also be extended in the cases of steady harmonic motion of viscoelastic systems.

In reference to the substructure deletion method the following theorem can be derived from the aforementioned continuum analysis. The governing stiffness equation for the discretized system leads to a unique solution so long as the number of degrees of freedom on $\partial B'$ is not greater than those on ∂B_1.

Numerical Form of the Viscoelastic Correspondence Principle

It is computationally economical to generate viscoelastic frequency responses from the corresponding elastic data base instead of repeating the numerical calculations for different damping characteristics. The limitation of requiring a closed form elastic solution in order to implement the classical viscoelastic correspondence principle has been overcome by an alternative analogy [4]. However, the constitutive model for the latter is restricted to materials with frequency independent Poisson's ratios. It has been reported that a large number of engineering materials, including metals and soils, demonstrates significant variations in damping ratios in equivoluminal and dilatational deformations. The intent of this task has been to extend the numerical method of [4] to include independent viscoelastic properties in bulk and shear. The proposed technique will be employed in economizing computational efforts in evaluating the foundation impedance matrices for structures embedded in visoelastic foundations.

Acknowledgment

This investigation has been conducted under a grant from the National Science Foundation (ENV 77-22524). Contributions of Professors M. Shinozuka, J.L. Sackman and J.M. Kelly are appreciated.

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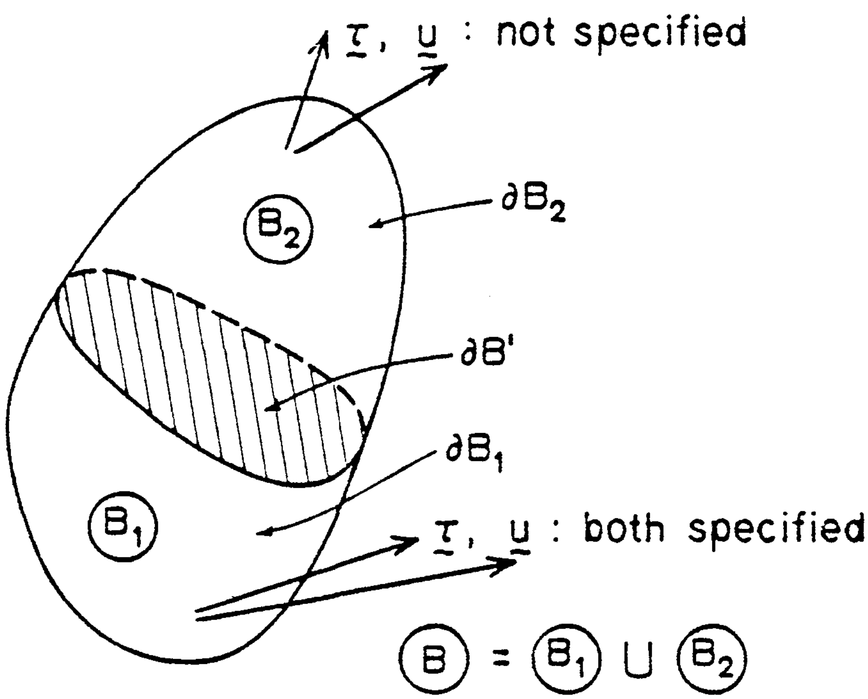

A NONCLASSICAL BOUNDARY VALUE PROBLEM

Fig. 1

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Dynamic Analysis of Shells of Revolution - Soil Systems

A finite element model has been developed to analyze shells of revolution including the soil effect under dynamic loading. The model consists of high-precision rotational shell finite elements, representing the axisymmetric shell, supported on an equivalent boundary system, representing the soil medium. The substructures method used for the dynamic analysis requires no deconvolution since it is essentially an inertial coupling method. Earthquake-type dynamic loading response studies are planned; however, the model may be used for other forms of dynamic loading.

Equivalent Boundary System

In an attempt to have a compatible representation of the three dimensional soil medium with the existing two dimensional shell element formulation, a frequency dependent dynamic boundary system at the common degrees of freedom between the shell foundation and the underlaying soil has been developed. This boundary system consists of frequency dependent translation or rotational stiffness and damping elements with lumped mass in each d.o.f. at the lower boundary of the foundation base. The stiffness elements have been obtained from the impedence matrix, while the lumped masses have been obtained from the condensed mass matrix of the soil model. A proportional damping matrix has been formulated from the final stiffness elements and the corresponding lumped masses.

The impedence matrix is obtained by inverting the flexibility matrix resulting from the solution of a harmonic force $e^{i\omega t}$ at the common d.o.f. between the structure and the soil individually in each of the degrees of freedom.

Axisymmetrical isoparametric quadratic solid elements with transmitting verical boundaries, placed directly at the edge of the structure, are used in modeling the soil medium. The lower boundary is assumed to be fixed at some depth from the foundation level. The total dynamic stiffness matrix of the soil is the sum of the dynamic stiffness matrix of the core and the boundary matrix resulting from the solution of a free wave propagation problem in the far field with the requirement of preserving the equilibrium at the vertical transmitting boundaries.

Foundation Modeling

It is planned to study only shells of revolution on shallow foundations to meet the inertial coupling requirement. The ring footing may be modelled as a special high-precision rotational shell element supported by the equivalent boundary system. The possibility of soil separation due to uplift when the system is subjected to large amplitude dynamic loading is included. The superposition approach is to be used to calculate the stresses in the ring footing, as well as in the lower lintel of the shell, in case of shells which are open at the base such as hyperbolic and similarly shaped cooling towers. The solution is composed of a continuous case and a self-equilibrated line loads case, both of which are represented in Fourier series. The effect of a variety of soil conditions on both the dynamic properties and the earthquake response of such towers is planned, with more attention to the base region.

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A series of studies on Dynamic Soil Structure Interaction are being carried out at M.I.T. under a grant from the National Science Foundation, Division of Advanced Environmental Research and Technology. These studies are coordinated with applications in the Panel Project of J. Becker and in a project on Off-Shore Structures sponsored by INTEVEP (J. J. Connor). Professor J. M. Roesset is the principal investigator until July 1st, 1978, and Professor Robert V. Whitman will be in charge of the project after this date.

Dynamic stiffnesses of surface and embedded rectangular foundations have been obtained for a series of cases using on one hand a finite element type formulation to determine the displacements at any point caused by a unit force and on the other the boundary integral equation method. The first procedure has been applied to the case of a finite soil layer on rigid rock (or a stratified soil deposit), and the second to an elastic or hysteretic half space. Approximate formulae have been obtained for the static stiffnesses as a function of the aspect ratio of the footing and the frequency variation of the dynamic stiffness coefficients has been investigated in terms of the same parameter. A report with these results will appear this summer. The work is continuing now, considering several rectangular footings and their interaction through the underlying soil with application to the study of soil structure interaction effects on prefabricated panel buildings.

The effect of various types of waves and their angle of incidence had been investigated before for the case of soil amplification. It is now being studied in relation to the motions of a rigid, surface or embedded foundation. The purpose is to obtain simplified procedures to determine the foundation motion from the specified earthquake at the free surface of the soil, similar to those already presented for the case of an embedded foundation and vertically propagating shear waves. This work is expected to be completed this summer.

Various nonlinear soil models are being compared in order to estimate the sensitivity of soil structure interaction analyses to the assumed constitutive equations for the soil. Previous studies had shown more discrepancy between the results of an equivalent (iterative) linear analysis and those of a true nonlinear analysis for the two (or three) dimensional case than for the simple 1D studies used in soil amplification, but the latter are also dependent on the soil model used. General plasticity models, the cap model of Sandler and DiMaggio and Prevost's model are being compared. A preliminary report will be ready this summer.

Other nonlinear effects such as sliding or uplifting of the foundation mat are being investigated. Results published to date had indicated an increase in the amplified response spectra in the high frequency range due to uplifting. This effect appeared in the present studies when assuming linear soil behavior but were not present when a nonlinear soil model was used. For the cases studied the effect of separation of the foundation from the surrounding soil was small for a surface foundation (even under severe horizontal and vertical seismic motions) and more pronounced for the case of embedded foundations. The main factor for the latter was the change in stiffness due to the separation of the lateral walls from the backfill. It was found, however, that the results are sensitive to the assumed initial conditions and state of stresses in the backfill. This work is now completed.

Previous studies on the dynamic stiffness of an isolated pile are being continued considering the case of vertical vibrations and simulated nonlinear soil behavior around the pile. The results of these analytical studies using a finite element approach with the consistent absorbing boundary of Kausel and Waas are being compared to those predicted by the P-y curves of Matlock. This work should be finished by the end of the summer. It is planned then to start considering the dynamic response of pile groups.

Additional work for next year includes the incorporation of uncertainties in soil properties and ground motion characteristics in soil structure interaction analyses through a probabilistic approach. It is intended primarily to set the basis for an appropriate formulation of the problem.

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Studies on the nonlinear dynamic response of building frames under seismic excitation are being conducted under a grant from the National Science Foundation. Professors J. M. Biggs and José M. Roesset are the principal investigators. The objectives of this work are to evaluate different design procedures, particularly those recommended by present codes in terms of the dynamic behavior of the resulting frames and the expected level of damage under various earthquakes, to study the effect on inelastic response of such earthquake characteristics as duration and intensity, and to perform a more comprehensive evaluation of various definitions of ductility as used at present, assessing their physical meaning and their relation to structural damage.

A series of steel and concrete frames have been designed according to the Uniform Building Code for vertical loads, wind and earthquake. The designs have been then checked against other recommended requirements such as the provisional ones of various drafts of the ATC-3 recommendations. The response characteristics of these frames (displacements, forces and ductilities) were then evaluated on the basis of simple static analyses (as suggested by the codes) and from nonlinear analyses. Results to date indicate for the steel frames ductilities within acceptable ranges (those estimated from code type analyses are somewhat smaller than the results of the nonlinear analyses, but even the latter are close to the assumed ones in the design). For concrete frames the design in some cases have led to buildings with excessive ductility requirements (particularly in the columns), while in others a more acceptable behavior was obtained.

The effect of earthquake duration is being investigated first for single degree of freedom systems with various force-deformation characteristics (including stiffness and strength and stiffness degrading models). Results are obtained both for real earthquakes, trying to assess the length of the record that must be used in nonlinear analyses, and for sequences of simple pulses.

Reports on these phases of the project are expected to be ready by the end of the year.

PROBABILISTIC SEISMIC SOIL-STRUCTURE INTERACTION OF A NUCLEAR REACTOR CONTAINMENT

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INTRODUCTION

Seismic ground motions are often assumed to be stationary random processes in view of the inherent conceptual and analytical simplicity. However, random variation of the amplitude and frequency contents of earthquake accelerations makes non-stationary representation much more realistic. The object of the investigation is a comparative study of the responses of a nuclear reactor containment type structure to stationary and non-stationary random ground motions taking into account soil-structure interaction.

The most important probabilistic properties for the response quantities are derived from the spectral moments of the output spectral density function which is obtained from the generalized spectral density function of the input ground motion and the system response function.

MODELING

The lumped parameter model used to simulate a nuclear reactor containment is shown in Fig. 1. The foundation is idealized as a rigid circular footing resting on an elastic half space, which is simulated by representing the translational and rotational degrees of freedom. Two types of modeling, taking into account the frequency dependence of the foundation, are considered: i) Veletsos and Wei (1) - Luco and Westman (2) representation of the elastic half-space, and ii) Luco's (3) extension of the formulation to layered elastic media. Linear behavior of the structure and soil, constant foundation mass, and constant structural damping are assumed. The rotatory mass moments of inertia at the different structural elevations, and at the foundation level are also considered.

ANALYSIS

For both stationary and nonstationary processes, the system transfer functions at the discrete frequencies are computed from the Fourier Transform of the equations of motion over a range of frequency interest. This formulation enables the easy incorporation of frequency dependence of the foundation parameters. The two ways for specification of the input spectral density function of the earthquake acceleration are: I) a stationary random process having a time-independent spectral density, and II) a non-stationary random process with a time-dependent spectral density. The direct spectral calculation for Case I is quite straightforward. For Case II many definitions have been proposed such as i) Page's (4) instantaneous spectrum, ii) Priestley's (5,6) evolutionary spectral density function, and iii) Mark's (7) physical spectrum. Assuming the random process to be a slowly time varying function, Priestley's evolutionary spectral density function will be constructed to investigate the nonstationary response of a multi-degree-of-freedom soil-structure system. The present investigation differs from those of Caughey and Strumpf (8) and Lin (9) in application, as it takes into consideration the soil-structure interaction problem in terms of frequency-dependent characteristics.

Extreme value statistics will be applied to construct the probability density function. The upper and lower bounds of the probability of exceedance can be obtained following the methods outlined by Shinozuka (10) and Roberts (11).

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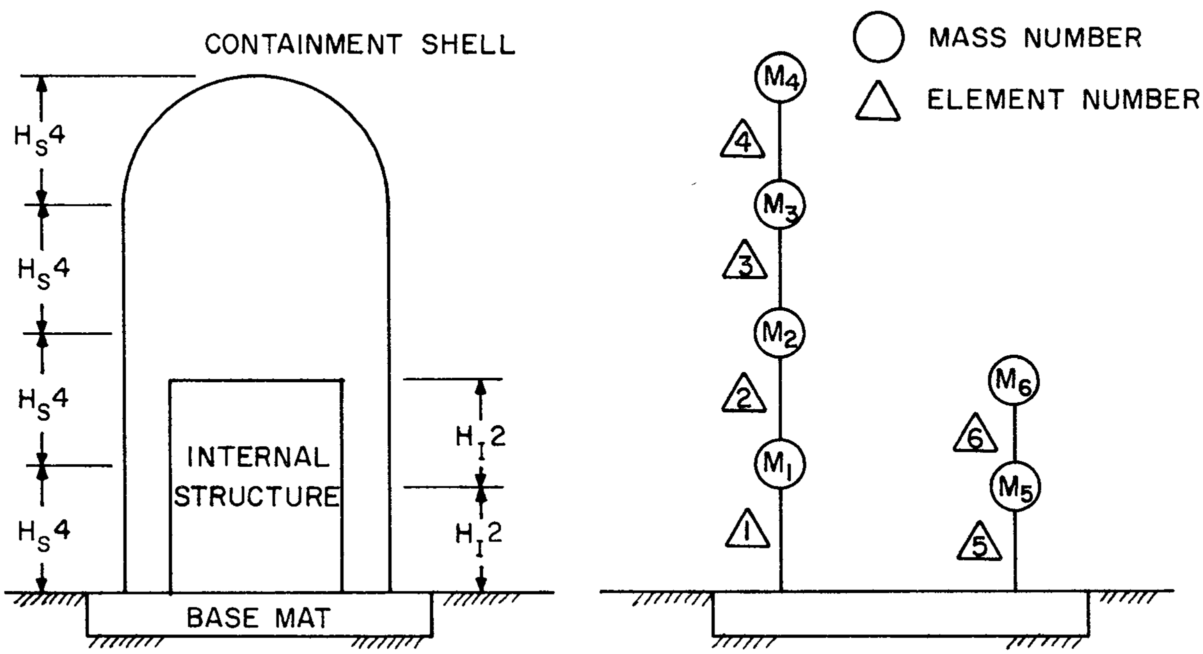

FIG. 1 STUDY MODEL: (a) CONTAINMENT SHELL AND INTERNAL STRUCTURE AND (b) LUMPED MASS STRUCTURAL MODEL. (REF. 12)

SEISMIC RESPONSE OF THE 'CUT-AND-COVER' TYPE UNDERGROUND NUCLEAR REACTOR CONTAINMENTS CONSIDERING NONLINEAR SOIL BEHAVIOR

BY

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INTRODUCTION

Underground siting for nuclear power plants has been suggested as an effective alternative to surface siting to provide increased containment protection. The 'cut-and-cover' concept can be used in any geological formation, and sometimes is the only solution for certain siting problems. Available information on the dynamic, especially seismic, response of 'cut-and-cover' type containments is restricted to the work of Blake et al [1], Moselhi [2], and Kroger et al [3].

ANALYSIS

This paper describes some parametric studies by El-Tahan [4] of dynamic soil-structure interaction for the 'cut-and-cover' reactor concept. The dynamic loading considered is a horizontal earthquake motion with duration of 20.48 sec and maximum acceleration of 0.15 g. The high frequency ranges, which must be considered in the study of soil-structure interaction for nuclear power plants, and the nonlinearity of soil behavior during strong earthquakes are adequately taken into account. Soil nonlinearity is accounted for in an approximate manner using a combination of the 'equivalent linear method' [5], and the method of complex response with complex moduli [6]. The structure considered is a reinforced concrete containment for a 1100 - MWe power plant buried in a dense sand medium, shown in Fig. 1. The analysis has been carried out using the computer programmes LUSH [6] (plane-strain finite element), and SHAKE [7] (one-dimensional wave propagation analysis).

Parametric studies for the response of the containment and the surrounding medium are carried out for: a) containment shape (high horseshoe, flat horseshoe, and semi-circular roof-vertical walls), b) relative stiffness of the containment and the medium, c) depth of burial of the containment (shallow, intermediate and deep embedments), d) relative stiffness of the medium and filling material (original fill, loose sand, stabilized sand and reinforced earth), e) thickness of the backfill jackets (10 ft. and 70 ft.), f) isolation of the containment using energy absorbing jackets around the containment (polyurethane foam and foamed concrete), and g) type of surrounding medium (sand and rock). Comparative studies are presented for rock vs. sand siting, and aboveground vs. underground siting in sand.

The response values determined are: i) time histories of accelerations, displacements and stresses, ii) maximum stresses and accelerations, and iii) acceleration response spectra. Figs. 2 to 6 show typical response plots.

The results indicate that: i) The high horseshoe shape is the best among the three shapes considered decreasing the containment stresses by 10-20%, ii) Flexible containments are better than rigid ones, iii) Successive reductions in containment stresses to 67% of the initial values are associated with each additional 70 ft. embedment depth, iv) The relative stiffness of the filling material and the medium has the most significant effect on the response. The lower the modulus of elasticity of the filling material, the greater is the reduction in the containment and medium stresses. A filling material with stiffness 30% lower than that of the medium, reduces the stresses by 30% in the containment, and about 20% in the medium, v) Using a jacket of energy absorbing material (polyurethane foam) in a sand medium reduces the containment and medium stresses by 65% and 40% respectively, vi) A reduction in the containment stresses of about 20% is achieved using a reinforced earth jacket, vii) Increasing the width of the backfill side-cover increases the stresses in the containment and the medium, viii) The response values of the medium near the containment are considerably affected by the interaction. The interaction effect is larger for aboveground siting, and ix) The dynamic loading on the containment in a sand medium is higher than that in rock.

Recommendations are made for further studies to account for more realistic modelling and material behavior, and more complex plant configuration and structural details.

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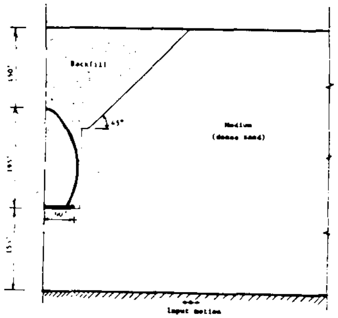

FIG. 1(a) CONTAINMENT, MEDIUM AND BACKFILL FOR A TYPICAL CASE

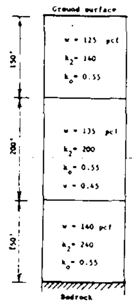

FIG. 1(b) SOIL PROFILE AND PROPERTIES

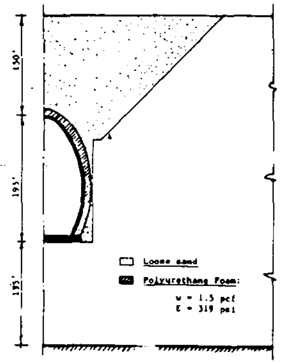

FIG. 1(c) POLYURETHANE FOAM JACKET

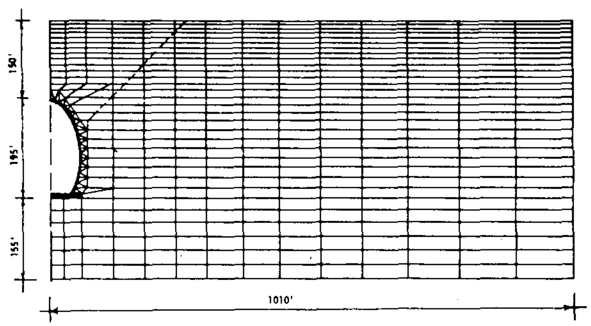

FIG. 1(D) FINITE ELEMENT DISCRETIZATION OF THE SOIL-STRUCTURE SYSTEM

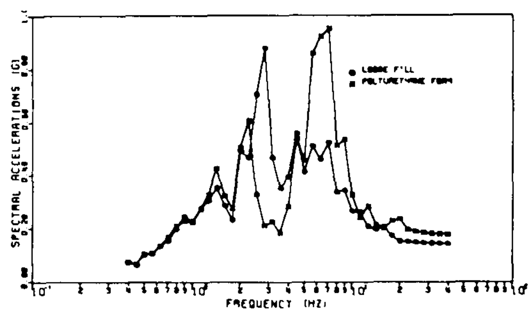

FIG. 4 ACCELERATION RESPONSE SPECTRA AT MID-HEIGHT OF THE CONTAINMENT WALL - LOOSE FILL AND ISOLATING POLYURETHANE FOAM JACKET (SPECTRAL DAMPING = 2%)

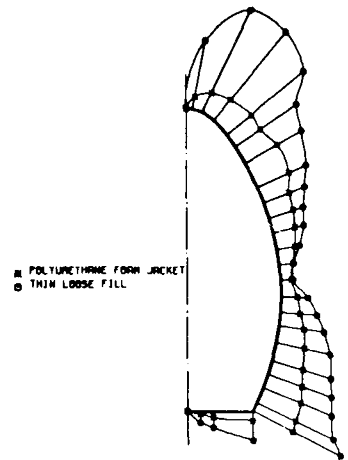

FIG. 2 EFFECT OF THE ENERGY ABSORBING JACKET (POLYURETHANE FOAM) ON MAXIMUM PRINCIPAL STRESSES IN THE CONTAINMENT (SCALE: 1 INCH = 400 P.S.I.)

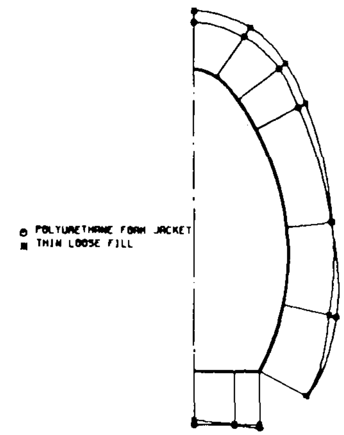

FIG. 3 EFFECT OF THE ENERGY ABSORBING JACKET (POLYURETHANE FOAM) ON MAXIMUM HORIZONTAL ACCELERATIONS IN THE CONTAINMENT (SCALE: 1 INCH=0.2G)

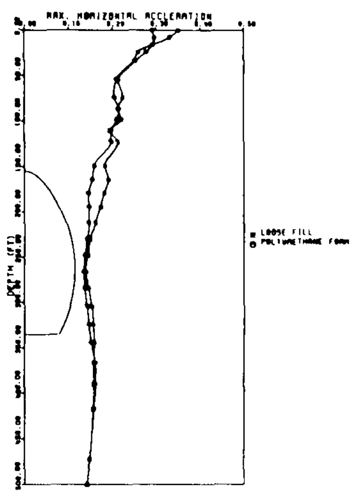

FIG. 6 MAXIMUM HORIZONTAL ACCELERATIONS IN THE SOIL AT A VERTICAL PLANE 10 FEET AWAY FROM THE CONTAINMENT - LOOSE FILL AND POLYURETHANE FOAM JACKET

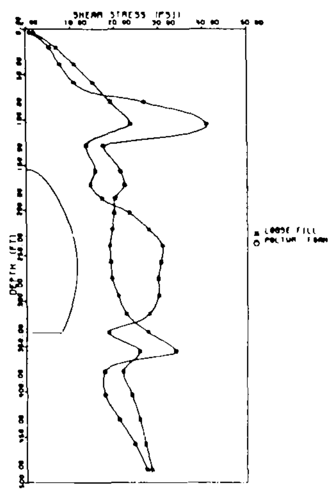

FIG. 5 MAX.MUM SHEAR STRESSES IN THE SOIL AT A VERTICAL PLANE 40 FT AWAY FROM THE CONTAINMENT - LOOSE FILL AND POLYURETHANE FOAM JACKET

PROBABILISTIC RESPONSE OF FLOATING NUCLEAR PLANTS TO SEISMIC FORCES

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INTRODUCTION

The difficulty in finding suitable land sites along the coast, power cost escalation, growing concern of environmental impact, and recent trends for standardization have stimulated interest in offshore siting concepts. This paper describes the calculation of deterministic and probabilistic dynamic responses to seismic forces of a floating nuclear plant restrained by mooring struts attached to the caissons within a protective breakwater. The probabilistic response is studied using a 2-D plane strain model considering frequency-dependent added mass and damping.

WORK COMPLETED

Deterministic Response:

The offshore nuclear power plant, shown in Fig. 1, similar to the one proposed for the Atlantic Generating Station, is chosen as the example problem. Assuming the platform structure similar to a ship structure compartment (2,3), the elastic properties are computed using anisotropic plate theory. The reactor containment building is modeled as a uniform shear bending beam with lumped masses based on frequency equivalence with the actual containment structure. A three-dimensional thick plate model with frequency-independent added water masses is used for the platform modeling. The effect of buoyancy on the FNP is simulated with one-dimensional axial stiffness boundary elements at the bottom nodes of the platform structure. Beam elements are used for the mooring struts. The excitation input is a ground acceleration component of S69E, recorded on alluvium overlying the sedimentary rock at Taft, California during the earthquake of July 1952 of magnitude 7.7, with a peak acceleration of 0.153 g. The seismic loading is considered to be acting at the ocean bed level, and at all the mooring struts of the 3-D model; the input accelerations in the x and z directions are assumed to be identical. A modal superposition analysis is carried out assuming a proportionally damped structure.

RESEARCH IN PROGRESS

Probabilistic Response:

i) Fluid Finite Elements -

Two-dimensional plane strain eight-noded isoparametric quadrilateral finite elements, with velocity potentials at the nodes as the unknowns, are used to subdivide the fluid medium. The modeling includes a free surface wave boundary condition. The evaluation of the frequency-dependent added mass and damping is based on the steady state two-dimensional field problem. The hydrodynamic forces associated with the added mass and damping values, evaluated at the fluid-structure interface nodes, are then incorporated in the dynamic equilibrium equations of the structure.

ii) Frequency Domain Analysis -

The platform structure is idealised using a 2-D plane strain model, and the differential equations of motion for the damped vibrations of the floating structure take into account the dynamic fluid-structure interaction effects. The axial stiffnesses of the boundary elements, representing the effects of buoyancy are included in the stiffness matrix. The complex frequency response method is used and the input motion assumed to be harmonic with the frequency. This implies that the response is also harmonic. The input data values of the strong ground motion are transformed into complex amplitudes using the Cooley-Tukey Fast Fourier Transform (5,6). The complex transfer function, relating the input forces to output responses, is evaluated as the inverse of the impedance matrix and the solution vector corresponding to the complex amplitudes of the input function determined from linear superposition. The displacement response in the time domain, obtained from the inverse transformation, is compared with the deterministic response computed from the 3-D model.

iii) Extreme Value Statistics -

The mean square value of the response is computed as the area under the output spectral density versus frequency curve over the range of frequency of interest. The moments of the output spectral density function are determined, and the spectral band width expressed in terms of the spectral moments. The frequency, at which most of the energy in the single peaked spectrum is concentrated, is obtained. The extreme-value probability distribution function, based on the work by Cartwright and Longuet-Higgins (7) which was later modified by Davenport (8), is used to obtain the mean of the peak values. The standard deviation of the extreme-values is then computed.

As the earthquake motions are transient and usually too brief to satisfy the stationarity condition, nonstationary effects also need to be considered.

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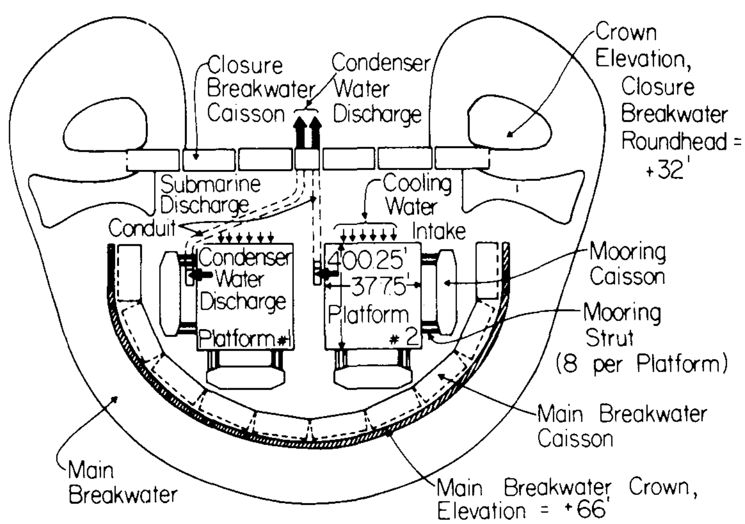


FIG.1. FEATURES OF THE ATLANTIC GENERATING STATION (REF. 1)

LEON RU-LIANG WANG AND MICHAEL J. O'ROURKE

Rensselaer Polytechnic Institute

A National Science Foundation sponsored project in the area of buried lifeline earthquake engineering is being conducted at RPI. The objectives of the project are to study thoroughly the seismic response behavior of buried water/sewer distribution systems, to develop a systematic way of assessing the adequacy in terms of vulnerability to seismic damage of these systems and to propose new design criteria.

Introduction

The earthquake behavior of buried water/sewer lines has recently been receiving more attention because of the impact of these systems upon the populus during and after a major earthquake by the loss of fire fighting capability, possibility of typhoid, etc.

The analysis of the response of buried pipelines, which by their nature have both temporal and spatial variations, is different from the response analysis of a building type structure. Since the width of most buildings is small compared to the wavelength of the seismic waves, a building is essentially subjected to point excitation. For pipelines, this condition does not exist.

Seismic Response/Damage Behavior

From a review of pipeline damages due to earthquakes, the following general conclusions may be drawn:

1. Pipelines with flexible joints experience less damage during an earthquake than pipelines with rigid joints;
2. Pipelines in regions of transition from one soil type to another experience the most damage. If the soil is uniform, pipelines in soft soil experience more damage than pipelines in firm soil.

Further studies by Japaneses indicated that the seismic response behavior of buried pipelines is governed by the ground displacement characteristics. The effect of the inertia force is found to be negligible. The relative motion between the soil and the pipe is small. During seismic excitation, the axial strains are found to be much larger than the bending strains.

Using an infinite beam on an elastic foundation model subjected to a static sinusoidal ground displacement, we have verified that the relative motion between the pipe and the surrounding soil is small and the axial strains are in fact much greater than the bending strains.

Vulnerability Analysis and Design

The flow chart for the seismic vulnerability analysis and design of underground piping systems is shown in Fig. 1. The vulnerability analysis quantifies the probability of failure of a pipeline due to earthquakes. The satisfactory design of a pipeline based on certain failure criteria and risk level is achieved by repeating the vulnerability evaluation for a number of trials.

Given the basic environmental inputs (seismic, geological and soil) at the site and the physical inputs (properties of pipe, joint and geometry) of the system, the vulnerability analysis requires completing the tasks in the heavy boxes in Fig. 1. These tasks are briefly described as follows:

Seismic Risk/Motion Studies - These studies supply the seismic input, which are probabilistic in nature, to the buried piping systems. The seismic risk analysis estimates the maximum ground acceleration, velocity and displacement for a given probability of exceedance associated with a given return period for the site. The ground motion study investigates the ground excitation characteristics such as expected wave form, traveling speed, etc. under various soil and geological environments.

Interaction Parameters and System Model - The buried pipeline is modeled as a beam on an elastic foundation. The soil-pipe interaction parameters are required for the seismic structural analysis. The required spring constants are for longitudinal (axial), lateral and vertical (flexural) and twisting (torsional) motion.

Seismic Structural Analysis and Failure Criteria - A general piping (water/sewer) system generally consists of few single large mains, more intermediate branches and a lot of small service pipes which forms a grid system. To achieve practical solutions, a component analysis procedure is being developed, which analyzes separately the long pipes, joint/junction interactions and simple grid systems. The analyses are quasi-static in nature, that is, the inertia terms are neglected. The ground displacements which are used as input come from the seismic risk/motion study while the soil springs come from the soil pipe interaction parameter study.

For evaluation of the adequacy of the piping system, a seismic failure criteria is needed, which is defined as reserve strength/ductility of a pipeline beyond its normal stress/strain conditions. This reserve strength/ductility is that which is available to resist the seismic loads. In this study, the effect of corrosion is also included.

The ultimate strength of buried pipes is being developed for flexure (plastic or rupture), tension (yielding of material), compression (yielding of material or buckling), bursting by hoop stress in water pipes, torsion and/or shear failures using Von Mises and other failure criteria.

Vulnerability Evaluation/Design Recommendation - Upon the completion of the above tasks, vulnerability evaluation of a given or trial system can be made. The stresses/strains, moments/curvatures resulting from the seismic structural analyses are compared with the reserve strains/curvatures of the pipe from the failure criteria study. For design of a new pipeline, the optimum design is achieved by repeating the same vulnerability evaluation procedure a number of times.

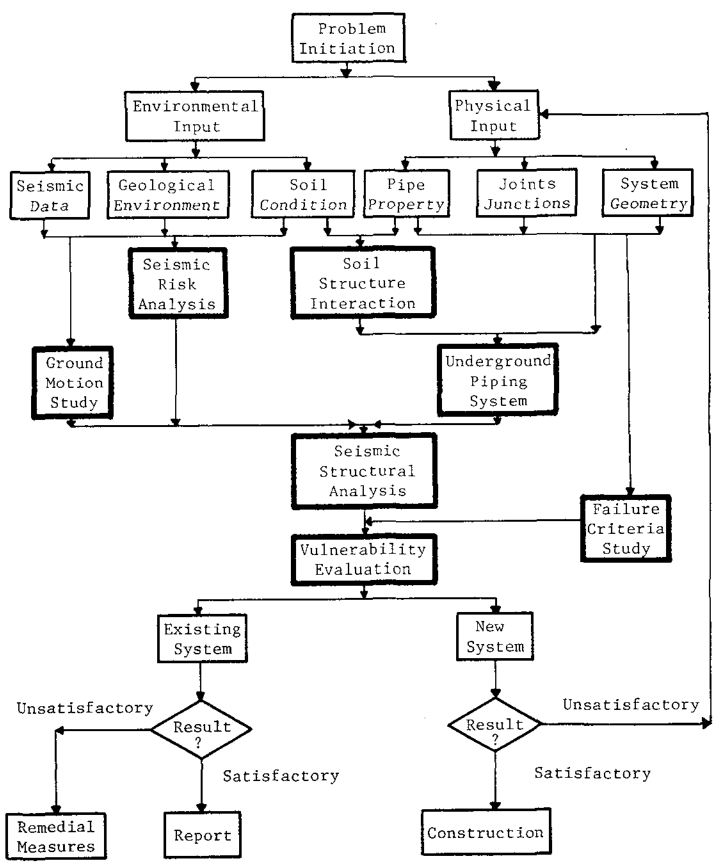
Future Research

Current research more or less emphasizes long straight pipes within uniform geological and soil environments. Significant progress has been made in solving this problem. Future research will include, but not be limited to, the following:

- Study of simple piping systems with varying soil conditions;
- Study of simple systems with varying geological environment;
- Response analysis of general buried piping systems;
- Study of vulnerability/serviceability of general buried piping systems;
- Proposed design methodology and recommendations, for general buried piping systems.

Figure 1 - Flow Chart

Seismic Vulnerability Analysis and Design
of
Underground Piping Systems



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Earthquake Response of Underground Pipelines

Dynamic response of buried pipelines to earthquake excitation is theoretically investigated. The study examines the effect which soil-structure interaction can have on the level of axial and bending stresses induced by seismic excitation travelling along the pipe under various angles of incidence. The problem is treated in terms of both deterministic and random vibrations.

The reactions of soil to the motion of the pipe are formulated by combining the static solution by Mindlin with the dynamic plane strain solution. This approach yields soil stiffness and damping at any embedment depth and also gives the cross-stiffness and cross-damping constants. With the soil reactions defined, the response of the pipe is solved by means of modal analysis, direct integration of the equations of motion and also, in the frequency domain. The stresses established are compared with those calculated using the standard assumption that the pipe exactly follows the motion of the ground. This comparison indicates that soil-pipe interaction can significantly reduce the stresses in both bending and axial cases. This reduction can be even greater if slippage between the pipe and soil takes place. This effect is also treated.

Some preliminary results of the study are described in Refs. 1 and 2.

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Since February 1978 a research program entitled, "Earthquake Response and Seismic-Resistant Design of Underground Pipelines" has been conducted at the University of Notre Dame. The research project has been sponsored by the Earthquake Hazards Mitigation Program, Division of Problem - Focused Research Applications of the National Science Foundation. The research efforts in the project are particularly concentrated on buried gas pipelines. As a first part of this research program an extensive and up-to-date overview on the seismic response of buried pipelines has been prepared [1]. As indicated in the stated overview, there exists a reasonably large, but as yet mostly uncorrelated, amount of data for the behavior and damage of buried pipelines during strong ground motion. With this wealth of information, researchers are noting similarities and are attempting to quantify the types and degrees of damage. Research is also underway with the aim of modelling the lifeline's behavior during an earthquake.

It would appear then research currently pursued has three main branches: (1) qualitative analysis of the types of damage, (2) quantitative analysis of damage, and (3) models for pipelines in a seismic environment. These three branches are by no means either exhaustive or exclusive; reports touching two or even all three topics are not uncommon. One trend, however, in the recent research is apparent, namely more emphasis on quantitative rather than qualitative analyses.

A major effort in the research program is devoted to the collection of information from natural gas utility and transmission companies for the determination of the necessary data relevant to the research project. In order to gather the stated data on materials, joints, operational procedures, geological information, damages due to earthquakes etc. in buried gas pipelines in a systematic way, a detailed questionnaire was prepared and has been forwarded to the gas companies. The next phase of the work will be the classification and evaluation of the collected data and the preparation of a self-contained report to be used by researchers and utility companies.

In a forthcoming report [2], a set of three decoupled equations are presented for the buried pipe modelled as a thin circular cylindrical shell. The static equivalents of these equations are readily seen to be Morley's equations.

This represents a departure with present earthquake engineering work on underground pipelines. When viewed as a shell, the pipe will exhibit deformations that are interrelated. An example in [2] clearly illustrates this: If the ground is deformed along the axis of the pipe, radial as well as axial displacements are encountered. A beam approach, on the other hand, gives only axial deformation.

An attempt has been made to model piecewise portions of ground acceleration a(t) as:

$$a(t) \approx \sum_{2}^{k-1} e^{-\xi_i |t-\tau_i|} \sin\omega_i t \; (1(t-\tau_{i-1}) - 1(t-\tau_i))$$

$$+ e^{-\xi_1 |t-\tau_i|} \sin\omega_1 t \; (1(t) - 1(t-\tau_1))$$

$$+ e^{-\xi_k |t-\tau_k|} \sin\omega_k t \; (1(t - \tau_{k-1}))$$

Here ξ_i and ω_i are constants determined by statistical methods and τ_i are the times corresponding to peaks on actual accelerograms. Furthermore, 1(t) is Heaviside's unit step function. Preliminary work has been done using the 1971 San Fernando and 1940 El Centro earthquake records.

It is anticipated that such analytical expressions, when integrated twice, will yield suitable analytical approximations for ground displacements. This expectation rests on the fact that integration may be viewed as a smoothing process. Such expressions for ground displacement would greatly enhance the amount of possible analytic work prior to the actual solution of the shell equations described above. These equations depend heavily on the ground displacements and, by using the underlying record for ground motion data (ie, accelerograms),it is expected that a reasonable pseudo-displacement input can be obtained.

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ONGOING EARTHQUAKE ENGINEERING RESEARCH

The research effort at Case has taken on two aspects: the experimental determination of soil properties under dynamic loading conditions, and the analytical investigation of structural system response to seismic loading. In the latter category, efforts are currently directed toward both deterministic and nondeterministic approaches.

Experimental Studies of Soil Properties

Experimental research in soil dynamics is presently centered on the response of naturally deposited one-dimensionally consolidated clays to both fast and slow cyclic loading. Resonant column tests on hollow cylinders have shown that the modulii and damping ratios changes substantially with direction. Slow cyclic loading tests on thin hollow cylinders have shown that the response is totally different depending on whether the clay is one-dimensionally consolidated (i.e. cross anisotropic) or randomly oriented (i.e. isotropic). No amount of disturbance at large strains totally destroys the structure, allowing the material to be modelled isotropically. (Ref. 3)

Work is proceeding on cyclic loading at various inclinations of the principal stresses on the axis of symmetry; both normally consolidated and overconsolidated clays are being studied. The degradation of modulii and damping ratios due to large strains are being observed and analyzed.

Analytical Investigations of Deterministic Response

One effort currently underway is in the area of developing frequency dependent stiffness matrices for foundation systems; viscoelastic, transversely isotropic halfplane foundations and imbedded flexible foundations are being considered.

For the first case, assuming a certain relationship exists between some of the five elastic constants, it is shown that Navier's equations of motion can be uncoupled, yielding two wave equations in terms of unknown scalar potentials. Following the method of Ref. 1, frequency dependent stiffness matrices are derived for viscous and hysteretic damping. These results allow a qualitative assessment of the effects of material anisotropy on the dynamic response of soil-structure systems without performing a complete soil-structure analysis.

For the imbedded case, a method is being investigated whereby the discretized equations, derived from an integral equation formulation for the isotropic halfspace, can be coupled with the finite element equations representing the foundation. The method will yield results analagous to the so-called impedance methods for surface foundations. Using this approach, it will be possible to analyze an imbedded foundation without having to discretize a large portion of the soil halfspace.

Analytical Investigation of Nondeterministic Response

A current area of investigation is the response of systems to nonstationary random excitation. Methods to handle nonwhite excitation are being developed and evaluated. An alternative which will be examined involves augmenting a modal equation with a filter and solving for the evolutionary moments of the resultant fourth order state vector. Such a procedure will be compared with simpler methods, e.g. using different intensities for the excitation of each mode. In connection with modal analysis, decay of correlation among state vector components will be studied. The importance of deterministic vs. stationary start conditions and the shape of evolutionary power of the excitation on response measures will be quantified by multiple analyses.

Additional objectives of this research are the computation (within the state-space formulation) of first crossing probabilities of low and intermediate thresholds for nonstationary response processes, and applying the state-space random vibration formulation to finite element models of soil-structure systems.

State space random vibration analyses of nonlinear systems will also be examined. The methodology will use piecewise linear models and direct time integration (i.e. no modal decomposition) of the equations governing the evolution of the state vector moments.

PROPOSED EARTHQUAKE ENGINEERING RESEARCH

Proposals in several areas are currently in various stages of preparation or consideration. They are primarily in the field of seismic response of structures.

Damping Characteristics of Building Cores with Integral Viscoelastic Layers

The objective of this research is to study the effect of incorporating vertical viscoelastic layers in the core (shear wall or braced frame) in order to increase available damping. Specific questions to be resolved are:

1. Effect on the damping level in the lateral load resisting element and in the structural system.
2. Effect on the stiffness of the lateral resisting element.
3. Effect on the system response.
4. Variation in effectiveness with different excitations.
5. Optimum material and configuration.
6. Typical architectural details.
7. Retrofitting to existing structures.

Analytical Study of Uplifting Response of Seismically Excited Structures

The objective of this research is the evaluation of the effect of allowing uplift to occur in structures during severe seismic excitation. It has been shown (Ref. 2) that requiring foundation anchorage can significantly increase the loads imposed upon a structure during a severe earthquake, as well as increasing foundation costs. Utilizing a verified nonlinear analysis procedure, various structural configurations, materials and excitations are to be examined analytically, comparing uplift response to more conventional "anchored base" response. Realistic prototype structural details designed to accomodate anticipated uplift motions will also be examined as a part of the research program.

Damage Identification in Structural Systems

The objective of this research is to develop and test methodology for quantitatively ascertaining unobservable damage to structural systems resulting from seismic or other attack. The primary decision making criteria would be based on structural characteristics derived from dynamic response data. Specific questions to be addressed are:

1. Nature and quantity of data desirable for a decision.
2. Probabilistic bounds on the accuracy of the decision (possibly using a Bayesian approach).
3. Most desirable type of excitation for obtaining data, e.g. ambient vs. forced sinusoidal or random excitation.
4. Interpretation of obtained data, e.g. separating data from noise, etc.
5. Rational basis for deciding upon need or economy of repair/replacement.

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G. RODOLFO SARAGONI

University of Chile

The University of Chile has been conducting the research project on "Seismic Risk and Protection" since 1975. This project will be continued through the O.A.S. project "Andean Seismic Protection" for a three year period starting in 1979.

The fields under study are seismic risk, ground motion characterization, capacity of strong motion to cause damage to structures, installation of strong motion accelerographs, microzonation of main chilean cities, soils dynamics and behavior of structural elements under cyclic loads.

1. Seismic Risk.

The major goal of this research is to obtain a seismic risk map of Chile in terms of probability of exceedence of peak ground acceleration values during selected economic life time. This research has considered: the acquisition of the statistics of chilean seismicity, the analysis of completeness of the earthquake sample, the analysis of attenuation equations for the local seismicity and special studies of the main historical earthquakes in order to establish as accurate as it is possible the exceedence rate for very large earthquakes.

2. Ground Motion Characterization.

2.1. Characterization of Earthquake Accelerograms in Mean Square Acceleration Sense.

In this study earthquake accelerograms are considered as samples of stochastic processes resulting from the multiple filtering through a set of soil layers of nonstationary processes generated at the source. Under this assumtion mean square acceleration tends to a chi-square function of the type $E\{a^2(t)\} = \beta e^{-\alpha t} t^{\gamma}$, where α, β and γ are three real constants. This function has shown to be a satisfactory approximation for the mean square acceleration function of earthquake accelerograms of U.S.A., Mexico, Perú and Chile for epicentral distance larger than 10 km. and on nonrocky soils.

Attenuation expressions for the parameters α, β and γ in terms of epicentral distance and Richter Magnitude has been established for the seismicity of the Western Coast of U.S.A. These attenuation relations permit to simulate earthquake ground motions for different magnitudes and epicentral distances by assuming that earthquake accelerograms are samples of stochastic processes resulting from the modulation of an stationary process $\{S(t)\}$ by a deterministic envelope $\psi(t) = \sqrt{\beta}\, e^{-\frac{\alpha t}{2}}\, t^{\gamma/2}$.

2.2. Duration of Earthquake Motions.

A definition of duration of strong motion region of earthquake accelerograms has been also given in terms of shape parameters α and γ. Attenuation expressions for the duration of this region in terms of epicentral distance and Richter Magnitude has been also estimated for earthquake accelerograms of the Western Coast of U.S.A. Similar attenuation expressions for the accelerograms generated at the subduction zone of Chile is in progress. The duration of the strong motion region and the overall duration of accelerograms can be related through shape parameters α and γ.

2.3. Probability and Power Spectral Density Functions.

Studies on the probability and power spectral density function of accelerograms are in progress using the characterization of earthquake accelerograms in mean square sense.

3. Capacity of Strong Ground Motions to Cause Structural Damages.

The influence of the parameters α, β and γ of the mean square acceleration and the power spectral density function of accelerograms in average response spectra has been established. Approximated close form solutions for average response spectra in terms of amplitude, duration and frequency content of accelerograms has been derived.

Identification of strong ground motion parameters that controls ductility requirements for simple nonlinear structures is in progress using deterministic and probabilistic methods.

4. Installation of Strong Motion Accelerographs.

This program considers the installation of 10 accelerographs in the Valparaíso - La Ligua - Santiago region. With this new array is expected to record in the next ten years an event of Magnitude 8.5 with epicenter at the sea in front of Valparaíso and other of magnitude 7.5 with epicenter near La Ligua.

With the O.A.S. project the accelerograph-national network will be expand from 37 accelerographs to 57. Some of the new 20 instruments plus some seismoscopes will be located at the same region in order to increase the reliability of the network in this area and the probability to obtain records at epicentral regions or populated areas.

New arrays of instruments will be also located to improve attenuation expression for earthquake ground motion parameters.

