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MITIGATION OF SEISMIC HAZARDS IN EXISTING UNREINFORCED MASONRY BUILDINGS

Performance of Undesigned & Modified Elements

Evaluation of Modification Methods

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MITIGATION OF SEISMIC HAZARDS IN EXISTING UNREINFORCED MASONRY WALL BUILDINGS

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PROJECT SUMMARY

The primary objective of this investigation was to ascertain if mitigation of seismic hazards posed by existing structures using unreinforced masonry walls can be accomplished by simple methodology. Sub-topics of this investigation are: Performance of the undesigned elements that participate in structural response; Evaluation of current modification methods applied to these undesigned elements.

Interviews with technical personnel and a survey of existing masonry buildings was made in representative areas in the United States that may be subjected to ground motion varying from moderate to severe. This survey indicates commonality of building construction methods, range of building dimension and use of masonry materials.

Analytical studies of a representative structure with flexible horizontal diaphragm were made by typical design procedures and simplified mathematical models subjected to various ground motions. The studies indicate that structural response of vertical and horizontal elements can be defined for analysis purpose by simple parameters. State of stress in the elements under dynamic loads at present cannot be determined within reasonable bounds by typical static analysis. Additional research is needed to formulate analysis rules.

Prior and current research into material properties of masonry was reviewed to extract general data applicable to unreinforced masonry. Current methods of sampling and testing of existing unreinforced masonry were reviewed to ascertain if properties obtained by test can be a predictor for the multiplicity of failure stresses that are related to failure modes. Static testing of unreinforced masonry is proposed to determine behavior of materials that have a wide variation of mortar and masonry unit strength. Mathematical analysis and dynamic testing of large scale wall panels is proposed to determine performance of unreinforced walls for forces normal to their plane.

Conclusion of this investigation is that development of a methodology for mitigation for seismic hazards in unreinforced masonry buildings is feasible. Test programs related to proposed research will furnish definitive data that will improve analysis of undesigned elements. Analysis to determine need for retrofit is cost effective. Current retrofit and modification methods have applicability. New techniques for strengthening unreinforced masonry have applicability.

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1.0 STATEMENT OF TASK

The preliminary investigation and research contemplated to be accomplished by this contract was as follows:

1. Evaluate prior pertinent research and test programs and extract usable information.
2. Conduct a field survey in selected cities in the United States that reasonably represent the full range of seismic zones in the United States.
3. Investigate the response to ground motion of this class of structure.
4. Categorize current structural alteration methods used to minimize life safety seismic hazards.
5. Explore techniques for identification of modes of failure and applicable analysis.

2.0 RESULTS OF PRELIMINARY INVESTIGATION

2.1 Evaluation of Prior Research

Evaluation of prior reseach and test programs yielded very little directly applicable information on unreinforced masonry material properties or properties of undesigned elements such as roof and floor systems as they exist in the completed structure. Evaluation of monotonic loading tests, cyclic and noncyclic, of common building constructions did furnish a preliminary understanding of a relative scale of stiffness. (References 2, 5, 6, 7, 11, 12, 13, 16, 17, 20, 21, 22, 23 and 24) Deduced material properties obtained from this literature search was used in the preliminary analysis procedures.

This evaluation of existing research and testing programs of masonry was very productive in a unique way. Static testing to failure of masonry materials, unreinforced and reinforced when load at first crack is recorded, can be utilized to confirm applicability of analysis techniques that will define zones of maximum stress and direction of stress as related to masonry unit orientation.

2.2 Field Survey in Seismic Zones

A field survey of the inventory of unreinforced masonry construction was made in Boston and Worchester, Massachusetts as representative of the North East United States seismic zone, the City and County of Charleston, South Carolina as representative of the South Atlantic Coastal seismic zone, Memphis, Tennessee as representative of the New Madrid seismic zone, Salt Lake City, Ogden and Provo, Utah as representative of the Wasatch seismic zone and the Los Angeles Basin as representative of the California Pacific Coast seismic zone.