5. Microzoning.

Microzoning of some major chilean cities has been considered by IDIEM and Civil Engineering Department using dynamic soils amplification models and microvibrations. During the last two years the following cities were studied Valparaíso, Viña del Mar, Coquimbo and la Serena.

Microzoning maps of the main cities will be incorporated to the new version of the chilean seismic code.

6. Soil Dynamics.

Studies of liquefaction of saturated sands using shaking table and theoretical model has been applied to real casses (Liquefaction at Pto. Montt during the 1960 chilean earthquakes) and it will be applied to the observed liquefactions at Caucete in the 23 of November 1977, San Juan, Argentina earthquake.

Some studies on earthquake stability of cohensionless soils has been also applied to real cases (Reñaca - Valparaíso 1971 earthquake).

7. Behavior of Structural Element Under Cyclic Loads.

Studies of the dynamical behavior of full size structural elements under cyclic loads has been initiated by IDIEM. Studies of epoxy repaired reinforced concrete beom column joints and repaired masomry walls has been done. Studies on the dynamical behavior of concrete shear wall is under progress.

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2 - University of Genova (Italy)

In 1977, at the Istituto di Scienza delle Costruzioni of the University of Genova (Italy) was established a research group oriented toward the development and the evaluation of numerical models for seismic soil-structure interaction. The group includes both university teachers and researchers from the Italian National Council of Researches (CNR).

The research project is sponsored by the National Council of Researches within the context of a broader nationwide spread effort in seismology and seismic engineering. A first phase of this effort is supposed to be completed by the end of 1980. It can be easily understood that the subject is of a great interest in the country, due to the significant seismic activity registered in the recent years. One of the major goals of the initiative is, on one side, to improve the efficiency of the seismological instrumentation network and to reach a better definition of the seismicity of the various italian sites and, on the other , to give a wider diffusion to the seismic structural analysis and design techniques among researchers and professionals.

The foreword characterizes the activity of the group, which is, therefore, devoted to both the development of computational technologies and the evaluation of the existing ones.

Following to a several years experience in conventional and finite element analysis of static and dynamic structural problems, a close insight has been taken into the formulation and approximation of the basic problems in soil dynamics and some problems of special interest have been focused, that will be briefly described in the following.

As concerning the finite element modeling of the soil, a major problem could be the choice of the boundary conditions to simulate the radiation damping. In particular, the various solutions proposed have already shown, through numerical experience, their respective advantages and disadvantages, but it seems that relatively few data are available, bringing to evidence the relationship between the cost of the analysis and the accuracy of the solution.

At least with respect to certain classes of problems, for instance, further studies on the application of viscous or consistent boundaries could be effectued.

Always in terms of cost/accuracy ratio, parametric studies can be carried out to evaluate the effectivness of the two-dimensional approxi= mations of three-dimensional problems, expecially in the case of some qui te popular simplifying techniques.

It is well recognized, indeed, that the consideration of fully three- -dimensional behaviour can significantly affect the results of the analy= sis for the case in which multiple structures interacts.
The relevant number of parameters influencing the phenomenon can, never= theless, make an extensive study unfeasible. The building-to-building interaction problem is, however, of some importance and a certain amount of research will be also devoted to it.

From the engineer's point of view, before applying expensive nume= rical models, it is interesting to know whether the effect of the inter= action will be significant or not. As in the case of a single structure interacting with the soil, it would be useful to take advantage of simpli= fied formulas or very approximate procedures.
In this context it could be, therefore, reasonable to work on two dimen= sional models, provided that this approximation leads to an overestimate of the effect and that simpler solutions are available.
For surface foundations, for instance, a valid answer is perhaps possi= ble. Previous researches show that numerical evidence can be produced at a reasonable cost.

With such simple models, in addition, other factors influencing the phenomenon can be taken into account, such as the angle of incidence of the incoming waves.

In conclusion, the activity of the research group will deal, in the next future with the above mentioned topics of the seismic soil-structure interaction problem, accordingly to a sequence including first the nume= rical evaluation of the already proposed techniques.

SESSION 3

STRUCTURAL ELEMENTS

Chairman: M. A. Sozen

J. O. JIRSA

The University of Texas at Austin
Department of Civil Engineering

Synopsis

In the design of structures for lateral loads, it is generally assumed that the direction of deformation coincides with a principal axis of the structure or member and with constant axial (generally compressive) forces on the columns. However, during recent earthquakes, some reinforced concrete structures designed using these assumptions exhibited shear distress. The observed damage may be partially attributed to multidirectional forces during the earthquake. The purpose of this investigation is to examine experimentally the influence of lateral loading history or sequence of application of bidirectional loads on the shear strength and hysteretic response of reinforced concrete columns and beam-column joints.

Background

It has been shown in analytical studies that the response of a structure to ground motion may be adversely influenced if lateral motion in both orthogonal directions is considered. Such analyses were based on models of hysteretic behavior derived from tests in which lateral loading in only one direction was imposed on the test specimen. Some experimental work has been reported on reinforced concrete members subjected to cyclic biaxial bending in which flexural failures were produced. The purpose of this study is to examine experimentally the influence of bidirectional lateral loading histories on short columns and beam-column joints failing in shear. In all the tests, the specimen geometry is constant with loading history the only variable.

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.

Column Tests

To date, a total of 22 columns have been tested. The test specimen is shown in Fig. 1. The test specimen is considered to be a short column framing into rigid floors which are simulated by the large end blocks. Three load cycles are applied at each deflection level. Previous studies have shown that the largest change in response generally occurs between the first and second loading cycles at a given deflection level. If a large change occurs during the third cycle, the specimen is deteriorating rapidly and failure is imminent. In some tests loading histories are imposed in which deformations are applied in both directions simultaneously and axial load is varied. A summary of the initial tests is given in Ref. 1.

Schematic elevation and plan views of the test setup are shown in Fig. 2. The lateral loads are applied with actuators fastened directly to the floor-wall reaction system built at the Civil Engineering Structures Research Laboratory of The University of Texas at Austin for three-dimensional structural loading [Ref. 2]. The vertical load is applied with an actuator which is supported by a structural steel frame braced laterally against the reaction wall and anchored to the floor. The loading and data acquisition are computer controlled. A key feature of the loading system is the hydraulic positioning actuators. The positioning actuators are paired and each pair controls the rotation in a plane.

Beam-Column Joint Tests

Testing of the beam-column joint specimens is scheduled to begin in Summer 1978. A very simple loading arrangement has been developed making use of the strong floor-wall reaction system. As in column tests, the primary variable will be the loading history with specimen geometry remaining constant. The joint will be subjected to various loading histories simulating the application of lateral deformations to the structure in both directions. Variations in axial load on the column will also be studied.

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2. Woodward, Kyle A., and Jirsa, James O., "Design and Construction of a Floor-Wall Reaction System," CESRL Report No. 77-4, Department of Civil Engineering Structures Research Laboratory, The University of Texas at Austin, December 1977.

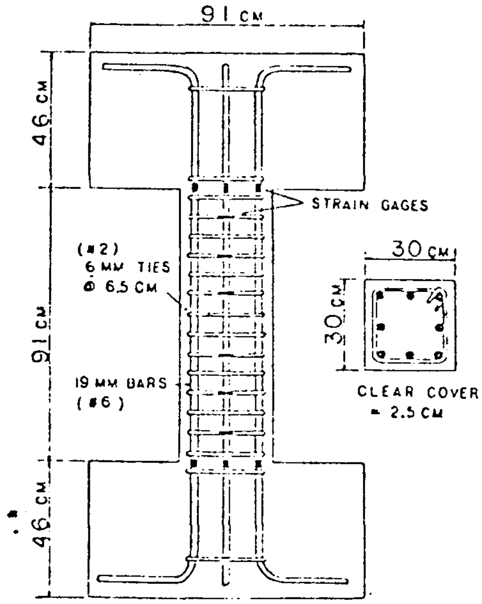
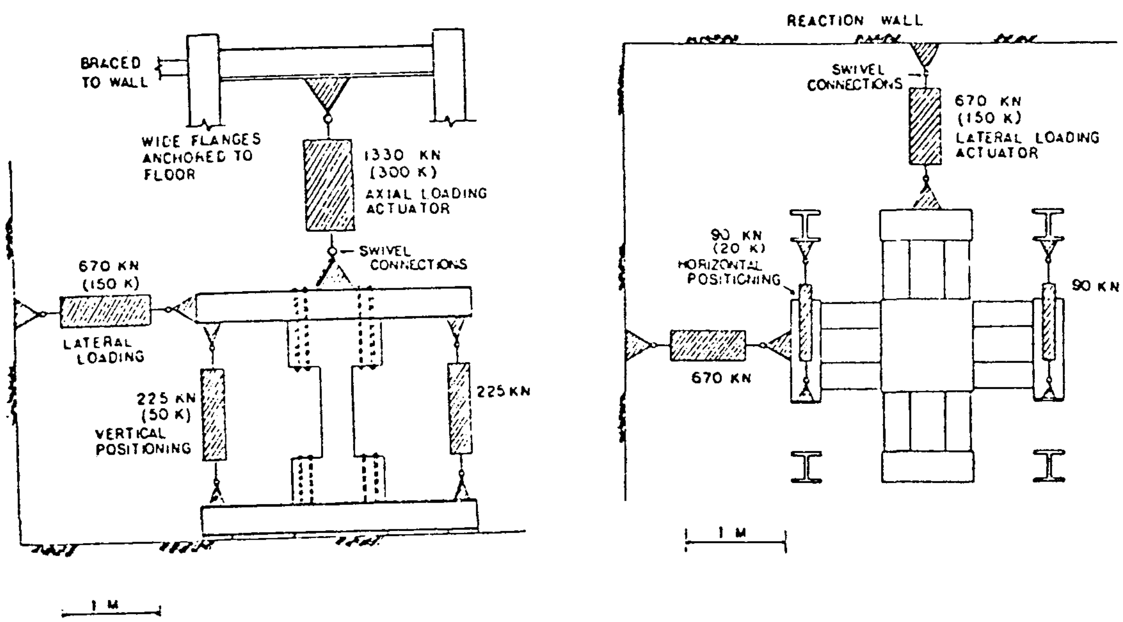


Fig. 1 Test Specimen



Elevation

Plan

Fig. 2 Test Setup

L. G. SELNA

University of California, Los Angeles

An experimental research program on biaxial behavior of building subassemblies is being proposed to the Applied Science and Research Application (ASRA) Directorate of NSF. It is planned for the program to start in November 1978.

Details of Project

The project involves testing of specimens which accurately represent important building components. The objectives of the experimental and analytical research on structural steel and reinforced concrete units are: 1) to investigate the seismic behavior of full scale specimens subjected to coordinated biaxial sway histories and overturning axial force histories; 2) to determine the minimum ratio of column flexural strength to floor system flexural strength which will force the hinging to occur in the floor system; structural steel beam with concrete slab and concrete beam with concrete slab floor systems will be tested; 3) to come up with design rules and simple math models for use by structural engineers concerned with design of buildings.

The research plan is divided into two phases - A and B. In Phase A the biaxial subassembly loading frame will be designed and constructed. Four pilot specimen tests will be performed in order to: 1) calibrate the loading devices and instrumentation, and 2) demonstrate in a preliminary way the importance of the slab to the lateral resistance of the specimens. Phase B will be devoted to the testing of 24 specimens. The ranges in geometric and strength properties of the specimens will be chosen to completely expose behaviors which are typical for prototypes. The principal research objectives will be satisfied by performing these tests.

ALAN H. MATTOCK

University of Washington

Shear Transfer Across a Crack Under Cyclically Reversing Load.

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 may occur in precast concrete connections, at cracks in monolithic construction, or at the interface between concretes cast at different times.

Both monolithic and composite specimens have been tested. In the latter, the shear plane was at the interface between the precast and subsequently cast concretes. In some cases the bond at the interface was deliberately destroyed. A crack was formed in the shear plane before shear was applied. Both small and large-scale tests were made. The concrete adjacent to the shear plane was reinforced so as to prevent failure due to propagation of diagonal tension cracks. The specimens were first subjected to 10 cycles of loading with a maximum shear equal to about half the shear transfer strength under monolithic loading. They were then subjected to groups of five cycles of loading, the maximum shear per cycle being increased after each group of five load cycles, until failure occurred.

The shear transfer strength under cyclic loading of the monolithic specimens, and of the composite specimens with a rough bonded interface, was about 80 percent of the shear transfer strength under monotonic loading, if the initial crack width was 0.015 in. or less. For an initial crack width of 0.025 in., the strength was about 65 percent of the strength under monotomic loading. When the bond at the interface of a composite specimen was destroyed, the shear transfer strength under cyclic loading dropped to about 60 percent of the strength under monotonic loading.

On first loading, shear resistance is primarily developed by interlocking of protrusions on the crack faces. The shear stiffness is very high initially. It decreases as the load is increased and the protrusions are sheared off. When the shear is reduced, the slip does not decrease until the shear drops to about half its maximum value. When the shear is reversed the behavior is similar, resulting in an open hysteresis loop for the first loading cycle. However, for subsequent cycles the stiffness at low values of shear is much reduced, and increases only as the maximum shear for that cycle is approached. This results in a pinched S-shaped hysteresis loop. This behavior is due to the shearing off of protrusions on the crack faces in the first cycle of loading. The remaining protrusions are not re-engaged until maximum shear is again approached.

When the maximum shear was increased at the end of each group of five cycles, additional permanent damage was done to the surfaces of the crack by the shearing off of additional protrusions, and the slip increased. With each cycle of loading, the crack faces were abraided and became smoother. This further reduced frictional resistance to shear which could be developed at low shears, resulting in a further reduction in shear stiffness at low shears.

As the maximum load per cycle increased, both the slip and separation at maximum shear increased. This would lead to the development of larger dowel forces and tensile strains in the rebars crossing the crack. It is therefore probable that at high values of maximum shear, an increasing fraction of the shear is resisted by friction between the crack faces and by dowel action of the reinforcing bars.

The slip at maximum shear tended to increase slightly each cycle, for about the first five cycles. Thereafter, the slip at maximum shear and the shape of the hysteresis loop remained essentially constant for a given maximum shear, until the maximum shear reached a value equal to about 90 percent of the shear which was to cause failure. At and above this shear, the slip at maximum shear increased with each cycle by progressively increasing amounts. The characteristic shape of the hysteresis loop also changed, in that after increasing as the shear increased, the shear stiffness then decreased again as the maximum shear was approached. During these final cycles of loading, the separation at zero shear commenced to increase, also particles of mortar fell from within the crack and finally some compression spalling of the concrete occurred adjacent to the crack.

It is believed that the change in slip and separation behavior was due to local crushing of the crack faces. Some of the mortar particles produced by this local crushing fell from the crack, but it is probable that other particles became trapped in the crack, wedging it open and acting like "ball bearings" when the crack faces moved relative to one another. The wedging action caused separation at all loads to increase. The "ball bearing" action combined with the local crushing of the crack faces was probably the reason for the increasing slips and decreasing shear stiffness at maximum shear, in the load cycles approaching failure.

The shearing off of protrusions on the crack faces in the first cycle of loading, and the damage done to the crack faces during the last few cycles before failure are reflected in changes in the value of the damping factor, calculated as proposed by Jacobsen(1).

$$\beta = \frac{1}{2\pi} \cdot \frac{\text{Area within hysteresis loop}}{\text{Area under "skeleton curve"}}$$

The damping factor for the first cycle of loading was about 0.18. Thereafter it dropped to about 0.10 and remained at this value until shortly before failure, at which point it increased rapidly to 0.22 in the cycle before failure. The significance of the individual numerical values is questionable, but is thought that the trends in variation of the values are of interest. It is also interesting to note that in the last few cycles before failure, the energy dissipated per cycle increased about 300 percent.

The "Effective Shear Stiffness" (slope of a line joining the points of maximum positive and maximum negative shear and slip,) decreases as the number of load cycles increases. Just before failure the effective stiffness is about 10 percent of its initial value. The shear stiffness near zero shear is initially about 40 percent of the effective stiffness. It decreases to about 30 percent of the effective stiffness for the same load cycle, as failure is approached.

This work has been funded by the National Science Foundation. The most recent reports are listed below.[2,3]

1. Jacobsen, L. S., "Damping in Composite Structures," Vol. 2 of Proceedings, 2nd World Conference on Earthquake Engineering, Tokyo and Kyoto, Japan, 1960, pp. 1029-1044.

2. Mattock, A. H., "Shear Transfer Under Cyclically Reversing Loading, Across an Interface Between Concretes Cast at Different Times," University of Washington, Structures and Mechanics Report SM77-1, June, 1977.

3. Mattock, A. H., "Effect of Reinforcing Bar Size on Shear Transfer Across a Crack in Concrete," University of Washington, Structures and Mechanics Report SM77-2, September, 1977.

PETER GERGELY

and

RICHARD N. WHITE

Cornell University

The following is a brief account of the various research projects concerned with earthquake engineering and seismology in the departments of structural and geotechnical engineering and geological sciences.

Shear Transfer in Thick-walled Reinforced Concrete Structures Subjected to Seismic Loadings

The hysteretic sliding shear transfer behavior of cracked concrete containing large reinforcing bars is studied experimentally. Interface shear transfer across cracks, dowel forces, and splitting behavior are evaluated. The results are used in nonlinear dynamic analyses of structures where sliding shear behavior is important, for example in nuclear containment vessels. (R. N. White and P. Gergely; NSF.)

Seismic Shear Transfer in Secondary Containment Vessels

This investigation includes experimental and analytical studies of the dynamic behavior of cracked reinforced concrete containment shells in which sliding shear behavior is significant. The experimental work includes tests with in-plane shear or punching shear loadings on slab-type specimens subjected to simultaneous biaxial tension. The effects of cyclic shear on cracking, reduction of shear stiffness, and capacity are studied. (R. N. White and P. Gergely; NRC.)

Interactive Computer Graphics in Dynamic Analysis

Several structural engineering research projects are conducted in a modern computer graphics laboratory. One of them, on progressive collapse analysis, is gradually developing dynamic analysis capabilities. The structure can be modified interactively after local damage has occurred in three-dimensional frames in order to study progressive collapse. The approach allows visual display of damage, in color, and the study of the effect of damage on subsequent behavior. (W. McGuire, J. F. Abel, and D. P. Greenberg; NSF.)

Behavior of Splices under Cyclic Loading

The behavior of reinforced concrete elements containing spliced bars is investigated for repeated reversed loadings in a pilot study. The ductility and strength as a function of loading history is evaluated for simulated earthquake forces. (P. Gergely.)

Geological Processes along the San Andreas Fault

Strain accumulation and release along the San Andreas fault is studied using the finite element method. The purpose is to learn how strain patterns relate to major plate boundary earthquakes. (D. L. Turcotte, and F. H. Kulhawy; USGS.)

Stress States in Plates

The effect of membrane and thermal stresses on the behavior of lithospheric plates is evaluated using the finite element method. It is planned to study how they may relate to global earthquake occurrence. (D. L. Turcotte and F. H. Kulhawy; NSF.)

Soil Behavior

Experimental studies have been and are being conducted to determine the repeated loading behavior of saturated clay soils. The goal is to determine their response to earthquake excitation. (D. A. Sangrey; NSF.)

In-Situ Soil Evaluation

Theoretical, experimental, and field investigations are being conducted to develop an in-situ device for evaluating the liquefaction potential of soils. With this device, simple field measurements may be made to determine soil response during earthquakes. (D. A. Sangrey and F. H. Kulhawy; NSF.)

Microzoning

Analytical studies have been conducted to evaluate how geological and historical data can be utilized to provide microzonation guidelines. This approach can be of use for planning studies. (F. H. Kulhawy.)

Seismotectonics of Subduction Zone: Intensive Field Studies of the New Hebrides Island Arc, and Global Studies of the Earth's Benioff Zones

New observations of the spatial distribution of earthquakes in relation to focal mechanisms and tectonic processes in a subduction zone will be made. The program includes high-resolution determination of detailed geometry and deformation in the New Hebrides island arc, and broad-scale regional syntheses of the best available data for comparative studies on a global basis. (B. L. Isacks and M. Barazangi; NSF.)

Recent Vertical Movements of the Crust in the Western U.S.: Reduction Analysis of Leveling Data and Its Interpretation in Light of Related Seismological and Geological Information

The objective of this research is to improve our understanding of seismic phenomena in the western United States and Alaska. Investigation of recent vertical crustal movements as delineated by comparison of precise leveling surveys and interpretation of data in northern California, the West Coast, the Rocky Mountains in central Colorado and southwestern Wyoming. (J. E. Oliver; USGS.)

Recent Vertical Crustal Movements: The Eastern United States

Study of vertical motions on both the regional and local scale. Integration of geological and geophysical as well as geodetic results to delineate patterns of possible neo-tectonic activity, discriminate tectonic from non-tectonic elevation changes, and evaluate the potential geologic hazard. (J. E. Oliver and L. D. Brown; NRC.)

Study of the Generation and Propagation of High Frequency Seismic Phases (including Pn, Sn, and T) in the Oceanic Lithosphere from Earthquake Sources Beneath Seismically Active Continental Margins and Island Arcs

The high-frequency seismic phases Pn, Sn, and T can be efficiently excited by earthquakes, particularly by those occurring in the very active subduction zones bordering much of the world's oceans. Earthquake activity in subduction zones may generate a significant part of the acoustic and seismic noise in the 1-20 Hz frequency bandwidth. (J. E. Oliver and B. L. Isacks; ONR.)

Fine Structure of the Crust and Upper Mantle from Analysis of Seismic Reflection Records

The investigation includes the collection and comparative analysis of selected deep seismic profiling results and some selected shallow results from both domestic and foreign sources, the formulation and testing of geologic models for the deep crust by computation of their seismic response, comparison with observed seismograms, and corrections for the disruptive influence of near-surface geologic variations upon deep seismic reflection results. (J. E. Oliver and S. Kaufman; NSF.)

Seismic Reflection Profiling to Determine Fine Structure of the Crust and Upper Mantle

Application of modern high-resolution seismic profiling methods of the petroleum industry to studies of the continental crust and upper mantle. Several sites have already been successfully surveyed in the U.S. (J. E. Oliver and S. Kaufman; NSF.)

Tilt Measurements in the New Hebrides Island Arc: Search for Precursors and Other Aseismic Deformation Related to Earthquake Generation in a Zone of Lithosphere Subduction

This work includes the operation of a network of 8 tilt meters, releveling of two arrays of benchmarks, studies of vertical motions recorded naturally by sea-level variations in the coastal tidal zones, and studies of seismicity based on teleseismic data and on data from temporary deployment of local seismograph networks in New Hebrides. (B. L. Isacks; USGS.)

Numerical Modeling of Tsunamis

The dynamic phenomenon of gravity waves generated by earthquakes and their effects on coastal facilities, including the influence of dispersion and nonlinearity, are investigated. The capability will include the analysis of tsunami generation by arbitrary sea floor displacement, propagation over variable water depth, amplification near coastal regions, and the effects on coastal structures. (P. L-F. Liu and J. A. Liggett.)

JAMES K. WIGHT

The University of Michigan

This report summarizes two experimental investigations of the behavior of reinforced concrete members under earthquake type loading.

The primary objective of the first investigation (1) was to determine the ability of intermediate longitudinal reinforcement to prolong the stable hysteresis action in reinforced concrete members subjected to large load reversals. To satisfy this objective, twelve T-shaped beam to column subassemblies were tested. Variables for the beam included the shear span to depth ratio which varied from 3.6 to 5.0, the longitudinal reinforcement ratio which varied from 1.27 percent to 2.62 percent, the transverse reinforcement ratio which varied from 0.63 percent to 1.1 percent, and the inclusion of intermediate longitudinal bars in half of the specimens. The intermediate longitudinal bars consisted of four bars placed in two layers at approximately the third points between the tension and compression reinforcement. The area ratio of intermediate to main reinforcement was approximately 0.25.

In general, the use of intermediate longitudinal bars together with vertical ties provided better confinement within the beam "hinging zone". The improved confinement prolonged stable hysteretic behavior and increased energy dissipation in comparison with members having only vertical ties. The percentage increase in energy dissipation for the specimens with intermediate longitudinal bars above that for specimens without the extra bars was clearly related to the maximum shear stress level experienced by the member. Beams with shear stress levels of less than $3\sqrt{f'_c}$ showed primarily flexural behavior and the use of intermediate longitudinal bars had very little effect. For beams with maximum shear stress levels between $3\sqrt{f'_c}$ and $6\sqrt{f'_c}$, the specimens with intermediate longitudinal bars dissipated an average of 27 percent more input energy. For beams with maximum shear stress levels greater than $6\sqrt{f'_c}$ the specimens with intermediate longitudinal bars again showed a 30 percent increase in energy dissipation capacity. However, even with this improvement, all beam specimens at this shear stress level were unable to endure enough load cycles to satisfy a consensus of criteria for acceptable behavior.

Buckling of the beam compression reinforcement was a significant factor in limiting the load carrying capacity of the majority of the specimens tested. The nature of the buckling noted in the specimens indicated that stirrup stiffness was more important than stirrup spacing in preventing buckling of compression reinforcement. Criteria should be developed to specify the size (stiffness) of stirrup bars in a beam plastic hinging zone, when used at the maximum allowable spacing of d/4, as a function of the size of the longitudinal bars.

The primary objective of the second investigation (2), which is directed by Professor Wadi S. Rumman, was to study the behavior of hollow circular reinforced concrete cross sections under cyclic reversals of flexure. The experimental work, which was the main part of the study, was made on eight cylinders that were 128" long, 16" outside diameter, 2" thick and reinforced by both longitudinal and circumferential steel. Four cylinders were tested for monotonically increasing bending and four other identical specimens were tested for reversed cyclic loading. In all cases an axial load was applied as is normally encountered in structures of hollow circular sections such as reinforced concrete chimneys, intake-outlet towers bridge piers and offshore platforms.

Theoretical work (3) has shown that ultimate strength, cyclic behavior and ductility can be described in terms of two dimensionless parameters namely the axial load parameter and the longitudinal steel parameter. The axial load parameter is expressed as W/rtf_c' where W is the axial load, r is the mean radius, t is the thickness and f_c' is the concrete strength. The longitudinal steel parameter is $\rho\ fsy/f_c'$ where ρ is the steel ratio and fsy is the yield stress of the steel. Two variations in each of these parameters were made in the experimental investigation.

The future goal of the research coupled with the theoretical investigations will be to establish simple but realistic moment-curvature relationships for reinforced concrete hollow circular sections in terms of the two dimensionless parameters. These relationships will be needed to study the response of reinforced concrete structures of hollow circular sections when subjected to severe earthquakes.

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2. Mokrin, Zamil, "Experimental Study of Reversed Cyclic Behavior of Reinforced Concrete Members with Hollow Circular Cross Sections," Ph.D. Thesis under preparation at The University of Michigan, Ann Arbor, Michigan.

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S. M. UZUMERI

Department of Civil Engineering, University of Toronto

Two experimental and associated analytical studies are in progress: (a) Effectiveness of rectangular ties as confinement steel in reinforced concrete columns, and (b) Behaviour of reinforced concrete beam-column joints under slow load reversals.

(a) Effectiveness of Rectangular Ties as Confinement Steel in Reinforced Concrete Columns

The knowledge of the complete stress-strain relationship of concrete is important for the prediction of the behaviour of reinforced concrete members. For plain concrete generally acceptable approximate relationships have been proposed. Passive confinement from lateral reinforcement change the behaviour of concrete.

Twenty-four reinforced concrete columns (12 x 12-in. cross section, 6-ft. 5-in. height) were tested under monotonically increasing compressive load to examine the effect of rectangular ties. Four different tie arrangements, resulting from different distributions of the longitudinal steel in the section, were studied. Other test variables included tie spacing, amount of lateral and longitudinal reinforcements and the stress-strain characteristics of the lateral reinforcement.

Rectangular lateral reinforcement is observed to enhance the strength and ductility of the confined concrete. The distribution of the longitudinal reinforcement around the core perimeter increases the efficiency of the confinement. A smaller spacing of ties results in higher concrete strength and ductility for the same amount of lateral reinforcement and vice versa. A higher confining pressure (higher steel stress and larger amount of lateral reinforcement) results in higher strength and ductility of concrete.

An analytical model was proposed on the basis of observed response from the experiment. The model includes the effect of experimental parameters. The work was carried out by Shamim Sheikh.

(b) Behaviour of Reinforced Beam-Column Joints Under Slow Load Reversals

Nine beam-column subassemblages were tested to examine the behaviour of joints under reversed cyclic loading. Both, height of the column (15 x 15-in. section), and the distance from the point of application of the beam tip load (12 x 20-in. or 15 x 20-in. section) to the centre line of the column, were 10 ft. An axial compression force ranged from approximately 10 to 80 per cent of ultimate pure axial load capacity. The transverse reinforcement within the joint area was varied between none to 1.6 times the amount specified by the ACI-352 Committee recommendations.

Within the limitations of the test program, the following conclusions may be drawn from the results of these tests:

- Magnitude of the column axial load had negligible effect in the stiffness and the degradation of the strength of the sub-assembly. (Figure 1)
- The crack pattern in the joint is influenced by the axial load level. Flattened cracks are observed for lower levels of column axial loads.
- The level of the column axial compression did not significantly affect the yield penetration along the straight lead embedment. (Figure 2)
- To ensure that the plastic hinge should form in the beam, the computation of the column strength should be based on the strength of the column core area only and the contribution of the cover concrete should be disregarded.

The analytical work is currently being carried out by M. Seckin, and soon to be completed.

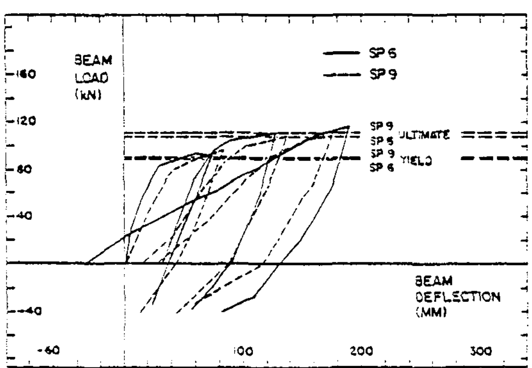

Fig. 1: Comparison of Behaviour of SP6 and SP9

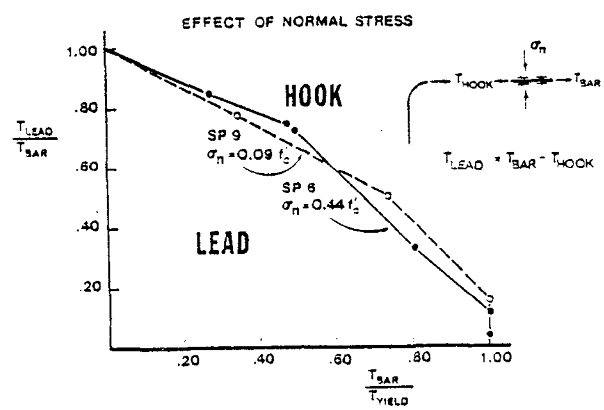

Fig. 2: Lead vs. Hook Contribution Interaction Diagram

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2. SECKIN, M., and UZUMERI, S.M., "Examination of Design Criteria for Beam-Column Joints", 6th European Conference on Earthquake Engineering, Yugoslavia, 1978.
3. UZUMERI, S.M., and SECKIN, M., "Behaviour of R/C Beam-Column Joints Subjected to Slow Load Reversals", Report 74-05, Department of Civil Engineering, University of Toronto, March, 1974.

MICHAEL P. COLLINS

Department of Civil Engineering, University of Toronto

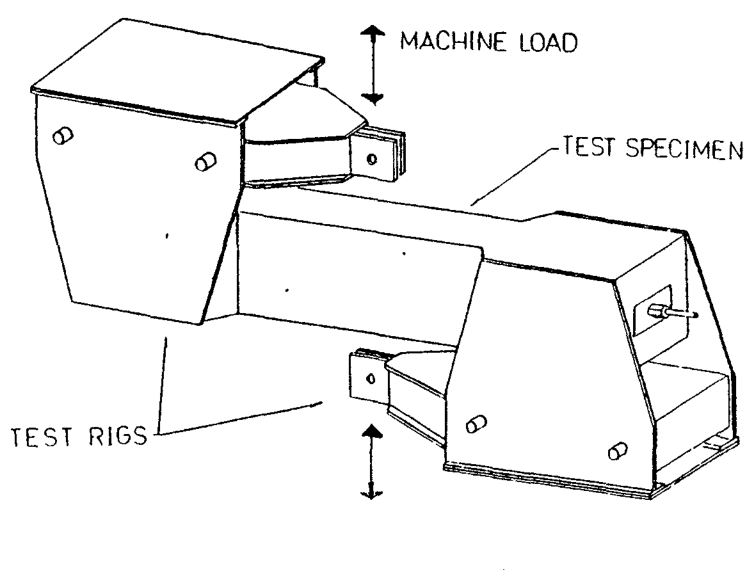
The following is a brief description of research on predicting of the shear and torsion response of reinforced concrete members subjected to load reversals.

The objective of this research program is to extend the compression field theory [1,2] so that it is capable of predicting the response of reinforced concrete members under repeated and reversed shear and/or torsional loading.

The test rig shown below has been used to test large column-like members under axial load and reversing shear. The axial load was supplied by Dywidag bars passing axially through the members while the shear was applied by a 220 kip MTS testing machine. The machine load was introduced via steel side plates which were connected to the specimen by 24 high strength friction bolts. This loading scheme produced a uniform distribution of shear cracks and avoided a "corner to corner" failure pattern.

Before the compression field theory can be used to predict the behaviour of the tested members it is necessary to have appropriate stress-strain relationships for the diagonally cracked concrete. Preliminary results would seem to indicate that stress-strain curves obtained by subjecting concrete cylinders to load reversals can not be used to predict accurately the behaviour of the diagonally cracked concrete.

To obtain more basic information on the stress-strain characteristics of diagonally cracked concrete subjected to load reversals, we are presently constructing a "pure shear" test rig. In this rig 36" x 36" x 3" reinforced concrete panels will be loaded by 40 double acting jacks so as to produce a state of pure shear across the panel.



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W. K. TSO

McMaster University

The following areas of research are supported by the National Research Council of Canada.

Dynamic Interaction of Interior and Exterior Coupled Shear Walls in High Rise Apartment Buildings

Typically the internal shear walls are coupled through the floor slabs (weakly coupled) while the end shear walls are coupled by deep beams (strongly coupled) in a flat-slab shear wall building. In the present study, a study is made on the behaviour of these walls during earthquakes. A time history dynamic analysis is carried out and inelastic action of the lintel beams between the shear wall is taken into account. Since the development of inelastic hinges along the coupled shear walls affected their stiffnesses, the proportion of inertial loads acting on the internal and external walls does not remain constant, but vary throughout the duration of the earthquake because of varying stiffness of the walls as a function of time. The parameters of interest in this study are: base moment and axial force of the wall, the shifting of inertial loads on the internal walls and external walls, the top deflection, and the pattern of inelastic hinges along the height of the coupled walls. Comparison has been carried out to evaluate the effect of the shifting of inertial loads between the two types of walls.

Torsional Response of Asymmetrical Structure Subjected to Simultaneously Applied Horizontal Ground Motions

A study is made on the estimation of the total responses of asymmetrical structures subjected to simultaneously applied horizontal ground motions. The total response is computed as the square root of the sum of the squares (RSS) of the uni-directional response. Preliminary calculation using El Centro 1940 and Taft 1952 as two typical seismic excitations on an asymmetrical structure shows that the RSS method of combining unidirectional responses is in general non-conservative when compared with the bi-directional excitation of the same structure. It appears that the phasing of the records has a large effect. Current effort is directed towards developing an indicator to measure the severity of combined bi-directional excitations.

TI HUANG

Lehigh University

Research work on the contribution of floor systems to the earthquake resistance of steel and concrete building structures is being conducted at Lehigh University under the sponsorship of the National Science Foundation - RANN. Behavior of various floor systems under repeated and reversible lateral loads is being studied. The ultimate goal of the investigation is to develop improved guidelines for seismic design of multistory building structures, with proper consideration of the structural effect of the floor systems either as parts of the primary lateral load system or as load transmitting diaphragms between several lateral load systems. More specifically, research objectives include the following:

1. To perform a critical review of the present state-of-the-art in the understanding of the behavior of floor systems in multistory building frames under earthquake loading.
2. To determine the structural characteristics of various floor systems under lateral repeated and reversible loads combined with gravity loads.
3. To define the effects of various floor systems in the transmission of earthquake loads either as diaphragms or as elements in the primary lateral load system.
4. To identify the primary parameters controlling the behavior of floor systems under combined seismic and gravity loads.
5. To formulate guidelines for seismic design taking into consideration the continuation of the floor systems.

Scope

Five commonly used floor systems are included in this study:

For Concrete Buildings:
- Flat plate and flat slab systems
- Solid slabs supported on edge (and intermediate) beams
- Slabs on closely spaced joists, including waffle slabs and grid systems

For Steel Building Structures:
- Solid concrete floor slab systems, with or without composite action with the supporting steel beams
- Concrete slab on metal deck floor system, with or without composite action with the supporting steel beams

Literature Study

An extensive survey has been made of the available literature dealing with the behavior and strength of various floor systems used in both steel and concrete buildings. Although much has been published on the behavior of floor systems in conjunction with beams and columns under gravity load, very little information has been found on their lateral load behavior. Connections between concrete floor and shear wall, and interaction between metal deck concrete slab and steel girder under lateral loads also appear to be areas where information is lacking.

Experimental Study

Work up to this point has been primarily concentrated on the experimental phase. A basic specimen configuration has been adopted, consisting of three consecutive square floor panels, supported on various combinations of columns and shear walls. At all exterior edges supported on columns, a quarter-span extension of the floor system is used to facilitate the anchorage of slab reinforcements and to approximate the location of lines of contraflexure.

Specimens for two floor systems have been designed, the flat plate and the slab on edge beams. They are both based on a prototype structure with 24 ft. column spacings and 12 ft. floor heights. A scale ratio of 4.5 to 1 has been chosen to conform to the floor anchor pattern in the flexural test floor of Fritz Engineering Laboratory. Both specimens are designed in accordance with ACI 318-77, with slab reinforcement proportioned for vertical (live and dead) loads only. Future specimens may have additional or redistributed reinforcement to provide improved lateral load resistance.

Specimens will be tested under a simulated uniformly distributed gravity load and a distributed lateral load. The loading and supporting conditions will be varied as listed below:

1. Gravity Load: Service dead load or full service load
2. Lateral Load: Monotonic or repeated with full reversal
3. Column Base: Sliding, with or without restraint to twisting, or fixed

Several of these tests may be carried out using the same specimen slab panel. By making these tests in an appropriate sequence, it is felt that meaningful information can be obtained for each of the support and load conditions.

Much of the loading and supporting fixtures are specially designed and fabricated. The first pair of specimens, of the flat plate type, are being fabricated at this time. Testing is scheduled in the later part of this summer.

M. L. PORTER and L. F. GREIMANN

Iowa State University

The earthquake resistance of composite floor diaphragms is being investigated under a National Science Foundation grant.

Program Overview

Steel-deck reinforced composite slabs with in-plane shear forces are to be investigated analytically and experimentally. Tests are to consider such behavioral characteristics as failure mode, maximum loads, ductility and degrading stiffness. Concrete and steel deck configurations are parameters to be varied which will affect these characteristics. Composite floor slabs with and without welded stud shear connectors will be tested. Welded seam joints and edge connections are to be utilized. Other parameters which affect the diaphragm behavior may be isolated.

Effects of gravity load on in-plane shear behavior will also be investigated. Initially, a series of one-way slab elements with stud shear connectors will be tested with vertical load only to study the effect of studs on shear-bond strength. Composite deck tests with combinations of in-plane shear and vertical load will follow.

An analytical model is to be developed which relates the significant diaphragm parameters to the behavioral characteristics. A nonlinear finite element model is anticipated which includes such features as nonlinear concrete behavior, orthotropy, and shear at the concrete/steel interface. Tenative design-type equations which predict gross behavior are to be formulated.

Current Status

A cantilever-type test fixture has been fabricated which is used to apply the in-plane shear forces to the diaphragm specimens. Associated instrumentation and closed-loop control systems have been assembled and checked out.

Two identical 15 ft. square specimens have been fabricated and tested. Both specimens had a 3-inch deep steel deck with a 5 1/2-in. concrete cover. Shear studs were used on the perimeter to connect the diaphragm to the edge beams. The first specimen was loaded essentially monotonically to a maximum displacement of about eight times the displacement at the ultimate load. A diagonal tension crack, running from corner to corner, occurred at the ultimate load. The specimen was unloaded, cycled three times at low loads and loaded in the opposite (negative) direction. At the maximum negative load, a diagonal crack formed perpendicular to the original crack. The load program for the second specimen was principally cyclic consisting of a series of three cycles between progressively increasing plus and minus displacement limits. Displacement limits were increased to a ductility of about eight. Failure of the second specimen was also characterized by perpendicular diagonal cracks running from corner to corner.

The envelopes of the in-plane load-displacement curves for the two specimens are shown in the figure below. For this specimen configuration, the envelopes are almost identical. Based on a preliminary assessment, the repeated cyclic load did not affect the strength of the diaphragm. Within the limits of the test (maximum displacement of approximately eight times yield), both specimens exhibited similar ductility and degraded stiffness behavior. In both cases the loads at large displacements dropped to approximately two thirds of the maximum strength.

Future Plans

Additional in-plane shear tests are planned with different specimen parameters. Results will be studied to compare and quantify ultimate strength, ductility, and stiffness for cyclic and monotonic loads. Work is beginning on the analytical phase. One way slab elements are to be tested and analyzed.

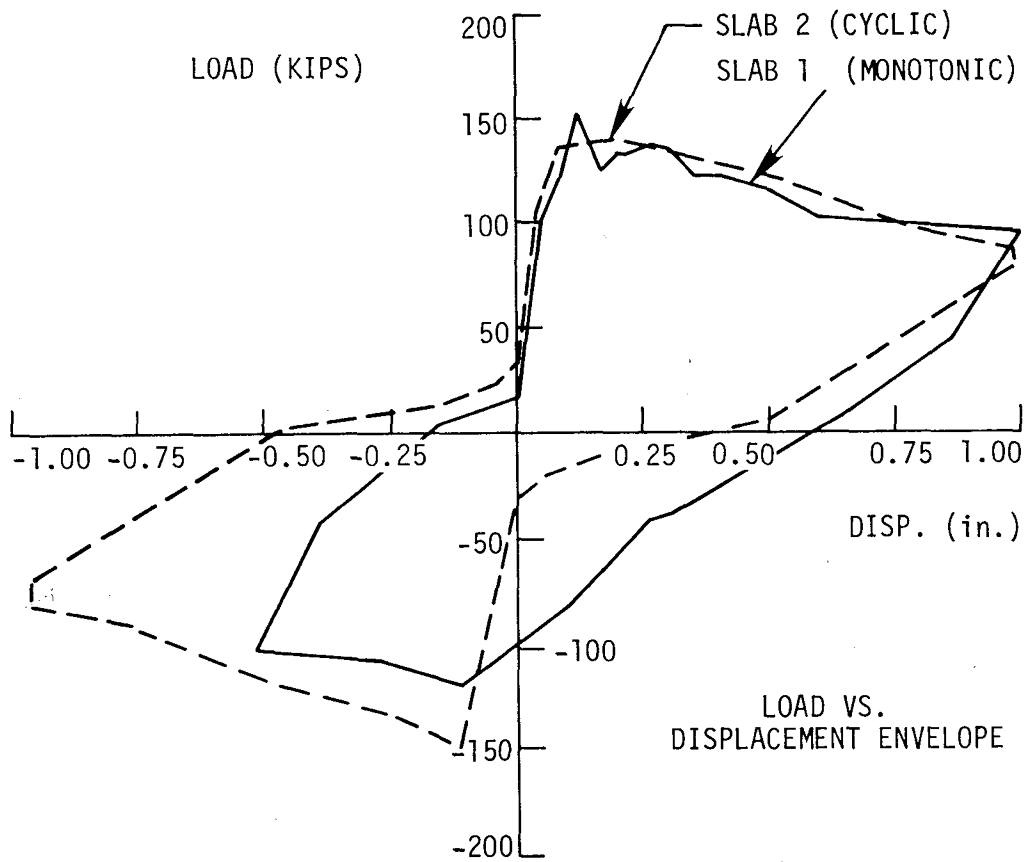

FIGURE. LOAD-DISPLACEMENT ENVELOPES FOR DIAPHRAGM ONE AND TWO

M.S. MIRZA, D. MITCHELL, B. STAFFORD SMITH and G.R. THOMAS

McGill University

This paper summarizes the objectives and findings of three research projects in Earthquake Engineering being conducted at McGill University.

1. Response of Reinforced Concrete Wall-Frame Systems (Mirza, Mitchell, Thomas)

An experimental program has been initiated in which the reversed cyclic response of reinforced concrete models is being studied. A series of tests on frames, walls and combined systems is underway. The objective is to study the interaction of frames and walls under reversed cyclic loading and free vibration tests on single and multiple storey structures. The free vibration tests are conducted at various levels of damage to enable correlation with stiffness and energy dissipation measured in the reversed cyclic static procedure.

Analytical studies are being conducted in parallel with the experimental programs to predict the behaviour of combined systems to general ground motion. Emphasis is being placed on the understanding of the wall-frame interaction during severe earthquakes.

2. Hysteretic Behaviour of Reinforced Concrete Shear Walls (Stafford Smith, Mitchell)

An experimental and theoretical project is under way to study the behaviour of simple reinforced concrete shear walls under reversed cyclic loading. The initial stage consists of a test on a one-fifth scale shear wall designed in accordance with the Canadian National Building Code and subjected to axial load, shear and moment in ratios calculated to represent those on a ten-storey apartment building. A detailed study is being made of the hinge formation and wall displacements.

Rather than extending current research efforts on shear walls, the purpose of the project is to retrace the steps of previous studies and to re-examine the fundamental characteristics and parameters of shear wall behaviour. The results of the study will help to confirm or, perhaps, question the definitions of, and emphasis currently being placed on these parameters. A more thorough understanding of these parameters and their relationship to the response of shear walls is, of course, crucial for the further development of methods for predicting the seismic behaviour of shear wall structures.

The first specimen is to serve as a pilot for the planning of subsequent series of tests. The tentative plan for the next stage of the programme is to investigate the influence of different levels of axial stress on the hysteretic bending behaviour.

The tests are on one-fifth scale walls with a cross-section of 36 in. x 3 in. They are constructed and tested in a horizontal position with shear loads applied vertically. A foundation clamping block is cast integrally with the base and the 8 ft. high wall is extended to an effective height of 14 ft. by a reusable bolted-on steel truss. The purpose of this is to achieve a more realistic moment: shear ratio at the base of the wall. The test model and arrangement was based on previous work at the PCA laboratories, with modifications to allow reversed loading.

3. The Diaphragm Connection of Concrete Slabs and Steel Beams by Stud Shear Connectors (Mitchell)

This project is a continuation of a series of tests conducted at the University of Washington to determine the behaviour of shear connections between concrete slabs acting as diaphragms and steel beams under reversed cyclic loading. The main variables under investigation are:-

(1) Solid concrete slab vs. slabs with ribbed metal deck,
(2) Geometry of the ribbed metal deck,
(3) Orientation of the ribbed metal deck (ribs parallel or perpendicular to the beam), and
(4) Loading history.

Companion pushout specimens are tested monotonically to compare reversed cyclic loading and monotonic responses. Initial findings indicate that solid slab specimens and specimens with the metal deck parallel to the steel beam exhibit reversed cyclic load resistances of approximately 80 percent of the monotonic strengths. These connections failed by shearing of the studs and exhibited ductile failures with good energy absorbing hysteretic responses. The monotonic and reversed cyclic loading responses of two solid slab pushout specimens are compared in Fig. 1. Specimens with the ribbed metal deck perpendicular to the steel beam failed by pullout of the studs exhibiting brittle failures (approximately 70 percent of the monotonic capacities) with poor hysteretic responses. It is hoped that the results of these test may offer guidance to the designer in deciding on the orientation of ribbed metal deck in floor diaphragms. An analytical study is planned in order to determine the effect of the reverse cyclic shear response of stud connectors in floor diaphragms.

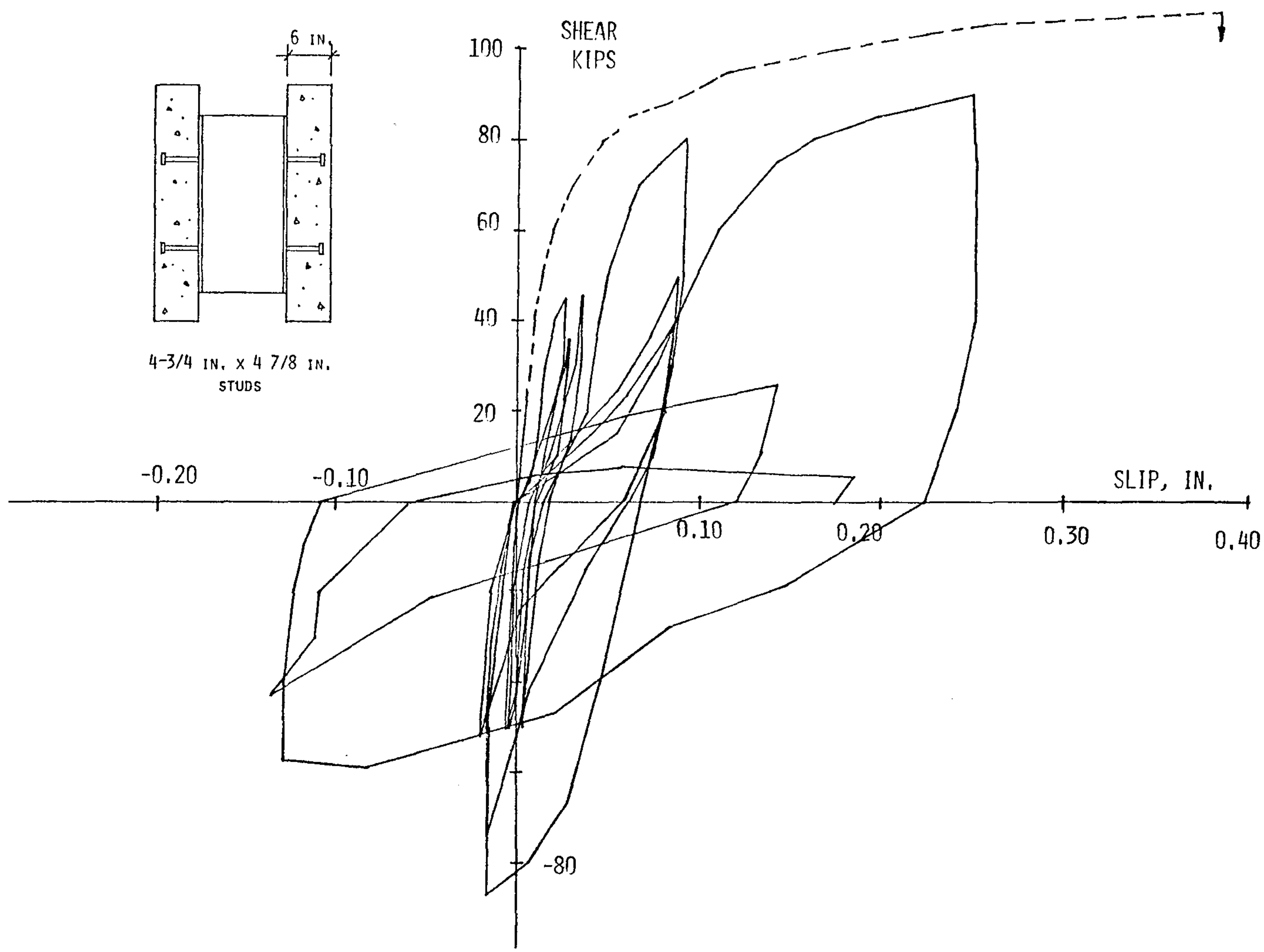

FIG. 1 Comparison of Monotonic vs. Reversed Cyclic Loading Response of Pushout Specimens Tested at McGill University.

C. W. ROEDER

University of Washington

A program of study to investigate the seismic resistance of mixed steel and reinforced concrete structures is in progress at the University of Washington. The mixed structure is formed by combining a steel moment-resisting space frame with reinforced concrete shear walls. The ultimate objective of this study is to determine the elastic and inelastic behavior of such a structural system; to develop analytical models to predict its behavior; and, to utilize design techniques which can improve the seismic resistance of the structure. The present scope of this study is primarily concerned with analyzing the system and developing suitable connection details for connecting the separate components. Experimental studies are also being performed to determine the elastic and inelastic behavior of these connections.

The Mixed Structural System

The proposed system is formed by combining reinforced concrete shear walls with a steel moment-resisting space frame. It is believed that this structure could offer considerable potential as a seismic resistant structure. The lateral stiffness of the shear wall should result in substantial economic savings in weight of steel over a purely steel frame, because the shear wall will effectively limit the story drift. Steel moment-resisting frames are usually ductile and they are expected to enhance the inelastic behavior and energy dissipation of the shear wall. In particular, the very stable stiffness and hysteretic behavior of a well-designed steel frame should help control the dynamic response of the structure in later cycles after the shear wall has started to deteriorate.

Further economies are expected by using non-structural concrete in the building to form the shear wall. For example, the concrete used in the fire protection of stairwells or elevator shafts could also be used to form the shear wall as shown in the floor plan of Fig. 1. Alternately, the shear wall could be formed by solid end walls as shown in Fig. 2. A series of preliminary designs are in progress for several alternate mixed structures. These designs are being analyzed by a linear elastic static analysis to refine the designs and pinpoint potential problem areas. Several of these analyses have been completed, and they indicate that the connection of the steel frame to the concrete shear wall is one definite problem area. As a result, a detailed study of several connections is under way. This study is discussed in greater detail in the next section.

Inelastic analyses of several prototype structures are also planned. These models would be developed from experimental results from tests on the separate steel and reinforced concrete components. These analytical results would be used to predict the possible behavior and interaction between the components. These analyses would also provide the basis for further experimental study.

Connection of the Individual Components

The connection of the steel space frame to the concrete shear wall is one, if not the most, critical parameter in the design of this mixed structure. Several alternate connection details are being considered. The first detail to be considered is obtained by imbedding a metal plate into the shear wall with headed metal studs as shown in Fig. 3. The beam is then connected to this plate by means of a bolted erection plate which is welded to the imbedded plate. If moment resistance is desired, the flanges of the beam are also welded to the plate. With this type of connection, the metal studs are exposed to both tensile and shear forces, but the tensile capacity is limited and a sudden brittle failure of the connection can occur. Some experimental [2,3] studies have been made at the University of Washington to evaluate the combined shear and moment capacity of stud connection. One major conclusion from these studies is that the stud connection is ductile when the shear force is high and the bending moment is low. Brittle connection failure may occur when the moment in the connection becomes too large.

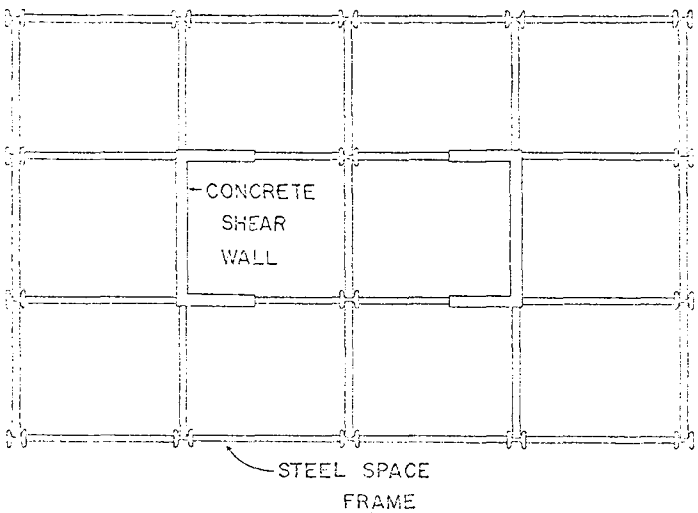

Figure 1.

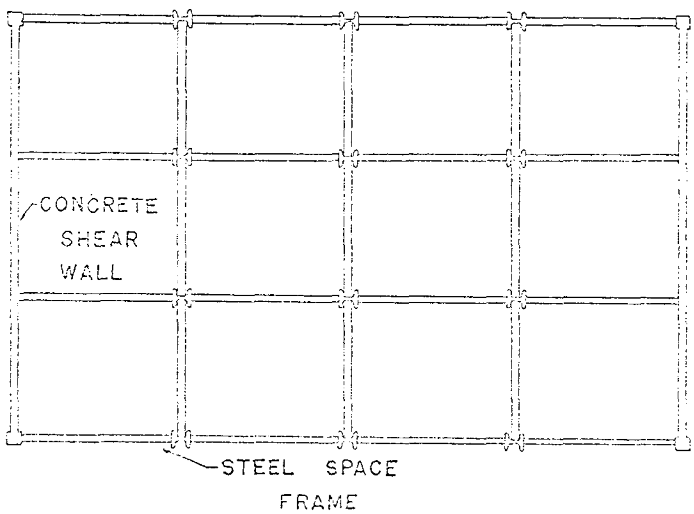

Figure 2.

Therefore, a series of analytical and experimental studies are being made to determine the optimum connection detail. Since the studs are ductile when the shear force is high and are brittle when the moment is high, a pin-type connection is desirable. This connection is formed as shown in Fig. 3. It is similar to the typical shear connection used in steel frame design. For design purposes, this connection is assumed to be nearly a pin connection. However, studies of bolted connections [5] show that substantial bending moment may be transferred by the bolts before sufficient rotation occurs to simulate a pin. If the connection is to be ductile, the studs must resist the transferred moment. Based on existing studies [1,2,3,4], a proposed design procedure has been developed, and a series of full-scale tests are in progress to evaluate this procedure.

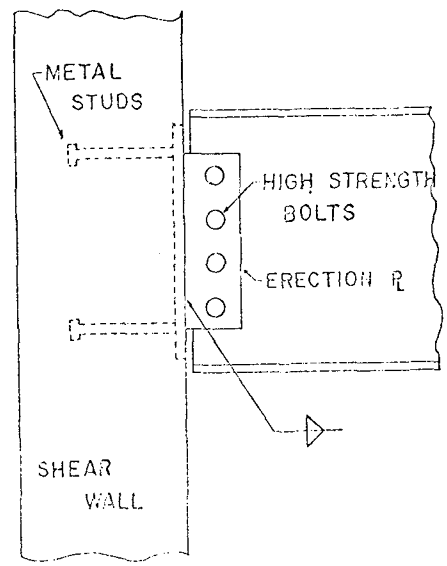

Figure 3.

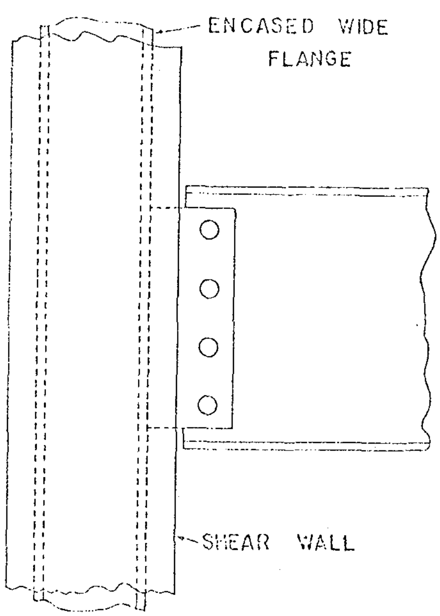

Figure 4.

Studies are also planned for other possible connections. The previous connection is probably most suitable for construction where the shear wall is built first by slip-forming construction and the steel frame is erected and attached later. An alternate construction method would be to erect the steel frame first, and then construct the shear wall. This latter type of construction would require a steel wide flange as a temporary column to support the ends of the steel structure. This temporary column would then be imbedded into the concrete shear wall as longitudinal reinforcement, as shown in Fig. 4. The actual connection detail would be very similar to those typically used in all steel structures; however, methods are needed to assure adequate bond between the concrete and wide flange, to assure composite action and to fully develop the tensile capacity of the wide flange. An investigation of the alternate connection is also planned.

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SUBHASH C. GOEL

The University of Michigan

This paper summarizes a current research program concerning the hysteresis behavior of bracing members and earthquake resistant design of braced frame structures of steel along with an associated study of torsion in 3-Dimensional Structures. Principal investigators are Professors Glen V. Berg, Robert D. Hanson and Subhash C. Goel. The research project is mainly sponsored by the National Science Foundation with a partial support from the American Iron and Steel Institute.

BRACING MEMBERS AND BRACED FRAMES

Objectives

The main objectives of this research are:

1. To study the hysteresis behavior of steel bracing members and connections by theoretical and experimental means.
2. To formulate suitable hysteresis models for such members to be used in computing the inelastic dynamic response of braced structures.
3. To formulate design recommendations for improved seismic resistance of braced frame structures.

Previous Research

Studies of the seismic behavior of bracing members and braced frames have been in progress at the University of Michigan for some years now. In an earlier study Prathuangsit (1) analyzed the cyclic behavior of axially loaded members with rotational springs at the ends to simulate the restraint provided by end connections. Prathuangsit concluded that the effective slenderness ratio is the most important parameter in governing the hysteresis behavior of these members. Singh (2) developed a simple multi-linear hysteresis model which uses the effective slenderness ratio as the main parameter. The coordinates of control points utilize empirical coefficients which are based on earlier experimental results by Kahn and Hanson (3) on small bar specimens of 1"x1/2" cross-section. Singh used his hysteresis model to study the effect of column uplift on the seismic response of a six-story braced structure.

Current Research

Recently, Jain (4) studied the hysteresis behavior of eighteen small-scale 1"x1"x0.1" square tubular specimens. These specimens were either directly welded to the end plates or utilized gusset plates for end connections. Similar tests have just been completed on six small-size single angle specimens which were direct welded to the end plates. The purpose of these small scale test was to check the validity of previous theoretical results as well as to study the influence of local buckling on the hysteresis behavior. While these results are in general agreement with the theoretical results some differences have also been noticed. These are with respect to influence of local buckling, strength degradation and "column growth" phenomenon on the hysteresis loops. Based on a quantitative analysis of the test results a modified hysteresis model is proposed which includes these characteristics in an empirical manner. Nevertheless, this model needs to be checked against test results of real size bracing members and connections which is discussed in the following section of this paper.

As part of his doctoral dissertation (4), Jain has also completed a theoretical study of the behavior of several concentrically braced frames (X and K) and frames with split-K bracing in the category of eccentric type. These frames were analyzed elastically and inelastically due to monotonically applied horizontal forces. Three split-K frames were also designed by current UBC procedure and subjected to 1.5 times the intensity of El Centro 1940 ground motion. The main variables were the relative strengths and stiffnesses of girders and bracing members. The results of this study reveal some very interesting aspects of the behavior of concentric and eccentric braced frames. The study is helpful in determining conditions under which the bracing members can be modeled as rigid-ended non-buckling, pin-ended buckling or rigid-ended buckling type. Relative merits and demerits of the performance of braced frames with different proportions are also studied.

Further Research

Our studies of the hysteresis behavior of bracing members thus far have been limited to members in which the axial displacement is applied in a direction parallel to their longitudinal axis. Also due to the limited capacity of loading equipment only small scale specimens with cross-sectional area under 1 in^2 could be tested. Next phase of this research project deals with nearly full-size members with realistic connections in which the member axis is inclined at an angle of approximately 45^o to the direction of end displacement.

One doctoral student has initiated theoretical study of such members. The method of analysis utilizes a numerical approach in which the member is divided into sufficiently small elements. The inelastic activity is concentrated at the ends of these elements whereas special elements are utilized to represent the end connections. The end displacement would be applied in small increments in order to generate the hysteresis loops.

The test program will utilize a psuedo-static loading equipment with a capacity of 240 kips. A four-hinge test frame has been designed to accommodate test specimens with horizontal and vertical projections of 8.5 ft. Thus, inclined bracing members approximately 12 ft. in length and area of cross-section up to about 8 in^2 will be tested. Test specimens will be built from single and double angles, channels, WF shapes buckling about their weak axis, and rectangular and circular tubes. The slenderness ratio will vary from 50 to 250 and the width-thickness ratios would encompass the permissible range of current AISC elastic and plastic design specifications. The connections will be bolted, fully welded and bolted-welded type with and without gusset plates.

Thus, an in-depth theoretical-experimental study of the hysteresis behavior of realistic bracing members is planned. The results of this study will be utilized to refine the hysteresis models which are currently being used. It is also anticipated that design recommendations will be formulated for the design of connections of bracing members for improved seismic resistance.

TORSION IN 3-DIMENSIONAL STRUCTURES

This study (5) deals with building torsion. A simpler 2-dimensional model is developed to represent moment frames and coupled shear walls or bracings with respect to their linear and nonlinear stiffness characteristics and eccentricities. The effects of torsion-translation frequency ratio, eccentricity-polar radius of gyration ratio, and especially ground rotation are examined from a random vibration approach with the idealization of ground rotation originally suggested by Newmark. The results obtained thus far for linear systems have shown that the calculated ground rotation is not nearly as significant as eccentricity. It is felt that more study should be done on the role of ground rotation in nonlinear structures before a definitive conclusion can be drawn. The need for recorded free-field rotation and translation accelerograms to verify the underlying assumptions is emphasized. The effects of the above parameters on ductility requirements is also being analyzed.

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SHUNSUKE OTANI

Department of Civil Engineering, University of Toronto

Introduction

The effect of biaxial horizontal earthquake motions on the inelastic response of reinforced concrete structures is one of the research topics at the University of Toronto. An effort at current research stage is aimed toward understanding the behaviour of reinforced concrete columns subjected to biaxial lateral load reversals through experimental program in the laboratory.

Objectives

The major objective of the experimental program is to study if a reinforced concrete column designed by current code provisions can behave in a sufficiently ductile manner subjected to static biaxial lateral load reversals.

The second objective is to study the dominantly flexural hysteretic behaviour of reinforced concrete members for use in the future development of analytical models. Although some efforts have been made to analyze structures subjected to biaxial horizontal earthquake motions, the stiffness characteristics of such members under multi-stress state were extrapolated from those under uniaxial stress reversal conditions through various hypotheses of the theory of plasticity. It is necessary to study the applicability of such hypotheses to a reinforced concrete member.

Experimental Program

Relatively slender columns (12 x 12 x 60-in.) have been tested in a pair: one subjected to uniaxial lateral load reversals and the other to biaxial lateral load reversals (Fig. 1). Two pairs of columns with lateral reinforcement sufficient to resist shear corresponding to flexural yielding were already tested, and two more pairs with critical amount of lateral reinforcement under preparation. Biaxial lateral loads were applied in one principal direction at a time so that the rate of stiffness degradation can be directly compared to that of the accompanying specimen under uniaxial lateral loading.

Test Results

The first pair of columns failed, after concrete crushing and surface spalling, by fracture of longitudinal reinforcement at location of welding in a critical region. The displacement ductility (= 2.9) of the specimen tested under biaxial loading was slightly smaller than that (= 3.5) under uniaxial loading, possibly because the residual strain of the corner bars of the biaxial column accumulated at a faster rate due to straining in the two directions, and reached a fracture strain at smaller displacement.

The second pair of columns failed by buckling of longitudinal bars at a displacement ductility factor of more than 10. Even at a displacement twice that corresponding to the initial yielding of tensile reinforcement, a significant stiffness reduction was observed (Fig. 2).

Publication:

Otani, S. and Tang, C.S., "Behaviour of Reinforced Concrete Columns Under Biaxial Lateral Load Reversals, (I) Pilot Test", Report 78-03, Department of Civil Engineering, University of Toronto, February, 1978.

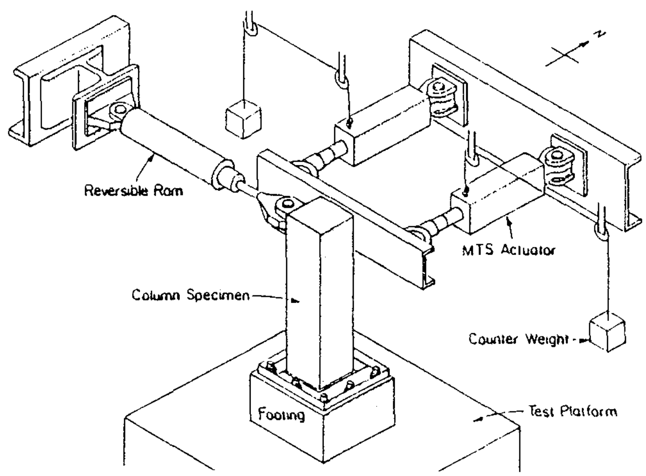

Fig. 1: Biaxial Lateral Load Reversal Test.

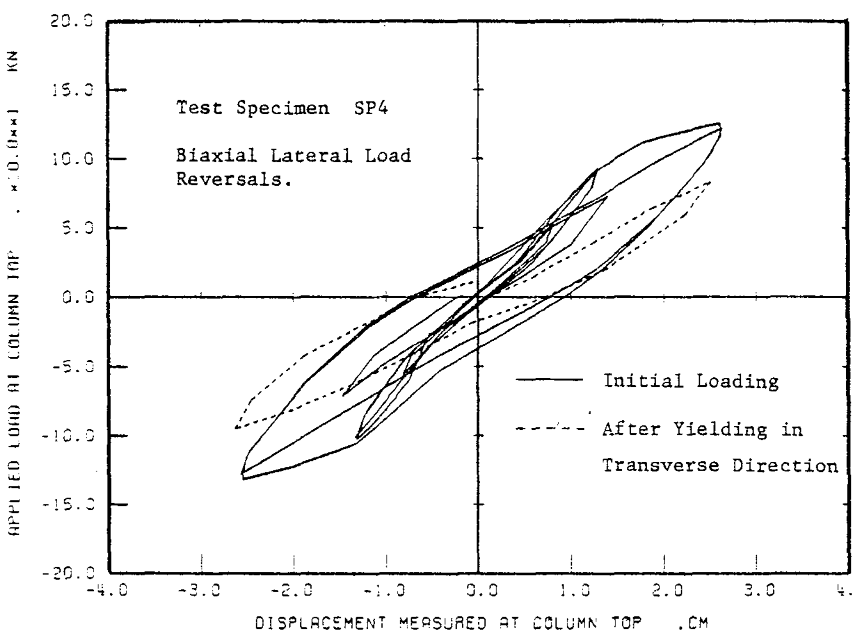

Fig. 2: Effect of transverse Lateral Loading.

L. F. KAHN

Georgia Institute of Technology

Introduction

Sponsored by the National Science Foundation, this experimental research examines several methods of strengthening existing reinforced concrete columns for improved earthquake resistance. Many existing structures have been built in areas of seismic risk before the advent of modern concepts of ductile concrete, and some reinforced concrete structures are being constructed in areas of moderate seismic risk without adequate seismic detailing. Of particular concern in these structures is the shear strength, ductility, and energy dissipation capacity of the first story columns; the connection of a "soft" first story with a stiffer structure above has proven to be a critical location.

Experimental Program

One-half scale columns were designed to model this first story column. As shown in Figure 1, the columns will be tested under axial and transverse loads; the enlarged center portion resembles the connection of the column to a stiff beam structure.

Six identical, 10-inch square, reinforced concrete columns have been constructed without any special transverse reinforcement which is recommended by current Uniform Building Code provisions. Columns are reinforced with four #7 grade 60 bars; concrete strength is 6400 psi. Four columns will be strengthened using various techniques as shown in Figure 2. It is expected that each system will improve to varying degrees the ductility and energy dissipation capacity of the column by confining fractured concrete and, thereby, reducing shear strength deterioration. One of the more important considerations in the research program is the constructability of each strengthening system; even though other schemes may be more structurally desirable, the four shown appear to be most easily applied to existing columns.

The columns will be tested under a constant axial load of 80 kips and under reversed-cycle transverse deflections of increasing magnitude. Measurements include loads, deflections, and strains of longitudinal and transverse column reinforcement and strains of the strengthening reinforcement.

The response of the columns will be compared with simple analytical predictions. The final goal is to determine and compare the extent to which the techniques improve the inelastic, earthquake resistant behavior of the columns.

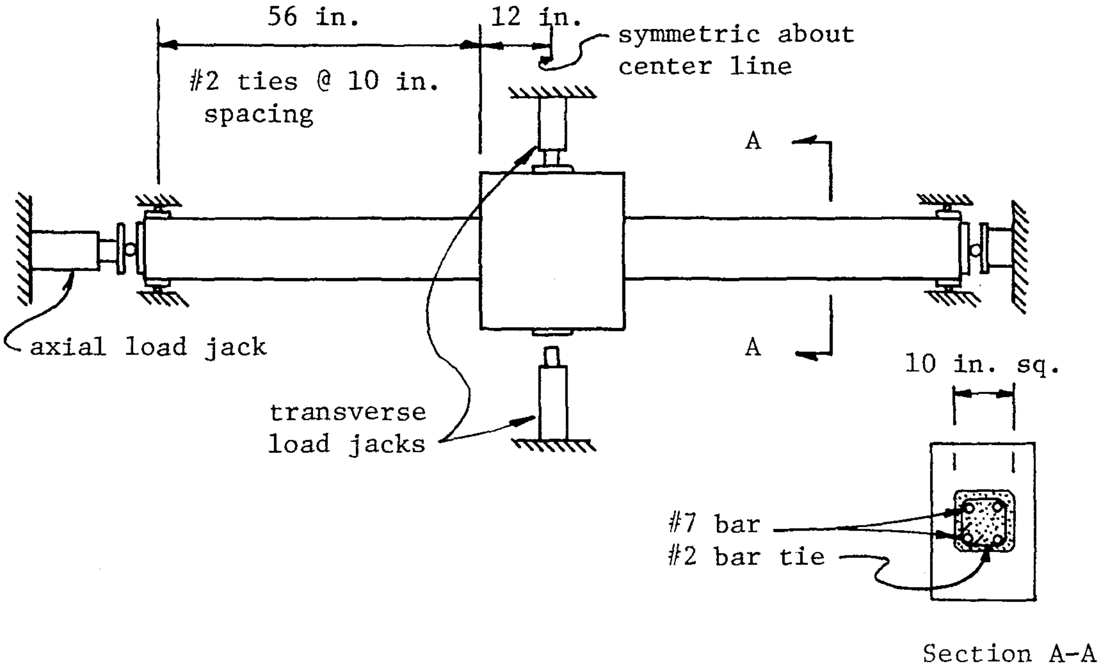

Figure 1. R/C column subjected to axial and transverse loads.

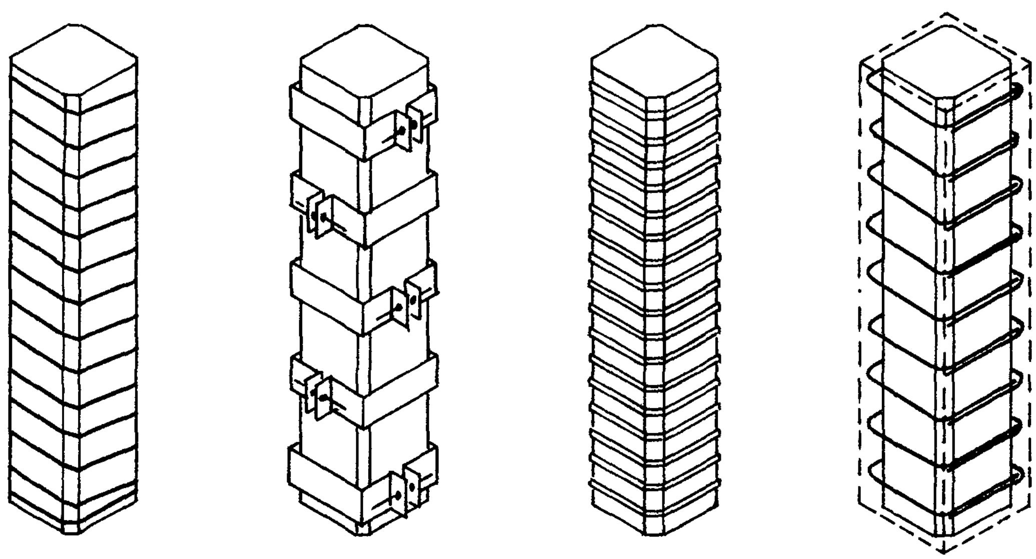

Figure 2. Strengthening methods, from left to right they are (1) rectangular spiral bar, (2) mechanically connected wide steel bands, (3) light, packaging-type steel bands, and (4) standard U-ties with gunite coating.

R. L. MAYES, H. D. McNIVEN, R. W. CLOUGH

University of California, Berkeley

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 six 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 and is described elsewhere in these proceedings.

The program on multistory buildings has been in progress for six years and consists of three major experimental parts. The first, which has been completed, is a series of seventeen in-plane shear tests on a double-piered test speciemn [1]. The second, which is in progress, consists of a series of eighty in-plane shear tests on a single-pier test specimen [2]. During both these test programs diagonal compression tests have been performed on square panels to determine the correlation between the diagonal tension stress of these tests and that of the pier tests. The third major part of the experimental tests, which is planned to begin in October 1978, consists of a series of tests on spandrel girders. In addition to this experimental work, recent Uniform Building Codes (UBC) have been evaluated to determine their adequacy in protecting masonry structures against severe damage or collapse in an earthquake [3]. In the next phase of the project analytical models will be developed to enable an inelastic analysis of perforated shear walls to be performed. The analytical models will be based on the experimental results.

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 15 ft. 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, and (5) Energy absorption characteristics. Results of these tests indicated significant variations of the pier behavior with the various test parameters--type of grouting, types of reinforcing, rate of loadings, etc. Most of the results were not conclusive and demonstrated the need for more extensive tests to establish definitive parametric relationships. One conclusion was definitive and it validated test results of others on cantilever type piers. The conclusion was that piers failing in the flexural mode of failure had desirable inelastic behavior and this was enhanced by the addition of 1/8-inch plates in the mortar joints at the toes of the pier.

The cost of the double pier tests, both in money and time, precluded carrying out the extensive parametric variations which are needed by this test procedure, and consequently a single-pier test system was devised which greatly simplified the investigation. Preliminary studies showed that single-pier results could be obtained which were comparable to the double-pier tests.

Approximately eighty single-pier tests were planned and fifty had been performed by June 1978. The major parameters 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, and (4) Type of grouting (full or partial).

Of the fifty single-pier tests performed to date, the height to width ratio of the piers has been either 2 to 1 or 1 to 1. Only one 1 to 2 pier has been tested. Consequently the conclusions of the study to date are based on piers with these ratios. The major conclusions are: (1) Desirable inelastic behavior is obtained with the flexural mode of failure. (2) In most piers the quantity of horizontal reinforcement required to force a flexural mode of failure significantly exceeds current code minimums. (3) For the 2 to 1 and 1 to 1 piers, the inelastic behavior of the shear mode of failure is not significantly enhanced with increased quantities of horizontal reinforcement. However, the one 1 to 2 pier tested indicates that the opposite is true for piers of this height to width ratio. More definitive conclusions will be available after additional 1 to 2 tests are performed. (4) The shear strength of comparable fully grouted hollow clay brick piers is almost double that of hollow concrete block piers. This fact is not recognized in current codes. (5) Partial grouting has an adverse effect on the inelastic behavior of hollow clay brick piers. (6) Partial grouting does not have an adverse effect on the inelastic behavior of hollow concrete block walls.

The results of evaluating recent Uniform Building Codes [3] indicates that the trend towards increasing conservatism which is evidenced in recent code changes is justified. The study suggests that the codes should be more conservative for buildings of moderate height.

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E. P. POPOV and V. V. BERTERO

University of California, Berkeley

Two major phases of current experimental and analytical research on earthquake resistant construction being conducted at Berkeley are highlighted in this presentation. One phase deals with the continuing work on the interior beam-column subassemblages of reinforced concrete, together with an in-depth study of bond deterioration under cyclic loadings; the other discusses structural steel bracing systems, including the behavior of the individual braces under cyclic loading, and constitutive relations for steel for generalized loadings. All of the work on R/C, as well as a significant part on structural steel, was sponsored by the National Science Foundation. The funds for research on eccentrically braced steel frames were principally provided by the American Iron and Steel Institute. Some of the publications resulting from this work are listed under References.

Reinforced Concrete Research

Subassemblages. Six cruciform half-scale subassemblages of normal weight concrete consisting of a column and a beam forming a typical interior joint of an R/C ductile moment-resisting frame were tested and the results analyzed [1, 2]. Earlier, the behavior of beams in such subassemblages was studied separately [3, 4, 5]. On noting severe deterioration of the subassemblages under repeating reversed lateral loadings, a solution for avoiding this problem was developed [6]. This was achieved by forcing the formation of plastic hinges way from the column faces.

Experiments on two additional subassemblages made of lightweight concrete have just been completed. The dimensions and material strengths of the latest specimens were like those of the first four subassemblages [1, 2]. For comparison purposes, the history of loading was made similar to that of the earlier tests. At deflection ductilities of 4 and higher, again, severe bond deterioration of the main beam bars passing thru the column was noted.

Monotonic and Cyclic Bond. The contribution to the fixed end rotation due to the pull-out of the main beam bars from a joint is ordinarily neglected. This effect, however, may contribute significantly to the total lateral deformation of a frame subjected to monotonically applied load, and may cause a complete loss of the overall stability for cyclic loadings. Both questions are related to the force transfer from a bar to concrete, i.e., to bond. Since experimental data in this area, particularly as it applies to the cyclic behavior, are very limited, a number of experiments were performed.

To date, 22 normal weight and 6 lightweight concrete specimens were tested. Very carefully instrumented #6, #8, and #10 single bars of 60 grade steel were cast into concrete blocks of different depths varying from 380 to 760 mm. The Concrete strength of most specimens was 30 MPa, although 20 MPa and 40 MPa concretes were used for some lightweight specimens. Dramatic deterioration in bond was observed in all cases of cyclic loading. Specimens loaded monotonically invariably performed better. #8 bars in 20 and 30 MPa lightweight concrete blocks of 640 mm depth pulled through before yielding. This was not observed with the normal weight concrete. A number of specimens were epoxy repaired and re-tested. The procedures employed were not found to be effective [7].

A mechanical model for predicting the pull-out of a bar from its concrete anchorage for monotonically applied loading, giving excellent agreement with experiments, was devised [8]. A refined computer model capable of giving a good simulation of the cyclic bond-slip behavior was also developed. Figure 1 illustrates analytically obtained results for such a case. Further experimental and analytical work is now in progress.

Structural Steel Research

Eccentrically Braced Frames. After reviewing the available literature on braced frames [9], eccentrically braced frames were selected for an experimental and analytical investigation which is now completed [10, 11, 12]. This novel framing system appears to offer several advantages: weight savings, simplicity of construction, and excellent energy dissipation under cyclic loadings. Currently, studies are under way to extend this approach to a split-K framing.

Cyclic Behavior of Braces. Although an enormous number of tests has been done in the past to determine the carrying capacity of columns, very little work was done on their behavior under severe cyclic loadings. It is believed that a comprehensive series of tests on individual columns subjected to cyclic loads just completed at Berkeley represents the largest effort to date both here and abroad. These experiments were done on structural shapes such as W 8 X 20, 6 X 3 1/2 X 3/8 double angles, 4 in. pipes, etc., for ℓ/r of 40, 80, and 120. An example from one of the column cycling tests is shown in Fig. 2. Reports are in preparation.

Constitutive Relations for Cyclic Plasticity. For rational analysis of structures under seismic loadings, constitutive relations for cyclic behavior are essential. Considerable progress was made in analytical simulation of structural steel behavior under such conditions [13, 14, 15].

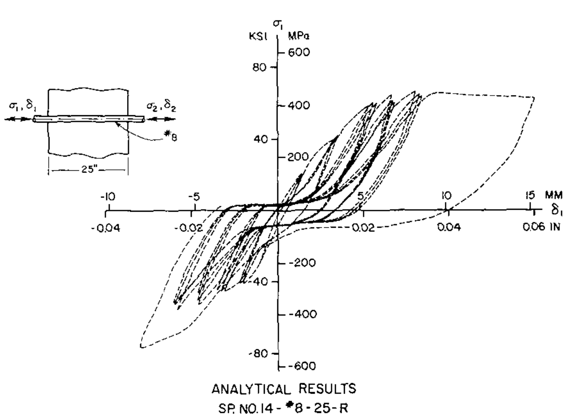

Fig. 1 Calculated Bond-Slip for #8 Bar

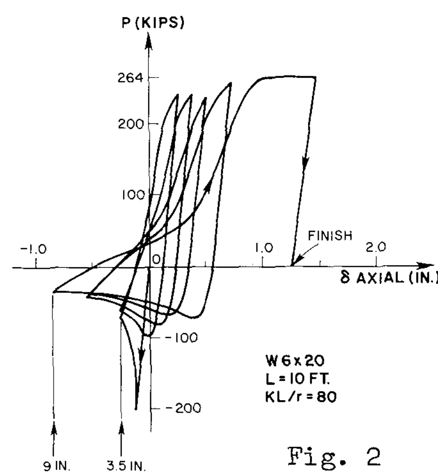

Fig. 2 Cyclic Column Behavior

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H.M. IRVINE

Massachusetts Institute of Technology*

Current earthquake engineering research projects conducted in collaboration with a colleague (R.C. Fenwick) and a graduate student (K.M. Dempsey) from the author's previous institution, the University of Auckland, are as follows.

Alternative Details for Reinforced Concrete Beam-Column Joints (with R.C. Fenwick)

The basic theory relating to the design of reinforced concrete beam-column joints has been reviewed and extended, with particular attention having been paid to the mechanisms by which forces are transferred through the joint region. Four specimens were tested to destruction under cyclic loading.

The tests show that a joint which contained bond plates to prevent a bond failure of the flexural reinforcement in the joint, and was proportioned to limit yielding of the steel in this area, had a markedly superior performance over specimens designed to comply with the ACI-71 code or the New Zealand Ministry of Works and Development code of practice for the design of public buildings (PW 81/10/1). Load and stiffness degradation were significantly reduced because the plates (which are welded to the flexural steel in both faces beam and column on both sides of the joint) allowed a large diagonal strut to be sustained and thereby provide an efficient means of load transfer in the joint.

Such alternative details offer one way by which joint congestion may be reduced coupled with possible reductions in beam depth and increases in flexural steel percentages. The difficulty of obtaining these objectives with more conventional details is presently of concern to designers and contractors in New Zealand and elsewhere.

Response of Torsionally Unbalanced Buildings (with K.M. Dempsey)

An analysis has been made of the coupled lateral-torsional response of a partially symmetric single storey building model to a single component of earthquake excitation. A modal solution of the two equations of motion was developed and particular attention was paid to the question of modal coupling, with a general criterion being produced for the existence of full modal coupling.

By employing the response spectrum concept, together with conservative rules for the combination of the modal maxima, simple analytical expressions may be derived for two equivalent static design actions - a shear and a torque - that account for the worst dynamic

* As from 1 September, 1978

consequences of torsional unbalance. If modifications are then made to the combination expressions (in keeping with the uncertainty of the simultaneous occurrence of peak modal responses) tabular results may be presented that are useful for analysis and design purposes. The tables cover wide ranges of the two independent parameters - a "frequency" ratio and an eccentricity ratio.

The model has been extended to a class of simple multistorey shear buildings with the result that the effects of eccentricity and the variation of stiffness with height on quantities such as base shear and overturning moment may be investigated.

SESSION 4

STRUCTURAL RESPONSE, EXPERIMENTAL

Chairman: J. Becker

JAMES M. GERE

Stanford University

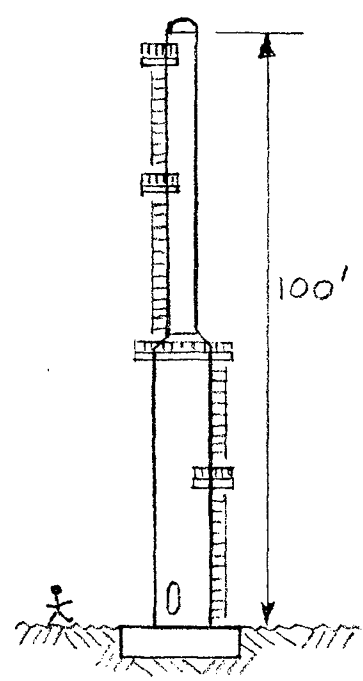
Several research projects currently being conducted at The John A. Blume Earthquake Engineering Center of the Department of Civil Engineering at Stanford University are described in this report and the two that follow (by Professors Helmut Krawinkler and Haresh C. Shah, respectively).

The laboratory facilities of the Center are utilized in these and other research projects; these facilities include a small shake table for model studies of structures, test sled, dynamic measuring equipment, laser interferometer, complete Fourier analyzer system, digitizer, and extensive computer and data processing equipment. The Center also has an earthquake engineering library, offices, and workrooms for faculty and students.

Seismic Analysis of Oil Refinery Structures

Oil refineries are composed of a great variety of industrial structures linked by a complex system of pipes. Extensive damage to these facilities has occurred in past earthquakes, presenting a hazard to the surrounding areas and resulting in the loss of refinery capacity. In order to improve upon the current methods of design, the behavior of oil refinery structures is being investigated through field testing of several vertical vessels (or tall columns) in a large refinery and through dynamic analyses of mathematical models of these tall columns.

This research project is supported by the National Science Foundation, Division of Problem-Focused Research Applications, with additional support from the Standard Oil Company of California. The Principal Investigators are Professors Haresh C. Shah and James M. Gere; the experimental investigations were performed by Dr. Charles A. Kircher of Stanford and the theoretical modeling was performed by Dr. Roger E. Scholl and Mr. R. Martin Czarnecki of the engineering firm of John A. Blume and Associates, San Francisco.



Three tall columns were selected for analysis because of their general suitability for testing and because they represent typical columns yet are varied in their dimensions and foundation conditions.

The main structures of these tall columns are cylindrical shells (about 0.5 in. thick) with heights from 31 to 109 feet and diameters of about 5 feet. Inside the columns are numerous horizontal "trays" and piping, and outside are platforms, ladders, piping, valves, and a reboiler structure. All of these components have an influence on the dynamic behavior of the columns.

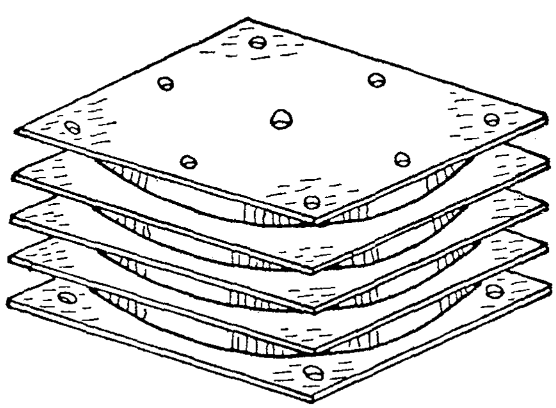
Vibration measurements of the motion of these columns, under both ambient and forced conditions, were recorded on site by the Fourier analyzer system utilizing accelerometers mounted on the columns at various locations. Natural frequencies, mode shapes, and damping were determined from power spectral density function analysis of the measured motion.

Mathematical analyses of the tall columns were made using several different methods: finite-element method, thin cylindrical shell theory, and lumped-mass beam theory. Results for frequencies and mode shapes were compared with the experimental measurements and generally gave satisfactory agreement. Detailed comparisons are currently in progress.

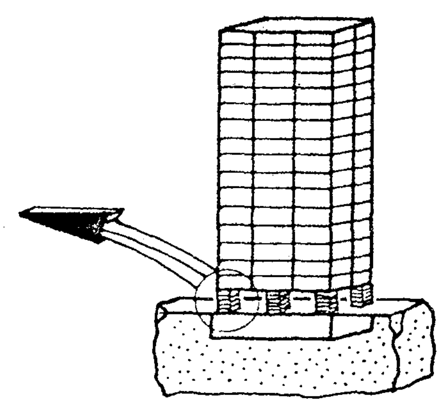
It is expected that eventually this study will provide recommendations for improved design procedures that can be used for tall columns in seismic regions.

Flexible Isolators for Buildings

The use of vibration isolators at the base of a building may provide a means of reducing the amount of damage during a severe earthquake. A commercially-available isolator in the form of a laminated sandwich of rubber and steel plates was tested on the shake table at model scales. The purpose of this study was to determine how the dynamic response of a building is altered by the use of vibration isolator devices. The testing was performed under the direction of Professor Haresh C. Shah, and the results are currently being studied. It appears that story shears and relative deflections between floors can be greatly reduced during earthquakes by the use of such devices.



(a). Typical isolator



(b). Locations of isolators in buildings

Geotechnical Engineering

The following earthquake-related studies in the geotechnical field are currently being conducted by Professors G. Wayne Clough and Edward Kavazanjian, Jr. under the sponsorship of the U.S. Geological Survey.

(a). Behavior of lightly cemented sands and silts under seismic loading. This type of material has received little study in the past, although it is very common in nature. Cemented sands (weak sandstones) tend to fail in a brittle manner, resulting in catastrophic slope failures such as occurred in the February 1976 Guatemala earthquake and in the April 1906 San Francisco earthquake. The objectives of the research are to determine the proper sampling and/or in-situ testing procedures for determining the characteristics of these materials and to test the materials under static and dynamic loading conditions.

(b). Seismic response of slopes in lightly cemented soils and weak sandstones. The purpose of this research is to predict the behavior of slopes and define the failure mechanism under ground shaking. Field studies of slope failure (in lightly cemented materials) that occurred during the 1906 San Francisco earthquake and the 1957 Daly City earthquake are being made in order to determine the mode of failure.

(c). Potential for reliquefaction of soils along the San Francisco waterfront. During the 1906 earthquake considerable liquefaction of sandy soils occurred along the San Francisco waterfront area, resulting in extensive damage to structures and breaking the primary water mains needed for fire fighting. This study is directed toward defining the present condition of the soils, which lie in the upper 40 feet of the ground. They consist primarily of dumped fills and dune sands placed there during the early-day development of the waterfront. Because the construction of a large excavation (up to 30 ft. deep) along the entire waterfront is currently in progress, there is an excellent opportunity to observe and sample the soils. Field measurements are being made of settlements, densities, and penetration, and lab tests for liquefaction behavior are being conducted.

HELMUT KRAWINKLER

Stanford University

A comprehensive study is in progress on developing the capability for reproducing on laboratory test facilities, at model scales, the dynamic response of large structures subjected to seismic excitations. The principal investigators for this project are Professors J. M. Gere and H. Krawinkler. Financial support for the research is provided by the Earthquake Engineering Program of the National Science Foundation.

An experimental study is also being conducted on the seismic behavior of industrial storage racks and their components. This study is part of a project on the development of seismic design criteria for such racks, sponsored jointly by the National Science Foundation and the Rack Manufacturers Institute, with John A. Blume as principal investigator.

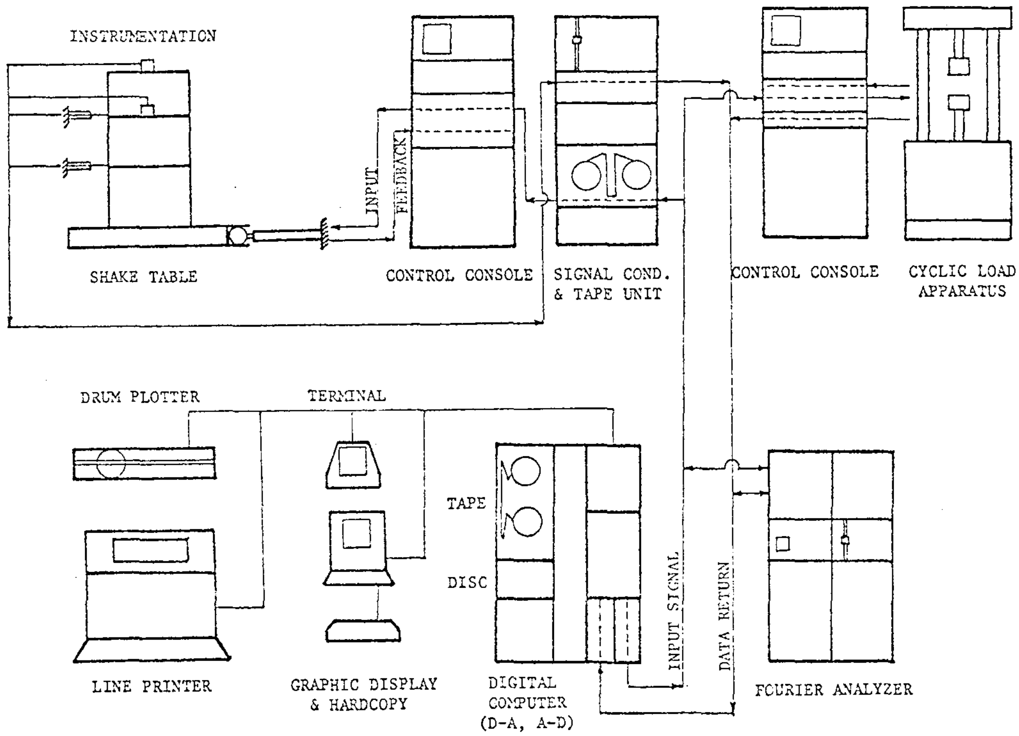
Scale Modeling and Testing of Structures on Small Shake Tables

The purpose of this project is to study the feasibility of model studies in earthquake engineering and develop methodologies for model testing of structures on small shake tables. The project is concerned primarily with the following subjects: (1) a synthesis and extension of dynamic modeling theory, (2) a thorough study of materials suitable for modeling of structures, (3) a development of experimental facilities for dynamic model studies, (4) a study of model fabrication techniques, and (5) a demonstration of the feasibility of the developed techniques by means of a series of model case studies.