A commonality of construction of unreinforced masonry buildings was discerned for the time period of pre-1934 on the California Pacific Coast and pre-1940 for all other areas. The predominant structure of this era used walls of three or more courses of solid masonry units, mainly brick, laid more or less solidly in lime mortar. Floors and roofs were constructed of heavy timber or dimension lumber with minimal interconnection of wall and floors or roofs. A small number of these structures use concrete floors and more or less complete concrete frames. In general, interior spaces are subdivided by masonry walls on a frequency equal to typical commercial lot subdivisions. Quality and strength of the brick varied across the United States with hard burned brick typically used in all areas except the Pacific Coast. Quality of lime mortar varied greatly from dense, minimally weathered mortar in buildings over 200 years old in the North East United States, to soft, highly weathered mortar on the Pacific Coast. In general, extensive deterioration of lime mortar is confined to the Pacific Coast. The quality of lime mortar in the Salt Lake Basin in 80 to 90 year old buildings was equal to the North East and give some indication that lime and sand sources influence the longevity of lime mortar.

Unreinforced masonry structural wall construction was utilized for multiple housing and moderate size commercial structures in the post-1940 era in all geographic areas surveyed with exception of

California. Hollow masonry units, mainly concrete, replaced solid masonry walls in all areas. Use of horizontal joint reinforcement to control shrinkage cracking became common practice in the mid 50s and almost universal by 1965. However, vertical reinforcement in grouted cells is omitted. A few minor exceptions to ungrouted units is use of reinforced cells in lieu of wall pilasters and for continuous bond beams at floor and roof levels.

Unreinforced masonry wall construction is now permitted in areas generally east of the Continental Divide. Western states generally adopted the Uniform Building Code, and when seismic design requirements were incorporated in the body of the UBC and use of unreinforced masonry was explicitly prohibited by this code, all masonry was reinforced with vertical and horizontal grouted reinforcement.

In the post-1946 period, important or large structures nearly always have a steel or concrete internal frame and unreinforced masonry walls are used as infilled wall panels. Multiple housing up to three stories use unreinforced masonry exterior walls and internal wood framing for floors, roofs, and internal partitioning. Commerical buildings generally use steel framing and steel deck, concrete filled at floors, for internal framing inside the unreinforced masonry walls. The steel framing is reasonably complete in that only joists and purlins may bear on the masonry walls. In many cases the single, hollow masonry unit that comprises the structural wall supports a solid masonry unit as a veneer or outer wythe of a cavity wall. Concern by the designer for thermal expansion and heat transmission of the facing units generally results in isolation of this facing from the structural frame.

This survey of existing buildings incorporating unreinforced masonry in seismic zones did confirm assumptions that these structures can be categorized by these general characteristics:

Construction materials that are combined with unreinforced masonry elements.

Size of structures, height and general plan dimensions.

Uniformity of distribution of unreinforced masonry walls around building perimeters.

Absence of, or minimal criteria used for lateral load design.

This survey also established that the information for additional categorization need be obtained and correlated from building officials, the construction industry, design architects and engineers, and masonry materials associations. The survey should be conducted by individuals familiar with past construction methods and cannot be delegated. In depth interviews are required in lieu of response to questionnaires.

2.3 Response to Ground Motion

The survey of existing buildings using unreinforced masonry walls indicated the predominant building is generally low to medium height with very few exceeding five stories. The plan dimensions of a structure or group of individually owned structures built with common walls generally exceeds the building height. The determination of base shear by current seismic design requirements for this structure would assume that the response is equivalent to a vertical element with a period of not less than 0.3 to 0.5 seconds and then that this response is reduced by an assumed minimum ductility. Other proposed seismic design recommendations (Ref. 17) describe the base shear by assuming the minimum period is 0.44 seconds to 0.33 seconds for medium to stiff soils and is 0.85 seconds for soft soils. This concept of establishing base shear for low period structures equivalent to maximum response in the acceleration portion of a response spectrum is logical when structural ductility is inherently required by the design recommendations. However, the class of structures investigated in this study does not approach the minimum ductility assumed by design requirements for new structures.

These design recommendations are intended to be applied as equivalent static forces representing the horizontal component of inertial forces. Vertical and rotational components of inertial forces are not included in the equivalent static solution. Theoretical incipient detachment of the wall foundation from the supporting soils would occur at value of K and C as shown on Figure 1. These plots have assumed that the wall is an infinitely rigid unit supported on an elastic medium. Vertical displacement of this soil medium would be very small but proportional to vertical load.

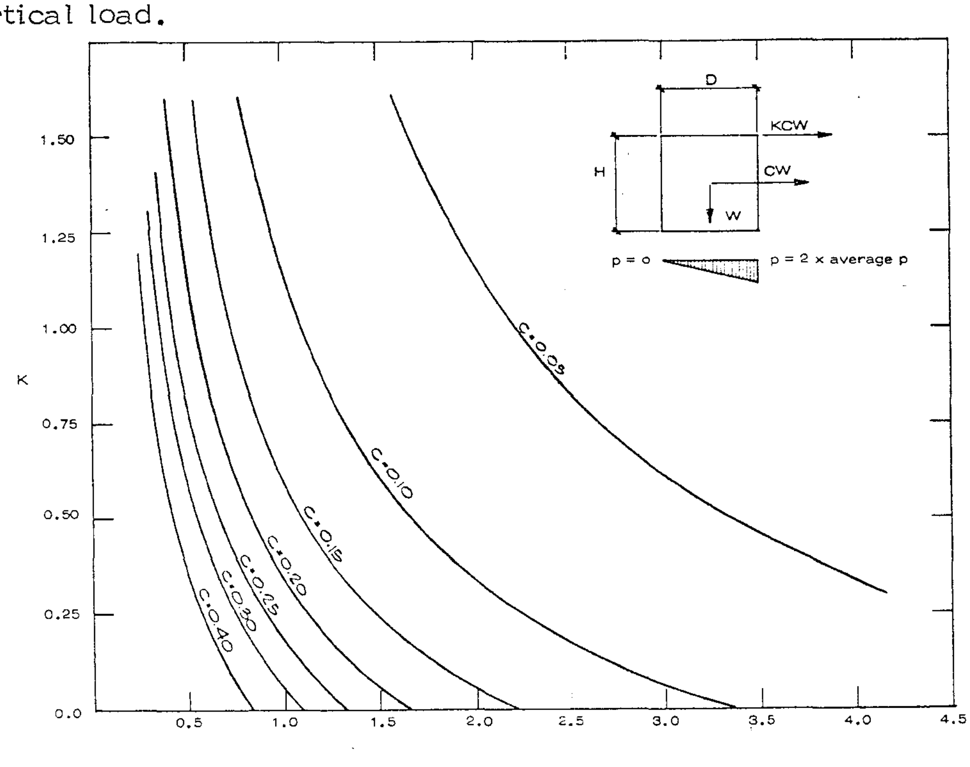


Figure 1

These plots are not related to any ground motion or dynamic response but assumes that the instantaneous response is equal to the factor "C" times the weight of the wall "W" and acts at about 1/2 the wall height and is combined in instantaneous time with a factor K times CW applied at the top of the wall. This force can represent the response of a horizontal diaphragm.

If detachment of the wall from its supporting soil were to occur at the response levels plotted, the displacement of the top of the rigid body can be represented by plots such as shown on Figure 2.