It was demonstrated in this research that, in theory, the response of all types of structures can be predicted from carefully designed model tests. In practice, certain limitations are imposed by the availability of suitable model materials. However, in most cases these limitations can be overcome through acceptable distortions (e.g., artificial mass simulation) which will not alter significantly the seismic response of the models.

From dynamic modeling theory various types of models can be derived which are suitable for different classes of structures. Steel structures are particularly suited for model studies since they permit the use of steel or several non-ferrous metals as model materials. Procedures for evaluating the feasibility of these model materials have been developed in this project.

In the course of this project, a comprehensive and integrated testing system was developed which, together with the documented testing procedures, can serve as a model for other research or professional laboratories interested in developing a model analysis program. A block diagram of the model testing system at Stanford is shown in the following figure.



Block Diagram of Dynamic Testing System at Stanford

The outcome of this research, which is still in progress through an NSF continuation grant, should be the development of a powerful tool which can be used by researchers and engineers alike in solving specific problems in earthquake engineering. There are a great number of topics which require experimental investigation and which cannot be studied sufficiently on prototypes because of size constraints, as for example overturning and uplift, soil-structure interaction, nuclear reactor components, offshore structures, tilt-up structures, etc. Many of these topics can be studied on models for which the fundamentals are developed in this research project.

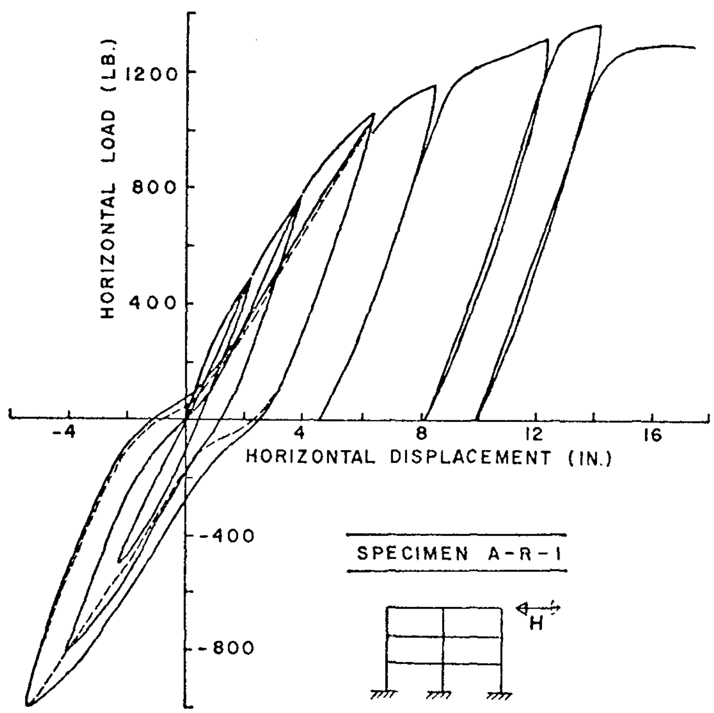
Shear and Moment Resistance of Thick-Walled Reinforced Concrete Cylinders

The load-deformation response of thick-walled cylinders, such as support structures of nuclear reactor containment vessels, is being studied analytically and experimentally by means of small scale models. In the course of this research, a material study on micro-concrete and model reinforcement has been conducted. Several 1:30 scale models of a 25 ft diameter support structure of a nuclear containment vessel with different shear to moment ratios are being tested. In the first test, excellent agreement was obtained between experimental results and analytical predictions for moment transfer. Analytical models for shear transfer mechanisms are being developed from the experimental data.

Seismic Behavior of Industrial Storage Racks

The objective of this experimental study is to acquire basic information on the response characteristics that govern the seismic behavior of industrial storage racks. This information, together with results from shake table tests carried out at the University of California, Berkeley, are intended to serve as a basis for the development of seismic design criteria for storage racks.

Monotonic and cyclic quasi-static tests were carried out on structural components, subassemblies and full-size rack assemblies. The types of specimens and loading histories were chosen such as to permit the evaluation of the force-deformation characteristics of all critical regions under seismic actions. The load-deflection response of a two-bay, three-level pallet rack is shown in the figure on the right. The procedures for selecting representative subassemblies and the methods developed for instrumentation and loading should prove useful for future industrial testing of similar structures.



Natural frequencies, mode shapes, and damping characteristics of the two-bay, three-level racks were obtained from forced and free vibration tests. Forced vibrations were generated by means of an electromagnetic vibration generator placed on top of the structure. Sinusoidal excitations were used for damping measurements and band-width limited white noise was used for the investigation of frequencies and mode shapes.

POLAT GÜLKAN

Earthquake Engineering Research Center
University of California, Berkeley

Introduction

To evaluate U.S. Department of Housing and Urban Development (HUD) criteria for single-story masonry dwellings, an experimental investigation of the design and construction requirements for these dwellings in Uniform Building Code Seismic Zone 2 regions of the United States was embarked upon at the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley under the sponsorship of HUD. Because of limited information on the shear and transverse strength of masonry structural elements and the response of masonry structures to earthquakes, the investigation was directed towards testing masonry houses constructed with full-scale components using the EERC shaking table. Additionally, pseudo-dynamic controlled displacement type tests have been performed on typical masonry wall-timber roof connections to determine their adequacy for resisting the inertia forces developed during seismic disturbances. This paper is confined to the shaking table tests only.

Test Structures

During the planning phase of the study the primary objective was to obtain structures which would be simple in concept and yet would contain the most significant components of simple masonry dwellings such as wall panels, corners, and wall-footing and roof-wall connections. To date, three houses measuring 16 ft by 16 ft in plan have been designed and constructed. Two of these have been tested, and the third will be tested during July, 1978. The first house was constructed from 4 in x 6 in x 16 in hollow concrete blocks and consisted of four L-shaped corner units 2 ft long on a side and four 8 ft long panels. Half of these units were reinforced nominally by #4 bars and the other half was plain. The second and the third houses (hollow concrete block similar to the first house and hollow clay brick, respectively) had the geometry shown in Fig. 1 which also indicates the instrumentation. With reference to this figure, panels A and A1 with the window and door openings are unreinforced while walls B and B1 each contain one #4 bar at either edge. Under actual testing conditions the 8 ft 8 in high wall panels are placed such that the 16 ft square timber roof encloses the plan area and can be anchored to the walls. In addition to the weight of the roof assembly, concrete slabs are attached to the plywood sheathing to provide a total roof load per unit length of wall periphery of approximately the same as that of a typical 40 ft by 50 ft prototype unit.

The test specimens are subjected to a series of base motions patterned after actual earthquakes with increasing intensity. The response is monitored through an array of measuring devices (Fig. 1). The structures are tested under a broad spectrum of conditions. In addition to changes in the type and intensity of the table motions, cracks which form during test runs are repaired, whenever possible and necessary, by coating the affected masonry walls with a surface bonding mortar. The roof truss orientation is changed as is the base fixity conditions of the footings.

Discussion of Observed Response

The research program reported in this paper has the objective of providing experimental information to determine the seismic resistance of typical one-story masonry dwellings constructed in moderately seismic regions of the United States. Evaluation of selected quantities describing the behavior of the first two test specimens which were simple in plan but which contained significant components of a masonry structure indicates the following:

(1) The response of the test structures to a series of base motions up to a maximum acceleration of 0.60 g was complex and was governed by the orientation of the roof structure, the base fixity of the in-plane walls and the cracks that developed in the unreinforced walls.

(2) The overall behavior is strongly dependent on the orientation and vibratory characteristics of the roof assembly. The in-plane response of walls is governed by the inertia effects transmitted from the roof. The out-of-plane response depends on the constraint provided by the roof.

(3) For strong base motions, failure consistently occurs in unreinforced masonry elements. It appears that a nominal amount of vertical reinforcement in narrow piers and jambs would have an extremely beneficial effect on preventing irrepairable damage.

(4) The surface bonding material used to repair the cracked unreinforced walls appears to be effective. Following the repair of of both in-plane and out-of-plane walls, the first house had to be subjected to base motions of increased intensity before similar cracking occurred again.

(5) The ordinary tools of structural analysis can be used to predict the response and strength in a gross sense. However, areas of stress concentration or the precise effects of cracking require more sophisticated analytical approaches for identification. In that sense also, reinforcement would tend to compensate for the uncertainties of simple structural analyses upon which the design of similar houses are based.

Acknowledgment

The principal investigator of the project is Professor Ray W. Clough. The ATC-5 Advisory Panel has offered valuable suggestions and guidance throughout the experimental phase of the studies.

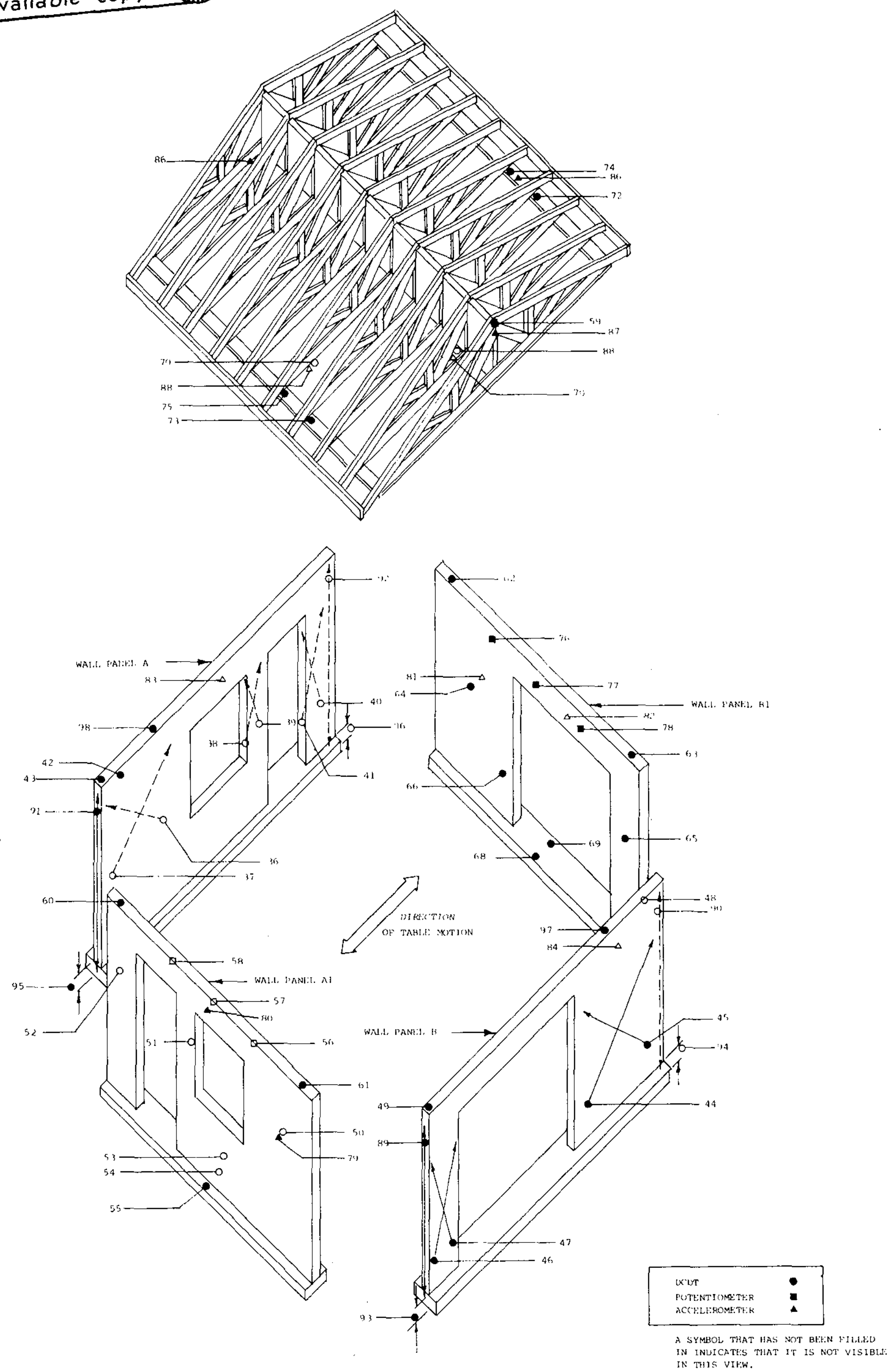


Figure 1. Test Structure and Instrumentation Layout

W. O. KEIGHTLEY

Montana State University

Two projects supported by the National Science Foundation are described: A low cost shock table for testing large scale models of masonry structures, and prestressed walls for damping earthquake motions in buildings.

Low Cost Shock Table

This facility was completed at the School of Earthquake Engineering, University of Roorkee, Roorkee, U.P., India, in August, 1977. Total cost of construction was $12,500, including the enclosing building. N.S.F. provided $5,000 for construction, plus travel for the author's family. An Indo-American Fellowship provided the author's travel, salary and $500 for construction, and the University of Roorkee provided the remainder.

The facility consists of a 36-m long railroad track, the central 20 m of which is depressed by 0.6 m to create a ramp at each end. Three condemned railway car frames with wheels were mounted on the track. The outer two frames were fitted with sides and bottoms and loaded with boulders and sand to become 32-ton rolling dead loads. The center frame was surmounted with a heavy steel platform, 6 m x 7 m, on which test structures were built. The facility can impart 2 g acceleration pulses of 0.1 sec. duration to 20-ton structures.

To conduct a test the central car and one dead load car are positioned on the level central part of the track. The other dead load car is pulled up the incline and then released from a predetermined point to roll down and collide with the platform car, which then rolls into collision with the stationary dead load car. Heavy coil springs between the cars moderate impacts so that the platform car receives a pair of half-sine acceleration pulses. There is no control of the system other than the height from which the rolling dead load is released, so there are some variations of table accelerations from pulse to pulse due to feedback from the test structures, etc. Useful observations resulted from one set of tests of four half-scale one room masonry houses. The vulnerability of walls transverse to the shocks, and the effectiveness of reinforcing were well demonstrated. Construction of a similar facility of 150-ton capacity, using several cars to support a 12-m square platform, is recommended.

Prestressed Walls for Damping Earthquake Motions in Buildings

This project has been funded by N.S.F. in the amount of $37,800, to extend over two years. Approximately 60% of the funds have been used to date. The goals are to determine if Coulomb damping is a feasible means for reducing earthquake effects on buildings and to develop and test in the laboratory practical devices for developing the friction forces and connecting them to the building frame.

Interfloor Coulomb dampers stiffen a structure and shorten the fundamental period before they slip, but at large displacements the period is not much affected. For tall buildings exposed to nearby earthquakes, which are rich in short periods, this is advantageous because it keeps the fundamental period outside the range of large dynamic amplification. Against distant earthquakes the stiffening at low amplitudes is also advantageous for tall buildings, but of less importance.

Two digital computer codes have been written to compute the response of planar elastic building frames with interfloor Coulomb dampers, assumed here to be prestressed segmented concrete walls that slip along preformed surfaces as the frame distorts. In one code the walls are rigid until they slip; in the other the walls are elastic when not slipping. Results from the two codes agree satisfactorily if the elastic walls are taken to be several hundred times as stiff as the columns. A third code is being prepared in an attempt to reduce computing time for tall buildings.

Intrastory Coulomb forces, present in every story, have been assumed to be proportional to the weight above the story (e.g., F/W - 0.06). Spectra for various response quantities (base shear, midheight shear, interfloor displacement, etc.) have been prepared for 8-story buildings with fundamental periods in the range 0.2-5.0 sec. and F/W ratios varying from 0.02 to 0.20. Optimum F/W ratios will be determined for each period for several earthquakes. Further studies will include the effect of varying the F/W ratio over the height of the building for better performance, and of omitting the dampers from some stories to meet architectural requirements. The computations to date show that significant reductions in interfloor displacement can be achieved in long period structures with F/W as low as 0.02.

The major task to be accomplished in this project is the development of pratical and economically feasible damping devices, and this will receive the major part of the effort for the remainder of the grant period. In the laboratory a loading frame has been built for racking 7-ft high walls with up to 30 kips force. Concrete planks have been made for constructing a segmented wall, but on assembly it was found the planks were warped due to crooked forms, and they may need to be ground flat before they can be used, or be produced in another manner. No experimental results have yet been obtained.

DIXON REA

University of California, Los Angeles

The inelastic response of small steel frames to earthquake type motions is being investigated experimentally. Base excitations of sufficient intensity to cause substantial inelastic deformations are being applied to shear type structures by means of a high performance shaking table. The experimental results will be used to check the accuracy of analytical models currently in use for determining the nonlinear response of steel frame buildings to earthquake loads. Mr. Alvar Kabe, a graduate student at UCLA, is conducting the experiments.

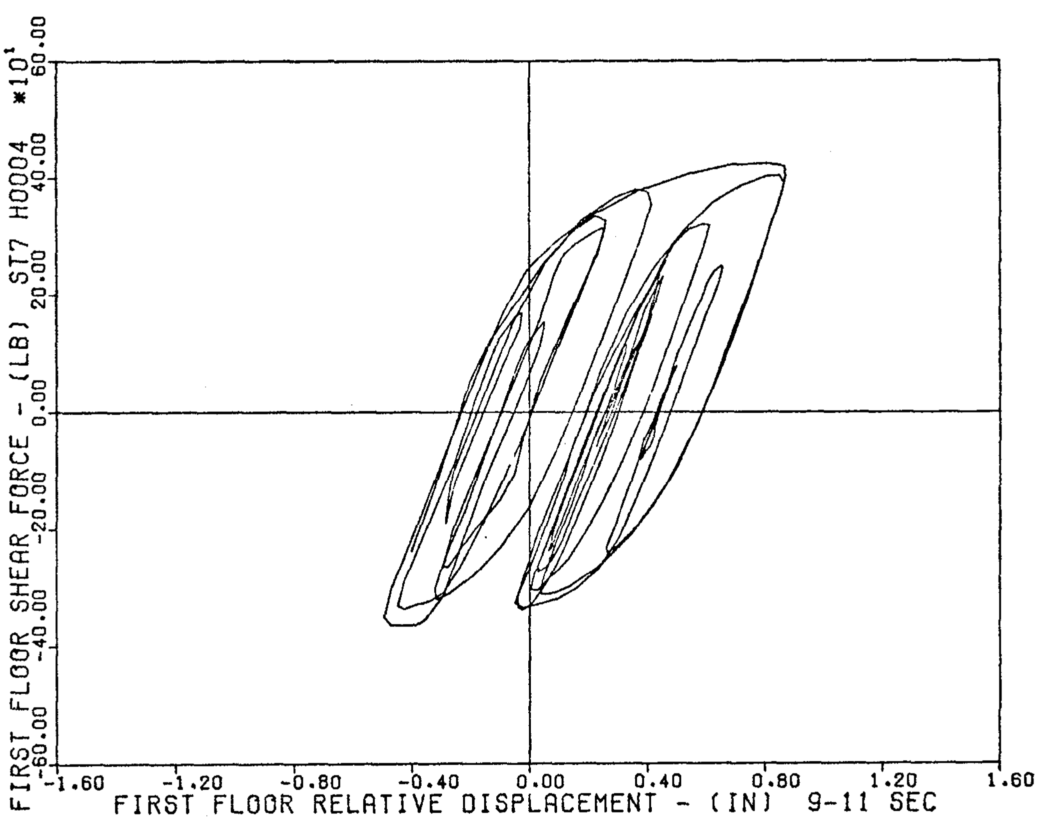
The shaking table for the experiments consists of a 400 lb. steel grillage measuring 6' x 3' in plan. The table is supported by four linear bearings that permit the table to move in one horizontal direction. The electro-hydraulic actuator that drives the table has a dynamic force rating of 7.5 kips and a stroke of 6 in ($\pm$ 3). The actuator is equipped with a 90 gpm servo-valve. Oil at an operating pressure of 3000 psi is supplied by a 20 gpm pump. The pump by itself does not have sufficient flow capacity to permit the actuator to achieve the high velocities required to produce inelastic deformations in steel structures. In order to achieve high velocities for short durations 5 and 2 1/2 gallon accumulators are fitted on the pressure and return oil lines respectively. In addition, 1 gallon accumulators are attached directly to the pressure and return ports of the servo-valve manifold. The maximum test specimen weight is 1500 lb. Fully loaded the table has a maximum acceleration of 3.5 g and a maximum velocity of 100 in/sec.

The structures consist of four columns clamped to floor frames. The columns are typically 8" lengths of 1/2" x 1/4" hot rolled A36 steel rectangular bars. The floor frames consist of 2" x 1/2" bars bolted together to form 12" x 24" rectangular frames. The flexural stiffness of the bars in the floor frames is large compared to the stiffness of the columns so that the structures are of the shear type. Steel plates are added to the floors to reduce the fundamental natural frequencies of the structures below 10 cps.

The excitation used most frequently in these experiments is a modification of a Taft (1952) accelerogram. In order to obtain the required intensities of excitation without exceeding the stroke limitation of the table, low frequency components of motion have been removed from the record by means of a 3 Hz high-pass filter. The magnitudes of the peak accelerations in earthquake simulations has ranged up to 3 g.

The inelastic nonlinear behavior of the structures has been evident in a number of ways. Decreases in the structures' fundamental natural frequencies of about 50% can be discerned in acceleration time histories. First floor relative displacements corresponding to ductility factors of 15-30 and permanent deformations corresponding to ductility factors of 10-20 have been achieved. Plots of first story shear force versus relative displacement show significant energy is dissipated by hysteretic damping. The first floor force-deformation history during 2 seconds of an earthquake simulation is shown in the figure.

It is planned to use the experimental data to evaluate the accuracy of existing computer programs for nonlinear dynamic analysis, particularly their accuracy in predicting permanent deformations. The data will also be employed in an effort to develop a simple method of predicting earthquake induced permanent deformations in steel buildings.



METE A. SOZEN

University of Illinois at Urbana-Champaign

Current work represents the second phase of an investigation of the behavior of reinforced concrete structures to strong ground motion with the overall objective of developing improved analytical models for design of reinforced concrete in linear and nonlinear ranges of response. The research procedure involves design and construction of particular structures according to a design concept. Each structure is subjected to base motions simulating earthquake motion. The results provide physical tests for the design concept as well as a benchmark for checking the results of analytical models for the structure.

The experimental program in the second phase of the project has included eight small-scale ten-story structures. The main structural variable in the first series of four structures was the story height. The story height was constant for the first two structures (H1 and H2). A third structure, MF1, had increased story heights for the first and tenth stories. The fourth structure, MF2, had the same geometry as MF1 but for a partial "double story" at the lowest level (Fig. 1). The lateral-load resisting system in the second series of four structures was made up of a pair of frames and a centrally located wall (Fig. 2). The main structural variable was the strength of the wall relative to that of the frames.

The base motions were patterned after components of records obtained during the Imperial Valley (El Centro 1940) and Tehachapi (Taft 1952) earthquakes. Time scale was compressed by a factor of 2.5 so that the frequency content of the base motion would be in the same range as the frequencies of the small-scale test structures. Each structure was subjected to a series of test runs with base motions of increasing intensity. Measurements included accelerations and displacements at all levels. Two structures in Series 1 and all structures in Series 2 were also subjected to steady-state base motions in order to obtain a measure of their dynamic characteristics. These tests were made following each earthquake-simulation run, with the maxmum displacement limited to less than half that recorded in the earthquake-simulation run.

The overall trend of the results has confirmed the applicability of the design concept used, which is essentially a method of linear modal analysis using a given response spectrum with the freedom of stipulating relative stiffnesses of the elements in the structural model, to determine design forces. In general, this result suggests that the designer need not be constrained by the relative stiffnesses, based on gross section, of the "elastic" model in assigning strength to different structural elements, provided the lateral displacements of the structure are tolerable. For example, although the geometry of the frame-wall structures remained constant in Series 2, designing (or reinforcing) the walls for radically different strengths resulted in acceptable response in all cases.

All test structures were proportioned so that the columns would experience only a limited amount of nonlinear action. The experiments indicated that this objective was achieved in tests at the "design" intensity.

In Series 2, the force between the wall and the story mass was measured as well as the acceleration at each level. The force, shear, and moment distributions at the instant of maximum response for structure FW1 are plotted in Fig. 3. The characteristic force reversal at the top and its influence on shear and moment distributions are recorded in the figure.

Another interesting observation is provided by the comparisons in Fig. 4 of the recorded base-shear histories for frame structures H1, MF1, and MF2 in tests with comparable base motions. The broken curves represent the total response while the solid curves indicate contributions of response components at 3 Hz or less. The influence of the increased flexibility of the first story is manifest in the subdued effect of the higher modes for MF1 and MF2.

Acknowledgments

The study is sponsored by the National Science Foundation at the Structural Research Laboratory of the University of Illinois, Urbana. Credit for planning and execution of the tests is due D. P. Abrams (Structures FW1 through FW4 of Series 2), H. Çeçen (H1 and H2), T. J. Healey (MF1), and J. P. Moehle (MF2).

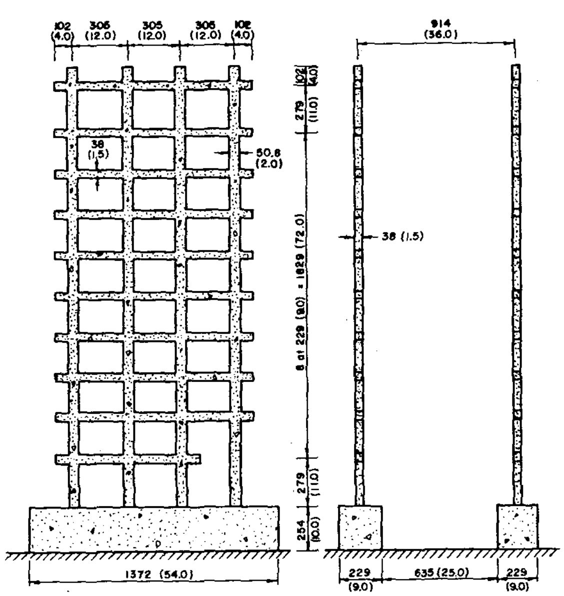


Fig. 1. Test Structure MF2

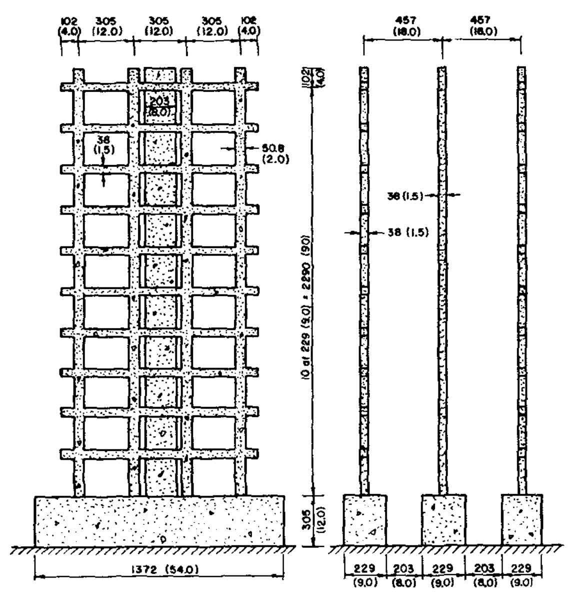


Fig. 2. Test Structure FW1
mm (in.)

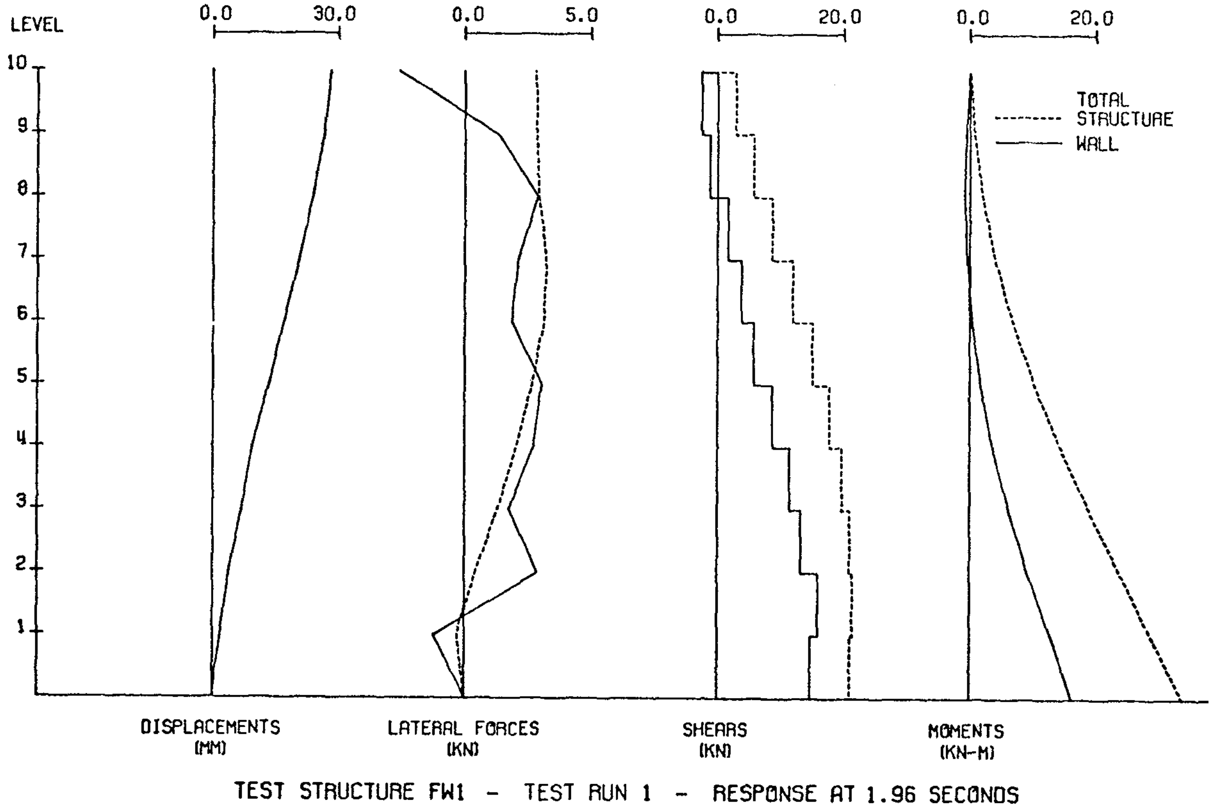


Fig. 3. Force Distributions in Test Structure FW1

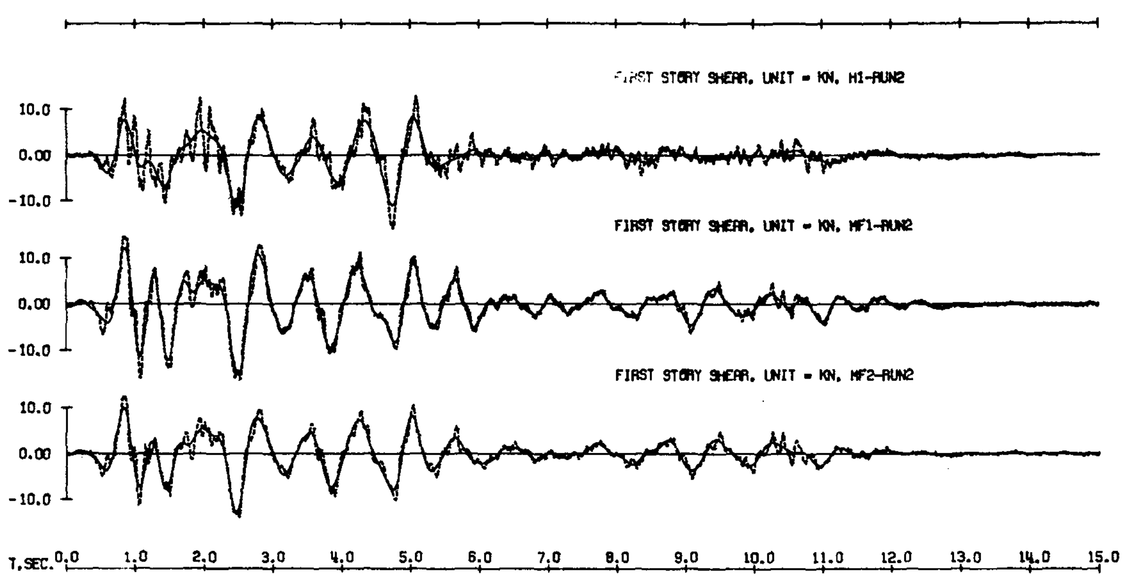


Fig. 4. Comparison of Measured Base Shears (Total Mass $\tilde{=}$ 4530 kg for each test structure)

T. V. GALAMBOS

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The National Science Foundation has sponsored research on the dynamic behavior of a reinforced concrete structure under large amplitude shaking.

Large Amplitude Shaking of an Eleven-Story Reinforced Concrete Structure

A twenty-year old eleven story reinforced concrete apartment building was subjected to the following studies:

1) Survey of dimensional and material properties
2) Small amplitude shaking
3) Large amplitude shaking in E.W. direction with cladding in place and in N.S. direction with cladding removed
4) Analysis of the dynamic properties.

The structure was approximately square in plan (40 ft x 45 ft), eleven stories tall, and it was composed of thirteen columns, beams, slabs, a stairwell and brick and/or block walls. The structure prior to the large amplitude shaking tests was in an undamaged condition.

The large amplitude shaking was achieved by moving a 60 kip mass of load placed on a bed of steel balls on the top floor of the building horizontally at differing frequencies and amplitudes by means of a hydraulically actuated piston which was attached at its other end to the structural frame. The maximum horizontal force achieved during the first-mode resonance was ± 30 kip.

The following test runs were made:

1) Sweep tests at relatively low force-levels to determine the natural frequencies and damping;
2) Mode shape surveys at low-force levels during resonance;
3) High force-level shakes at and near resonance to damage the structure.

Measurements were taken to determine the frequency and the magnitude of the applied force, and accelerations were measured to define the complete dynamic response of the structure during the tests.

During the E-W shaking the walls were left in place. Extensive damage was achieved during first-mode high force-level tests on the infill walls, the stairwell and the beam-to-column joints in the first three stories from the ground up. During the N-S tests the cladding was removed, and extensive damage was observed on all joints of the W-face of the structure up to the ninth level, and two columns on the third level were completely crushed.

Data analysis consisted of the determination of the mode-shapes, the first and second mode resonance frequencies, the damping and the base shear. Extensive damage to the structure occurred mainly during the high force-level first mode shaking, resulting in major changes in stiffness and in the frequencies. Mode shapes were not affected appreciably by the changes in the structural properties. The damping analyses revealed no consistent results except that damping was in each instance relatively small, varying from approximately 2 percent to 8 percent.

The testing was performed during the period June through November 1976, and the final report will be completed by July 1978.

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The research effort described herein uses existing direct small scale modeling techniques developed originally for cast-in-place R/C and P/C structures (and extended over the past four years to industrialized construction)(1) to investigate the seismic resistance of Large Panel (L.P.) precast concrete buildings. The need for this research stems mainly from the fact that industrialized buildings made of discrete wall and floor panels are unlike the more familiar ductile frame systems and have inherent weaknesses because of their numerous connections which prevent monolithic continuity. These special features of LP buildings must be studied and understood in order to mitigate any seismic risk which arises from the fact that these systems are very cost effective in the residential construction market.

Cyclic Behavior of Connections

The behavior of joints between precast panels under simulated earthquake loadings must be well established before applications of LP buildings into more active seismic regions can be made. In order to evaluate the large numbers of variables that influence the behavior of various critical joints in the typical L.P. structure, large scale testing programs must be undertaken. The high costs of full scale testing can be greatly reduced through the use of small scale direct modeling techniques. An internally funded exploratory program was undertaken at Drexel University to study the cyclic shear behavior of vertical joints between precast wall panels(2). Twenty eight 1/16 scale models of joint assemblies consisting of one story high vertical joints and upper and lower horizontal joints were loaded in monotonic and cyclic shear. Parameters investigated include the joint concrete strength, the amount of reinforcement and the joint geometry. The results of these studies indicate that the shear-slip curves of vertical joints of the plain wet type have decidedly pinched hysteritic behavior with little energy absorbing capability as shown in Fig. 1. Ultimate shear strength reductions of the cyclically loaded specimens over companion monotonically loaded specimens were of the order of 13-15 percent. It was shown by the exploratory tests that small scale direct models can contribute valuable information for evaluating the performance of various joints and subassemblies under cyclic loads.

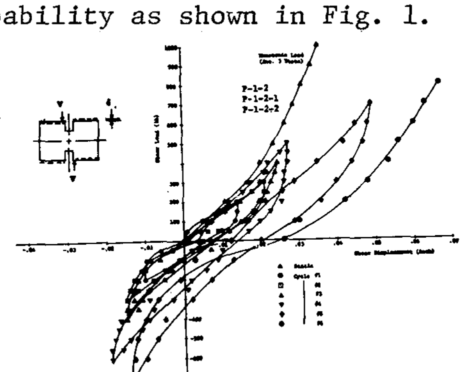

Fig. 1 Cyclic Shear Load Behavior of Vertical Joint P-1-2-R-3

Drexel University Shake Table

Drexel's electro-magnetically driven 4 x 6 feet shake table is housed in the Structural Dynamics Laboratory of the Department of Civil Engineering. A schematic layout of the major components constituting the shake table are shown in Fig. 2. These consist of the following:

1) MB Vibration Exciter model C25H, having a sinusoidal frequency range of 5-2000 Hz and a maximum force of 2,800 lbs., with a velocity capability of 50 inches/second and a displacement limit of 0.5 inch double amplitude.
2) MB Power Amplifier model T351-B, having an AC power output of 6,000 volt amperes from 30 to 6000 Hz and a field supply of 6 kw.
3) Ling Electronic model S6000 (24 k) Random Vibration Control and Analysis System (RVCAS) which consists of the following components:
(a) Model 1811 Memory Unit (b) Model 1421 Analog Control Element
(c) Model LDP-1801 Central Processing Unit (d) Model 1803 Power Supply
(e) Power Access Panel (f) Model 1753 Teletype System

The MB Vibrator (Fig. 2) is positioned to move in a horizontal direction and is attached to a 2 inch thick 2024-T351 aluminum slab riding on two rails through a system of self aligning sleeve roller bearings supported on a specially fabricated welded steel table.

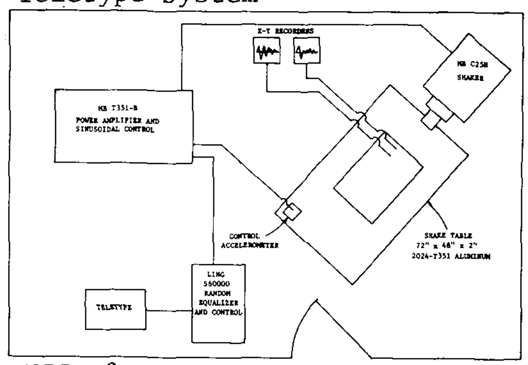

FIG. 2 PLAN VIEW OF THE DREXEL STRUCTURAL DYNAMICS LABORATORY

The seismic model test essentially consists of applying a suitable horizontal vibration on the foundation or base attachment of the model for a predetermined time duration and then measuring the resulting strains, displacements and accelerations in the model. A schematic of the set-up for measuring accelerations of a small model cross-wall type building is shown in Fig. 3. The data acquisition and data reduction system consists of the following:

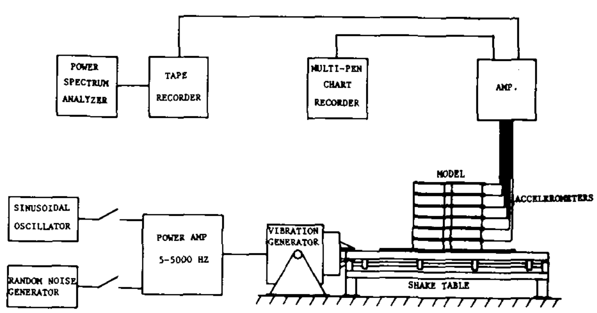

Fig. 3 Instrumentation and Test Set-Up for Model Testing

1) Lockheed Store 4 tape recorder with a frequency response of 0 to 300 KHz at 60 inches per second.
2) Metraplex multiplexing system using frequency modulation providing 16 channels of information.
3) Digital Group Z80 34K micro computer with dual standard floppy-disk drive.

During the test the micro computer will set up the system, start the analog tape recorder, record a test description header block on the tape and terminate the tape.

Three-Dimensional Small Scale Models of L.P. Buildings

In order to study the dynamic response of panelized structures, two small scale models have been constructed and tested on the Drexel shake table. The first model tested was a 1/40 scale elastic model made of P.V.C. plastic representing 6 stories of one bay of an actual cross-wall L.P. structure(3). The 0.20 inch thick P.V.C. sheets representing the wall and the slab components were glued together and thus resulted in a monolithic plate structure representative of the elastic range of behavior of the concrete prototype. Cut steel plates were attached to the floors and roof levels to simulate the dynamic characteristics of the prototype. Although the model did not attempt to simulate the discrete joints of the actual large panel structure, it was felt worthwhile since very little experimental data exists on the dynamic behavior, elastic or otherwise, of such systems.

The second model, currently under test, is a 1/16 scale ultimate strength model of a single bay of a typical cross-wall 6 story 56' x 225' apartment building(4). All wall and floor units are 1/2 inch thick and were cast in a horizontal position in Plexiglas molds. These were then positioned on a plywood base and grouted into place one floor at a time (Fig. 4). Vertical, transversal, longitudinal and peripheral ties were provided as in the prototype. Additional mass in the from of steel plates are attached to each floor slab. The test program calls for the determination of the natural frequencies and mode shapes using low amplitude vibrations and then subjecting the model to scaled values of actual earthquakes. Comparisons with analytical predictions are also planned.

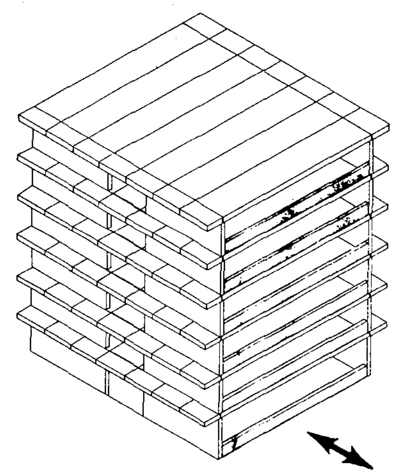

Fig. 4 Isometric View of 1/16 Scale Model

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W.M. Jakway[1], P.H. Gerwien[2], W.E. Whitman[2], J.M. Plecnik[2]

[1]Dart Environment and Services Co., Dart Industries
[2]California State University, Long Beach

Earthquake related research is currently concentrated in two distinct areas. First, the behavior of concrete structures damaged by earthquakes, repaired with epoxy adhesives, and subsequently subjected to fire exposure and/or simulated seismic load conditions. Second, the design and behavior of glass reinforced plastic (GRP) storage vessels under seismic load conditions in Zones 3 and 4. The epoxy research is sponsored by the National Science Foundation and the fiberglass research is funded by Dart Industries.

I. Behavior of Epoxy Repaired Structures Under Fire Exposure and/or Seismic Loads

Since epoxy adhesives are organic materials, their properties are highly sensitive to temperature. The primary goal of this research program is to investigate the behavior of epoxy repaired cracks in concrete structures (with emphasis on shear walls) under fire exposure and/or seismic loads. "Hot" tests refer to experiments performed on specimens during or immediately after fire exposure. "Residual" tests refer to tests where the specimen is subjected to a specified fire exposure, cooled at room temperature for 7 days; and subsequently tested for various mechanical properties. To achieve this goal, the following four objectives are being investigated.

Objective One: Suitability of Different Epoxy Adhesives for Crack Injection

Although a multitude of different epoxy adhesives are commercially available, only a limited number are useful for injection of cracks in concrete with a width range of 0.005 in. to 0.25 in. This objective will be achieved through the following using "hot" and "residual" tests.

(a) Comparison of the performance of the various epoxy adhesives using the standard deflection temperature test and the Arizona Slant Shear Test.

(b) A double shear type specimen has been developed to determine the "hot" and "residual" shear strength properties of epoxy adhesives.

(c) Izod type impact energy tests are being conducted to determine the "residual" impact energy of epoxy adhesives.

(d) Tests for "hot" and "residual" static compressive strength properties have been conducted on cylindrical specimens and the results are provided in Fig. 1.

Fig. 2 provides "residual" compressive strength test results conducted at 3 hertz and a linearly increasing sinusoidal load pattern designed to simulate seismic loads. The maximum residual strengths occur at a temperature of about 230°F for this group of epoxies which possess heat distortion temperatures of about 130°F.

Objective Two: Behavior of Epoxy Repaired Concrete Shear Walls During Fire Exposure

This objective is being accomplished by testing more than 250 epoxy repaired shear wall type specimens ranging from standard ASTM E-119 fire wall specimens (10-ft x 10-ft) to the more economical small-scale specimens (18-in x 14-in). Both the ASTM E-119 and the Short Duration High Intensity (as developed by B. Bresler) type time-temperature curves are being used for fire exposure. Results from the small scale specimens indicate that under a 2-hour ASTM E-119 fire exposure, pyrolysis of the epoxy is complete to a depth of about 3-inches for a 0.10 in. epoxy repaired crack width.

Objective Three: Nature and Extent of Residual Strength of Epoxy Repaired Concrete Shear Walls

After fire exposure has occurred in an epoxy repaired structure, the subsequent residual strength properties of the epoxy repaired components must be determined to evaluate the technical and economic feasibility of repairing the damage caused by fire. Hence, this objective will attempt to determine (a) the extent of damage suffered by the epoxy repaired crack under ASTM E-119 and SDHI fire exposures and, (b) the feasibility of re-injecting the crack where complete pyrolysis of the epoxy has occurred.

Objective Four: Catalog of Epoxy Repaired Structures

An attempt is being made to catalog at least 50 of the larger repaired buildings and bridges in the Los Angeles Basin which were initially damaged by the 1971 San Fernando Earthquake. The primary objectives of such a cataloging process are as follows:

(a) To investigate the type and extent of damage due to earthquakes in various types of structures.

(b) To analyze the repair process utilized in a particular structure.

(c) To determine the relative performance of the various repair techniques during subsequent fire exposure and/or earthquakes.

II. Design and Behavior of GRP Storage Vessels

Storage vessels containing corrosive fluids are most economically designed with glass reinforced fiberglass materials. Fiberglass construction not only provides excellent corrosion resistant properties but also allows for an efficient anisotropic placement of glass reinforcement for maximum economy. This research is centered on the most efficient design of continuous filament wound GRP storage tanks in seismic zones 3 and 4. Research currently in progress is limited to tanks with a height/diameter ratio of more than 1.0 and the results are as follows:

1. Since fluids cannot transfer shear stresses, seismic loads may be modelled by a constant uniform pressure on half the tank wall equivalent to the lateral force required by the codes.
2. Due to excessive forces in the tie-down lugs from the overturning moment, the most efficient tank designs consist of a height diameter ratio of less than 3.
3. Due to the anisotropic nature and the thin shell behavior of the tank wall construction, the stress distribution in the tie-down lugs cannot be adequately determined for seismic loads by design techniques used for metal tanks.
4. Finite element analysis appears to be necessary for GRP tanks with height/diameter ratios of less than 3 since the standard bending analysis for short or long beams does not apply.