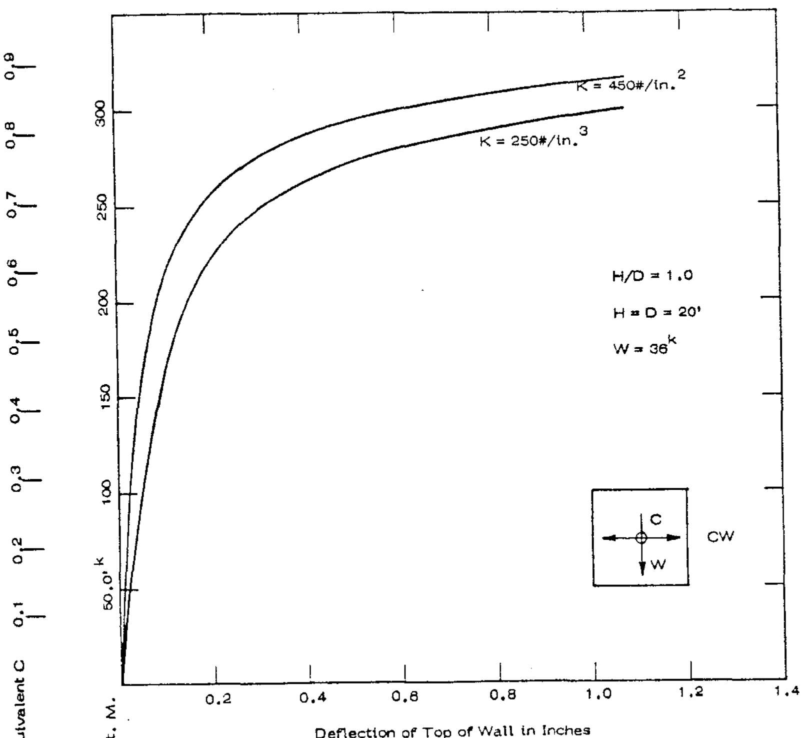


Figure 2

These plots represent the same assumptions made in Figure 1 and have and inherent contradiction in that the plotted displacement results in a significant rigid body rotation on the soil contact surface. These two plots assume the support medium can be described as a foundation with an elastic modulus of the values noted.

If only moment and shear displacement of a fixed base oscillator is considered, the approximate elastic period of fixed base walls loaded with only their own weight is shown of Figure 3.

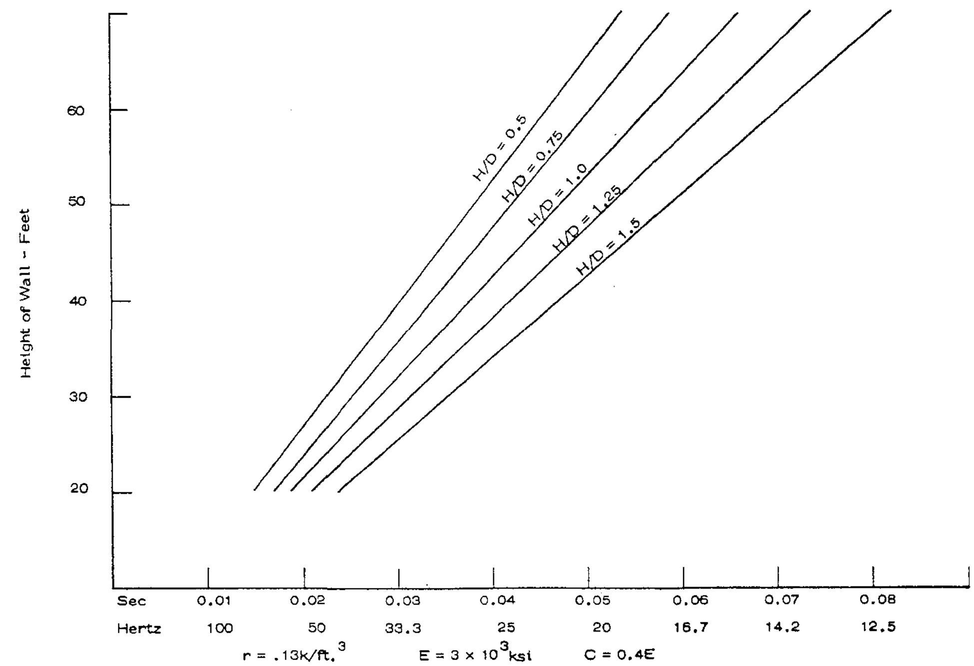


Figure 3

The density of wall is $0.13^{k}/ft^{3}$. The modulus of elasticity is $3.0 \times 10^{3} k/in^{2}$, shear modulus 0.4E. Families of plots for other densities and moduli will be displaced horizontally by a ratio of $\sqrt{\gamma/E}$ to the plotted physical properties. These plots do not consider base rotation, increase in apparent wall density due to attached diaphragms or reduction in wall stiffness due to openings. However, computation for a 40 foot high wall, 40' in width, with the material properties noted indicated the period change is small for typical opening configuration. If the wall is perforated with windows at all levels, and doors and windows at the 1st level, that are 50% of the overall dimension both horizontally and vertically, the increase in computed period is less than 20%.

The limitations of the simplifying assumptions used were evaluated by preparing a simple dynamic model. To determine response of the rigid wall, a mathematical model of a rigid block supported on flexible soils was constructed. Variables of the model included height, height/width ratio, unit weight of wall and dynamic characteristics of the supporting soils. The supporting soil was modeled as a series of compression only springs with an elasto-plastic behavior. Bounds of the range of elastic soil properties, definition of upper limits of elastic properties and post-elastic behavior were obtained from independent soils engineering consultants. This model is fully described in an associated study performed by Agbabian Associates.

The dynamic response of this mathematical model with the dimensions used is of a mass subjected to horizontal displacement nearly equivalent to ground displacment. This indicates that the predicted displacements ignoring vertical and rotational inertial forces are overstated. It also indicates that a model that has only soil springs influencing the top displacement is inadequate. Force displacement plots such as Figure 2 are mainly influenced by soil spring displacement. Internal elastic displacements were only 3 to 5% of the total computed displacement in the linear portion of the plot. However, rotational displacement is very small as indicated by the dynamic model, and the initial premise that internal elastic displacements are insignificant is not conservative and the rigid body mathematical model must be modified to include both internal deformations and soil deformations.

These preliminary studies indicate that the vertical element of the selected representative buildings may be considered very low period oscillators and be considered to transmit ground displacement to all levels of the horizontal diaphragms. Further research with more complex dynamic models is needed to determine bounds of amplified response and the change in amplification equated to easily determined parameters.

Response of horizontal diaphragms that are coupled to the vertical oscillator were studied by use of mathematical models. Discussion of these models and the results of the studies are fully described in the associated study conducted by Agbabian Associates. Therefore, this report will only comment on physical property data furnished for the study and on the results of this study. The physical properties of the diaphragms were described as shear beams with deflection equal to "K" times load times span. Results of large scale monotonic loaded specimens (Ref. 23 and 24) were used to establish both the value of the constant "K" and a hysteretic monotonic loop. Properties of diagonal sheathed and straight sheathed diaphragms were extrapolated from standard wall tests (Ref. 8) that make direct stiffness comparisons.

These comparisons indicate the stiffness of a plywood sheathing is about five times stiffer than diagonal sheathing and 20 times stiffer than straight sheathing. The displacements of the mathematical models represent construction, with the exception of the plywood sheathed diaphragm, that does not occur in the bare state in any representative buildings. The lumber sheathed diaphragms are either roofed, double sheathed with flooring or finished with materials that bind the boards into a composite skin. Plywood diaphragms when used as a roof will be covered with roofing materials. Testing of roofed plywood assemblages (Ref. 4 and 18) had displacement under dynamic loading much smaller than could be extrapolated from the properties as determined by static testing of the bare diaphragms.