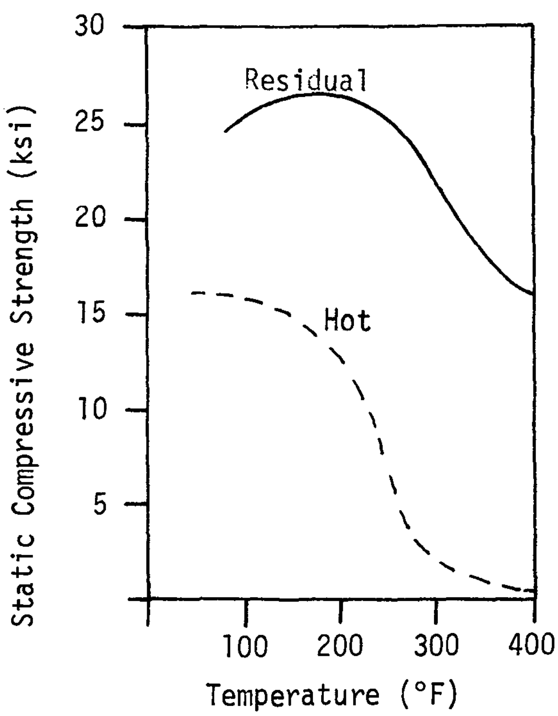

Fig. 1. Static Compressive Strength

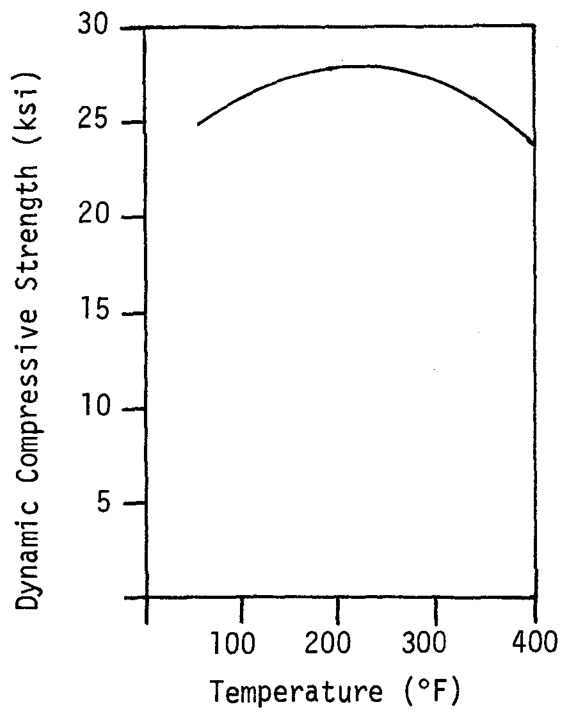

Fig. 2. Dynamic Compressive Strength

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University of California, Berkeley

SEISMIC BEHAVIOR OF TALL LIQUID STORAGE TANKS

Background

In 1974, a group of industrial organizations, under leadership of Chevron Oil Field Research Company, suggested the earthquake simulator facility be used to study the seismic behavior of ground supported thin wall cylindrical liquid storage tanks. Under their sponsorship, together with support from National Science Foundation, comprehensive seismic tests were carried out on two one-third scale metal tanks with 12 x 6 ft and 7-3/4 x 15 ft diameter x height dimensions. Preliminary results from the broad tank model were reported at the 1976 UCEER Conference; the final report on that study was published in January 1977 (UC/EERC Report No. 77-10, by D. P. Clough).

Because the most important seismic effect on ground supported storage tanks is the overturning moment resulting from horizontal accelerations, it was expected that the aspect ratio of the tank would be a significant response parameter, and the results of the tall tank study, which has now been completed, confirmed that expectation. The test procedures and principal results of the tall tank test are summarized here.

Experimental Procedure

The tank model was fabricated from aluminum sheet of 0.009 and 0.063 in. thickness; the elastic modulus of the aluminum provided similitude with gravity effects in a steel tank three times larger. Test parameters included the earthquake history and intensity, water depth, open or closed roof condition, and most importantly the base fixity: free or clamped. Up to 150 channels of instrumentation were used in some tests, including strain gages, water pressure and wave height gages, and tranducers for measuring radial and tangential displacements as well as base uplift.

Tests were performed by applying the specified seismic excitation at a predetermined intensity level, with the time scale speeded up by a factor $\sqrt{3}$ to maintain similitude. A single horizontal component and/or the vertical component were employed, and the peak table acceleration generally was set at 0.5g. Over 100 such tests were performed with the tall tank, but only the principal results of the "standard" test will be mentioned here -- involving the El Centro earthquake, open top tank with 13 ft. water depth, and fixed base.

Response Behavior

The most important finding of this experimental study is that the earthquake loading excites significant cross-sectional distortion of the tank. Such distortion is expected in a tank free to uplift at the base, but is not indicated in the theoretical behavior of a fixed base tank. If the tank initially is a perfect circular cylinder, it is expected to deflect laterally without changing its circular shape when subjected to an earthquake. At present there is no adequate explanation for the observed behavior, and no analytical procedure can predict this type of response; but it is believed to result from initial eccentricities in the tank geometry due to fabrication.

Because the tank response showed important out-of-round distortions, it was necessary to measure the response at several positions around the circumference. All major response quantities -- strain, displacement, and hydrodynamic pressure -- were measured at eight sections equally spaced around the tank. From the eight measured values of a specified response quantity, the amplitudes of the eight lowest Fourier components of the circumferential distribution were evaluated.

Peak values of such Fourier components obtained in a standard fixed base test are shown in Figure 1; these indicate the relative contributions of the various harmonic components during this typical earthquake response. Clearly the displacements show important components of the cos 2θ and cos 3θ form (coefficients A_2 and A_3) in addition to the expected cos θ motion. Further study of the figure shows that the stresses are less influenced by the out-of-round response than are the displacements, but the isometric plot of axial stresses shown in Figure 2 demonstrates that the effect of the higher order terms is far from negligible. In this plot, the time axis extends toward the right, while position around the circumference is represented on the diagonal axis. The plot at time $t = 0.19978$ seconds, for example, shows clearly that a significant cos 2θ variation is superposed on the basic cos θ stress distribution. Thus, this depiction of the axial stress at a section 5 in. above the base demonstrates that the higher harmonic has an important effect on the stress distribution.

Conclusions

Results of this study show that the seismic response of fixed base tanks differs significantly from theoretical predictions, and demonstrates the need for analytical procedures which can predict the out-of-round response. Although not described here, the results for the tank with base free to uplift also show important deviations from design predictions. In order to better understand the observed performance, static "tilt" tests are presently being carried out with the tall tank -- supporting it on a rigid platform that can be tilted to any desired angle. Measurements of the static stresses and deflections developed during this investigation may shed some light on the observed shaking table behavior. It is interesting to note that uplift is initiated with a tilt angle of less than two degrees for the case when the base is not clamped.

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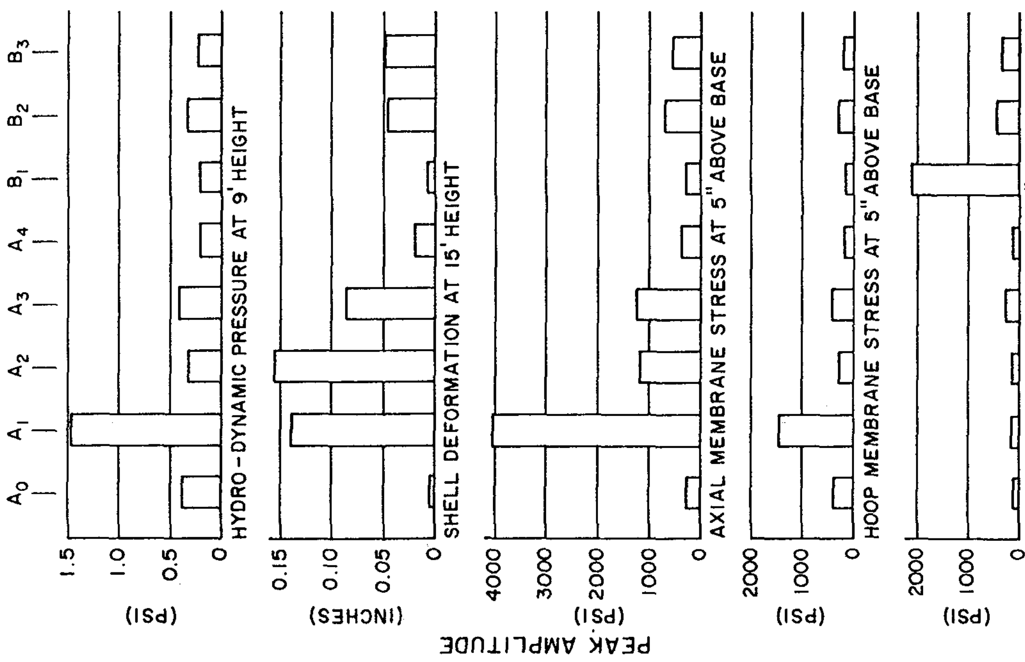

Fig. 1: Peak Response to El Centro Earthquake at 0.5g
(Fourier coefficients of circumferential distribution)

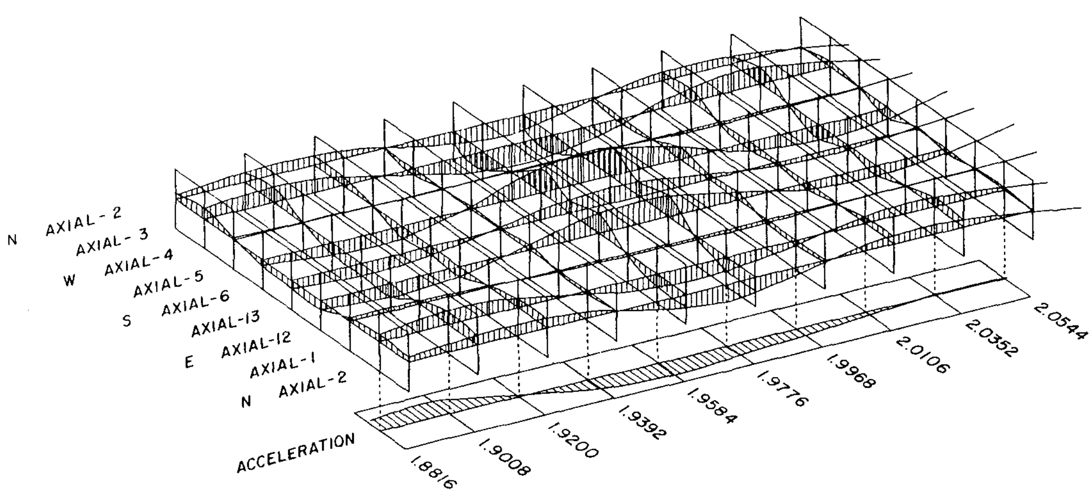

Fig. 2: Axial Stress due to El Centro Earthquake at 5 in. Above Base
(Variation with time and around circumference)

A.M. ABDEL-GHAFFAR and R.F. SCOTT

California Institute of Technology

Earthquake-response characteristics of an earth dam and its dynamic properties are being studied with the support of the National Science Foundation and the Earthquake Research Affiliates of the California Institute of Technology. The investigation has two aspects:

(1) Determination of the dynamic characteristics of earth dams from their earthquake response records,

(2) Full-scale dynamic tests of an earth dam.

Dynamic Characteristics of Earth Dams from their Earthquake Records

An investigation has been made to analyze observations of the effect of two earthquakes (with $M_L = 6.3$ and 4.7) on Santa Felicia Dam, a rolled-fill embankment located in Southern California. The dam is 236.5 ft high and 1,275 ft long by 30 ft wide at the crest. The purpose of the investigation is: (1) to study the nonlinear behavior of the dam during the two earthquakes, (2) to provide data on the in-plane dynamic shear moduli and damping factors for the materials of the dam during real earthquake conditions, and (3) to compare these properties with those previously available from laboratory investigations.

From the recorded motions of the dam, amplification spectra were computed to indicate the natural frequencies of the dam and to estimate the relative contribution of different modes. A comparison between these natural frequencies and those obtained by two elastic shear-beam models was made to obtain representative dam material properties. In addition, field wave-velocity measurements were carried out as a further check as well as to study the variation of shear wave velocity at various depths in the dam. The amplification spectra showed a predominant frequency of 1.45 Hz in the upstream-downstream direction; in this direction the response was treated as that of a single-degree-of-freedom hysteretic structure. A digital band-pass filtering of the crest and abutment records was used to obtain the hysteresis loops which show the relationship between the relative displacement of the crest with respect to the abutment and the absolute acceleration of the dam. A method, using some of the existing elastic-response theories, is described which enables the shear stresses and strains, and consequently the shear modulus, to be evaluated from the hysteresis loops. The equivalent viscous damping factors were calculated from the areas inside the hysteresis loops. The shear moduli and the damping factors were determined as functions of the induced strains in the dam. Finally, the shear moduli and damping factors obtained for the dam were compared with previously available laboratory data.

Full-Scale Dynamic Tests of an Earth Dam

This recently completed experimental work consists of forced-vibration, ambient vibration and Popper tests on Santa Felicia earth dam in Santa Clara Valley. The Popper test uses pressure waves (which hit the upstream face of the dam) originating from a controlled submerged release of gas under pressure in the reservoir water. Santa Felicia Dam is a rolled-fill embankment located in Santa Paula, Ventura County; it is 236.5 ft high, 1,275 ft long and 30 ft wide at the crest. For the forced-vibration tests, the dam was excited into resonance by two mechanical vibration generators capable of producing forces up to 10,000 pounds. The naturally occurring vibrations of the dam caused by winds and the spilling of the reservoir were measured during the ambient tests. The measurements taken on the dam included, as first step, the determination of the natural frequencies, damping and preliminary mode shapes. Then the more important modes of vibration of the dam's three-dimensional response were recorded. The Santa Felicia Dam was chosen for the experiments because of the available data on how the dam behaved during two California earthquakes: the strong, 6.3 magnitude San Fernando earthquake of 1971 and a 1976 earthquake of magnitude 4.7. The experimental data obtained will advance the understanding of the dynamic characteristics and behavior of earth dams; in addition, it will add considerably in developing better methods of testing dams for earthquake resistance and in designing more earthquake-resistant dams.

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4. "Shear Moduli and Damping Factors of an Earth Dam From Two Earthquake Records", A.M. Abdel-Ghaffar and R.F. Scott, to be submitted to the Journal of the Geotechnical Engineering Division, ASCE, July 1978.

ROGER M. ZIMMERMAN

New Mexico State University

Research efforts have been directed towards earthquake effects on bridges. Three efforts are summarized as initial starts. These are:

(1) Measurement of On-Site Dynamic Properties of Bridges
(2) Develop a Classification System Relating Earthquake Collapse with Bridge Type
(3) Perform Earthquake Analyses on Multiple Simple Support Prestressed Concrete Girders Having Rocker Type Pin Supports

The first effort is in the proposal stage and the others are M.S. theses that are in the latter stages of completion.

Measurement of On-Site Dynamic Properties of Bridges

The primary objectives of this effort are to develop nondestructive techniques that can be used to determine the resonant frequencies, vibrational mode identification, and damping ratios for existing bridges. The initial effort is directed towards developing an electromagnetic induction system that can be used as a measurement device. The follow-up effort is directed towards incorporating these sensors in a mobile unit that can be used to measure these properties for in-service bridges.

The principle that is to be studied in the initial effort is that of fabricating three coils into a unit such that their major axes are orthogonal. It is proposed that these units be attached to various locations on a bridge and that the bridge be excited to a resonant frequency by external means. An electromagnetic field will be brought up near the sensor unit and will be fixed in space through external supports. The vibration of the triaxial coil in the electromagnetic field will generate current in the coils and this can be related to the vibration of the sensor unit. Thus amplitude-time traces can be measured for each of the coils. By performing various electronic operations, the orientation of the static field can be determined and also the damping can be calculated. From these measurements the desired dynamic properties can be obtained relatively easily and inexpensively.

The sensor units will be designed and proof tested in the laboratory prior to field use. Upon satisfactory development the field tests will commence. An eccentric mass variable frequency oscillator will be used to excite the bridges to resonance. These will have frequency ranges to cover the flexural, torsional, and longitudinal modes. The electromagnet will be placed on a truck-operated boom such that it can be raised and positioned in near proximity to a sensor. Six sensors are planned for the first tests and the plan is that the electromagnet be moved from each sensor for these measurements.

The follow-up research efforts are to be directed towards developing a van type unit that can be used to measure and process the signals simultaneously. Long range goals are that a single unit can process all dynamic data in one stop. The development of such a unit should provide a useful tool for earthquake evaluations of the many bridges and other similar structures that are already in service.

Earthquake Collapse - Bridge Type Classification System, J. Tegtmeier

The objective of this effort is to utilize existing literature and experiences to develop a simple classification system that can be used to relate bridge collapse to the primary parameters that describe bridges. Collapse parameters are divided into their degree of susceptibility by classifications of low, intermediate, and high. These are subjective terms, and a point range is assigned to each category. Bridges are divided into seven parameters. The span is identified by its basic type, i.e., two span indeterminate, multiple simple supports, etc., and basic dimensions. The second span related parameter is that of the straightness of the centerline and the third is the skewness. Intermediate piers are identified by the type, and height factors. The sixth parameter is the foundation type, both at the abutment and at the piers and the seventh parameter defines the support details. The effort is defined such that these parameters have subheadings and guidelines for their use.

The classification scheme is to add the point values for each of the paramaters and multiply the sum by an importance factor. Bridges can be rated on a single value basis. A number of examples are worked out.

Earthquake Analysis - Multispan Simple Support Prestressed Concrete Girders - R. Brittain

It has been noticed that the design of multispan simple support prestressed concrete bridges has led to the use of relatively flexible supports at the ends of the spans. Expansion joints between the spans are made with elastomeric seals or slide units. In some cases expansion joints are air gaps between spans. Most bridges of this type are designed such that there is minimum interference in the thermal expansion of the prestressed girders. A common support detail is to provide a rocker support at one end that is formed by placing a linkage with curved surfaces at each end between the girder and the pier cap. The rocker linkage can be 9 inches (23 cm) long. In some older bridges it is noted that the pin end of these girders is made of a similar unit to the rocker with the difference being that the pier end of the rocker linkage is welded to a plate that is bolted to the pier cap. This is a relatively flexible connection and it is theorized that there is a high potential for longitudinal vibrations to be induced under seismic activity.

The research effort is a dynamic analysis and earthquake resistant evaluation of this type of bridge using ICES STRUDL-II, Dynamic Analysis.

J.L. BOGDANOFF and T.Y. YANG

Purdue University

Literature on free vibration and seismic response analyses of fossil fuel steam generators and their supporting structures is sparse. Analyses have only been made for extremely simplified models. In this National Science Foundation sponsored study, free vibration and response spectrum analyses have been performed for two steam generating structural systems by using realistic three-dimensional finite element models.

A 600 MW Fossil Fuel Steam Generating Plant (Zone III)

A 600 MW steam generator and its supporting structure located in Zone III of the seismic risk map have been studied. The structural design was based on the pseudo-static loads as specified in the Uniform Building Codes.

The steam generator and the steel supporting structure weigh approximately 17,200 kips and 11,500 kips, respectively. The steam generator is supported by 276 hanger rods at the top and 20 horizontal tie rods at the sides. The supporting structure was designed with hinged joint conditions. It has 439 joints and 1085 beam, column, and bracing members.

Based on the assumption that the steam generator is a rigid body hung by an arbitrary number of rods, a set of six analytic equations of motion was derived. Six basic frequencies and modes were obtained for the steam generator with 276 hanging rods. Alternatively, the steam generator was modeled by 48 lumped masses interconnected by rigid bars and hung by only 4 equivalent rods. The mass and sectional properties of the 4 equivalent rods are such that the three lowest basic frequencies and modes obtained from the two separate analyses agree with each other. The lumped mass model was used to connect with the finite element model of the supporting structure. The connecting members include four equivalent hanging rods and 20 horizontal tie rods. The three-dimensional finite element model includes 1085 truss bar finite elements.

Twelve natural frequencies and mode shapes were obtained for the total system by using SAP IV program. The 12 frequencies range from 0.84 to 2.9 Hz. The torsional motion about a vertical axis dominates the third mode and appears in nearly every mode in various proportions.

Based on the 12 natural frequencies and modes, a response spectrum analysis was performed for the system by using the acceleration data of El Centro earthquake of May 18, 1940. The statistical maxima of the response quantities, such as displacements and axial stresses, were obtained based on the root-mean-square of the various modal response spectra. A computer program was developed to plot each vertical and horizontal plans and print the ratios of the axial stress to yielding stress and to buckling stress for each member. Based on the assumption of no damping, it is found that out of 1607 members, the axial stresses exceed the yielding stress in 158 members and the buckling stresses in 309 members. Out of 20 tie members, the axial stresses exceed both the yielding stress and buckling stresses in 4 members. The 158 yielded members are mostly located in the lower portion of the major columns. The 309 buckled members are mostly the cross bracing members.

Critical damping coefficients of 0.5%, 1%, 2%, and 5% were later considered. It was found that the deflections of a typical column were reduced by approximately 1/3 for 0.5% damping and by 2/3 for 5% damping.

A 1200 MW Fossil Fuel Steam Generating Plant (Zone I)

A 1200 MW steam generator and its supporting structure located in Zone I of the seismic risk map has been studied. The system was designed with no seismic considerations.

The steam generator and the steel supporting structure weigh approximately 24,200 kips and 17,530 kips, respectively. The steam generator is supported by 277 hanger rods at the top and 11 horizontal tie rods along three edges. The steam generator with the hanger and tie rods were modeled the same way as that described in the previous section. The steel framing structure was designed with rigid joint conditions. The three dimensional finite element model includes 415 joints, 878 beam and column elements, and 415 cross bracing truss bar elements. Two concrete working decks were modeled by 38 isotropic quadrilateral plate elements. The grid beams between major beams were modeled by 150 orthotropic quadrilateral plate elements.

Twelve natural frequencies and mode shapes were obtained for the total system by using SAP IV program. The 12 frequencies range from 0.71 to 3.1 Hz. The torsional motion dominates many modes including the first and third modes.

Based on the 12 frequencies and modes and the same El Centro earthquake, response spectrum analysis was performed. The statistical maxima of response quantities such as the three forces and three moments at the end of each element were obtained. The principal direct and shearing stresses were obtained by using bi-axial stress formulas. A computer program was developed to plot every plane frames and print the ratios between the direct and shearing stresses to the respective yielding values for each member. Each member net axial force was also compared with its buckling load. Based on the assumption of no damping, it is found that out of 1290 steel members, the maximum direct stresses exceed the elastic limit in 277 members, the maximum shearing stresses exceed the elastic limit in 142 members, and the axial forces exceed the buckling loads in 319 members. The axial stresses in 9 out of 11 tie members exceed both the yielding and buckling stresses. The overly stresses members are mostly in the lower front portion of the structure that surrounds the airheater. The lowest parts of all the major columns are also overly stressed. The buckled members are mostly the cross bracing members. The most critical members are the horizontal ties.

Conclusions

(1) This research is a first major effort to the dynamic analysis of fossil fuel steam generators and the supporting structures by using complex 3-D structural models.

(2) The study is based on linear elastic and small deflection theory.

(3) Two power plant designs have been studied, one with and one without seismic considerations.

(4) The equations of motion for a steam generator with an arbitrary number of hanger rods have been derived. Dynamic loads in hanger rods are sensitive to location of horizontal tie rods. There appear to be optimum locations of horizontal tie rods that significantly reduce dynamic load in hanger rods. Variable length hanger rods may prove advantaneous in controlling dynamic loads in hanger rods.

(5) Torsional motion of steam generator with respect to its top supporting structure will significantly increase dynamic loads in hanger rods in four corners of steam generator.

(6) The use of dampers as horizontal tie rods appears to offer advantages over elastic tie rods in reducing dynamic load in hanger rods.

(7) Vertical motion can be neglected in all but the top of supporting structure.

(8) If a steam generator is supported significantly below top, elasticity of steam generator may have to be considered.

(9) Model must include the fact that vertical hanger rods cannot take compression if horizontal and vertical ground accelerations are above 0.15 g.

(10) Twelve natural frequencies and modes have been found for each system. The information provides insight to the dynamic behavior of such type of structures. The information may serve as comparison basis for simplified model studies. Reliable simplified models are more practical and are studied by C.T. Sun.

(11) In both systems, torsional motions are dominant in lower modes. Thus such systems must be modeled to account for 3-D motion including torsion. The systems should be configured in so far as possible to reduce torsion.

(12) Response spectrum analysis has been performed using the El Centro earthquake of May 18, 1940. With the assumption of no damping, vulnerable structural members have been identified. The information may be useful to designers of similar systems.

(13) The stresses obtained should be reduced considerably if damping is considered.

Valuable discussion and help from H. Lo, A. Schiff, and C.T. Sun are appreciated.

VITELMO V. BERTERO, EGOR P. POPOV, AND STAN W. ZAGAJESKI

University of California, Berkeley

Research sponsored by the National Science Foundation in the area of seismic-resistant design of R/C structures is being conducted on structural walls and ductile moment-resisting frames.

Seismic Design Implications of Hysteretic Behavior of R/C Structural Walls[1,2]

The ultimate objective of this investigation is to develop practical methods of seismic-resistant design for combined, R/C frame-wall structural systems. To achieve this objective, integrated experimental and analytical studies are being conducted.

Experimental Studies.--A series of experiments has been conducted on eight 1/3-scale wall component models of the bottom three stories of both a ten- and a seven-story frame-wall building system. The parameters studied included the cross section of the wall (rectangular vs. barbell); methods of concrete confinement of the edge members (spiral vs. square ties); arrangement of the reinforcement in the wall panel [vertical and horizontal vs. diagonal (45°)]; and the effect of loading history (cycles with reversed deformation vs. monotonically increasing loads).

The composite graph of Fig. 1 illustrates the results obtained on barbell models. Comparison of the behavior of rectangular and barbell cross sections under monotonic loading is shown in Fig. 2, and under cyclic loading in Fig. 3. These figures indicate the significant effects of the loading history, as well as the superior behavior of barbell-type wall cross sections.

Analytical Studies.--These studies have been devoted to predicting the mechanical behavior of wall-frame structures when subjected to severe seismic excitations. Extensive instrumentation during the experimental studies permitted the contributions of the following sources of deformation: flexure, shear, and fixed-end rotation due to straining of the reinforcing bars in their embedment length at the foundation, to be determined independently. Excellent agreement has been obtained in predicting the behavior under monotonically increasing loads. Satisfactory agreement has also been obtained in predicting the hysteretic behavior under cyclic loading, particularly up to the first cycle beyond the first yielding.

Seismic Design Implication of Results Obtained.--Despite the limited number of specimens studied, the following observations can be made: 1) It is possible to design and construct R/C wall components capable of developing large ductilities even when those components are subjected to full deformational reversals inducing nominal unit shear stresses up to $10\sqrt{f'_c}$ (f'_c in psi); 2) The hysteretic behavior of barbell-type walls is considerably superior to that of rectangular cross sections; 3) Although behavior of the wall with diagonal, 45° reinforcements was better than that of the wall with vertical and horizontal reinforcements, the superior performance of the former does not justify the extra costs it involves;

4) Use of present code specifications for design forces, load factors, and design and detailing of critical regions can lead to a wall, which, in a major seismic ground motion, can actually develop shear forces that are considerably higher than those for which it has been designed.

Earthquake-Resistant Design of Ductile Moment-Resisting Frames[3,4,5]

A comprehensive, computer-aided seismic-resistant design procedure has been developed and is now being evaluated. As currently formulated, the procedure is applicable to the design of ductile, moment-resisting R/C space frame structures which are expected to experience a severe earthquake ground motion during their service life.[3]

The design procedure consists of five steps which are grouped into a preliminary and a final design phase. The steps in the preliminary phase are repeated until an acceptable preliminary design is established. A spectral analysis technique is employed to define the seismic design story shear forces. Member design is based on a storywise optimization procedure, which uses a linear programming technique. A weak girder - strong column design criterion allows formulation of a simplified optimization problem for each story with beam design moments as unknowns. The optimization objective is to minimize the volume of flexural reinforcement. Design constraints are established to insure that equilibrium conditions are satisfied and that a serviceable and practical design results. Once an acceptable preliminary design is obtained, a final design is carried out using a more refined story subassemblage. When a design is obtained, a series of linear and nonlinear structural analyses is carried out in order to evaluate the design's acceptability in the preliminary design phase and its reliability in the final design phase.

The procedure has been applied to the design of a ten-story, three-bay frame. The effects of different design earthquakes and design procedures on the material volume required and dynamic response have been evaluated.[3,4,5] The results indicate that 1) an increase in the severity (intensity) of the design earthquake can increase the material volume required. However, the latter increase must be weighed against the improved behavior of these designs at all limit states; 2) optimum values of beam design moments are sensitive to how the objective function is formulated; variations in these values can change the distribution and magnitude of local inelastic deformations; 3) nonlinear dynamic response is particularly sensitive to the characteristics of the input ground motion; and 4) applications of the developed inelastic procedure result in designs whose performance (required inelastic deformations throughtout the structure) is more in line with the supplied deformation capacities than those based on standard elastic design procedures.

The sensitivity of the optimization solution of variations to the contribution of the beam reinforcement to the objective function is currently being investigated. Ultimate load elastic moment envelopes, which are used to determine the beam contribution, typically differ from envelopes constructed on the basis of the optimization solution. In general, reformulation of the optimization problem on the basis of moment envelopes corresponding to a previous design solution will result in a new design that will require practically the same volume of material, but with different values for the beam design moments. Additional designs, based on new design constraints and current UBC (1976) seismic design provisions, are planned. The new designs will be compared with results obtained from a new solution (with respect to formulation of the objective function) of the optimum design problem presented in previous studies; in addition, the effect on nonlinear dynamic response of the maximum reinforcement ratio assumed in member design will be studied.

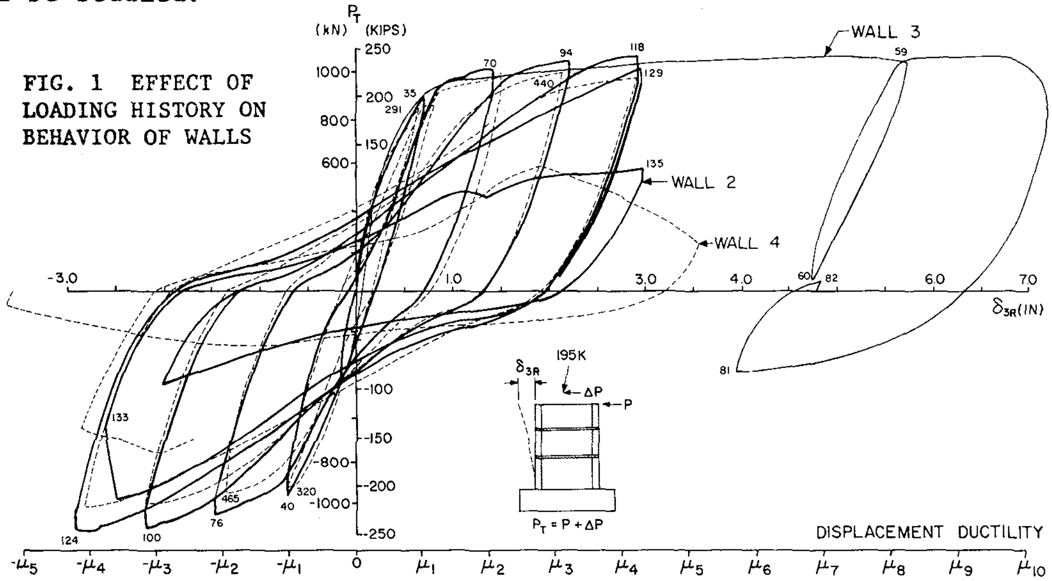

FIG. 1 EFFECT OF LOADING HISTORY ON BEHAVIOR OF WALLS

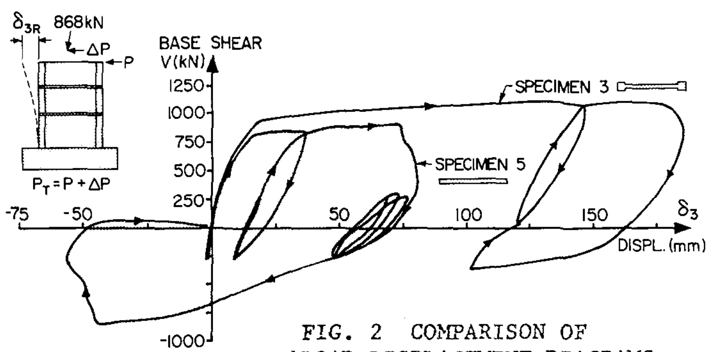

FIG. 2 COMPARISON OF LOAD-DISPLACEMENT DIAGRAMS FOR SPECIMENS 3 & 5

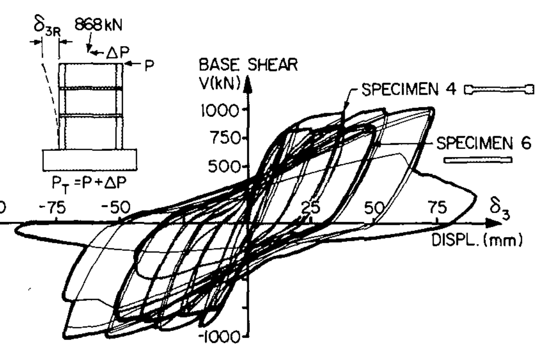

FIG. 3 COMPARISON OF HYSTERETIC BEHAVIOR OF SPECIMENS 4 & 6

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SESSION 5

STRUCTURAL RESPONSE, ANALYTICAL

Chairmen: A. S. Veletsos
C. A. Cornell

S.F. MASRI and F.E. UDWADIA

University of Southern California

Summary of the Research Activities in the
Civil Engineering Department

Response of Mechanical Equipment to Earthquake Excitation
Investigators: J.C. Anderson, S.F. Masri, F.E. Udwadia, P. Seide

The major objectives of this comprehensive analytical and experimental study are to:

a) Investigate the effects of nonlinear system modeling and scaling on the ability to predict the structural response characteristics of complex mechanical components.
b) Develop simplified nonlinear models for certain types of mechanical equipment
c) Develop design curves for preliminary design of systems with geometric and material nonlinearities under transient dynamic loads
d) Evaluate the effects of uncertainties in system characteristics on the response of the system
e) Develop probabilistic response spectra for equipment components under earthquake excitation.

System Identification Techniques
Investigators: S.F. Masri, F.E. Udwadia

Analytical and experimental studies are underway to develop efficient parametric and nonparametric identification techniques for use with nonlinear structural dynamic systems. Techniques for parametric and nonparametric identification of building structural systems have been developed and their applicability demonstrated by using real data obtained from the response of full-scale structures to wind and earthquake loads.

Finite-Element Programs
Investigator: V.I. Weingarten, H. Miura

Work is continuing on the development of a generalized structural analysis finite element program (SAP 6) to determine the response of structures to earthquake loading by using various techniques. New capabilities which will be added to the program include:

a) soil-structure interaction
b) wave-structure interaction
c) geometric elasticity and general shell element.

Local nonlinearities and interactive graphics capability for pre- and post-processing are also being developed.

Distant and Local Tsunamis in Coastal Regions
Investigator: J.J. Lee

The main emphasis is on the coastal effect of tsunamis generated at distant sea and those generated by coastal earthquakes or landslides. The study includes (1) theoretical analysis to obtain governing equations, (2) numerical study to obtain the final solution based on the governing equations derived in the theoretical study, and (3) experimental studies to provide confirmation to the numerical solutions.

Specific problems currently under study are:

a) Propagation of the nonlinear dispersive wave in regions of variable depth and variable width including the dissipation effect.
b) Propagation of local tsunamis into deeper ocean.
c) Effects of local topography on nonlinear wave propagation such as that due to sea mounts or submarine trenches.

Seismic Risk and Structural Reliability
Investigator: A. Der Kiureghian

Several problem areas in analysis of earthquake induced ground motions and evaluation of seismic risk are being investigated. Special emphasis is being given to the analysis and quantification of uncertainties associated with various processes and procedures employed in such evaluations. It has been found that uncertainties associated with intensity attenuation laws have significant impact on the prediction of future ground motion intensities at a site.

Reliability analysis of structures under combinations of stochastic loads are being studied. Methods are being developed to evaluate lifetime extreme values of combinations of earthquake and other loads. These methods are being used to determine reliability-based safety and load factors for structural design. Recent developments show that relatively simple second-moment procedures can be developed to analyze the complex problems of stochastic load combination.

Automatic Digitization of Strong-Motion Accelerograms
Investigator: M.D. Trifunac

A new method for automatic digitization of strong-motion accelerograms recorded on 70mm film is being developed. It utilizes a rotating drum-type photodensitometer, with minimum pixel size of 12.5 x 12.5 , coupled through the direct memory access to a mini-computer. Digitization of an accelerogram involves three steps: (a) Digitization of film record and storage of coordinates and of light transmitted for pixels with intensity higher than a selected threshhold, (2) automatic search through disk memory to synthesize lines and (3) operator graphics interaction to (a) manually correct difficulties which could not be handled by automatic search program, or (b) insert missing data. The time required to complete all steps necessary to place raw digitized data onto a magnetic tape is more than one order of magnitude faster than for methods involving hand digitization and punched card or tape outputs. The work is now in progress to improve the capabilities and efficiency of the existing software.

Investigation of Strong Earthquake Ground Motion
Investigators: M.D. Trifunac and F.E. Udwadia

Studies are carried out on basic scaling relationships for amplitudes and for duration of strong ground motion. Empirical scaling laws have been developed to characterize strong motion for use in engineering design and in terms of simple and readily available scaling parameters such as earthquake magnitude, source to station distance and Modified Mercalli Intensity at the recording station. The effects of local geologic conditions, components direction and the distributions of observed amplitudes and durations are also considered and included into the scaling relationships whenever it can be shown that such effects modify the final result significantly.

Strong-Motion Accelerograph Array in Los Angeles
Investigators: J.G. Anderson, T.L. Teng, and M.D. Trifunac

Work is in progress to design and deploy a strong-motion accelerograph array in the metropolitan Los Angeles area. This array will consist of approximately 80 stations and will be designed to facilitate measurement of variations of strong motion with soil and geologic properties beneath each site. At north and northwest this array will have stations on basement rock while in the central Los Angeles basis, it will be on top of sediments 33,000 feet deep. Absolute time will be recorded at each station to facilitate wave propagation studies. The triggering level of all stations will be chosen to record local earthquakes with magnitude $M \gtrsim 3.5$.

Seismic Behavior of R/C Frames with Degrading Stiffness
Investigator: J.C. Anderson

Studies are continuing on the development of analytical models which represent the degrading stiffness characteristics of reinforced concrete beam-column connections. Current efforts are directed toward correlating analytical results with those obtained from laboratory tests of full-scale beam-column subassemblies. Experimental work is being done at SUNY Buffalo. Output from the analytical model is being used as input to the subassembly. Output from the subassembly test is then compared to that of the analytical model.

Automated Earthquake Resistant Design
Investigator: J.C. Anderson

An automatic strength design procedure is being developed for inclusion in the ETABS frame analysis program. This will be particularly applicable to earthquake resistant design of steel frames using the response spectrum approach and to unsymmetrical frames which are subject to torsional effects. Preliminary results show that starting with average section properties, a final design can be obtained with only a limited number of iterations. The system also allows considerable engineering-computer interaction.

Development of a Methodology for Sensor Location in Building Systems
Investigator: F.E. Udwadia

A general methodology for locating sensors in dynamic structural systems is being evolved with an eye towards increasing the capability of determining the system properties from measurements made at the chosen sensor locations.

Inverse Geophysical Problem
Investigator: F.E. Udwadia

A new algorithm for the simultaneous estimation of earthquake hypocentral locations, origin times and crustal velocities has been developed and its utility demonstrated by taking a two-dimensional non-homogeneous earth profile and applying the technique to it. P and S wave arrival time information is used to do the inversion.

Questions of Uniqueness Related to Inverse Problems
Investigator: F.E. Udwadia

The conditions under which the identification problem leads to unique solutions and the degree of nonuniqueness obtained in the general identification of dynamic systems is being investigated.

Constitutive Stress-Strain Relations for Soils
Investigators: F.E. Udwadia and R. Bloch

A six parameter constitutive relation for sands is being investigated to model pure shear, triaxial, unconfined compression and hydrostatic compression test data. A strain energy function in terms of the stretch ratios is being investigated.

Effect of Local Topography of the Amplitude of Surface Motions Caused by Earthquakes
Investigators: F.E. Udwadia and M. Dravinski, P. Seide

Analytical studies are being carried out on the effect of wavy and random surface boundaries on the amplitudes of surface motions created by plane wave inputs at various angles of incidences.

<u>Finite Element Methods</u>
Investigator: L.C. Wellford, Jr.

Current earthquake-related research in structural dynamics include:

a) Development of perturbation procedures for soil-structure interaction.
b) Studies of the use of nonlinear eigenvalue problems in structural dynamics.
c) Development of finite element methods for nonlinear wave propagation studies.

RICHARD K. MILLER

University of California, Santa Barbara

National Science Foundation sponsored earthquake engineering research is currently proceeding on analytical aspects of the response of structures with localized nonlinearity. Specific areas under investigation include the development of approximate analytical techniques for such problems as the dynamic interaction of adjacent structures with a nonlinear seismic connection, and wave propagation at a nonlinear frictional interface. A separate but related project is concerned with the identification of optimal passive vibration isolation systems for large structures.

Response of Structures with Localized Nonlinearity

In the most general case of dynamic structural response, nonlinear behavior occurs simultaneously at many locations throughout the structure. Such general problems often require elaborate analyses and excessive computation. Furthermore, detailed numerical studies of such problems are often difficult to generalize due to the large number of parameters involved. Consequently, there is a general need for simpler and more efficient analysis techniques capable of reducing computational costs, identifying important parameters, and interpreting the response in terms of simplified behavior for use in design. However, such efficient techniques are quite difficult to develop for general nonlinear structural systems.

A class of structural systems for which more efficient analysis techniques may be feasible is that of structures with localized nonlinearity. Due either to intentional design or prevailing circumstances, the nonlinear behavior in such systems occurs at only one location within the (otherwise linear) structure. Examples might include adjacent structures with a flexible seismic connection, structural systems on flexible supports, and adjacent elastic bodies with a frictional interface. The application of approximate analytical techniques is made possible in such systems by the localization of nonlinear behavior. Each of the following projects attempts to capitalize upon this fact in order to contribute toward the development of more efficient analysis techniques for determining the earthquake response of locally nonlinear systems.

Interaction of Adjacent Structures with a Nonlinear Connecting Element

In recent studies [1,2] an approximate analytical approach was developed for determining the effect of a nonlinear flexible support on the harmonic response of a linear structural system. In current studies this basic technique is being extended and applied to the more general case of adjacent structural systems with either symmetric or asymmetric nonlinear structural coupling. The primary objective is to determine the effects of the nonlinear coupling on the effective natural frequencies, mode shapes, and damping ratios of the system, and to investigate the nature of the steady-state harmonic, stationary stochastic and transient earthquake response. Particular attention is being focused on problems of vibro-impact of adjacent structures at an expansion joint, or similar connection.

Wave Propagation at a Frictional Interface Between Elastic Media

An approximate analytical approach was recently developed [3,4] for determining the effect on normally incident SH waves of a frictional boundary plane between semi-infinite elastic media. In current investigations this technique is being applied to the more general problems of obliquely incident planar harmonic SH, SV and P waves at a boundary with various models for dry friction. Results for many types of friction generally indicate that for low amplitude incident waves the boundary behaves as if perfectly bonded, and for large amplitudes as if perfectly lubricated. Maximum energy absorption occurs at the boundary for an intermediate amplitude of incident waves. A new model for slip at an interface with kinematic locking is being investigated. The effects on attenuation and dispersion of Love-type surface waves in a frictionally bonded layer are currently under investigation. Planned investigations will examine the effects of a frictional boundary on the propagation of random and transient pulses.

Identification of Optimal Passive Vibration Isolation Systems

Recent experimental studies [5] have shown that passive vibration isolation systems for multi-story buildings can substantially reduce structural response to strong ground motion. The objective of this study is to identify the force-deflection behavior of that isolation system which provides optimal protection of a given structure from ground motion. Current investigations are concerned with the comparison of various criteria and constraints for the minimization of linear structural response to steady-state harmonic and stationary stochastic base excitation. Planned investigations will extend the optimization search from passive linear to passive nonlinear isolation systems for otherwise linear structures.

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BARRY J. GOODNO

Georgia Institute of Technology

Introduction

The seismic behavior of highrise buildings and building components and damping in free-standing tower structures are currently under study in several research programs sponsored by the National Science Foundation. The objectives and scope of these programs are described below.

Cladding-Structure Interaction in Highrise Buildings

The exterior cladding of a modern highrise building is usually regarded as nonstructural by building designers and its effect on building performance neglected. Recent reports of distress in curtain wall elements have indicated that the cladding is not nonstructural in function as assumed but may actually provide a considerable amount of resistance to low level excitations and help to control interstory drift and building motion affecting occupant comfort.

In a recently completed study (Grant ENG-73-04216), double-pane glass cladding components (Fig. 1) were investigated to determine the nature of local cladding pressure loads and response. A combination of full-scale field measurements of loads and response and controlled laboratory simulation and testing using a full-scale window test facility were carried out by J. I. Craig and R. B. Deo to assess the causality of differential pressure loads in exciting response of large insulating windows. Results of field and laboratory studies demonstrated that substantial dynamic response is not likely due to pressure loading. However, for certain locations and under specific conditions, relatively large pressure power levels were observed over frequency ranges including the cladding fundamental frequency. For these critical locations, a significant causality existed between the input pressure and the dynamic response.

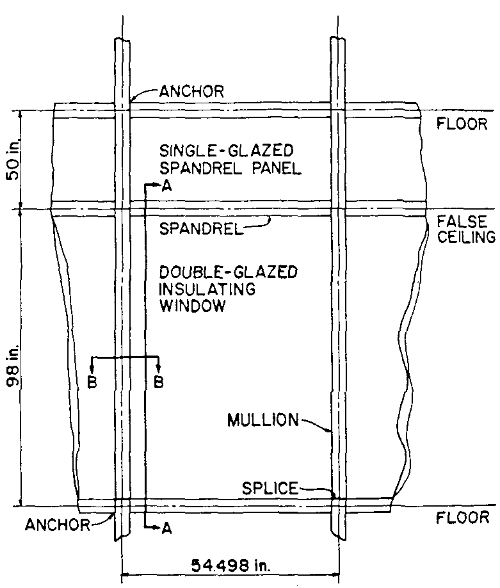

Fig. 1. Glass Cladding

Companion analytical studies by the author resulted in development of a discrete element analytical model of a typical portion of the cladding including frame, gaskets, and insulating window (Fig. 2), which permitted a wide range of cladding configurations and loading types to be considered. Panel response to static and dynamic pressure loading and racking distortions introduced by differential motions of adjacent floors, both treated as deterministic functions of time, were the principal loadings consider-

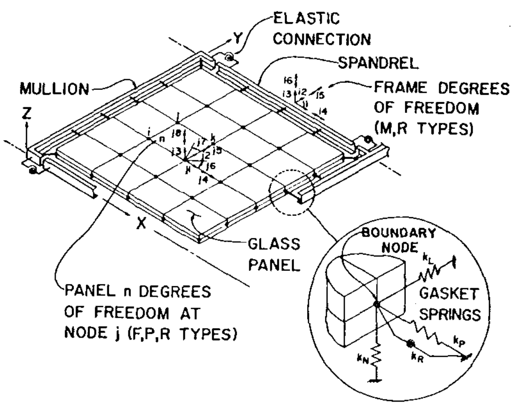

Fig. 2. Analytical Model

ed. Sensitivity studies were conducted to determine the influence of system properties on the response of the panel-frame assembly. Response was shown to be sensitive to gasket rotational stiffness and frame flexural stiffness for selected panel aspect ratios. In general, the finite element model produced frequency and displacement results which were in good agreement with laboratory and field test values. Out-of-phase double panel modes were predicted both at relatively low frequencies and at frequencies beyond the range of practical interest. Detailed results of the study are contained in the final report (Ref. 1).