It is expected that stiffness and damping will be very significantly affected by nondesigned material that exists in usual construction. If the increased stiffness were disregarded, the response of the horizontal elements would be understated and result in non-conservative analysis of the vertical elements. If the increased stiffness and damping were not utilized in the mathematical model the displacement would be overstated and the designer may require retrofitting to control displacement of attached walls. It is expected that the performance of unreinforced masonry walls for forces perpendicular to the wall plane will be directly related to absolute and relative displacement of horizontal elements. Therefore, information as to bounds of response for typical construction assemblages is needed. Cyclic and dynamic testing of large size diaphragms is needed to define force-displacment relationships and internal damping. The range of tested materials should include those wood and steel constructions predominantly used in conjunction with unreinforced masonry elements. For those structures that have concrete floors and roofs, representative material properties can be selected from prior research and testing.

2.4 Evaluation of Current Critical Element Analysis Methods

Current seismic design of a structure similar to a representative unreinforced masonry building would consider the design of the following elements to be critical. The intent of seismic design requirements is to limit damage that could cause partial collapse.

a. Connectors of structural elements.

b. Vertical elements for forces normal to their plane.

c. Vertical elements for forces in their plane.

d. Horizontal displacement of portions of the structure that would cause instability under vertical loads.

e. Compressive failure of vertical elements.

f. Foundation settlements that contribute to failure of any of the other described failure modes.

When ground motion and structural response can be reasonably defined, items a, e and f can be analyzed by methods familiar to the practicing engineer. Analysis of items b, c and d depends on definition of ground motion, structural response, and dynamic deformation characteristics of horizontal and vertical elements. Analysis to determine possible instability depends on computation of relative displacements. These computations must consider the dynamic state of all elements and cannot be readily determined by psuedo-static methods.

Current analysis methods of critical elements utilize very simplified methods that do not consider dynamic states of stress and displacements. These methods are adequate for new structures in seismic zones since the recommendations require that the construction have a minimum ductile performance. For failure modes that are not considered to have adequate ductile performance, load factors are utilized to reduce the inherent ductility requirements. The masonry elements in this class of structure do not have an apparent ductile behavior. Therefore, analysis techniques must be altered to include dynamic stresses and displacements.

2.5 Identify Analysis Needs

Analysis of unreinforced vertical elements for forces normal to their plane cannot be made by familiar methods unless the masonry element remains uncracked when displaced by structural response relative to ground motion. It is anticipated that post cracking behavior will be satisfactory if the fracture zone does not have a shear failure or if the dynamic displacements of the cracked wall is within an envelope of static stability. Stresses associated with these dynamic displacements need to be determined by computer modeling verified by dynamic testing. From this complex analysis simplified analysis rules will be developed. The simplified rules need to predict an upper bound of satisfactory performance equivalent to the prediction of all other input data.

Analysis of vertical elements for forces in their plane requires definition of an instantaneous stress in a reasonably complex structural element. Dynamic analysis for in-plane forces in a wall with regular or random opening configurations must be reduced to reasonably simple psuedo-static solutions that approximate the dynamic solution. Masonry units laid in mortar and coursed in the length of the wall can be expected to have at several disparate moduli of rupture. Orientation of principal tensile stress with masonry unit surfaces will need to be defined as well as the magnitude of the stress. Review of the few available cyclic tests of unreinforced masonry (Ref. 14) does not indicate that post cracking displacements approach hysteretic type displacements that can modify structural response. Additional analysis to study this behavior is proposed in Section 4.

Finite elements studies made to determine structural response can define boundary loads at the foundation level and distribution of inertial forces in the wall at any time. Finite element analysis of walls with regular and random opening configurations will be made to correlate stress predictions that include all internal distortion of the medium. Variations of commonly used analysis methods will be studied for equivalence. Superposition of analysis methods that produce reasonable equivalence will be studied. The end point is a manageable analysis method that can predict critical stress points and magnitude of stress. The analysis will predict a "best estimate" stress value rather than an upper bound. Similar "best estimates" need to be used to predict design ground motion for the seismic zone, response of the structure to ground motion, combination of orthogonal forces, combinations of vertical and horizontal forces and prediction of failure strength of the existing masonry materials. Analysis will then indicate when retrofitting is required. Risk of exceedance of any mean value will need to be evaluated.