Subsequent work on behavior of claddings has shifted attention from consideration only of detailed response of individual components to encompass study of the interaction of the overall cladding system with the primary structure. The principal goal of this research program (Grant ENV-77-04269) is to assess the role of cladding systems in the structural performance of modern highrise buildings under moderate seismic excitation. The work involves a balanced combination of analytical and experimental studies, aimed at identifying the influence of heavy precast concrete (Fig. 3) and lightweight glass (Fig. 1) curtain wall systems on the

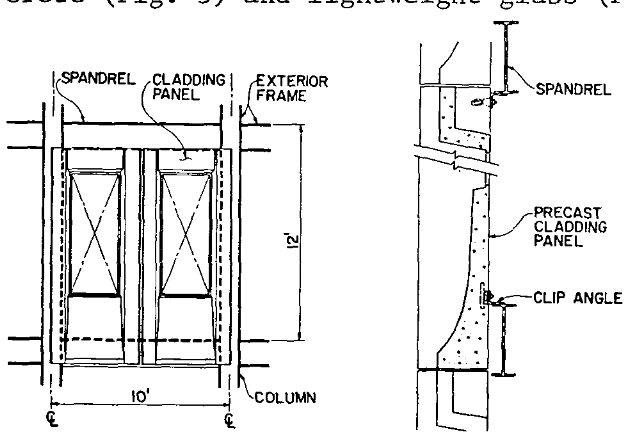

Fig. 3. Precast Concrete Cladding

dynamic properties and response of two existing multistory buildings. A third structure (which is one of two twin office towers), with precast brick masonry cladding panels, will be studied during construction to determine its properties before, during, and after installation of the cladding. Field testing will be conducted by J. I. Craig. Analytical models for the claddings will be developed by K. M. Will and the author and incorporated into existing multistory building models (Fig. 4) and computer programs. At present, finite element models of the exterior frame, cladding panels, and connections are being assembled for curtain walls of various types. Preliminary findings for one of the prototype structures, a 25-story office building of core construction with precast concrete curtain wall (Fig. 3), are summarized in a recent paper (Ref. 2). The importance of the cladding connections is recognized and the forces experienced by the cladding-connection subsystem will be determined so that rational procedures for curtain wall design can be found. Analytical and experimental data will be compared to calibrate the analytical models, and structure response to a variety of moderate seismic loadings will be computed to determine the influence of present-

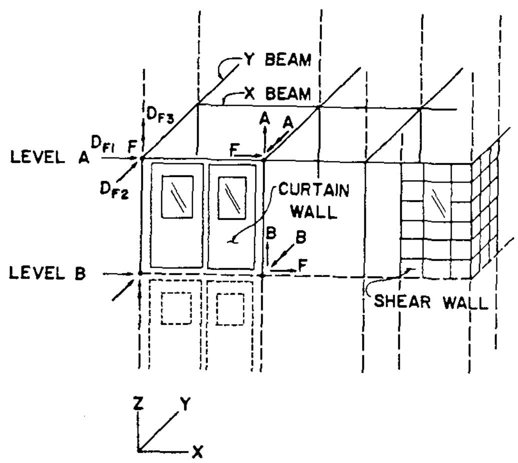

Fig. 4. Building Substructure with Curtain Wall Model

day cladding systems on the performance of modern multistory buildings. With improved understanding of the behavior of curtain wall systems in modern multistory buildings, the building facade can be integrated into the building structural system and used to perform a load-carrying function.

Damping in Free-Standing Towers

The possible use of add-on dampers to reduce the wind and earthquake-induced response of large latticed steel communications towers was considered in this study (Grant ENG-75-10320). The principal objective was to determine the number, size, and distribution of viscous damping elements required to significantly reduce tower response for selected loadings. A 319m television tower in Atlanta (Fig. 5) and a 46m communications tower in Hawaii served as prototype structures for the study. Substructuring procedures were used to develop reduced tower models for dynamic analysis (Ref. 3). Overall tower response was confined to the linear range but procedures for study of the nonlinear behavior of tension-only members were developed. The study showed that tower response was more dependent on size and distribution of dampers than on the actual number of dampers used, for the structural models and loadings considered. Efforts to obtain useful field data on the dynamic properties and ambient response of the 319m tower are continuing.

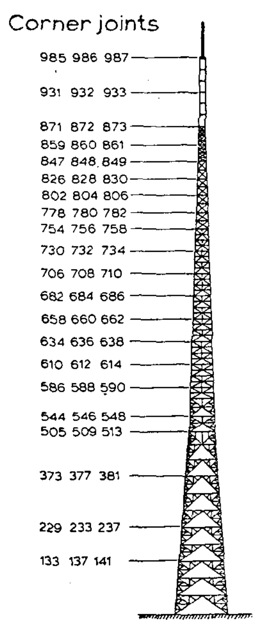

Fig. 5. 319m Latticed Steel Tower

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W. J. HALL, N. M. NEWMARK, A. R. ROBINSON
D. A. W. PECKNOLD, W. H. WALKER and D. A. FOUTCH

University of Illinois at Urbana-Champaign
(NSF Grant No. ENV 77-07190)

The goal of the research program described below is to provide simplified methods of design of building structures to resist dynamic loads arising from natural hazards such as earthquakes and, to a lesser extent, wind. The research will emphasize the development of new and improved methods of analysis. Work is underway in three interrelated areas as follows: (1) simplified methods of analysis and design for excitation arising from earthquake and wind; (2) response of subsystems to dynamic motions; (3) design of multi-degree-of-freedom systems with special attention to inelastic behavior. Some of the studies have been in progress for several months and specific results have been obtained. The graduate student and professor investigating each phase of the project are indicated in the text. The research is being supported by the National Science Foundation under Grant No. ENV 77-07190.

Simplified Methods of Analysis and Design

The response of elasto-perfectly-plastic systems combined with various damping levels is being analyzed with the purpose of assessing the reliability of inelastic design spectra currently used. Earlier studies were aimed at developing an empirical amplification factor versus damping relationship valid over a wide range of damping values. Results of these studies are expected to be published in October, 1978 (R. Riddell--Prof. N. M. Newmark).

Simplified approaches to dynamic soil structure interaction are also being investigated. This study involves consideration of the analysis of earthquake records in a manner to account for wave dimensions and building size as they affect lateral, vertical, rocking and torsional motions and response. A numerical averaging approach applied to free field records has proven useful in estimating the effect of building size on response. The reduction in high frequency response was shown in some cases to be as high as a factor of two or three which can have a significant effect on design (J. R. Morgan--Prof. W. J. Hall and Prof. N. M. Newmark).

A second study in the general area of modeling of buildings and soil structure interaction is just beginning (K.-Y. Shye and Prof. A. R. Robinson). This investigation currently involves investigation of the frequency dependence of foundation parameters and of techniques for handling non classical damping, in a manner to permit single calculation of interaction effects.

Another study deals with vertical acceleration and its influence on P-Δ effects accompanying lateral motion. The nonlinear coupling of lateral modes also is being considered. The procedure used for the nonlinear coupling problem is to represent the effects of one or more of the higher modes as high frequency motions superposed on the lowest mode. Ranges of significance for pertinent parameters and design recommendations are being sought which adequately account for the effects of vertical acceleration coupled with lateral motion and including the nonlinear coupling of lateral modes (A. C. Stepneski--Prof. A. R. Robinson).

A continuation of studies of the design and behavior of low-rise steel frame buildings is underway (F. Cotran and Prof. W. J. Hall). In this study, special attention will be given to reserve strength and margins of safety attained by present design practice. Previous work on this topic have been published in a doctoral thesis by C. J. Montgomery.

The effects of coupled lateral and torsional motions for low to moderate height buildings is also being investigated. One parameter being considered is the difference in phase of seismic waves arriving at a building site (C. Rivero--Prof. W. H. Walker).

Two topics dealing with wind loads on structures are also being studied. One is an investigation into the feasibility of using a unified design procedure to account for the dynamic effects of earthquakes and wind loads in medium rise buildings. Present methods of analysis are quite different for each case although the equations of motion are similar. One goal of the study is to provide recommendations applicable to building codes for simplified design procedures for wind loads (P. Cevallos-Candau--Prof. W. J. Hall and Prof. N. M. Newmark). Another wind-related study is concerned with the effects of variable direction of the wind on the lateral and torsional response of buildings. Again, a major goal is to provide analysis methods suitable to the design office (E. Safak--Prof. D. A. Foutch).

Response of Subsystems to Dynamic Loads

A study of tuned secondary systems utilizing concepts in classical dynamics and applied mathematics has three goals: the development of numerical procedures for accurate computation of secondary response; the attainment of a qualitative understanding of secondary response phenomena; and the development of techniques for obtaining fast but reliable secondary response estimates (G. C. Ruzicka--Prof. A. R. Robinson).

The formulation of approximate methods of predicting the maximum response of single and multi-degree-of-freedom secondary systems with single or multiple attachments to a multi-degree-of-freedom primary system is currently in progress. Initial studies have yielded a simple and accurate procedure for the analysis of multi-degree-of-freedom secondary systems with one point of attachment (R. Villaverde--N. M. Newmark). Initial study of further work in this area involving nonlinear behavior is starting (J. Nau and Prof. W. J. Hall).

Design of Multi-Degree-of-Freedom Systems

One study is aimed at deriving an approximate method of analysis for nonlinear multi-degree-of-freedom systems. The method is an iterative one which utilizes only elastic response spectra and elastic modal analysis techniques. The mode shapes and frequencies are of the elastic system are adjusted to account for the nonlinear behavior. Initial studies indicate that predictions of story ductility are generally within 20% of those computed in time history analysis (V. Tansirikongkil--D. A. W. Pecknold). Another study in this same general area is under development (S.-Y. Kung and Prof. D. A. W. Pecknold).

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Prepared by D. A. Foutch 4/17/78

P-T. D. Spanos

University of Texas at Austin

Earthquake engineering research is being conducted in the area of structural responses to simulated earthquakes. The earthquake excitation is modeled as the product of a broad-band stationary random process by a deterministic envelope function which accounts for the non-stationary nature of the seismic motion. The research effort is focused on two areas: the response of linear structures, and the response of non-linear or hysteretic structures.

Response of Linear Structures

An approximate method has been developed for the determination of the statistics of the energy of a lightly damped linear structure subjected to non-stationary random excitation (earthquake). In addition, this method can provide readily applicable formulae for the determination of the mean-square value of the structural response. Currently, the accuracy of the method is examined by comparing solutions generated by its application with available exact, nevertheless, extremely cumbersome, solutions. Various modulating envelopes proposed in the literature for simulation of earthquakes are considered, and a variety of parameter studies are planned. Ultimately, the analytical background of this method will be used to develop a computer package for the generation of artificial earthquakes with specified average response spectra.

Response of Nonlinear or Hysteretic Structures

Responses of lightly damped nonlinear or inelastic structures to non-stationary random excitation (earthquake) are investigated. Various models of nonlinear, yet elastic, structures are considered. The phenomenon of hsyteresis is studied by using a model consisting of an infinite collection of elastoplastic elements the yield limits of which are specified probabilistically. The original structure is replaced by an equivalent linear structure the damping and stiffness of which depend on the response amplitude itself. Based on the equivalent linear structure, solution techniques are developed for the determination of the response amplitude statistics. These statistics can be used to estimate the failure potential of the structure during a potential earthquake. To date, only the special case of random excitation modulated by a Heaviside Step function has been studied in detail. Theoretical developments and numerical applications pertaining to excitations with modulating envelopes yielding more realistic models of actual seismic motion records are undertaken. Parameter studies of the effects on the response statistics of the nominal frequency and damping of the structure, the degree of nonlinear or hysteretic behavior, and the duration and intensity of the earthquake excitation are planned.

Y. K. WEN

University of Illinois at Urbana-Champaign

This research is conducted as part of a research study of safety evaluation of structures to earthquakes and other natural hazards sponsored by National Science Foundation under grant NO. ENV 77-09090.

The objective of this research is to develop innovative and computationally efficient analytical methods for the study of response of nonlinear-inelastic systems under stochastic loadings. The goal is to evaluate the resistance and ultimately the probability of failure of structures under dynamic natural hazards.

This summary covers the progresses in (1) modeling of hysteretic restoring forces and (2) approximate analytical methods for random vibration of multi-degree-of-freedom (M.D.F.) inelastic structures.

Modeling of Hysteretic Restoring Forces

A large class of inelastic systems including softening, hardening, degrading and nondegrading systems, with smooth skelleton curves and various hystereses, are modeled by a four-coefficient (parameter) nonlinear differential equation. For the degrading systems, the stiffness and the energy dissipation capacity are modeled as decreasing functions of the expected total energy absorbed by the system. The system parameters for a particular structural construction are based on experimental evidence. The emphasis is on mathematical tractability to facilitate the response analysis.

Methods for Random Vibration of M.D.F. Systems

(1) Method of Equivalent Linearization (M.E.L.)

The existing M.E.L. is not satisfactory for inelastic systems since it relies on a Krylov-Bogoliubov (K-B) technique (a narrow-band assumption and an averaging over one cycle of oscillation) which may seriously overestimate the energy dissipation capacity of the system and underestimate the r.m.s. response, e.g., by up to 60% for a nearly elasto-plastic bilinear system.

In the present M.E.L., the foregoing restoring force model allows one to linearize the equation of motion of the system in closed form. The linearization does not require a K-B approximation and is mathematically more tractable. The excitation is a filtered Gaussian shot noise which allows consideration of nonstationarity and spectral content. The accuracy of this method has been verified against simulation for a single-degree-of-freedom (S.D.F.), nearly elasto-plastic system for all ranges of response level (fig. 1). The accuracy and efficiency for M.D.F. and degrading systems is presently under investigation. Satisfactory results have been obtained for two-degree-of-freedom systems. Computationwise, for a N-degree nondegrading system under white noise excitation, the covariance matrix of the 3N response variables (a displacement, a velocity and a hysteretic force for each degree of freedom) is obtained by solving 3N linear algebraic equations iteratively. For nonstationary solution and degrading systems, the time-dependent covariance matrix is solved by a numerical integration of ordinary differential equations.

(2) Method of Substitute Structure

In this method, each element of a M.D.F. system is replaced by a linear counterpart with a dutility-dependent stiffness and damping based on tests or time history analyses of S.D.F. systems. The dampings are combined to obtain "smeared" modal dampings for the systems. The statistics of the maximum response (ductility) of each element are obtained by a linear random vibration analysis and a iteration procedure. The main advantage of this method is that it requires relatively insignificant computation time, e.g., 1 sec. of execution time on the IBM 360-75 system for an 8-story single-bay steel frame.

Numerical results of the seismic response of multi-story buildings are satisfactory qualitatively compared with empirical results (fig. 2). Given that the ductility is extremely sensitive to the excitation intensity and spectral content. This method may be useful in gathering the preliminary information of the maximum response statistics of a M.D.F. system.

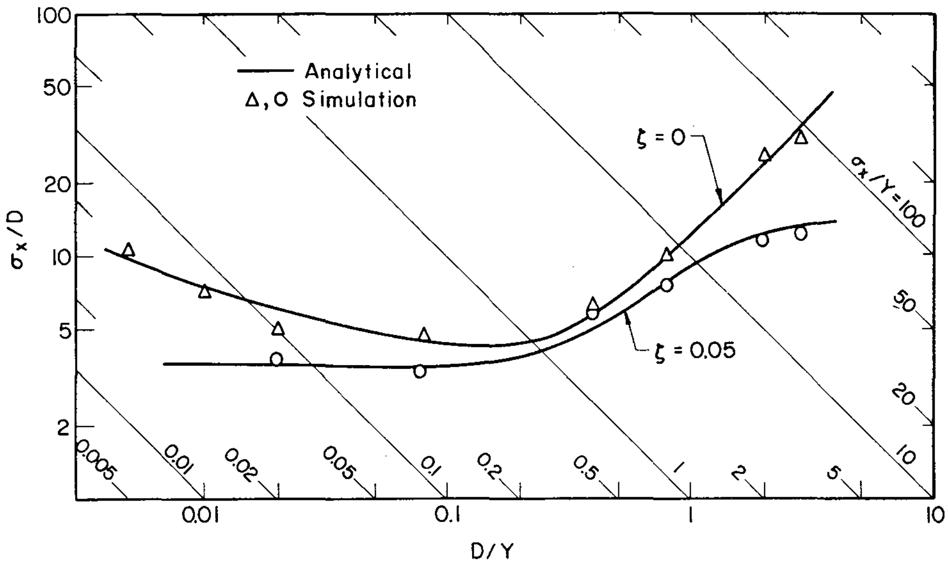

Fig 1. Comparison of the Nondimensional r.m.s. Responses with Monte-Carlo Solutions (Y = Yield displacement, ζ = vicous damping ratio, D = excitation intensity).

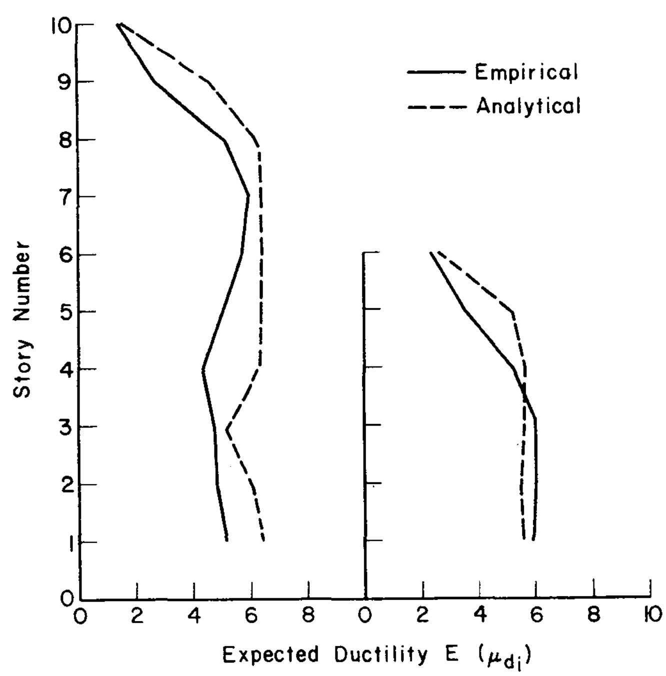

Fig. 2. Comparison of the Expected Interstory Drift Ductilities of Multi-story R.C. Buildings.

E.H. VANMARCKE and J.M. BIGGS

Massachusetts Institute of Technology

National Science Foundation sponsored research is being conducted on seismic safety evaluation of buildings. The purpose of the research is to evaluate the effectiveness of the total seismic design process which consists of steps beginning with seismic risk assessment through dynamic analysis and the design of structural components. Alternative methods of analysis and design are being considered. Specifically, these alternatives are built around three different approaches to dynamic analysis: (1) time-history analysis, (2) response spectrum model analysis, and (3) random vibration analysis. Many of the results of the research have been reported in detail in technical reports and professional publications [1-11]. Several reports describing more recent results are in progress.

Seismic Safety Assessment

The principal steps necessary to adequately predict the effect of earthquakes on structures, to evaluate the safety of alternative designs, and to proportion the structure itself are:

1. The representation of earthquake ground motion
2. The evaluation of the dynamic properties of the system
3. The use of analytical methods to determine the response
4. The design of the structure to ensure its integrity during the computed response

In each of these activities there are many uncertainties as to proper procedures and criteria. In each there are alternative methods and representations with corresponding different levels of accuracy, reliability and cost. The proper procedure in any step depends, in some degree, on the methodology used in other phases. Current procedures often lack consistency and balance between the amount of effort devoted to and accuracy obtained in the various steps. The research involves evaluation of alternative existing methods of seismic analysis and development of new methodology, primarily based on random vibration theory. Based upon these studies of methodology, together with previous and concurrent studies of seismic risk and of the reliability of component design procedures, techniques are being developed for evaluating structural seismic safety provided by a given analysis-design procedure, input intensity, and resistence function.

The overall objective of the project is to evaluate quantitatively the safety of constructed facilities designed for earthquakes, as a function of the techniques used to define the design level earthquake motion, to predict seismic load effects, and to select structural components. Smooth design response spectra, real or simulated ground motions, and spectral density functions are being considered as alternative representations of the input to the analysis-design procedure. Of special concern have been the requirements for compatibility among these three ground motion representations, and how each representation can be tied in with the description of site seismic risk.

Strong-Motion Duration of Earthquakes

A highlight of the project is the recent work on ground motion duration. A new and simple procedure has been developed for estimating the strong-motion duration and the r.m.s. strong-motion acceleration of earthquake ground motion records. The strong-motion duration s_o is found to be nearly proportional to the quantity I_o/a^2_{max}, in which a_{max} is the maximum ground acceleration and I_o is the Arias Intensity or the integral of the squared accelerations. The proportionality factor is equal to the square of the peak factor (the ratio of the maximum to the r.m.s. strong-motion acceleration). A less important factor influencing the relationship between s_o and I_o/a^2_{max} is the predominant period of the strong phase of the accelerogram. The main features of the proposed definition of the strong-motion duration s_o (and the corresponding r.m.s. strong-motion acceleration σ_o) are that it preserves the total energy I_o, and it guarantees a consistent and predictable relationship between a_{max} and σ_o.

The proposed duration is expected to be of service in the development of improved procedures for specifying ground motions for seismic design by permitting quantitative treatment of the correlation between duration and other ground motion parameters, as a function of earthquake source parameters and distance. Characterization of strong earthquake motions as limited-duration segments of a stationary stochastic process permits effective use of methods of random vibration to predict seismic response of many structures. The limited duration captures the essential transient character of earthquakes, while the spectral density function represents the frequency content during the strong phase of the earthquake. Random vibration analysis also yields excellent predictions of elastic as well as inelastic response spectra of earthquake ground motions.

Safety of Linear Elastic Systems

In the first phase of the project, emphasis has been placed on performance criteria which can be evaluated by elastic analysis procedures. Methodology for overall seismic safety assessment has been developed for structures whose behavior is linear elastic up to allowable response levels. It incorporates realistic descriptions of uncertainty in structural period and damping, in motion frequency content and duration, and in site seismic risk. Using this methodology, the project has evaluated design methods which aim at limiting the likelihood of yielding anywhere in the structure under an "operating basis" earthquake. The emphasis thus far has been on component reliability, but system reliability can also be approximated with reasonable accuracy.

Safety of Inelastic Systems

The current emphasis in the research is on safety analysis relative to inelastic performance criteria. This requires work on prediction of inelastic response of real buildings and study of resistance parameters characterizing "inelastic" performance criteria. The information on the distribution of inelastic load effect and resistance is being incorporated into an overall seismic safety analysis. This safety evaluation in turn constitutes the basis for a realistic evaluation of design procedures aimed at preventing excessive damage or collapse.

Information is being gathered about the variability of story ductility factors for multistory elasto-plastic shear buildings with given dynamic properties. Two approaches are being pursued: (a) inelastic response distributions are obtained by time-integration of several sets of real and simulated accelerograms; (b) a promising start has been made on research to predict inelastic MDOF system ductility factors by approximate random vibration theory.

Project Reports

1. "Frequency Content of Ground Motions during the 1971 San Fernando Earthquake." Arnold et al., R76-3, 1976
2. "Simulated Earthquake Motion Compatible with Prescribed Response Spectra." Gasparini & Vanmarcke, R76-4, 1976
3. "Comparison of Seismic Analysis Procedures for Elastic Multi-Degree Systems." Vanmarcke et al., R76-5, 1976
4. "Variability of Inelastic Structural Response Due to Real and Artificial Ground Motions." Frank et al., R76-6, 1976
5. "A Study of the Uncertainties in the Fundamental Translational Periods and Damping values for Real Buildings." Haviland, R76-12, 1976
6. "Studies on the Inelastic Dynamic Analysis and Design of Multi-Story Frames." Luyties et al., R76-29, 1976
7. "Random Vibration Analysis of Inelastic Multi-Degree of Freedom Systems Subjected to Earthquake Ground Motions." Gazetas, R76-39, 1976
8. "Inelastic Response Spectrum Design Procedures for Steel Frames." Haviland & Biggs, R76-40, 1976
9. "On the Safety Provided by Alternate Seismic Design Methods." Gasparini, R77-22, 1976
10. "Strong-Motion Duration of Earthquakes." Vanmarcke & Lai, R77-16, 1977
11. "Inelastic Dynamic Design of Steel Frames to Resist Seismic Loads." Robinson, R77-23, 1977

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Inelastic Response Spectra from Elastic Spectra

It has become common practice to specify a design earthquake excitation by means of an elastic response spectrum. This approach has proved quite useful for the design of linear structures. However, the manner in which design elastic response spectra may be used in the design and analysis of nonlinear structures is not well understood. The goal of the research described here is to develop simplified techniques for estimating the peak response of inelastic systems to earthquake excitation given the properties of the system and the elastic response spectrum of the excitation. The problem is being approached from two different points of view: 1) simulation studies of the earthquake response of certain strongly deteriorating structural models, and 2) analytical studies of systems with deterministic nonlinearities.

Progress to date resulting from the simulation study of six deteriorating nonlinear systems includes:

1) A demonstration of the appropriateness of effective linear period and viscous damping parameters for describing inelastic response in the midperiod range of 0.4 - 4.0 seconds.

2) The identification of optimum linear system parameters for a class of deteriorating systems.

3) An examination of existing analytical techniques for predicting inelastic response based on elastic response spectra.

4) The development of improved analytical techniques for predicting the effective period and damping of strongly deteriorating systems.

5) The suggestion of empirical design formulae for estimating the effective period and damping of deteriorating hysteretic systems and the verification of these formulae.

6) A preliminary examination of the destabilizing effects of gravity on the earthquake response of strongly deteriorating structural systems.

In the analytical area, a method has been developed whereby a non-stationary random process having a prescribed response spectrum may be generated. A technique has also been developed for obtaining the approximate response statistics of nonlinear multi-degree-of-freedom systems subjected to such non-stationary random excitation. The accuracy of the approximate technique has been studied using Monte-Carlo simulation.

Further efforts on this project will be directed toward extending the period range of applicability for the simulation studies and looking further into the collapse of deteriorating structures when gravity effects are included. The analytical techniques developed will be extended and improved.

Application of Equivalent Linearization Techniques to Nonlinear Continuum Problems

An investigation has begun into the application of the technique of equivalent linearization to problems relating to the dynamic response of a nonlinear solid continuum. The goal of this research is to develop an efficient approximate analytical technique suitable for analyzing the dynamic response of such systems to deterministic and random excitation. At present, primary consideration is being given to the steady-state response of one-dimensional nonlinear elastic structural models subjected to harmonic excitation. Various different linearization schemes have been examined. The existence and uniqueness of the equivalent linear elastic parameters as well as the accuracy of the linearization approach has been examined. Some of the most promising linearization schemes have been incorporated into a simple finite element code and example problems have been solved.

Future work will be directed toward a systematic study of the accuracy of the most attractive linearization techniques and adaptation of these techniques into a three-dimensional finite element code.

Formulation of a Strain-Space Analog to Plasticity Theory

The goal of this research is to develop a strain-space analog to plasticity theory employing multiple yield surfaces and including both kinematic and isotropic hardening. It is believed that the new theory will provide increased accuracy and efficiency in numerical calculations of the dynamic behavior of soils and other systems exhibiting plastic behavior.

It has been shown that the traditional development of plasticity theory in terms of stresses and stress histories possesses an analog in strain-space and the two theories can be made equivalent through suitable selection of model parameters. Using the strain-space formulation, a single set of constitutive laws can handle strain hardening, strain softening and ideally plastic behavior. The strain-space theory affords certain practical advantages in solving dynamics problems since it can directly accommodate a displacement formulation of the type used in most finite element and finite difference schemes. This formulation has been adapted to a two-dimensional quasi-static finite element code. The accuracy and other features of the formulation are being examined.

In future work it is hoped that the new plasticity formulation can be applied to several problems of importance to earthquake engineering such as soil-structure interaction in the nonlinear range, soil failure, modeling of hysteretic structural behavior, etc.

All of the research projects described above are currently supported in whole or in part by the National Science Foundation, Division of Problem Focused Research Applications.

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Earthquake engineering research sponsored by the National Science Foundation is being conducted in the general areas of the analysis of the earthquake response of structures, the characterization of strong earthquake motions and the examination of some structural dynamics problems of earthquake engineering.

Earthquake Response of Structures

The work in this area is concerned with the determination of structural properties from records of earthquake response. The problem is being approached by applying techniques of system identification in both the time and frequency domains. In the time domain, an optimal filter approach and a modal minimization technique have both been examined in the recently completed thesis work of James L. Beck (Beck, 1978). The investigation is conducted within the framework of an output-error approach wherein optimal estimates of the parameters of the model are obtained by minimizing some measure-of-fit between the observed structural response and that calculated from the model subjected to the recorded excitation. The first technique studied, an optimal filter method, has the capability of treating nonlinear models, but this advantage appears to be offset by problems of convergence in the presence of the types of errors and noise found in measurements of earthquake response.

A new-output error technique has been developed to overcome these difficulties. It is restricted to linear structural models, but it has proven to be reliable and efficient for determining modal parameters from earthquake records. It converges rapidly enough that non-linear behavior can be studied by looking for changes in modal periods, dampings and participation factors in successive portions of the earthquake response. The method has been applied to two multi-story buildings that experienced the San Fernando earthquake. The results include better estimates of properties of lower modes than have been obtained by other approaches as well as new estimates for properties of higher modes. The increased information results from the systematic determination of modal properties and the accompanying very good replication of measured response.

Beck's study also includes work on the uniqueness and reliability of parameters determined by applying systems identification to earthquake response records. Because earthquake records are only obtained from a small number of locations, and because of measurement noise and other limitations in the data, it is shown that it is necessary in practice to estimate the parameters of the dominant modes in the response, rather than trying to find the stiffness and damping matrices.

In the frequency domain, Graeme McVerry has developed a technique for determining the parameters of linear, time-invariant models from earthquake response. The estimates of the parameters are obtained by minimizing the difference between the unsmoothed finite Fourier transform of the recorded acceleration response and its calculated counterpart over a selected frequency band. The least-squares fit is obtained using an iterative, Gauss-Newton technique to solve the non-linear algebraic equations which result from setting the partial derivatives of the mean square error to zero. A special feature of the work includes the extension of the theory to include the effects of the initial and final conditions in the expression relating the transform of the response acceleration to that of the ground motion. This result allows the frequency domain approach to be applied to selected segments of the recorded response.

This work, which is still in progress, has been applied to three multi-storied buildings which were subjected to the San Fernando earthquake. Reliable estimates of modal parameters have been obtained and many of the drawbacks of traditional transfer-function approaches appear to have been overcome.

Characterization of Strong Earthquake Motions

The work in this area is comprised of three parts. The first, which is complete, concerns the determination of the local magnitude, M_L of earthquakes from strong motion accelerograms. (Kanamori and Jennings, 1978) In this study the equation of motion of the Wood-Anderson seismograph subjected to the recorded acceleration was solved to produce a synthetic seismogram which can be read in the standard manner. A significant result from this study is the determination of $M_L = 7.2$ for the Kern County earthquake of 1952. This earthquake, which has a Magnitude of 7.7 on the basis of surface and body waves, produces the largest local Magnitude of any earthquake so far recorded. The local magnitude is considered more pertinent to engineering applications than other magnitude scales because it is determined in a frequency range, and at distances, more relevant to the measurement of strong ground motion in the engineering sense.

An extension of this work, now in draft, treats the problem of determining M_L from seismoscope records. The method uses results from random vibration theory to extrapolate from the seismoscope response to that of the Wood-Anderson instrument by applying corrections for gain, period and damping. The method has been verified by application to sites where simultaneous accelerometer and seismoscope data have been obtained. The technique is then used to determine M_L for earthquakes where only seismoscope data or similar information is available, such as the Guatemalan earthquake of 1976 and the 1906 San Francisco earthquake.

A third phase of the work, just beginning, concerns the application of the results to the problem of determining earthquake-resistant design criteria. Because the conditions of the design earthquake are typically given by geologists and seismologists in the form of earthquakes of specified magnitudes on certain portions of faults, it was decided to investigate simple statistics of earthquakes with the same M_L and recording distance. To do this, the strong-motion data were examined from the viewpoint of selecting small samples clustered about some magnitude and distance, for example $M_L = 6.4$ and $\Delta = 25$ km. Preliminary examinations of four such samples of ten records each have shown that means of spectral ordinates appear to be established reliably by these samples. Furthermore, the estimate of standard deviations about the mean appear to be reliable also, and indicate a degree of dispersion under the given conditions that is significantly less than that found by regression analyses of much larger samples of ground motion. It is hoped that the approach can be used to obtain a simple, yet reliable description of the variations expected in motions that have the same local magnitude.

Problems in Structural Dynamics

The only study sufficiently advanced for discussion is that being performed by John Psycharis, who is investigating the problem of the dynamics of tipping systems. The problem arises not only because some, typically small, objects have tipped and fallen during earthquakes, but also because calculations for the earthquake-resistant design of buildings subjected to very strong earthquake motion sometimes indicate partial uplift of the foundation. Occasionally, expensive provisions are made in the design to generate the tensional forces required to prevent uplift. The studies are still in the exploratory stages wherein different systems such as rigid bodies, simple oscillators, and shear beams are examined as they rock and tip on foundations idealized by springs, Winkler supports, and an elastic half-space. The intent of the research is to clarify the basic mechanics of the problem and to develop simple approaches for use in design to estimate the changes in periods, damping, etc., that accompany the rocking response of structures.

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National Science Foundation sponsored earthquake engineering research is being conducted in the subject area of identification of structural damage. In addition, the possible control of structural damage is also discussed.

Identification of Structural Damage

In the iterative process of structural design and analysis, engineers use mathematical representations which result from generalizations of existing knowledge in the structural engineering profession. After the structure is constructed, each civil engineering structure possesses its own special characteristics, which cannot be described precisely with a general mathematical model. During this past decade, much effort has been concentrated on the identification of such special characteristics of existing structures [e.g., 1]. Meanwhile, there has been an increasing interest in applying motion-controlling devices in civil engineering structures[2].

To effectively control the motions of the structure, it is necessary to know as much about the actual structural system to be controlled as possible. Although various mathematical models are available for use in structural analysis and design prior to the construction of the structure, such a priori mathematical models need to be up-dated and modified with the use of field data from testing the actual structure. Such estimation and modification of dynamical characteristics of actual structural systems make use of techniques of system identification. In 1976, Hart and Yao [1] reviewed the literature and discussed broader research interests in the subject area of structural identification. Later, S. J. Hong Chen summarized available information in convenient tabular forms in her M.S. thesis [3], an up-dated version of which is included in a recent technical report [4].

Due to uncertainties inherent in structural resistance as well as in future loading conditions, structural damage cannot be completely avoided even with the effective use of motion-control devices. Such damage can cause changes in subsequent characteristics and behavior of the structure. The possibility for the identification of additional characteristics such as damage and reliability is discussed by Liu and Yao recently [5].

The investigation on the identification of structural damage is being conducted by J. T. P. Yao, E. C. Ting, and S. J. Hong Chen at Purdue University in collaboration with H. D. McNiven, B. Yanev, and J. Pfeifer at the University of California at Berkeley. The same experimental data as obtained by the Berkeley team will be used by all investigators at both universities. The Purdue team is primarily concerned with damage assessment and reliability evaluation, while the Berkeley team is interested in applying system identification techniques to steel structural frames with masonry infill walls.

Control of Structural Damage

Civil engineering structures are subjected to various types of loading conditions such as dead, live, thermal, wind, and earthquake loads. Most of the time, the structure is subjected to static or quasi-static loads such as the dead weight of the structure or the movable furniture load in a building. Occasionally, the structure is subjected to severe dynamic forces resulting from wind storms or strong earthquakes. Motion-control of structures in such dynamical loading conditions can be classified according to the devices used such as passive [6,7] or active [8], or according to the purpose such as for comfort [9,10] or for safety [11]. Various methods have also been proposed and studied in detail by many investigators [12-17].

A schematic diagram as given in Figure 1 shows the interrelationships between structural damage and possible actions including control, repair, and demolition. Basically, linearly elastic structural response and tolerably small nonlinearity in structural behavior can be associated with no-damage and repairable damage when structural control devices can be effective in avoiding or minimizing such damage. If and when permanent and moderate damage occur, the structure must undergo a detailed inspection. If it is found necessary, the structure must stop functioning and major repairs should be implemented. When the damage is found to be severe, the structure must then be demolished. At present, attempts are being made to define structural damage including the possible application of the theory of fuzzy sets [18-19].

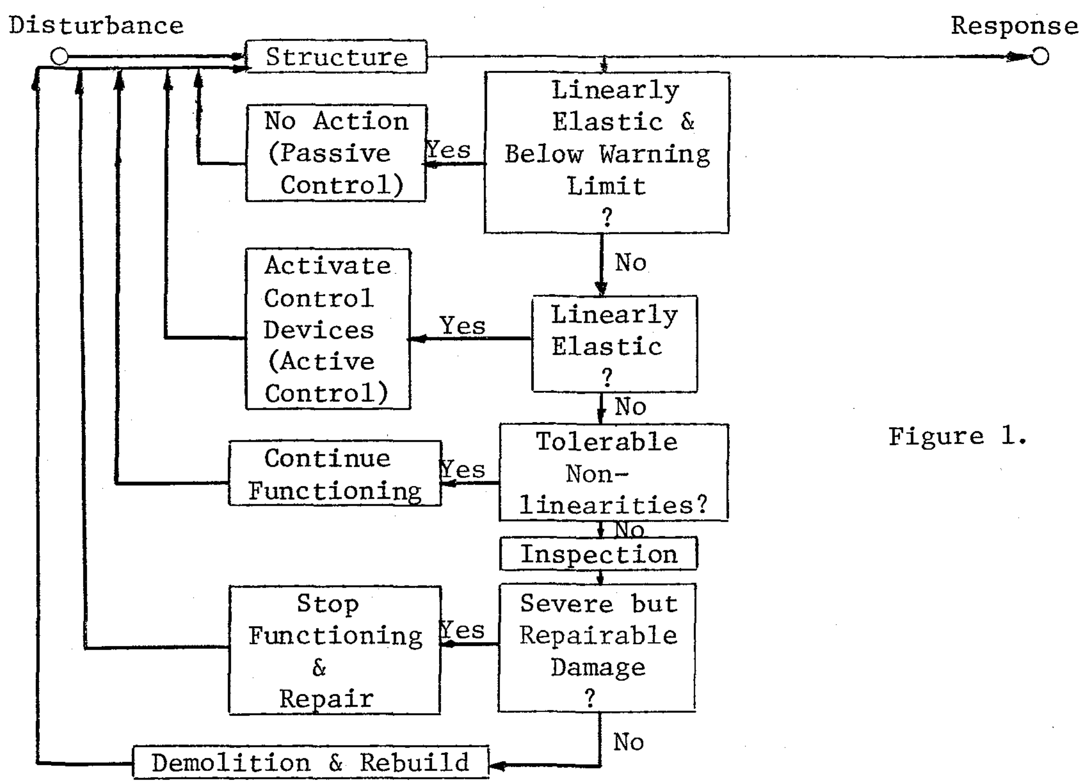

Figure 1.

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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 are supported by the National Science Foundation, the University and others.

Three-Dimensional Earthquake Motions on Inelastic Building Systems

This project deals with response behavior of two general inelastic structural models subjected to three-dimensional ground motions. Model A represents a building system in which the floor slabs are thick and perfectly rigid in the floor plane but flexible out of it. Model B corresponds to a general space frame in which the rigidity of the floor diaphragms, if any, is negligible. Analytical procedures and two computer programs that are pertinent to these two models have been developed for studying the following specific objectives: 1) to identify the structural parameters that cause a system to be sensitive to three-dimensional ground motions, 2) to observe the response history of various typical structural systems to the interacting ground motions, 3) to study the ductility demands at critical sections of the constituent structural members, and 4) to observe the energy absorption characteristics for engineering evaluations.

Several typical building systems varying from two to ten stories, having symmetric and unsymmetric structural planes or elevations, doubly or singly symmetric columns, and with and without bracing members have been selected to study the dynamic response to the El Centro, 1940, and Taft, 1952, earthquakes. It has been found that the interaction of three earthquake components significantly increases both the internal axial forces and moments and that the increase of some members is several times greater than that resulting from one component only. The increase becomes more significant for taller structures. Braced systems are more sensitive to the interaction of earthquake motions than unbraced systems. Efforts are being made to optimize the computer program core and to study structural systems with shear-walls.

Optimum Design of Plane Tall Steel Structures for Simultaneous Multicomponent Static, Dynamic, and Seismic Inputs

This study deals with the optimum design for various plane steel structures subjected to the multicomponent input of static loads, dynamic forces, and seismic excitations for the purpose of: 1) examining the effect of the interaction of ground motions on their relative stiffness requirements, overall stiffness distribution at critical regions, and on the entire system, 2) selecting suitable structural systems for certain types of loads, and 3) providing member properties for detailed design. The structural systems that have been studied are trusses, unbraced, single-braced, double-braced, and K-braced frameworks in which the constituent members are bar elements for bracings and truss-members and beam-column elements for columns and girders. The beam-column elements are either the built-up sections or the hot-rolled wide flange sections available in the AISC Steel Construction Manual. The structures can be subjected to static loads, dynamic forces, and horizontal and vertical ground motions. The dynamic forces and the seismic excitations can be used on the basis of either direct integrations or response spectra. In addition, the equivalent lateral seismic force recommended by the Uniform Building Code can also be used for the design.

The recommended design method is based on an optimal criterion and a recursion relation for which the behavior constraints of static and dynamic displacements and stiffnesses as well as the constraints of natural frequencies are presented. Other constraints are the desirable sizes of the members and the limitation on the difference between the maximum and minimum moments of inertia of any given system.

The structural formulation, which is based on the displacement method, takes into consideration the consistent mass formulation and the second-order effect resulting from the static and dynamic forces that act axially on the columns. The columns and girders are considered to have axial and bending deformations, thus each node of a structural system has three degrees of freedom. Various displacement constraints can be applied to individual nodes with any specific numbers. A sophisticated computer program designated as ODSEWS (Optimum Design of Static, Earthquake, and Wind Structures) has been developed for the design of static loads, dynamic forces, and seismic excitations, as well as for any combination of these.

The project is nearly completed and the final report will be released at the end of 1978.

Optimum Design of Three-Dimensional Building Systems for Multicomponent Earthquake Motions

It has been recognized by the earthquake research community that analytic and design methods are needed and the emphasis should be placed on three-dimensional structures and on the development of computer-aided optimum design methodologies. This project is designed to study the optimum design of three-dimensional building systems subjected to static loads, wind forces, and three interactive components of earthquake motions.

The objectives of the research are as follows: (1) mathematical formulation of optimization and structural models, (2) investigation of seismic forces and structural systems, (3) development of computer program for optimum design, (4) computer analysis of design options, and (5) assessment of critical structural parameters and systems. The research will lead to a practical method of seismic design which is more rational and reliable than those methods commonly used today.

Related Publications

1. Cheng, F.Y. and D. Srifuengfung, "Optimum Design for Simultaneous Multicomponent Static and Dynamic Inputs," Energy Technology Conference and Exhibition, American Society of Mechanical Engineers, Sept. 1977, Proceedings of Structural Optimization Methods published by ASME and Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

2. Cheng, F.Y., "Comparative Studies of Buckling Capacity of 3-D Building Systems," Presented at the International Colloquim on Stability of Structures Under Static and Dynamic Loads, May, 1977, Proceedings, pp. 179-193.

3. Cheng, F.Y., E. Uzgider, and P. Kitipitayangkul, "Analysis of Space Frames Subject to Multicomponent Earthquakes," Conferencia Centro Americana De Ingenieria Sismica, San Salvador, El Salvador, Jan. 1978, Proceedings, Vol. I, pp. 105-116.

4. Cheng, F.Y. and D. Srifuengfung, "Optimum Design of Seismic Structures Based on Energy Distribution," Annual Convention of the American Society of Civil Engineers, Pittsburgh, 1978, paper no. 3142.

5. Cheng, F.Y. and P. Kitipitayangkul, "Multicomponent Earthquake Analysis of Mixed Structural Systems," Proceedings of the U.S.-Japan Seminar, Tokyo, Jan. 1978.

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Earthquake engineering research is being conducted in three areas: the non-proportional damping of structural systems, seismic response of irregularly-shaped low-rise buildings and dynamic response of R/C connections. National Science Foundation sponsors the first two projects while the last one is supported by the University.

Non-proportional Damping of Structure Systems

After earthquake responses of structures had been observed, analytical models could often be developed to interpret the recorded behavior of structures. Because they were usually fine-tuned, models ranging from those with detailed finite element discretization to the ones simulating only a few basic modes of vibration of structures were sometimes found effective in data correlation study. However, controlled experiments such as shaking table tests of structures could give more insight into the actual behavior of representative structures, from which detailed examination of model validity is feasible. The objectives of this study are to develop a damping model for structures where non-proportional energy dissipation can be dealt with and to investigate the significance of small-amplitude damping properties for their adoption in analytical modeling. A procedure to assign an individual Rayleigh damping mechanism for each part of a structural system has been developed and incorporated into the computer program DRAIN-2D of Berkeley. With non-proportional damping introduced to the foundation-structure interaction model for the three-story steel structure tested on the Berkeley shaking table(1), preliminary analytical results have been obtained. It is demonstrated that the degree of correlation between the computed and the experimental results is at least as equally impressive as that using a uniform damping model(2). More detailed parametric study is being undertaken to supplement these findings.

Seismic Response of Irregularly-Shaped Low-Rise Buildings

This study aims at developing analytical models and design criteria for low-rise buildings where the coupled torsional and translational vibration is significant but the structural properties are not readily accountable in a typical general-purpose computer analysis. The eventual need of performing inelastic dynamic analysis for this type of building and the difficulties which may arise in defining the yielding mechanisms for structural members subjected to complex stress states are recognized. Therefore, the analytical model is being formulated using equivalent member properties in a sense of finite element substructure analysis. A structure is assumed to consist of a few types of super elements: deformable joint, thin-walled I-section, panel and interface elements, etc., all three-dimensional in nature. Each super element will be considered as an assemblage of simple elements such that its yielding mechanism can be approximated with the resulting behavior of individual simple elements. Response patterns and failure modes of steel buildings with irregular plans will be investigated first. Design criteria will be generated after a series of parametric studies is accomplished for buildings subjected to ground excitations at arbitrary incident angles.

Dynamic Response of R/C Connections

A model for the dynamic inelastic response of connections is being developed and tested to determine the effect of accuracy of modeling connection behavior on the predicted response of a moment-resisting frame to earthquake loading. The dynamic response of a ten-story one-bay concrete frame to several earthquake ground motions is used to generate the time history for testing full scale connections built to duplicate the analyzed structure. This displacement record is used to dynamically test the connections and the resulting hysteretic behavior is used to adjust the connection model.

Preliminary results indicate that the connections, with 24-inch and 30-inch deep girders, are much more flexible than anticipated. A new model for connection behavior is being developed which includes girder depth as one of the variables. The tested connections produced hysteretic behavior which indicates little loss of strength due to concrete deterioration.

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The reported research is on the determination of the earthquake response of the structural systems which consist of high rise steel frames and reinforced concrete shear walls, employed to provide the required lateral stiffness. The research also includes the definition of the earthquake resistance of these structural systems where the shear walls were weakened by previous earthquakes.

Shear Wall Stiffened Steel Frames

There has been an increased usage of reinforced concrete shear walls in conjunction with steel frames. The economical advantages of this type of construction, up to 20-30 story high buildings, have been proven. However, the available information on the interaction of the frame-shear wall systems has been limited; and most of the reported studies have been confined to in-depth investigations of particular aspects of the problem area. The lack of information in the area of assigning initial dimensions to the frame and the shear wall has inhibiting effects in the widespread use of this type of structure by the designers.

The objective of the research is to conduct a parametric investigation on steel frame-reinforced concrete shear wall systems of various dimensions subjected to lateral loadings. The loadings considered are wind and horizontal ground motions. The results are to be presented in tabular and graphical format to aid the designers to have a better appreciation of the type of structural interaction and the effects of selected design parameters on the lateral stiffness of the building.

The Scope of the Research

The total research program is subdivided into three problem areas:

(1) Steel frames stiffened by reinforced concrete shear wall, the total being planar and subjected to loadings such that no out-of-plane deformations are produced. The thrust of the investigation is to determine the optimal shear wall dimensions. Pilot studies are also being conducted for the stiffening of reinforced concrete frames with reinforced concrete shear walls.

(2) Planar steel frame-reinforced concrete shear wall systems have been subjected to a prior earthquake and the shear wall has suffered deterioration of various intensities. The structural systems are reanalyzed to define the extent of the loss of the lateral stiffness and the response of the structures when subjected to another earthquake. The study is aimed at the definition of the threshold levels

of deterioration to the shear wall, whereby major repairs should be undertaken in order for the structure to withstand a second earthquake.

(3) Three dimensional steel frames are stiffened both by the floor systems and by open tubular, i.e. U-shaped, shear core. The stiffness of the legs of the core is changed by altering their thicknesses, thereby introducing torsional response in the structure. Through the study of the benchmark locations in the structure, suggestions are to be made about the extent of eccentricity that can be built into the core, without substantially changing the lateral response of the structure.

Analytical Modeling

The investigation is deterministic and of an analytical nature. Finite element method is utilized for the analysis of the structures. Comparisons with experimental results are made where possible. The structure is assumed to be linearly elastic. The deterioration due to previous earthquakes has been simulated by the reduction of the stiffness of the appropriate elements. The linear elastic analysis of the investigation substantially reduces the computational effort as compared to one that may employ inelastic and geometrically nonlinear formulation. The cost reduction permits the examination of a substantial number of structural configurations within an attainable computational budget.

The frames are discretized by beam-column elements, planar shear walls by membrane elements, and floor slabs and open tubular shear cores by plate bending elements with membrane stiffness capability. The analysis employs program SAP4CNK (a version of SAPIV modified by C. N. Kostem). Earthquake analysis is being carried out using ground response spectrum as input. A minimum of 10 modal shapes and periods is being extracted for use in the modal superposition technique.

Parametric Investigation

The reported research is essentially a parametric study towards the definition of the earthquake response of steel frames stiffened by reinforced concrete shear walls. Initially five steel frames were considered, having 2 to 5 bays, and various heights, the tallest building being 25 stories high. The frames have been designed as unbraced frames and braced frames. In the case of braced frames, the bracings have been removed prior to analysis.

The height of the shear walls is always kept the same as that of the frame. The thickness and the width of the shear walls have been changed with practical increments from the narrowest bay space to at least one and one half times the widest bay space. With the exception of a few pilot cases, the shear walls are always placed adjacent to the outermost line of columns.

Lateral loadings considered are wind loadings, providing positive pressure only to one side of the frame, and earthquake loadings. The earthquake response spectra considered are (1) linearized el Centro Earthquake of 1940, (2) 1971 San Fernando Earthquake recorded in the basement of the Kajima International Building, and (3) recording of the previous earthquake obtained near Pacoima Dam. Comparisons are being made with the current SEAOC code.

D. G. ROW

University of California, Berkeley

A general substructure technique is being developed under National Science Foundation sponsorship to form the basis for computer programs to evaluate the nonlinear response of structures during earthquakes. In particular, the technique is being developed for:

1. The response of large nonlinear structures.

2. The response of structures with known localized nonlinearities.

A General Substructure Technique for Large Nonlinear Systems

The substructure technique has gained in popularity for linear analysis because it provides a convenient means of partitioning complex structures into manageable units. Additionally, the technique offers flexibility in structural description, computational savings for the case of repeated substructures, and a manageable data structure. Substructuring techniques are equally attractive for the static and dynamic nonlinear analysis of large structures. Here again, the structural description and subsequent data checking are simplified, and substantial computational savings may be possible.

A general multi-level substructure scheme has been developed for the static and dynamic anlaysis of large nonlinear structural systems. Structural description is achieved through a "building block" procedure which minimizes the geometric input data. This procedure is a generalization of standard finite element assembly. The relation of each actual substructure to the complete structure is mapped through a connectivity tree. This tree provides the basis for data management and implementation of a systematic analysis procedure.

With most solution strategies, nonlinear static or dynamic analysis requires a large number of linear analyses. If, because of nonlinear behavior, the structural stiffness is changing at each step, the equation assembly and solution effort can constitute a significant proportion of the total solution effort. For a structure assembled as a single unit, a complete reanalysis may be required if the nonlinearities are localized. A major computational advantage of the substructure technique is that only those substructures which change in behavior need to be reanalyzed at each step. Large computational savings result when the major source of nonlinearity is material dependent.

At present the program is operational for static analysis. The dynamic analysis capability can be implemented with minimal additional development. Ultimately, it is planned to incorporate mixed explicit and implicit solution strategies to further reduce computation for certain classes of problems. It must be noted that the analysis of large fully nonlinear structures, subjected to even moderate length earthquakes, is very costly. However, the substructure technique minimizes such costs and allows larger structures to be analyzed for a given computer capacity. The latter is an important consideration in light of the increasing popularity of minicomputers.

Analysis of Structures With Known Localized Nonlinearities

In many cases of earthquake induced response, the nonlinearities of a system are at a number of predetermined spatial locations. For instance: "soft story" buildings; building impact; foundation uplift; structures on nonlinear soils; elastic piping systems on nonlinear supports. By partitioning the structure into linear and nonlinear substructures, efficient analyses can be performed using the techniques described above.

At present a technique is being developed for the analysis of elastic piping systems on nonlinear supports subject to seismic motions. The piping system can be divided into a convenient number of linear substructures. These linear substructures are analyzed for their primary modes of vibration under fixed support conditions. The internal degrees of freedom (d.o.f.) of the linear substructures are then expressed in terms of as many mode shapes required for accurate dynamic representation. The step-by-step analysis is then performed on the reduced system, consisting of the nonlinear support d.o.f. and the generalized internal linear substructure d.o.f.

This technique will allow very efficient analysis of large piping systems and will be directly applicable to most other linear/nonlinear systems.

H. D. MCNIVEN

University of California, Berkeley

The author is the Principal Investigator on three Grants from the National Science Foundation. The research described here is the work supported by two of those Grants. The research carried out under the third Grant is described in another report of the meeting. In the description, research will not be distinguished by Grant, but according to individual programs. Whereas each program has a unique identity, all have the unifying theme of the mathematical modeling of the dynamic behavior of a structure or a structural element. In most, but not all, of the construction of mathematical models, system identification is used in the formulation which needs accurate experimental response data for the estimation of the parameters of the model. In some of the work, the experiments have been performed by ourselves, in others we use the data reported by others.

Mathematical Model of the Linear Response of Masonry

To understand the dynamic response of masonry, it is important to know the stress field throughout the masonry created by the forcing function. Such knowledge would give insight into the beginning of cracking and what measures might be taken to strengthen the masonry in appropriate places. Because of the inhomogeneous structure of masonry, such a stress field is difficult to obtain.

We have constructed a model which replaces the masonry by a homogeneous, anisotropic material that displays the same dispersive properties as an arbitrary layered material. We have used the theory of mixtures and the conservation of linear momentum to create the model. Dispersion is accomodated through an elastodynamic operator which appears in the final theory through approximations. The model displays hexagonal symmetry which introduces fifteen constants and, with the four dispersive constants, makes a total of nineteen. The nineteen constants are found partly from the theory of mixtures and partly by matching properties of frequency and phase velocity spectra of infinite trains of both P and S waves travelling in various directions. The resulting model is remarkably accurate. Not only are the spectra referred to predicted accurately, so are the transient experimental responses reported in the literature. We are proceeding to model a masonry wall which, because we can exploit generalized plane stress, will contain only seven constants. Experiments are now being planned for such walls so that the seven can be found using system identification.

Effect of the Strain Rate in the Behavior of Steel and the Ramberg-Osgood Model

In work we had done on the nonlinear model of a single story steel frame, and reported at the last meeting, there were two questions which remained unanswered. The model predicted the acceleration response very accurately, but predicted a displacement response which was in phase with the experimental but showed a vertical shift. We were aware that the shift followed the first major excursion into the plastic strain response. We were suspicious about the ability of the Ramberg-Osgood hysteretic model to reproduce this particular excursion. We were also curious about the influence to loading rate on the parameters of the model.

To investigate both of these questions, we performed quasi-static tests on the same frame with virgin columns. We found, as others have, that the influence of this strain rate is restricted to this same first major excursion into the plastic zone. The slower the strain rate, the more rounded is the hysteretic loop and the more difficult it is to model.

We also found that the reason for the displacement shift is that the Ramberg-Osgood model is incapable of reproducing a half loop displaying pure plastic strain. Ramberg-Osgood always predicts some work hardening behavior giving the wrong reversal point at the end of the first major excursion.

Linear and Nonlinear Models of a Three-Story Steel Frame

A few years ago, experiments were performed on the shaking table at the Earthquake Engineering Research Center of the University of California by Clough and Tang, in which both the linear and nonlinear responses to earthquake type inputs of a three-story steel frame were recorded. Having completed the model of a one-story steel frame, the logical next step seemed to be the three-story frame starting with the linear model and progressing to the nonlinear. Formulation of both models proved to be exceptionally fruitful. From the study involving the linear model, we have been able to accomplish a number of objectives. We have constructed a nine parameter model that predicts almost exactly the response both for translation of the floors and rotation of the joints to earthquake excitations. The model gives physical insight into the behavior of the structure, and we are in a position to advise engineers how to model such a frame so that it can predict the response more accurately than the method presently employed. We also learned a great deal about system identification as it applies to earthquake structures. We now have a clear picture about which response data will and which will not lead to a unique set of model parameters. We have gained insight into the question of appropriate insufficient data.

The nonlinear model was developed as an extension of the linear model in which the linear stiffness is replaced by a bilinear stiffness. The nonlinear model proves to be as successful as the linear model. The floor acceleration-time and rotation-time profiles are predicted almost exactly. In addition, we produce an equivalent linear model from the nonlinear response data and are able to gain insight into the appropriateness of such a model.

It should be stated here that the nonlinear response data revealed that the structure was forced into a response that was only mildly nonlinear, so that the model formulated may or may not predict behavior that is more highly nonlinear.

The Nonlinear Response of Reinforced Concrete Beams

The nonlinear behavior of reinforced concrete beams is extremely complicated, almost defying the process of modeling. We are fortunate to have at our disposal experimental data on such response provided in reports by Ma, Bertero and Popov. These experiments were performed as quasi-static tests, and the hysteretic behavior which results shows the relationship between moment and rotation. The behavior is extremely complicated reflecting the complex behavior of the steel when extended into the range of very large strains, the stiffness and degradation of the stiffness of the concrete and the complicated behavior of the slip between steel and concrete. Our approach has been to use system identification to model each of these phenomena separately and, then, to combine the separate models to produce a final model to mimic the gross behavior.

For the reinforcing steel, we found that the model of Menegotto and Pinto is the most appropriate. We have been able to match experimental results very accurately when the strain grown continuously, cycle by cycly, to strains some 60 times the yield strain. To do this, we had to make the parameters of the model strain dependent. We have found models that predict the linear and nonlinear behavior of the concrete, including its degradation as failure begins and progresses. We found that without accounting for slip between steel and concrete, this model was not adequate. We now have a sub-model that produces very faithfully experimental data on this very complex behavior. The resulting model for the gross behavior of the beam is now completed and, using the parameters from the three parts, have found that it predicts the gross behavior quite well. It still remains to allow all parameters to be free and to use system identification to establish the best set to predict the gross behavior.

The Influence of Partitions on the Model for the Response of a Single Story Steel Frame

Now that we have a model for the response of a single story steel frame, we seek the influence on the model of a variety of partitions. This program is at an early stage and only the experiments have been completed. There are three types of partitions: two masonry, one prefabricated steel stud, and one timber stud.

Tests were performed with different partitions under identical excitations and with similar partitions under various boundary conditions. The system was subjected to the El Centro, Taft and Pacoima earthquakes repeatedly with increasing intensity. The displacement, acceleration and strain time histories were recorded.

The masonry partitions contribute significantly to the response but, if the excitation is severe, do not survive. The stud partitions contribute little to the response but survive the severest excitations with superficial damage. With the response data we are proceeding to formulate the mathematical models.

G. H. POWELL

University of California, Berkeley

National Science Foundation sponsored earthquake engineering research is being conducted on techniques and computer programs for analysis of inelastic dynamic response. The emphasis is partly on developing general purpose computer programs and partly on solving a number of special problems.

Computer Programs

Three computer programs have been released to date, a fourth will be released in a few months, and a fifth is being planned.

The first program, DRAIN-2D (Dynamic Response Analysis of Inelastic 2D Structures - Kanaan and Powell) was released in 1973. The program performs analyses of plane inelastic structures for ground motion effects, using a simple step-by-step solution strategy with equilibrium correction but no iteration. The structural elements may be of a variety of types, and the program has the particular feature that new elements can be developed and added with relative ease. DRAIN-2D is rather simple-minded, and is old fashioned in some of its techniques, but is easy to use and computationally efficient. It has been used in research projects at Berkeley, at the Portland Cement Association, and other institutions. The program has also received a significant amount of application in practice, notably by the New Zealand Ministry of Works and Development.

The second program, ANSR-I (Analysis of Nonlinear Structural Response - Mondkar and Powell) was released in 1975. The program can perform large displacements and/or inelastic analyses for static forces, ground motion effects and dynamic forces, and is applicable to arbitrary 2D or 3D frame or finite element systems. The program has a more sophisticated solution strategy than DRAIN-2D, allowing both step-by-step and iterative schemes. New elements can be added with relative ease, following a standardized procedure. The element library is limited because development efforts have concentrated on the basic program rather than the elements. The available elements include a truss bar, beam, beam column, 2D solid, axisymmetric solid, and 3D solid. This program is clearly and logically written. It is a useful research tool, and has been used as the basis for at least one commercial program for nonlinear analysis.

The third program which has been released is DRAIN-TABS (1977 - Guendelman and Powell). This program allows arbitrary plane frames of DRAIN-2D type to be linked together by rigid floor diaphragms, as in the well-known TABS program, so that three dimensional buildings can be analyzed. This program uses substructuring to improve the computational efficiency.

A fourth program, which will be released during 1978, is ANSR-II. This program is substantially more powerful than ANSR-I, possessing a restart capability; the ability to consider arbitrary sequences of static and dynamic loads; an out-of-core equation solver; an option for unsymmetrical element stiffnesses; and an option for out-of-phase support motions. A further extension, ANSR-III, is being planned, incorporating some of the recent developments considered in the following section.

Current Investigations

Investigations are currently being conducted in four areas, namely (1) improvement of the basic program capabilities; (2) development of new element types; (3) incorporation of new material models into existing elements; and (4) particular problems associated with the analysis of large precast panel buildings.

A study of substructuring techniques for incorporation into a general purpose program has recently been completed (Row, 1978), and a building-block scheme has been developed which is both general and convenient to use. For nonlinear structures, substructuring has somewhat different advantages than for linear structures. The most important advantage in the nonlinear case is that localized nonlinearities (or, in general, any system which is partly linear and partly nonlinear) can be considered efficiently. There can also be advantages in handling the data base and in reducing the amount of input data. Other improvements being studied for the basic program include more stable iteration options, explicit and combined explicit-implicit step-by-step integration schemes, and generalization of the data base and data handling procedures.

New element types under development include the following: (1) beam-column element with both large displacements and inelastic effects, with interaction between biaxial bending, axial force and torque (Riahi, 1978); (2) a fluid drag element for seismic excitation of submerged structures (Riahi, 1978); and (3) various panel and joint elements for analysis of large panel buildings (Schricker, 1979). Inelastic material models are also being studied, particularly for soil (Abdullah, 1975; Al Shawaf, 1978) and concrete (de Villiers, 1977). A particularly large amount of research is needed to establish accurate and reliable models for complex inelastic materials under cyclic loads.

Attention is also being devoted to the inelastic analysis of large panel structures. Initial studies are being conducted on plane structures using special purpose panel and joint elements being developed for DRAIN-2D. It is expected that three dimensional structures will subsequently be analyzed using ANSR. A particular feature of this study is that a weakness has been exposed in the step-by-step solution strategy of DRAIN-2D. We have known for a while that this strategy had difficulty with impact problems. Analyses with impact have been successfully conducted (e.g., lift-off studies for column bases - Huckelbridge, 1977), but only with rather soft impact. In large panel structures, gap opening and closing occurs at joints, with very large stiffness changes. We have found that the basic step-by-step strategy is both unreliable and inaccurate for this type of problem, and are having to explore more sophisticated strategies. The inelastic analysis of large panel structures poses difficulties because the behavior of the structure depends greatly on the joint characteristics. Not only does slipping or opening of joints lead to large stiffness changes, but the computed response appears to depend greatly on the properties assumed for the joint. For example, an apparently small amount of strain hardening assumed when a joint slips can greatly alter the computed response. Caution must be exercised until procedures of proven reliability have been developed for analysis of these structures.

J. BECKER, J. M. ROESSET AND J. M. BIGGS

Massachusetts Institute of Technology

A study into the "Seismic Resistance of Precast Concrete Panel Buildings", initiated nearly three years ago, is being carried out at the Massachusetts Institute of Technology under the sponsorship of the National Science Foundation. The investigators on this project are Professors J. M. Becker, J. M. Roesset, and J. M. Biggs. The primary objective of this project has been to develop a fundamental understanding of how large panel precast concrete structures will behave when subjected to an earthquake. It is felt that such a fundamental understanding is a prerequisite for the aseismic design of panelized structures. The project has approached this objective through the gathering of relevant information and using this information in the development of appropriate analytical models for simulating seismic response.

Large Precast Panel Building (LPPB) Systems

Panelized building systems are constructed of large precast concrete panels used as both vertical and horizontal structural components. Vertical elements, referred to as panels, are combined to create both load bearing and non-load bearing shear walls. Horizontal elements act as both floor and roof systems for gravity loads and as shear diaphragms for resisting lateral loads. Precast concrete panel construction has found its widest use in residential construction where the panels may serve as multi-functional building elements.

The existence of connections throughout the panelized building creates a structure threaded by an interconnected system of discontinuities. Seldom does the complexity of a connection allow for the development of strength comparable to that of the surrounding panel. By the very nature of the construction process, the connection introduces natural planes of low stiffness and weakness in which large deformations (e.g., slippage) may be required for the development of ultimate strength. Thus, connections are not just additional elements to be designed based upon an overall analysis procedure, rather they may in themselves provide a fundamental mechanism for altering structural behavior.

The dependence of the seismic response on connection behavior has been confirmed by observations of earthquake damage. A bulk of the experimental effort world wide has been on the testing of connection details and assessing their role in the behavior of assemblies of precast elements. The exception to this dependence upon connection behavior is when the panels have significant penetrations the cause localized distress due to shear distortion within the panel.

The seismic resisting elements of large panel structures are both load-bearing and non-load bearing shear walls. These lateral load resisting elements can be divided into two basic types: the simple or isolated wall and the composite wall. A simple wall is a vertical stack of precast panels, one panel in width, in which the behavior of the system is dependent upon the horizontal connection. A composite wall is created when two or more simple walls are connected through vertical connections (this differs from a coupled shear wall in that the connection is only a shear transfer mechanism).

These simple and composite walls are coupled together through two basic mechanisms: lintel coupling of coplanar walls or the more general case of floor coupling. While the former case has been the subject of a great deal of discussion, the latter case has received little attention. The normal assumption of rigid floor diaphragms is highly questionable given both the decreased stiffness of precast floor systems and the relative rigidities of the floor and wall systems. This issue of floor coupled walls raises questions about the generalized response of large panel type structures. In examining the generalized response of these structures several basic issues have been addressed: the role of the floor in the seismic response, the distribution of forces among the lateral load elements, the importance of soil structure interaction and effect of non-simultaneous excitation of the foundation elements.

The basic issues raised in the above discussion have provided the focus for the activities of this research project. The remainder of the discussion is thus directed at two basic areas: the seismic response of simple and composite wall structures and generalized dynamic behavior of cross wall structures.

The Seismic Response of Simple and Composite Wall Structures

In order to model both the simple and composite walls as individual lateral load resisting elements, the following simplifying assumptions were made: 1) all nonlinear-inelastic behavior is lumped in the connection regions, thus allowing the panels to be modeled as linear elastic elements, 2) the floor diaphragm was assumed to be rigid thus allowing mass to be distributed on the basis of relative stiffness, and 3) the foundation was assumed to be rigid. The latter two of these assumptions are known to be questionable and their individual impact is being assessed in the studies on generalized behavior.

Initial studies indicated that the horizontal connection of the simple wall would be subjected to an opening or cracking phenomina even during low intensity earthquakes. In addition to this opening problem, it was necessary to account for shear transfer through friction mechanisms along the entire length of the horizontal connection.

In order to model these phenomina, it was decided that each panel could be handled as a substructure, constructed from PSR elements in which all internal degrees of freedom are eliminated through static condensation. Thus it was possible to construct a simple wall in which the panels would be connected by a series of finite elements. These connection elements could then have the necessary nonlinear-inelastic properties associated with reported experimental data. Having explored several possibilities it was decided to use a bond type element which has two intergration points on its centerline. This model in effect gives a distributed series of horizontal (shear) and vertical (axial) springs. The dynamic analysis using this model was carried out using a time step intergration based on a central difference formulation.

Results of a series of parametric analyses carried out indicate the severe distress that can be created in horizontal connections. For taller walls, greater than ten stories, the dominant response is one of overturning. Since the shear distribution (controlled by friction) is directly proportional to the overturning compression block, the concentration of force transfer in this continually varying zone indicates the potentially serious demands placed upon the horizontal connection. One possible mechanism that may help mitigate this situation is the possibility of an overall shear slip taking place in the horizontal connection. Such a slip could serve both to control maximum force levels and to dissipate energy.

For lower structures, five stories or less, the significance of overturning is decreased and the possibility of shear slip increased. Regardless of which mechanism is involved overturning and/or slip, concern must be shown for the possible degradation of the horizontal connection because of its role in the overall stability of the structure.

The behavior of a T shaped composite wall has been modeled making use of an early version of the simple wall model explained above. The transverse wall was constructed of substructures similar to the simple wall in order to model shear lag effects. The vertical connection, a dry embedded type, modeled using a spring element with a degrading stiffness whose parameters were determined by the experimental work of Nellie and Spencer.

The preliminary results of this analysis indicated that such embedded dry connectors have little if any energy dissipating qualities; however, such connectors can help develop a couple between the walls. As the connections degrade, the overall softening of the structure can lead to a favorable shift in the response spectra. The necessity of having a durable connector, that is one that can maintain itself through many large deformation reversals, is essential in designing composite walls. It was also observed that as the connection degrades the system degenerates into the lower bound behavior associated with the simple (web) wall.

Generalized Dynamic Behavior of Cross Wall Structures

Because of their common use within the United States, it was decided to study the generalized dynamic behavior of panelized construction in a cross wall configuration. These studies include the soil structure interaction of an isolated cross-wall on a strip footing, the effect of floor flexibility of force distribution in the structure and the impact of non-simultaneous excitation of foundation elements.

The inclusion of the possibility of soil structure interaction had a marked effect upon the response of an isolated cross wall. In these studies both the soil and the structure were considered to be linear elastic elements. The observed effect in the parametric studies were associated more with shifts within the response spectra than with any damping phenomena. In lower structures these shifts caused a significant increase in deformation, due to rigid body rotation, with little change in force level. In the taller structures it was observed that the effect on deformation was only moderate to minimal, but the force levels were noticeably decreased. The general conclusion was, that with the exception of extremely rigid soils, it is necessary to consider soil structure interaction for at least shallow foundations.

Experimenters have reported that precast floors have lower inplane stiffnesses than associated with equivalent cast-in-place floors. When incorporating this possibility into a series of linear elastic parametric studies, a noticeable redistribution of wall forces was observed. In general this distribution of wall forces was to increase the forces associated with interior walls. The largest impact on redistribution was for lower structures where the wall stiffness is more significant relative to the inplane floor stiffness. It was also observed that inplane force levels expected in the floor diaphragm often exceeded those associated with common tensile transfer details at floor-wall intersections.

The possibility of differential excitation of foundation elements has been discussed by other researchers. The parametric studies carried out in this area indicated that such a situation has two significant features. First it can excite both asymmetric and floor dependent modes not normally observed in the similtaneous acceleration case. Second, large forces can be induced in the floor systems in a building lower levels because of differential movement of the foundations. This boundary layer like effect died out after approximately five stories.

Comments of Future Research

In recent years LPPB systems have become economically and architecturally viable systems in the American construction industry. The research conducted at MIT has shown that these systems can potentially be used in regions of significant seismicity, but only with a more detailed understanding of their basic response mechanisms. To help achieve this understanding, it is necessary to initiate both detailed experimental programs for typical connections and subassemblies and appropriate field studies of actual structures. In addition to these experimental and field studies, it si necessary to continue the development of appropriate analytical tools to interpret and extend these results. Of basic importance to the industry, is the development of interm guidelines for the designer which can also provide a basis for guiding research into its most fruitful areas.

ANSHEL J. SCHIFF

Purdue University

This brief report describes National Science Foundation supported research dealing with the earthquake response of power systems and improving the seismic response of elevators.

Earthquake Response of Power Systems

A methodology to evaluate the earthquake response of power systems has been described in detail elsewhere (1-7). Briefly, a power system in a hypothetical metrapolitan area has been modeled in great detail. Taking into account the location of power system elements relative to the active part of a casual fault, site soil conditions, mounting structure characteristics, and equipment fragility, the type and number of equipment failures are determined. Using computer simulation methods the power system is first reconfigured taking advantage of system redundancy and system flexibility designed into substations. Then using DC load flow calculations overloaded circuits and components are eliminated by redistributing generation, opening lines to shift load flows and dropping load. This is done in a manner similar to what a utility would do under emergency operation conditions to maximize service to its customers. This is done by judiciously opening lines so that the grid type network is converted to a radial type network with each radial carrying load at or near its maximum capacity. The restoration process is then simulated to determine the extent and duration of service disruption. This is done in such a manner so that the number and types of available work crews are dispatched to repair tasks taking into account availability of spare parts, repair times for various tasks and utilizing expedient repair methods which would be utilized under emergency conditions.

For the system modeled it has been found that 1) if the user is not totally isolated from a source of power, adequate supply will be available to meet important needs, 2) some sites were found to be problem sites in that the equipment and soil properties combined to yield equipment failures which had very detrimental effects on system performance, 3) allocation of resources during the restoration could have significant effects on restoration time, 4) the use of more spare transformers designed as mobils would reduce restoration time, and 5) the system could restore service to all users within a week utilizing temporary, emergency repairs.

While not utilized in the present study, the methodology could be used to evaluate the effects of changing seismic specifications of equipment or modifying equipment at specific sites. To have maximum impact it would be necessary for utility personnel to utilize the simulation so as to improve its accuracy and get a better understanding of how their system might respond to different earthquakes. Finally it could be used as a training tool for dispatchers so they could experience how their system responds when it is modified due to extensive damage.

Improving the Seismic Response of Elevators

This project is co-directed by Prof. Henry T. Y. Yang. The project can be divided into three parts. One part is to model the elevator counterweight-rail system so that dynamic response can be evaluated. Nonlinear effects due to counterweight-counterweight frame gap, counterweight-frame-rail gap and geometric changes in the counterweight frame and rails will be included. Sensitivity of response to changes in system parameters will be evaluated with the objective of improving the earthquake response of the system. A second part will model the dynamic response of elevator ropes (support and compensating cables) so that methods of controlling their motion can be evaluated.

The third part of the project is to gather data to determine the magnitude of excitations elevator equipment can be expected to experience from earthquakes and to determine to what extent the seismic response is dependent on the structural system used to resist lateral loads in the building. A survey will be made of existing data and strongmotion records. In addition seismic structures of varying structural systems will be instrumented to determine their response from ambient excitations. A microprocessor based data acquisition system will be used to collect the data. The data is being collected with the help of several elevator companies who will help in installing the instrumentation. Data will also be used to determine input motions which excite ropes and to determine if there are potential problems associated with the use of vertical triggers.

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IRVING J. OPPENHEIM

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Three research activities have yielded results in the past twelve months, and are described herein. The first activity was supported by the University, and the second was supported by the Office of Naval Research, contract number 0014-76-C-0345, with Professor S. J. Fenves. The third research project was supported by the National Science Foundation through grant PFR 75-20977.

Ambient Vibration Test of a High Rise Masonry Building (1)

A twenty storey reinforced masonry apartment building was the subject of roof level measurements of both ambient and man-induced vibrations. Analytical predictions of frequencies in the East-West (short plan dimension) direction were carried out using the ETABS analysis program. Measured frequencies were seen to correspond to coupled shear wall behavior, even though the building was designed with simply supported lintels, and uncoupled wall behavior. Examination of the lintel detail over corridor openings revealed the origin of this unsuspected coupling action. It results from the embedment of lintels within the wall, and subsequent application of bearing stress. There is a danger that lintels so detailed may be subjected to negative moments for which they were never intended.

Torsional Instability of Structures under Lateral Ground Motion (2)

Earlier research results (by Rosenblueth and Elorduy, and by Tso) on single storey structures showed dynamic magnification, or instability, to occur when lateral and torsional frequencies are in proximity. Extension of these results to multi-storey buildings (by Hoerner, and by Kan and Chopra) preserved the implications for behavior learned from the single storey structures. There exists, however, an alternate type of frequency incidence for multi-storey structures with large eccentricity. While elastic proportional theory does not predict anything extraordinary to accompany this effect, non-linear theory may reveal an instability.

A two storey structure was modelled, with a mild elastic non-linearity. Using variational methods, stability bounds were established, and regions of instability were shown to exist. Structures displaying such regions of instability were then analyzed for transient response to simulated accelerograms. Storey rotations in the mildly non-linear case exceeded those in the linear case by 40%. However, the implications for structures with practical non-linear/hysteresis properties have not yet been established.

Vulnerability of Water and Transportation Systems to Seismic Hazard (3,4)

The authors have proposed the simulation of losses resulting from lifeline damage. Those losses include repair and replacement costs, and also societal and user losses. The ability for analysts to simulate loss is required before any future benefit/cost analyses can be applied to mitigation strategies.

A method has been developed which processes the seismic risk for a system with scattered component resistances, and yields a limited number of lifeline damage "scenarios," each with an annual probability of occurrence. This is a discrete representation of the more continuous and complex damage states which result from seismic risk to a system. An example based upon the Pittsburgh water system was presented; loss levels, in dollars, were estimated as a function of site MMI. Losses included pipe and treatment plant repair costs, together with estimates of industrial, fire, and service costs during the period required for the restoration of service. The loss function was integrated over the probability density function for site MMI, yielding an annual expected loss under 3¢ per capita. A hypothetical translation to a highly seismic region, together with adverse component behavior, produced an annual loss of $4 per capita. This figure is a notable portion of the annualized system cost.

Transportation system study has centered on traffic modelling for a highway corridor under large perturbation. A heavily used corridor (characterized by AM and PM peak periods) could incur losses of $50,000/day during the period required for bridge repair. Those results, however, have not been processed into a seismic risk analysis. Future work includes the re-processing of the highway corridor analysis, and application of the water system procedure to a western site. Other research activities within this area include a micro-economic model of highway corridor user losses, and a network analysis procedure which permits some degree of aggregation of service characteristics.

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A. S. VELETSOS

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Following is a brief report on an analytical study of the dynamic response of thin-walled liquid-storage tanks to earthquake motions. The tanks considered are cylindrical, fixed at the base, and excited by a horizontal component of ground shaking. The upper surface of the liquid is considered to be free.

Analyses of the dynamic response of such systems (Refs. 1-5) reveal that, for tanks of truly circular cross sections, both the hydrodynamic pressure exerted by the liquid on the tank and the radial components of the resulting displacements are proportional to $\cos\theta$, where θ is the circumferential angle measured from the plane of excitation. However, the results of a comprehensive experimental program on aluminum tank models conducted recently at the University of California, Berkeley (Refs. 6,7), have revealed response mechanisms that are not fully compatible with, or explainable by, the analyses referred to above. More specifically, the circumferential distributions of the radial displacements measured in the test program were not proportional to $\cos\theta$ but included components of higher order of θ. Furthermore, the components corresponding to $\cos 3\theta$ and $\cos 4\theta$ were found to be substantially greater than (up to about 3.5 times) that corresponding to the $\cos\theta$ distribution. Naturally, these results have raised serious questions concerning the reliability of the theoretical predictions.

The objective of the study reported here was to assess the possible effects of an initial out-of-roundness on the dynamic response of tanks, with a view toward understanding and interpreting the unexpected results of the Berkeley tests. This is an exploratory study of the problem and the analyses employed are highly approximate.

Consider an initially out-of-round cylindrical tank that is being filled with liquid. Filling the tank produces uniform hoop forces which tend to reduce, but not completely eliminate, the initial irregularity. The dynamics of the tank-fluid system may effectively be examined in two parts.

The first part concerns the effect upon the response of the system of the part of the irregularity that remains in the filled tank. Such out-of-roundness induces hydrodynamic pressure components which are of higher order than $\cos\theta$, and these additional pressures, in turn, induce radial displacements of the same circumferential distribution.

The latter displacements were estimated approximately as follows. An analysis was first made of the hydrodynamic pressure induced in a nearly circular rigid tank with an initial irregularity proportional to $\cos n\theta$, where n is an arbitrary integer. It was found that a $\cos n\theta$ irregularity produces a pressure component that is proportional to $\cos(n-1)\theta$, and one of smaller amplitude that is proportional to $\cos(n+1)\theta$. These pressures were then used to compute the static values of the radial displacements produced in a flexible tank. The dynamic displacements were finally determined by multiplying the static displacements by an appropriate amplification factor, which is a function of the dynamic properties of the tank and the characteristics of the ground motion.

From the results of such analyses it has been concluded that the irregularity remaining in the filled tank cannot, by itself, be responsible for the observed behavior. For realistic distributions and amplitudes of out-of-roundness, the higher order displacement components computed on this basis were generally a small fraction of those actually measured in the test program.

The second part of the problem concerns the influence that the hydrodynamic pressure has on the portion of the initial out-of-roundness that is eliminated during the process of filling the tank with liquid. For the purpose of assessing this effect, it is adequate to consider only the effect of the primary component of the hydrodynamic pressure, which is proportional to $\cos\theta$. Because of its non-uniform distribution, the hydrodynamic pressure increases the total pressure exerted by the liquid on one side of the tank, and decreases the pressure on the opposite side. On the side where the pressure is decreased, there is a partial recovery of the part of the initial irregularity that was removed by the filling of the tank.

Both the reduction in the initial irregularity due to the filling process and the subsequent recovery due to the ground shaking depend on the properties of the tank, the geometry of the initial irregularity, and, of course, on the magnitudes of the hydrostatic and hydrodynamic pressures. For the test tank studied, it was found that the higher order irregularities, i.e. those associated with small wave lengths, are affected more than the low order irregularities.

There are no measurements of initial irregularities for the test tank considered in this study. However, from measurements of the radial displacements produced in another tank by filling it with water, the peak amplitude of the initial irregularity was estimated to be of the order of 1/4 in. This corresponds to about 3.5 wall thicknesses or to 1/300th of the tank radius. The latter values are larger than those normally expected in actual structures.

The analyses that have been carried out reveal that irregularities of these amplitudes, in combination with circumferential distributions of $\cos 8\theta$ or greater, would produce dynamic displacements of the order of those actually measured in the test program. Expressed differently, the measured displacements must be due to the reduction of the initial out-of-roundness due to the filling of the tank and its subsequent partial recovery due to the dynamic excitation.

As a by-product of this study, it has been concluded that the circumferential distributions of the response for the test tanks could not be defined accurately by the number of sensors used in the experimental program. With the eight displacement sensors per section employed, it is possible to define only displacement components with circumferential distributions up to $\cos 4\theta$. The higher order components, which based on the results of this study are believed to have been major contributors to the response, must have been interpreted incorrectly as being due to lower-order components. In particular, the conclusion to the effect that the radial displacement components were dominated by components proportional to $\cos 3\theta$ and $\cos 4\theta$ does not appear to be justified.

It should be noted that the dynamic response of an initially out-of-round thin-walled liquid-storage tank is highly complex, not only because it is sensitive to the distribution of the initial irregularities but also because the relationship between pressure and deflection is a non-linear one.

Future phases of this investigation will deal with further studies of the effects of the numerous factors that influence the response, and with an evaluation of the design implications of the effects of initial irregularities.

This report is based on a dissertation by J. W. Turner, submitted to Rice University (Ref. 8).

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Response of Liquid Filled Storage Tanks with Domes to Seismic Excitation

Several reports issued previously under this National Science Foundation sponsored program have been concerned with (a) analytical, and (b) finite element approaches to the problem of determination of small amplitude elastic response of a cylindrical liquid storage tank to seismic excitation of the rigid base slab to which the tank is attached. In those studies the case of an empty tank was investigated first, then the case of a tank filled to an arbitrary depth with a perfect, incompressible liquid was studied. The lower extremity of the tank was assumed to be rigidly clamped to the base slab and the upper extremity has simplified boundary conditions corresponding to either a free, simply supported, or clamped edge. There was no dome or cover on the tank in these earlier investigations. The analytical solution was based upon mode superposition and the finite element approach treated the tank as a collection of ring-shaped elements and the contained liquid as a set of elements that were rectangular in any diametral plane. Certain of the computer codes developed in these earlier investigations are available through NISEE.

For the past year work has been in progress on extension of the studies mentioned above to include the case of an elastic dome on top of the tank. The earlier computer programs have been generalized so as to be able to account for tanks whose thickness varies along the direction of a vertical generator. Also, a new computer code has been developed and coupled to the cylindrical tank program with the new code being capable of accounting for the elastic behavior of any arbitrarily shaped dome of revolution attached to the cylindrical tank. The entire structure is necessarily axisymmetric but liquid motions inside the tank lead to unsymmetric loadings. A computer code has been developed to predict response of the tank-dome system to small amplitude liquid motions induced by seismic effects acting on the rigid base slab of the system. A report and accompanying computer code covering this aspect of the program will be available in late June, 1978.

Work is now underway to investigate more realistic boundary conditions at the bottom of the cylindrical tank. It is known that uplift between anchor bolts occasionally occurs in such tanks and this feature of the structure is currently under investigation.

The work is sponsored by the Earthquake Engineering Program of the National Science Foundation under Grant NSF-ENV-76-14833.

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Hydrodynamic Pressures on Sloping Dam Face

The work described here grew out of an effort by my colleague Allen Chwang and myself to explain and extend Karman's momentum-balance method. Karman, in a discussion of H. M. Westergaard's paper, presented a very simple analysis which gave practically the same result as Westergaard obtained by a more complicated analysis (Trans. ASCE, No. 91, 1933). Karman's momentum-balance analysis was for a rigid vertical dam impinging on incompressible fluid; and it was rather mysterious in that unjustified steps were involved but good results were obtained. A rationalization and extension of Karman's method has been developed.

Writing the equations of motion for the fluid in the infinite strip (dy) (Figure 1), and writing the equation of conservation of mass and equation describing the kinematics of flow at the surface of the dam, gives the following equations:

$$p_o = \rho b_x a_{xo} \qquad \left(\text{where } b_x = \int_o^\infty \frac{a_x}{a_{xo}} dx\right) \tag{1}$$

$$-\frac{d}{dy}(p_o b_y) + \beta p_o = \rho b_y a_{yo} \qquad \left(\text{where } b_y = \int_o^\infty \frac{a_y}{a_{yo}} dx\right) \tag{2}$$

$$b_y a_{yo} = y a_o \tag{3}$$

$$a_{xo} = a_o(b_y - \beta y)/b_y \quad ; \qquad a_{yo} = a_o y/b_y \tag{4}$$

The quantities b_x and b_y define equivalent breadths as determined from horizontal and vertical motions respectively. The preceeding equations can be reduced to the following general equation of motion:

$$\frac{d}{dy}\left[\frac{b_x}{b_y}\left(b_y^2 - \beta y b_y\right)\right] - \beta\frac{b_x}{b_y}(b_y - \beta y) = -y \tag{5}$$

The essence of Karman's method is to assume $b_x = b_y = b$ and the resulting equation can be integrated for the effective breadth.

$$\log_e\left(\frac{B^2 - \beta By + 2y^2}{2h^2}\right) = \frac{2\beta}{\sqrt{8-\beta^2}}\left\{\tan^{-1}\left(\frac{\beta}{\sqrt{8-\beta^2}}\right) - \tan^{-1}\left(\frac{2B - \beta y}{y\sqrt{8-\beta^2}}\right)\right\}$$

$$\text{for } \beta^2 < 8 \qquad (6)$$

$$\log_e\left(\frac{B^2 - \beta By + 2y^2}{2h^2}\right) = \frac{\beta}{\sqrt{\beta^2-8}}\left\{\log_e\left(\frac{\beta - \sqrt{\beta^2-8}}{\beta + \sqrt{\beta^2-8}}\right) - \log_e\left(\frac{2B - \beta y - y\sqrt{\beta^2-8}}{2B - \beta y + y\sqrt{\beta^2-8}}\right)\right\}$$

$$\text{for } \beta^2 > 8 \qquad (7)$$

When the foregoing equations are evaluated for various values of β the pressures on the face of the dam are as shown in Figure 2, where they are compared with the exact values. Figure 3 shows the total normal force on the dam. This shows that a convenient rule of thumb is that $F = 0.5\ \rho h^2 a_o$.

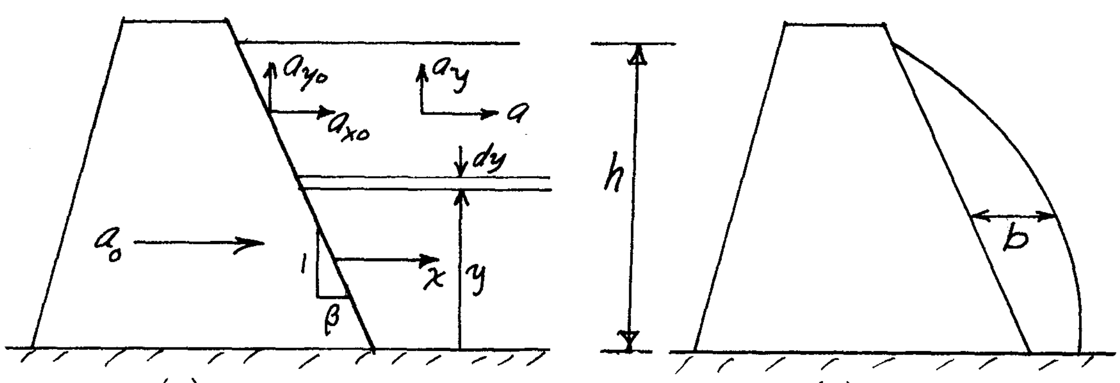

Figure 1

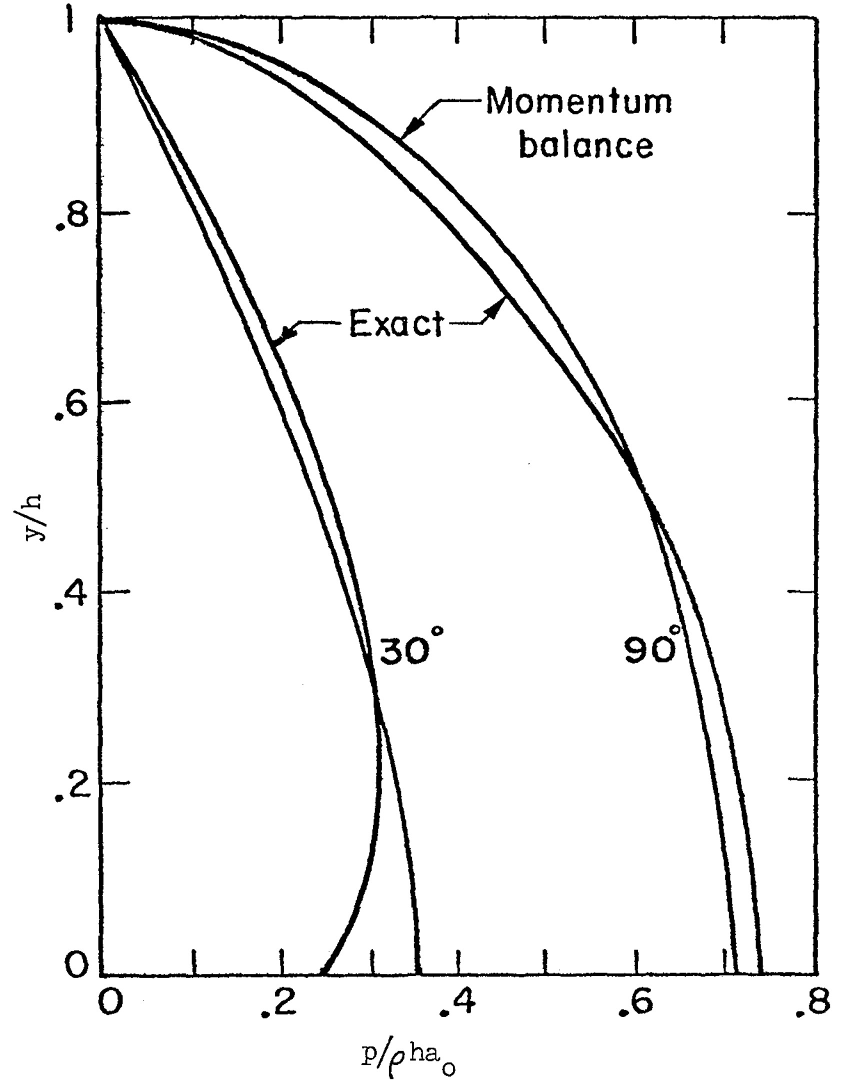

Figure 2

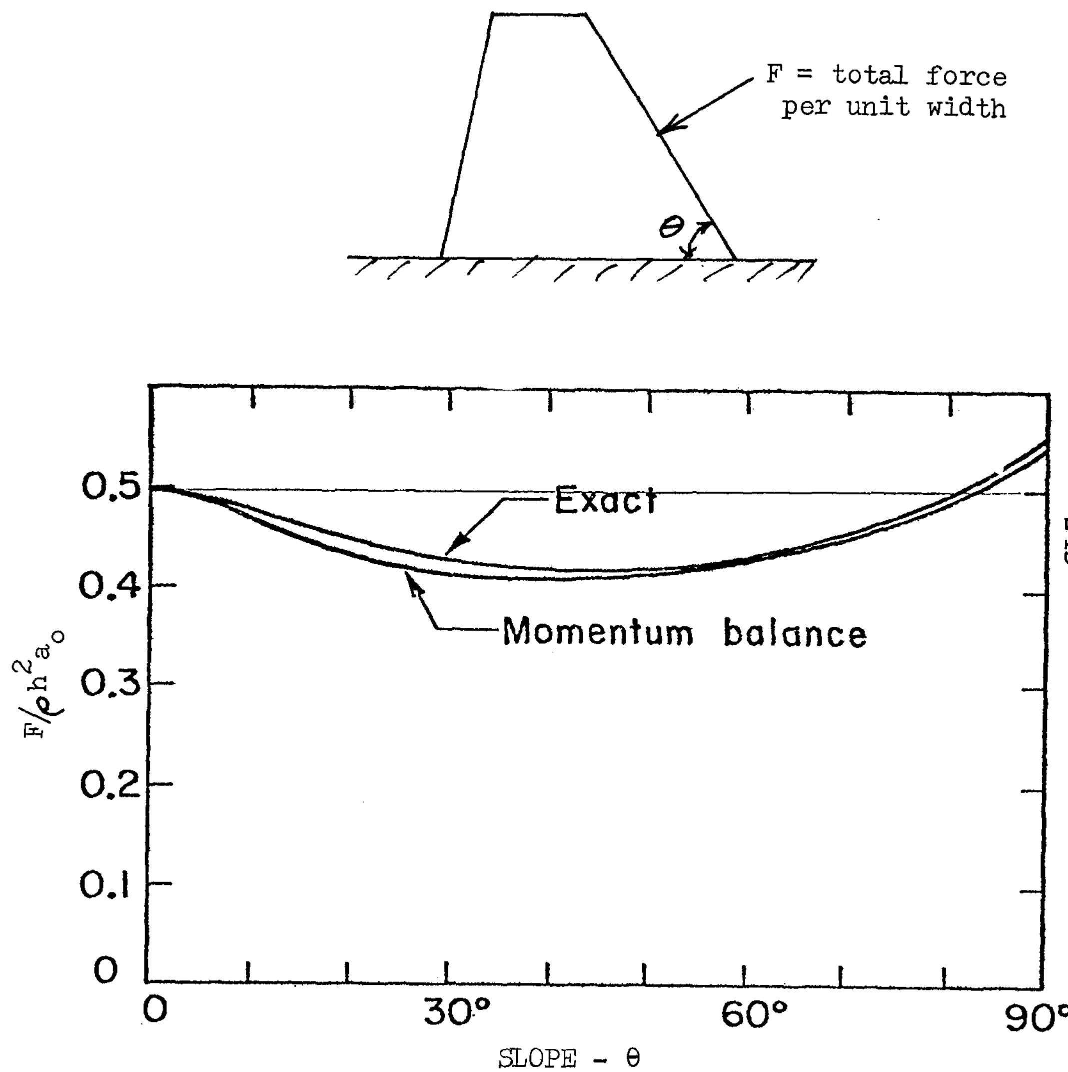

Figure 3

S. A. MAHIN and V. V. BERTERO

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This paper summarizes current research at Berkeley sponsored by the National Science Foundation in the areas of Post-Earthquake Damage Analysis, Definition of Design Earthquakes and Prediction of Mechanical Behavior of Buildings. The latter two areas are part of a project intended to provide the engineering profession with a summary and evaluation of recently acquired knowledge in specific areas of seismic-resistant design.

Post-Earthquake Damage Analysis

A number of major buildings damaged during the 1971 San Fernando and 1976 Guatemala earthquakes are currently being studied in detail in order to: (1) identify the structural and/or construction causes of observed damages and, thereby, assess the adequacy of current seismic-resistant design, analysis and construction methods; and (2) suggest improvements in current seismic-resistant design practices. To perform such studies, it is necessary to review and integrate pertinent research results from a wide variety of disciplines including engineering seismology, soil mechanics, structural analysis and dynamics, etc. Analytical results obtained for these buildings using various linear elastic and nonlinear structural idealizations are compared and evaluated in terms of their ability to predict observed structural damages and their effectiveness as design guidelines.

On the basis of previous field inspections and analyses [1], and current investigations, a number of observations may be made. Conventional linear-elastic dynamic analysis techniques cannot be reliably interpreted to predict structural behavior when substantial inelastic deformations occur. Nonlinear dynamic analysis techniques are useful in such cases, but have significant theoretical and practical limitations. Since realistic modeling of building-soil systems is important, studies related to determining the contribution of reinforced concrete floor slabs [2], stairways, and structural and nonstructural walls to the overall structural response in the elastic and post-elastic ranges are being performed. All of the case studies have reiterated the importance of proper selection of structural system, detailing, workmanship and inspection.

San Fernando Earthquake. A completed study of the Olive View Hospital Main Building [3] has clearly pointed out the importance of considering the effect of nonlinear behavior in design and indicated that certain aspects of the building's behavior may have been due to unusual ground motion characteristics that occurred near the fault rupture. The Holiday Inn, a 7-story instrumented R/C frame building in Van Nuys, is currently being studied in order to investigate the contributions of flat slab floor systems and nonstructural partitions to lateral resistance.

Guatemala Earthquake. A detailed description and overall assessment of damages to more than 40 buildings in Guatemala City is nearing completion. This report focuses on the effect of the type and detailing of the structural system and nonstructural elements on observed seismic damages and on problems encountered in repairing these damages [4]. Two three-story buildings with R/C moment-resisting frames are being studied in detail. One building has a long span, waffle slab which has been studied using finite element procedures. The analyses of this flexible building indicate that 'nonstructural' masonry partitions had a significant effect on the response. In the investigation of the other building, a new analytical technique for modeling infilled panels has been developed for the elastic range.

Definition of Design Earthquakes

Problems in establishing design-earthquakes for structures situated near potential sources of major earthquakes have been examined, and currently available methods have been reviewed. Based on extensive studies of single (SDOF) and multiple (MDOF) degree-of-freedom systems [5, 6], it has been found that the information necessary to define critical design forces for structures subjected to moderate ground shaking (where serviceability is the controlling design criterion) is not sufficient for major ground shaking (where safety considerations typically predominate). This is because the types of excitations that control the response of elastic and inelastic systems are fundamentally different.

In particular, theoretical studies and San Fernando earthquake records indicate that severe, long duration acceleration pulses may be associated with near-fault ground motions [6]. Such pulses put unusually large inelastic deformation demands on conventionally designed structures. Response of SDOF (in the form of nondimensionalized inelastic response spectra) and MDOF systems to these and other types of records have been studied to determine the information needed to define ultimate state design earthquakes.

The reliability of two types of inelastic design response spectra derived directly from linear elastic design response spectra using modification factors which account for ductility are being evaluated [7]. The effects of different accelerograms, hysteretic characteristics and damping values on the inelastic response of SDOF and MDOF systems designed using these methods are being investigated considering maximum displacement ductilities, maximum and permanent drifts, hysteretic energy dissipation, etc. Results indicate that the methods considered do not reliably limit ductilities to specified values, even for ideal elasto-perfectly plastic, single degree of freedom systems, and can sometimes lead to substantially unconservative designs. Additional studies are currently being completed on the effects of aftershocks and ground motion duration on ductility requirements.

Evaluation of Analytical Methods for Predicting Seismic Response

Present analytical methods for predicting the behavior of buildings during severe ground motions have been reviewed to provide the design profession with a summary of current analytical capabilities and limitations [8]. This material is being evaluated in view of present knowledge of the seismic behavior of buildings and the needs of the design profession.

Modeling. While elastic analysis programs are widely available, considerable uncertainties exist regarding modeling of key building components such as slab or slab-beam systems [2] and non-structural wall elements. To study the effectiveness of nonlinear analysis methods, an investigation is being conducted on (1) defining, calculating and interpreting ductility values [9]; (2) modeling flexural elements using lumped vs. spread plasticity models; and (3) methods for accounting for stiffness deterioration on R/C members and joints.

Behavior of Critical Regions. Available programs for assessing the inelastic behavior of different design details have also been examined. Studies related to the effect of axial load, spalling, buckling of longitudinal reinforcement and shear on the behavior of flexural elements have been performed [3] and indicate a number of deficiencies or ambiguities in current design and analysis methods.

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SESSION 6

SEISMIC RISK, SEISMIC DESIGN & CODES

Chairman: R. W. Clough

A. H-S. ANG

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This is a program of study supported by the Division of Problem-Focused Research Applications of the National Science Foundation under Grant ENV77-09090. The principal objective of the study program is to develop realistic assessments of the safety (in terms of the probability of failure) of structures to extreme natural hazard conditions, with emphasis on earthquake and storm wind forces.

The program will require several phases of study aimed at the following:

(i) Definition or Description of Specific Hazard -- Because most natural hazard events occur at random in space as well as in time, the intensity levels of a specific hazard would properly require probabilistic descriptions, including random process characterization of the forcing function during a specific phenomenon.

(ii) Response Prediction -- For the prupose of safety evaluation, the response analysis must include the range of response approaching collapse under a random process excitation. Properly, the analysis should include structures with nonlinear-hysteretic behavior; therefore, the modeling of nonlinear-hysteretic systems for dynamic response analysis would be an important part of this study.

(iii) Definition of Limiting Response Capacity -- This is the level of response of a structure beyond which collapse or failure will occur. The limiting response may be the maximum inter-story displacement, or may be defined in terms of the hysteretic energy capacity of the structure. In any case, its definition should be consistent with the predicted response, as well as take into consideration the nonlinear behavior of the structural material.

(iv) Uncertainty Analysis -- This requires a systematic analysis and assessment of the uncertainties in the definition of specific hazards, in the prediction of the response, and in the determination of the capacity of a structure.

(v) Failure Probability Calculation and Risk-Based Criteria Development -- This involves the evaluation of the failure probability for various levels of damage including ultimate collapse, and the development of bases for design to achieve specified acceptable failure probabilities.

Specific Studies Underway

Several specific studies have been initiated and are in progress; these may be summarized briefly as follows:

1. Further Studies of Seismic Risk Analysis -- The fault-rupture model for seismic risk analysis, previously developed by Der Kiureghian and Ang (1977), is being improved to include further applications. In particular, the attenuation of ground motion intensity in the near-source region from the closest rupture is being examined. Since very little near-source data are available, an analytical approach is being used to derive the necessary attenuation equation. This will be based on an analytical method of wave propagation in a half-space developed by Seyyedian and Robinson (1975). The method can be used to calculate the motion on the surface of a half-space due to a sudden slip, resembling that of a fault break of an earthquake. The method, however, is a two-dimensional approximation of a three dimensional problem; consequently, the results may be limited to the near-source regions.

2. Lifeline Seismic Risk Studies -- The probability of damage of a lifeline system to seismic hazard is being developed using the Der Kiureghian and Ang model. Aside from the ground shaking due to the passage of seismic waves, the hazard of fault ruptures running through a given lifeline network system will also be examined.

3. Random Response of Nonlinear-Hysteretic Systems -- Several methods of random vibrations are under investigation for structures with nonlinear-hysteretic behavior. This phase is described in the report of Dr. Y. K. Wen.

4. Modeling of Nonlinear-Hysteretic Systems -- The modeling of a structure with nonlinear-hysteretic behavior should be limited to simple models; in particular, the model should be suitable for the dynamic response analysis by random vibration methods. Rules for developing such simplified models for dynamic response analysis purposes is currently under investigation with the cooperation of Dr. D. Foutch.

5. Structural System Collapse Probability Evaluation -- This study is concerned with the analysis of the probability of collapse of structural systems in general. The approach currently under investigation is to formulate the collapse of a structural system as a problem of network-graph theory. Although the results will be of significance to safety against earthquake and wind forces, the objective of this study is the development of methods for structural system reliability in general and is supported by NSF Grant ENG 77-02007.

6. Reliability of Box Girder Bridges -- This study is an examination of the safety and reliability of box girder bridges in Japan, including the consideration of safety under wind and earthquake loads. Experimental data from Japanese tests of steel box girder components are being used in the study.

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A method of risk analysis for underground lifeline systems has been developed, and some results are presented for the water transmission system in Tokyo City. Also, simple procedures are discussed for estimating earthquake-induced relative motions, taking into account the extent of the lifeline and the local site geology.

Seismic Risk Analysis of Underground Lifeline System

The topological or the network characteristics of the system are analyzed for the evaluation of its possible unserviceability. The unserviceability results from failures of the individual reaches of pipeline under the shaking and depends on the local ground conditions, the intensity of the earthquake and the resisting capacity of the pipe. The local ground conditions, the intensity and the occurrence of earthquakes are treated as random quantities with characteristics unique to an area. Fig. 1 shows a flow chart indicating the procedure of the risk analysis and design decision.

The method is illustrated by evaluating the unserviceability probability of the (modified) water transmission system in the city of Tokyo. It is assumed that the shear velocity of the base rock is 600 meters/sec, and that the peak spectral acceleration of the base rock is 30 gal. This acceleration value is converted into a corresponding surface strain value at a node of a mesh by means of the following expressions. The maximum base rock acceleration α, is amplified in accordance with the ratio between the shear velocities of the surface layer and of the base rock by means of $V_{max} = m\alpha/2\pi f$ where V_{max} = maximum particle velocity at the surface, m = magnification factor, and f = fundamental frequency of overlying soil layer. Free field strain is estimated by the formula $\varepsilon = V_{max}/\bar{c}$. In this example, $\bar{c} = 4Hf$ (H = thickness of overlying soil layer) was assumed for convenience. (Improved procedures for estimating $\bar{c}$ for lifeline engineering are discussed in the section below.)

The water transmission system is overlain by a mesh whose spacing is 1 km and the mean strain ε_o and the standard deviation σ_ε of the free field strain ε are calculated for each unit area. The failure strain of the pipe is found from the appropriate damage matrix. The probability λ' is calculated for each area element. From such estimates of failure of individual pipes the probability of unserviceability of the entire system can be estimated. The result of such a step is shown in Fig. 2, which shows the probabilities of failure of the fourteen tie-sets of the network and of the transmission system itself as a function of the failure strain ε_f in an individual pipe. The figure shows that the tie-sets (I, II, III, IV) from the water supply station A are always destroyed, the one (XIV) from C is frequently destroyed and in most cases the water is supplied to the node from station B.

Free Field Relative Motions for Lifelines

Earthquake-induced relative motions at two locations on the ground surface are caused by body and surface waves, which are affected by various physical characteristics, such as change of material stiffness, magnitude, epicentral distance, etc. Our current studies consider only the fundamental mode surface waves (Love and Rayleigh), and it is assumed that the direction of propagation is parallel to the lifeline and induces axial strains (Rayleigh wave) or shear strains (Love wave) in the pipe. Methods for estimating $\bar{c}$, in the free field strain are being studied by use of Fourier transform techniques. Future work will include higher modes and, eventually, body waves.

Dispersion curves derived from actual earthquake time histories recorded at two locations during the San Fernando (1971) earthquake are known to be quite similar to theoretical dispersion curves corresponding to the site geology (K. Toki). Therefore, one method for estimating ground motions is to assume that a wave recorded at a point propagates horizontally with the dispersive characteristics associated with the local geology. Relative ground displacement, $\Delta u(x_1, x_2, t)$ at two points, x_1 and x_2 can be expressed by an inverse Fourier transform

$$\Delta u(x_1, x_2, t) = (1/2\pi)\int_{-\infty}^{\infty} F(i\omega)\, \exp[i\omega t + ik(\omega)(x_1 - x_2)]\, d\omega$$

where $F(i\omega)$ is the Fourier transform of displacement recorded at a site, and $k(\omega)$ is a theoretical wave-number, associated with a Love or Rayleigh wave at that site. Let $\Delta u(d)$ denote the maximum relative displacement for all time ($d = |x_1 - x_2|$; separation distance). An average maximum strain $\bar{\varepsilon}$ can be defined as $\bar{\varepsilon} = \Delta u(d)/d$. The phase velocity $\bar{c}$ can be estimated by equating $\bar{\varepsilon}$ to ε; hence $\bar{c}(d) = V_{max} \cdot d/\Delta u(d)$. Figure 3 shows normalized relative displacement versus separation distance for several different earthquakes recorded at Ferndale. For small separation distances, normalized relative displacement increases rapidly with d, and is essentially independent of earthquake. Equivalent phase velocity, $\bar{c}(d)$, is shown in Fig. 4 for both Love and Rayleigh waves. For very short separation distances (less than about 20 m), $\bar{c}$ is reasonably estimated if it is replaced by the near-surface shear wave speed (approx. 150 m/sec in the top 10 m at Ferndale). These studies will be extended, considering other site geologies, earthquake magnitudes, epicentral distances, etc., by studying the relationships among d, λ and h (λ = wave length; h = layer depth). The results of these studies should yield a simple procedure to estimate the equivalent phase velocity $\bar{c}(d)$, and hence the relative displacement, for near-surface underground lifelines of various lengths.

K. Toki, Proc. of U.S.-Japan Seminar on Earthquake Engineering Research, Tokyo, pp. 15-28, (1976).

This was supported by NSF ENV P76-9838 and PFR 78-06265.

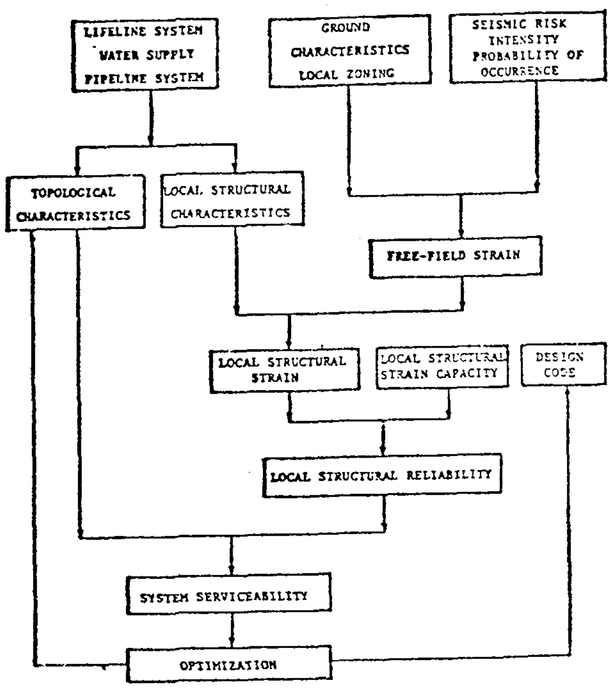

Figure 1 Flow Chart Indicating Analysis Procedure

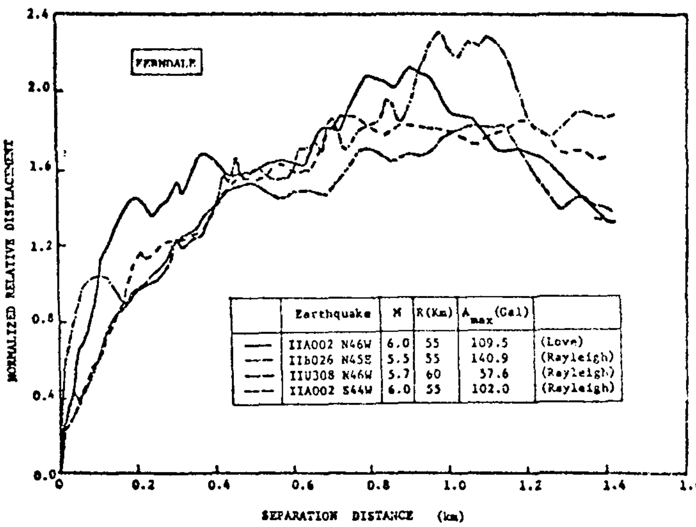

Fig.3 Normalized Relative Displacement

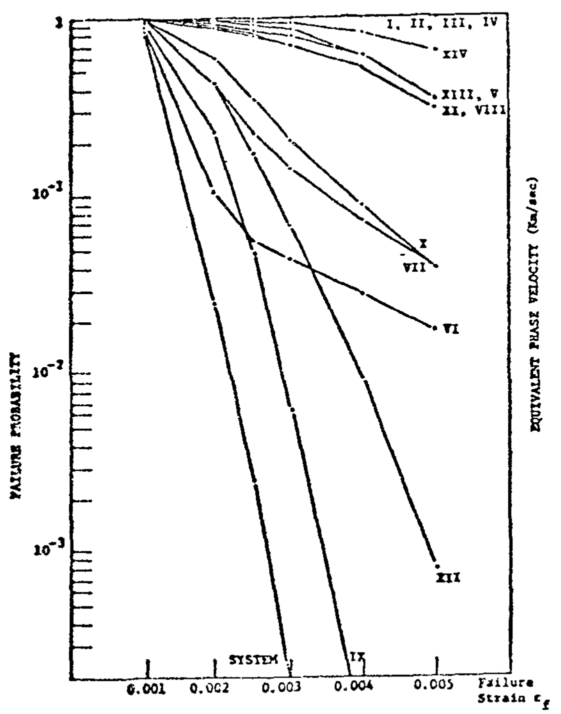

Figure 2 Relationship Between Failure Probability (of Tie-Sets and System) and Failure Strain

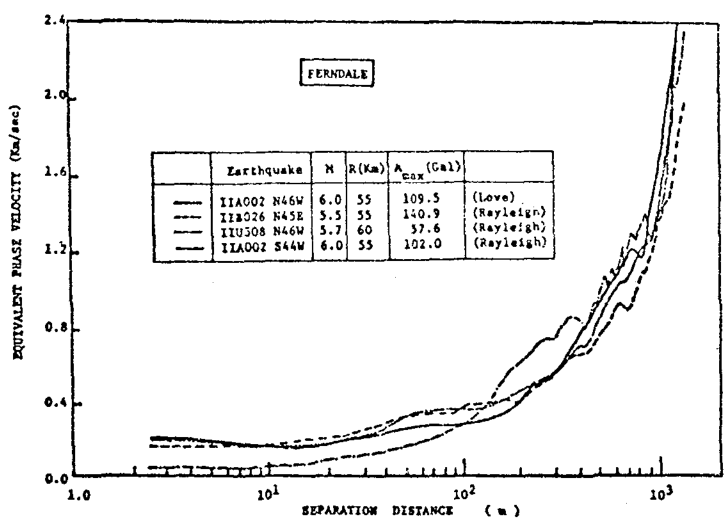

Fig.4 Equivalent Phase Velocity $\overline{C}(d)$

HARESH C. SHAH

Stanford University

Research in seismic risk analysis and decision analysis is being conducted at The John A. Blume Earthquake Engineering Center at Stanford. Five research projects presently in progress are described in this report.

Generalized Study on Seismic Risk Analysis

A reassessment of all currently available models and procedures for risk analysis is being carried out. This research will propose a reevaluation of randomly oriented recordings as a proper data base. Close consideration is given to the source mechanism of the event, and a more reasonable distance measure (other than epicentral distance) is proposed. A more stable ground motion parameter is suggested as characterizing the intensity of strong ground motion. Using ground motion records which are oriented in radial and transverse directions with respect to the epicenter, the root mean square (RMS) is being studied as a more stable parameter. In conjunction with this study, the necessary step of defining the "significant" duration of the record is also being carried out. Relating this parameter to the source mechanism, strength of the event in terms of magnitude, and the closest distance to the fault, more stable relationships for ground motion can be developed.

This research project is supported by the National Science Foundation, Division of Problem-Focused Research Applications. The principal investigators are Professors Haresh C. Shah and David M. Boore. Assisting on the project are Mr. Martin McCann and Professor Anne S. Kiremidjian.

Related research projects under the direction of Professor Kiremidjian are the development of a Markovian model for earthquake occurrences, the reliability of the State of California Water Project to seismic loadings, and the determination of seismic hazards in Honduras.

A Monte Carlo Simulation Approach to Lifeline Risk Analysis

Seismic risk analysis for lifelines can be approached by means of a Monte Carlo simulation analysis. A model of the lifeline is subjected to a simulated, earthquake generating, stochastic process in which the underlying mechanism is based on a seismic model that takes into account the geology and historic seismicity of the region. The network is exposed to the stochastic process for the period of time of interest to the designer and for a sufficient number of times to allow the evaluation of the system by statistical inference methods. Both tasks, the determination of the appropriate simulation time span and the statistical inference, are being investigated. This research is currently supported by the Blume Center.

Development of Lateral Load Resisting Requirements

A risk based methodology is being developed so that a lateral load level for a seismic region can be rationally obtained. This load-level is calibrated to be between the 1973 UBC and the 1976 UBC. A new quality factor in design, inspection and conceptualization, is introduced. This methodology is currently being recommended to Central American countries and Algeria, and the research is being supported by those governments.

Public Policy Issues in Earthquake Engineering and Earthquake Prediction

The primary objective of this study, which is supported by the Blume Center, is to provide a method of cost-benefit analysis under uncertainty of two major means of mitigation of earthquake effects: earthquake engineering and earthquake prediction. The problem presents several aspects: technical, economic, legal, and political. The last two have been left for further study. Rather than identifying the decision maker and his preferences, the objective is to provide him with a probabilistic evaluation of the seismic losses--direct and economic--and of their potential mitigation through public policy measures.

A Frequency Domain Stochastic Approach to Determine Seismic Design Parameters

Under this project a model of release of the seismic energy in an earthquake is developed by assuming that a seismic event is created by the progressive rupture of small coherent patches over the entire rupture surface. The motion at the site created by the rupture of a patch is analytically found by using a dislocation model where the fault plane is assumed to be a geometrical discontinuity across which there exists a sudden discontinuity in the strain tensor or one component of the displacement vector. The solution is limited in the present case to body S-waves in the radial direction of propagation from each patch source, since on the average this is believed to be the most significant component for engineering purposes. The research is being performed by Mr. Jean Savy with Professors Boore and Shah, and it is supported by the Blume Center.

ROLAND L. SHARPE

Applied Technology Council

The Applied Technology Council (ATC) is conducting three projects with the common objective of translating research results into a format usable by design professionals. Three approaches are used. The first project, ATC-3, utilized a nationwide group of 85 persons assembled into three Advisory Groups and 5 Task Groups. The Task Groups were further divided into 14 Task Committees. The second project, ATC-5, is being conducted in parallel with the masonry project at University of California, Berkeley (UCB), described by Dr. P. Gulkan. There is continuing interaction of practicing design professionals and researchers. The third project, ATC-6, uses a Project Engineering Panel composed of four researchers, four private design engineers, four state highway officials, and two Federal Highway Administration representatives.

The ATC-3 project, "Tentative Provisions for Development of Seismic Design Regulations for Buildings", was initiated in November 1973 and completed in December 1977. A brief outline of the ATC-3 project is presented in Figure 1. The work was conducted under a contract with the National Bureau of Standards with funding by the National Science Foundation. A total of 25 professors (researchers) and 48 practicing engineers and architects participated in addition to 8 code promulgators and 4 representatives of the federal government. The large number of participants was selected so as to obtain reasonable geographical representation, required areas of expertise, and diversity of viewpoints. Copies of the final document should be available from ATC in August 1978. The close working relationship between researchers and practitioners shortened the research-results-to-practice time by several years.

The ATC-5 project, "Seismic Design and Construction Guidelines for Single-Family Dwellings in UBC Seismic Zone 2", was initiated in May 1978 and is scheduled for completion in May 1979. An outline of the project is given in Figure 2. The work is being conducted under a contract with the U.S. Department of Housing and Urban Development (HUD). A project Advisory Panel of three practicing engineers and a home builder and the Subcontractor, a practicing engineer, the ATC Project Director, and a representative of the ATC Board of Directors provide technical expertise for the project. This project is of special interest because:

1. The ATC Project Advisory Panel has been assigned the responsibility of meeting and consulting with the UCB research team which is conducting a series of shaking table tests and connection tests of masonry dwellings and components; and,

2. When the testing is completed, the ATC subcontractor will use the results (after evaluation and discussion with the ATC Project Advisory Panel) to develop the design and construction guidelines. HUD plans to adopt the guidelines after subjecting them to appropriate departmental review, assessment, and adoption procedures.

The ATC-6 project, "Seismic Design Criteria for Highway Bridges", was initiated in July 1977 and is scheduled for completion in December 1979. An outline of the project is shown in Figure 3. The work is being conducted under contract with the Federal Highway Administration. In order to ensure, insofar as possible, input from the latest research and technology, from the private design and construction sector, and from state highway departments, a Project Engineering Panel was selected comprised of 4 university representatives, 4 private design firms, 4 state highway officials, and 2 Federal Highway Administration representatives. The project is proceeding in three phases: development of guidelines, testing of guidelines, and finalization of guidelines based on evaluating the results of the testing. It is of interest to note that very little information is available on the seismic response of bridge structure, design and modeling of abutments, analysis and design of connections, and when to use a particular type of analysis such as equivalent static, response spectrum, or time history analysis. The draft guidelines, when completed, will be subjected to testing by using them to redesign 12 to 15 existing bridges. The viability, cost, and difficulty in using the guidelines will be evaluated and the draft provisions will be modified as appropriate. The final guidelines will be submitted to the American Association of State Highway and Transportation Officials (AASHTO) for consideration and adoption.

In conclusion, the above projects demonstrate three methods of bringing researchers and users together and thereby shortening the time necessary to translate research results into practice. Each of the methods can be useful; however, the range of subject matter involved must be considered.

DESCRIPTION	FIGURES Figure 1	Figure 2	Figure 3
PROJECT	ATC-3	ATC-5	ATC-6
SPONSOR	Contract with NBS with funding by NSF	HUD	FHWA
OBJECTIVES	• Review state of art and existing codes • Develop comprehensive provisions for buildings • Use as source document	• Review and advise on masonry testing at UCB • Develop seismic design and construction guide-lines	• Develop new and improved seismic design criteria; incorporating, where possible, state of art in research • Evaluate impact on design and construction specs
PROJECT PARTICIPANTS/PANEL	25 professors (researchers) 43 practicing engineers 5 architects 8 code promulgators or officials 4 government reps.	3 practicing structural engineers (Los Angeles, Phoenix, and Memphis) 1 home builder (Phoenix) 1 subcontractor (Phoenix)	4 university 4 private design firms 4 state highway officials 2 federal highway reps.
PROBLEM AREAS:		• Required amount of reinforcing • Reinforcing details	• Period determination • Design and modeling of abutments • Connections • Type of analysis
DESIGN APPROACH:	Strength design		Inelastic capacity design
COMPLETION SCHEDULE:	December 1977 (complete)	May 1979	December 1979
FINAL REPORT AVAILABLE:	August 1978: ATC-3-06 Available on request; contact ATC		

A. G. DAVENPORT AND G. P. SOLOMOS

The University of Western Ontario

The determination of the parameters of the distribution of the peak ground acceleration A is attempted on a new basis. This combines the method of Maximum Likelihood with the condition of getting minimum Total Expected Cost. In this way it is hoped that a better design criterion than the 100 year return period acceleration can be established.

Using the assumption that the occurrence of large shocks at a site are independent of one another and that they can be considered as Poisson arrivals, the distribution of the extreme annual acceleration can be found as:

$$f(A) = \frac{-a}{c} \left(\frac{A}{c}\right)^{a-1} e^{-\left(\frac{A}{c}\right)^{a}}, \quad or \quad F(A) = e^{-\left(\frac{A}{c}\right)^{a}} \qquad (1)$$

where A is the peak ground acceleration in g, and $a < o$, $c > o$ are the parameters to be determined.

The likelihood function of the above distribution form is:

$$L(a, c \mid A_1, A_2, \ldots, A_n) = \Pi f(A_i) = e^{-c^{-a}(A_1{}^{a} + \ldots + A_n{}^{a})} \left(\frac{-a}{c^{a}}\right)^{n} (A_1 A_2 \ldots A_n)^{a-1} \qquad (2)$$

where A_i, $i = 1, 2, \ldots, n$ is the peak acceleration of each of the n years. Setting the partial derivatives of the logarithm of the function L equal to zero the values of a and c which maximize this likelihood function can be found numerically. Also, dividing the values of $L(a, c \mid A_1, A_2, \ldots, A_n)$ by the value of the volume under the surface of it, the values of the joint PDF function $f(a,c)$ of a and c can be found.

A simple function is chosen for the Expected Total Cost, C_t, of the structure.

$$C_t = C(a_o) + E[CL] \qquad (3)$$

where a_o is the design acceleration in g

$C(a_o)$ is the total initial cost of construction and

$E[CL]$ is the expected cost of losses due to damage

$$C_t = C(a_o) + Q \times C(a_o) \times P[A \geqslant a_o]$$

$$C_t = (C_o + C_o S a_o) + Q(C_o + C_o S a_o)(1 - e^{-(\frac{a_o}{c})^a T})$$

$$ETC(a, c, a_o) = \frac{C_t}{C_o} = (1 + S a_o)(1 + Q[1 - e^{-(\frac{a_o}{c})^a T}]) \tag{4}$$

where C_o is the cost of the building designed for all normal code requirements
S is a mean value of the slope for the Initial Cost Premium curve
Q is the importance factor
T is the lifetime of the building

The ETC function depends on the values of a and c. For a_o given, the expected value EC of ETC can be found numerically:

$$EC(a_o) = \int_0^{\infty} \int_{-\infty}^{0} ETC(a, c, a_o) f(a, c)\, da dc \tag{5}$$

Going back, we try to fit a curve of the original form (4) to the above derived points.

For $a_o = A_o$ we get a minimum for EC equal to EC_{min}. The two conditions for this minimum value are:

$$EC_{min} = (1 + S A_o)(1 + Q[1 - e^{-(\frac{A_o}{c})^a T}]) \tag{6}$$

$$\left(\frac{d\,EC}{d\,a_o}\right)_{a_o = A_o} = S(1 + Q[1 - e^{-(\frac{A_o}{c})^a T}]) + (1 + S A_o)(Q \frac{a\,T}{c} (\frac{A_o}{c})^{a-1} e^{-(\frac{A_o}{c})^a T}) = 0 \tag{7}$$

Solving the system of the above two simultaneous equations, one can get:

$$a = \frac{S A_o (1 + Q[1 - K_1])}{Q\, T\, K_1\, K_2 (1 + S A_o)}, \qquad c = \frac{A_o}{K_2^{\,1/a}} \tag{8}$$

where

$$K_1 = 1 - \frac{1}{Q}\left(\frac{EC_{min}}{1 + S A_o} - 1\right), \qquad K_2 = \frac{1}{T} \ln K_1$$

The city of Vancouver is taken as an example, where, N = 57 years and the maximum likelihood method gives a = 1.328, c = 0.00314.

For different values of the parameters T, S, Q we get different values of a and c, which also differ significantly from the ones given by the method of maximum likelihood.

All the above pairs of (a, c) are tried in the PDF of the peak ground acceleration

$$f(A) = \frac{a}{c} \left(\frac{A}{c}\right)^{a-1} e^{-\left(\frac{A}{c}\right)^{a}}$$

The curves of $f(A)$ for different (a, c) are almost identical. This indicates independence of the a and c from the cost function's parameters.

On the a, c plane all these (a, c) pairs, which minimize the Total Expected Cost function appear to form a straight line passing very close to the mode of the distribution.

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D.L. ANDERSON, N.D. NATHAN, S. CHERRY, S. YOSHIDA

University of British Columbia

This research synopsis describes a few of the earthquake engineering projects in progress in the Department of Civil Engineering at the University of British Columbia.

(1) Seismic Hazard Evaluation of Existing Buildings

The question of earthquake hazards in existing buildings obviously poses socio-economic problems. This study is concerned with the investigation of a method of determining the compliance of such structures with existing building codes.

A simplified, linear method is being developed for predicting the behaviour, including inelastic response, of existing reinforced concrete structures with known properties and strengths, when subjected to a given type and intensity of earthquake motion, as represented by a linear response spectrum. The technique involves an extension of the Shibata and Sozen substitute-structure method, which was originally proposed as a design procedure. When applied to the retrofit problem, it computes damage ratios corresponding to the existing member strength via an elastic modal analysis in which reduced stiffnesses and substitute damping factors are used iteratively. By this means it is possible to describe, in approximate general terms, the location and degree of damage that would occur in a building as a result of earthquakes of different intensity. Remedial measures which will ensure ductile behaviour emerge from this procedure. The technique can usefully assist civic authorities to determine modifications in buildings, when necessary, to achieve required levels of safety in the light of present knowledge.

The original substitute-structure design method is subject to fairly stringent constraints. Investigations are presently being conducted to determine if all of the constraints are necessary, and which apply to the retrofit method.

(2) Minimum Seismic Requirements for Masonry Walls

Computer analyses are being conducted to establish the seismic forces required in the design of masonry walls with respect to transverse loading. Buildings of masonry load-bearing wall and masonry in-fill panel construction are included in the study. The object is to design individual wall panels so that they will not fall out of their supporting members under the influence of inertia forces.

Preliminary studies have led to the development of acceleration coefficients or acceleration envelopes of dynamic amplification (response) as a function of storey height and fundamental period.

This permits estimates to be made of the transverse design forces from which minimum steel requirements can be evaluated at various levels. Shake table tests of typical wall panels are being planned to add to the results of the analysis. An M.A.Sc. thesis on this phase of the work has just been completed.

The effect of racking forces (in-plane shear) on the seismic design of masonry walls is also being studied. The objective here is to develop general guidelines for determining the amount and spacing of steel reinforcement to ensure that the desired ductile characteristics of such walls are achieved. The experimental phase of this program is about to be initiated.

Computer studies of structures with masonry in-fill panels exhibiting degrading stiffness and degrading strength are in progress. The object is to investigate the load deflection history that such panels undergo in the event of a major earthquake. Ultimately, this information will be used in the design of future experimental programs on wall panels.

(3) Earthquake Response Based on Energy Absorption

The performance of high-rise structures in earthquakes is being studied by means of a three-dimensional program with non-linear stiffness capability in which the energy distribution is continuously determined. The energy lost in viscous damping and in hysteretic damping, as well as the recoverable stain energy, the kinetic energy, and the energy fed back to the ground are recorded. It is hoped by this study to shed more light on the design process.

DAVIS C. HOLDER

University of Colorado

The science of seismic design, an open book to the Structural Engineer, remains a mathematical mystery to the Architect; the art of aesthetic design, as natural as breathing for the Architect, is an unmitigated nuisance and an unreasonable complication to the Engineer. And yet, it requires the combined efforts of both to create a building which is both safe and desirable. Current efforts at the University level to educate Architects in seismic design fall far short of the real need, since these courses are truly intended to assist the young graduate in meeting his registration requirements. He is taught that by manipulating a few dimensions in a memorized procedure, he can predict the "period" of a building. The output from the equation is a complete mystery to him; he generally has no notion whether a period of .10 second is better than 1.00 second or what could be done to improve it. In short, he is given a watered-down and relatively meaningless version of seismic engineering in one "easy" lesson, at the end of which, he still has absolutely no feeling for the phenomenon or the reaction of a building to it.

The practicing Architect, aware of his mathematical shortcomings, is delighted to turn the problem over to a Structural Engineer, which is precisely what he should do; however, by the time the Engineer begins his work, the building is usually dimensioned, materials and basic systems have been selected and the parameters within which the structural design must proceed are firmly locked in place. Now, it is a well known and thoroughly documented fact that a good Structural Engineer can do anything -- and so a workable project develops from the scenario just described. The probability, however, of achieving the best structure or finding the most economical solution of the problem is remote under these circumstances. How much better it would be if the Architect had a genuine framework of seismic concerns to guide him in his original planning - criteria as meaningful and important to him as the spatial requirements, or attractive combinations of shapes and colors.

In regions of high seismic risk, the Architect has developed a sort of intuition about shape and seismic action, a sense of materials and building reactions. He may not be able to quantify - that is the function of the Engineer - but his initial planning reflects concern for, and valid treatment of, seismic principles; the Engineer does not find himself locked into limiting parameters. In the regions where seismic history is less frightening, practitioners have developed no such intuition - and, as a result, buildings are being constructed which provide little resistance to seismic disturbance. Denver, for example, is considered relatively free from earthquake hazard; current building procedures reflect little concern for the phenomenon. Yet, in 1967, quakes of magnitudes in excess of 5.0 (Richter scale) were recorded in the metropolitan area. Inspection of the minor damage done at that time seems to indicate that a magnitude of 6.0 represents the threshold of serious structural damage and that such a quake would result in a veritable rain of balconies, to say the least. In most cases, resistance to earthquake could have been provided at little or no extra cost at the time of construction, although retrofit measures would be prohibitively expensive, now.

Today, conferences are being held around the United States between Engineers, Building Officials and municipal authorities for the purpose of establishing or altering seismic building codes; conspicuously absent from most of these conferences are the building designers - the Architects. The building team member who is most often the principal-the individual whose early decisions affect the project the most - is accepting the codes and procedures provided by others, without any architectural input.

In awareness of this situation, the University of Colorado has instigated a program of research and education in its Architectural curriculum which will lead toward a clear definition of Architectural concerns in seismic design. Building shapes, elasticity of materials and connections, building attachments, fenestration, mechanical systems and utilities are a few of the items, not highly technical in nature, but having vital effects on the appearance of a building as well as its resistance to seismic disturbance. It is hoped that with this approach, Architects will become interested and more fully aware of the necessary inter-relationship between aesthetic design and seismic risk. It is hoped that the Architect will then play a more active role in the establishment of codes and customs, providing reasonable protection from earthquake damage even in areas of low seismic activity. It is further hoped that the work of the structural Engineer will be made easier by the fact that seismic resistance will be considered at an early enough stage to influence the overall building design.

C. Joshua Abend

SYRACUSE UNIVERSITY

UNMET TECHNOLOGICAL NEEDS IN EARTHQUAKE RESCUE STRATEGIES

This report brings attention to identifying research requirements related to human risk and hazard in earthquake occurrences. Admittedly inquiry relating to structural integrity and other earthquake engineering aspects are important however the direct mitigation of human suffering and loss also presents a significant engineering and research challange. The purpose of this presentation is to communicate and bring visibility to the problem by outlining some dimensions as a basis for investigation, technological application, and solution finding.

Specifically, one of the serious unmet requirements during the immediate post earthquake emergency period is search and rescue of entrapped victims. What is required is more optimum and rapid techniques and procedures to deal with the problem of identification, location, and extraction of victims. At the present time such methods appear generally to be AD HOC and are approached as improvised procedures dependent upon local resources and initiatives. For the most part rescue operations require rubble removal which is often time consuming and labor intensive. Even the use of heavy earth moving or lifting equipment must be approached with caution; nor is such equipment appropriately designed nor is it always immediately available. Excluding the factor of availability, cost, and complexity of heavy equipment, there is also the matter of time loss in finding victims by random or inexact methods. What may be needed is apparatus compatible to meet such specific relief needs. This appears to be a universal requirement in earthquake disasters regardless of culture, geography and structure.

In regard to this area several questions can be advanced.

1. Can we now accurately predetermine the structural characteristics and behavior of collapse? Can predictive model- be established for particular locals, buildings, and building clusters indicating the effect and configuration of failure patterns?

2. Can such research be applied in pinpointing the most likely location of victims - the most probable location of hazardous and safe zones?

3. What available technologies can be employed as either sensing or signaling devices as regards location of victims?

4. To what extent can such equipments distinguish between living or expired persons?

5. What modes of pre-earthquake planning and communication can be established as a means of assisting rescue operations?

6. In what ways can we develop apparatus or systems to quickly and discretely remove the rubble of structural failure?

Several steps might be taken as a means of addressing these questions. The first being a clearer definition of the problem relative to present experience. Secondly, would be the research step of defining criteria and investigation leading to promising solution areas. Finally, the matter of exploring engineering design, specifications, and implementation must be approached.

In carrying out the above points, the following areas should be examined. To begin with the acquisition and study of historical data related to specific earthquake experience with regard to search and rescue procedures and effects. This research should identify and underscore failure modes in relief operations. Such initial survey can be applied to find clues or define directions leading to possible optimization and solutions. In the final step potential technological applications and techniques might be examined to derive new concepts leading to innovative apparatus, equipment and related procedures.

The problem of entrapped victims differs from problems of structural response yet its relationship is clear and it must be considered as a factor related to seismic risk; it is also apparent that it relates to aspects of both seismic variables, structural response and building codes. The author has been encouraged by the interest of National Science Foundation in structuring this problem and is at the present time developing a research approach aimed at achieving new solutions and alternatives. The results of such efforts may supply some answers sought by other Federal and State agencies in related disaster assistance programs. Contact by researchers investigating areas of relevant interest is welcomed.

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1755 Earthquake

The earthquake which made Boston "seismic" occurred on 18 November 1755, just two weeks after the great earthquake in Lisbon. This earthquake is the controlling event for determining the safe shutdown earthquake for nuclear plants sited in this part of New England, and is the reason for Boston being placed in Zone 3 of the UBC zonation map.

Reports of this earthquake, as found in contemporary newspapers, journals, diaries, and ships' logs, have been quite thoroughly researched by Weston Geophysical. The felt area was enormous--approximately 10^6 square kilometers. Based upon correlations from recent northeastern earthquakes, it is now believed that the 1755 event had a magnitude of 6^+. From accounts of ships at sea, it appears that the epicenter was off shore of Cape Ann, perhaps 75 km from downtown Boston. Current thinking relates this epicenter to a pluton in the region. Damage consisted primarily of the partial or total collapse of brick chimneys, occurring in all near-coastal towns from south of Boston to southeastern Maine. In Boston, the gable ends of some brick buildings collapsed. Accounts indicate that damage in Boston was heaviest over filled land along the water front. These were no reported structural collapses. Until recently, this earthquake was listed as having an epicentral intensity of MMI IX. Weston Geophysical now assigns a maximum MMI VII on land, with the corresponding epicentral entensity taken at MMI VIII.

Several months ago, MIT received NSF support for a detailed study of construction practice in the first half of the 1700's. The aim is to quantify, however crudely, the seismic resistance of the then-existing buildings, so as to improve past estimates of the intensity of ground shaking in the 1755 quake. In effect, we as engineers are taking a hard look at damage reports which heretofore have been interpreted primarily by seismologists.

In Boston, and especially in other towns and in the countryside, the principal construction used heavy wooden posts and beams with diagonal bracing. Exterior walls were filled with bricks and clay mortar, and were covered by clapboards. A massive, centrally-located chimney may well have been the major lateral force resisting element. Brick houses had also become common in Boston itself, as a result of a disastrous fire earlier in the century. Fortunately, good examples of the houses built at that time still exist. In co-operation with local historians, we are now studying the details of the framing in these buildings and assembling information concerning the mortar and the bricks used at that time. This information will be used as a basis for simple analyses to estimate seismic resistance. It is a challenging and exciting bit of detective work.

Duration

The new seismic design provisions recommended by ATC-3 use zoning maps based upon effective peak acceleration and velocity (EPA and EPV). The principal reason why EPA differs from peak acceleration (A) is duration, which is widely recognized as affecting the damage caused to structures. However, quantification of this effect is still lacking. Since duration affects elastic response only slightly (at least for most ground motions), it is essential to consider inelastic response-and strength-degrading behavior is likely to be of particualr importance.

There is one material for which such behavior has already been studied in detail: cyclic mobility or liquefaction of saturated sands. By combining together results for strength vs. number of cycles of straining and for number of cycles vs. magnitude, it is possible to obtain an expression for EPA/A as a function of magnitude. Going a step further, an "attenuation law" relating EPA (as it relates to liquefaction) to magnitude and distance may be developed. Results will be described in a paper to the Second Microzonation Conference. This approach is currently being extended to buildings.

Probalistic Loss Estimates

Perhaps the best way to express earthquake risk, from the viewpoint of society, is by the probability of experiencing different levels of life loss (e.g. 10 or 100 or 1000 fatalities) during any one possible future earthquake. To do this for a given metropolitan region means evaluating the probability that different intensities of ground shaking may occur, and also considering the quantity and quality of buildings and other structures in the area. Aside from the evident lack of data, which means that any probabilities must be quite crude, these are severe technical difficulties in carrying out such an analysis: (a) many different types and sizes of buildings are present, and (b) any one earthquake may cause different intensities of shaking in different portions of the region.

A preliminary study of this type has been carried out for Boston, primarily to learn how to deal with these various issues. A crude inventory of buildings was made, and all buildings were assigned to one of three categories of seismic resistance--each characterized by a damage probability matrix. Considering the size of a building and its occupancy, experience was used to estimate average fatalities for the several damage states. Using all this information, the expected life loss for each magnitude and epicentral location could be computed and the results then combined as in a seismic risk analysis. The initial conclusions are 10^{-3} to 10^{-2} annual risk of about 100 earthquake-caused fatalities in a single earthquake, and 10^{-4} for about 1000 fatalities. Some further details appear in notes prepared for the EERI Seismic Risk Course of this past February. The approach appears especially useful for pinpointing those portions of a metropolitan region which give the greatest risk.

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This paper will report very briefly on several probabilistic seismic studies underway or recently completed. The summaries will serve as little more than pointers to relevant technical reports available now or shortly. The studies cover ground motion defnitions and predictions, statistical issues (e.g. questions associated with limited sample sizes) in seismic hazard analysis, procedures for combining load effects due to two or more independent types of loads, and probabilistic/statistical analysis of the seismic and internal accident behavior of secondary containment structures of nuclear power plants.

The prediction of the peak (elastic) response of a simple oscillator given the magnitude and distance of a seismic event can be accomplished in several alternative ways. The most customary way in practice is to predict first the peak ground acceleration (PGA) and then to predict the peak response (S_v) given the PGA. But other ground motion parameters are possible including peak velocity or, as investigated recently (Cornell, Banon, and Shakal, 1977), the ordinate of the (smoothed) Fourier amplitude spectrum at 1 cps. Still other prediction paths include direct regressions of S_v on magnitude and distance. In the eastern U.S. the situation has dictated use of Modified Mercalli Intensities (both, for example, epicentral Intensity, I_o, in place of event magnitude and site intensity, I_s, in place of peak ground acceleration of the ground motion). In this case still more combinations of elements to provide prediction paths are possible and used in practice (e.g., I_o to I_s to PGA to S_v). The study cited above used a uniform set of (western U.S.) data to explore the implications of these alternative prediction paths, both in the mean and in the variance of prediction. Generally, of course, there is an increase in variance as more elements are introduced, i.e., as less direct paths are taken. But it is disconcerting to learn that quite different mean values are also obtained, i.e., some paths are biased relative to others.

A study (Schumacher, 1977) of the statistical implications of estimating seismic hazard curves, either directly from empirical site data or indirectly using seismic hazard analysis, led to the conclusion that it is uncertainty in the underlying model rather than uncertainty in any particular model's parameter values that dominates the statistical uncertainty in seismic hazard analysis. The study was conducted using both analytical methods and numerically simulated sets of samples (of different sizes) to find the sample-to-sample variability in seismic hazard curves estimated from each of the samples.

A project on structural loads, including seismic, wind, snow, building occupancy, and other loads is addressing the question of load combinations both in probabilistic and deterministic (i.e. practical code scheme) terms. At the probabilistic level, a simple but quite general approximate rule for calculating the probability G(a) that the extreme value of the sum of two random load processes $X_1(t)$ and $X_2(t)$ exceeds level a is given by a "point-crossing" expression (Madsen, Kilcup, and Cornell, 1978; Larrabee and Cornell, 1978):

$$G(a) \simeq \nu_1 * f_2 + \nu_2 * f_1$$

in which ν_i and f_i are respectively the mean upcrossing rate and the marginal (arbitrary point-in-time) distribution of process i, and (*) denotes the convolution operation. The result applies to continuous and discontinuous stochastic processes (e.g. randomly arriving pulses of arbitrary shape and random duration. Applied to the sum of a seismic load effect process, S(t), of effectively zero-duration events and to another load effect process (e.g., wind or temperature) X(t) the result reduces to

$$G(a) = \nu_X(a) + \int_0^a \nu_S(s) f_X(a - s)\,ds$$

Current work is related to extending the analysis to include dynamic load effects and to deriving practical safety-checking procedures for codes.

Finally, attention is directed to a study of the seismic reliability of secondary containment structures (Fardis, 1977). Focus was on procedures for incorporating both the probabilistic and the statistical uncertainty in the analysis. Because it is important to safety, the study required the investigation, at least approximately, of seismic behavior well above the design acceleration (SSE). Critical failure modes identified included crack propagation in the liner and pipe-rupture induced by tilting of the containment.

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