2.6 Evaluate Current Structural Alteration Methods

Current structural alterations of existing buildings generally are intended to upgrade to the original strength if the original load and stress condition can be readily described or to upgrade to a required strength under load conditions defined for new construction.

Structural alteration to satisfy seismic design recommendations generally fall in the latter category. Force conditions intended for new construction are coupled with restrictions on materials and combination of materials. Design stresses specified are for materials used for current or acceptable construction. Ability of prescribed new constructions to limit displacements is generally assumed when design methods utilize recommended force levels and materials stresses. Therefore, retrofitting has generally introduced structural materials meeting current design recommendations into an existing structure.

The basis for design of structural alteration was to assume the structural response was near equivalent to that prescribed for design of new structures and prescribed structural materials or overlays of acceptable materials would be added to the existing structure. The reftrofitted structure would have load paths for the design loads through materials prescribed for new construction and the stress in these materials would be equivalent to prescribed stresses. Variations from this general procedure would be at the designers or regulating governmental agency's options. Acceptability of variations are generally judgemental.

Ability of non-designed materials present in a structure to limit displacements for the entire time period of the ground motion has not been evaluated by usual test procedures. Reported observations of structures subjected to ground motion has indicated that undesigned materials can limit displacements and therefore collapse of structures. However, observation teams in areas subjected to strong ground motion generally report on earthquake damaged structures rather than on minimal damage to structures that must rely on undesigned elements to limit displacements.

Cost effective structural alteration methods should utilize existing non-designed materials in conjunction with retrofitted materials to limit displacements. Analysis to determine when existing materials have adequate strength, such as masonry walls for in-plane forces, or adequate performance must be refined. Allocation of available hazard mitigation funds to analysis rather than retrofitting may be very cost effective. However, the effectiveness of analysis to determine need for retrofit and to define degree of retrofit is dependent on an adequate definition of structural response and material properties. Definition of displacements that are not based on damage limitations primarily but on reasonable risk of partial collapse again depends on definition of design ground motion and structural response to ground motion. Performance of undesigned materials throughout the entire time of ground motion must be defined by cyclic or dynamic test procedures. At present this performance can only be extrapolated from observation of structures subjected to moderate or strong ground motion.

Past methods that have been used to retrofit existing structures have been effective in damage control. This has been verified by the reconstruction program for California schools under the Garrison Act. Construction costs of the Garrison Act rehabilitation have been quoted as 80 to 110 percent of replacement costs. This cost of reconstruction work is due to the criteria that design and construction materials must conform to current seismic design requirements for new buildings. This criteria implicitly required design for an earthquake hazard risk which is not considered applicable to this study. Therefore, only the construction methods for providing strength or stiffness are transferable for the purposes of this study.

Investigation of pre-1940 unit masonry structures within the city limits of San Fernando and subjected to the February 9, 1971 earthquake (Ref. 15) had an equal number of "no damage" as "severe damage" and equal numbers rated as "slight damage" and "moderate damage". These buildings, pre-1940, are almost entirely structures which are the object of this study. Minimal work identified as parapet corrective work on the public ways was recognized as having significant value in preventing partial collapse. This corrective work generally was limited to construction of a bond beam at or near the roof line and anchorage of this bond beam to existing roof construction. This minimal corrective work appears to be very cost effective and can be included in recommended retrofit work.

Additional research is needed to evaluate stiffness of horizontal diaphragms covered with usual finish materials and capacity of common anchorage methods in unreinforced masonry materials. Retrofitting with materials used in current new construction can generally conform to current work and current stress levels when subjected to force levels determined by proposed research. New materials that provide an overlay on existing materials to increase strength will be evaluated by their application to dynamic and static test specimens.

2.7 Identify Methods of Defining Material Properties

Prior masonry test programs using static and cyclic loads (Ref. 3, 10 and 14) have directed their effort mainly to testing of reinforced masonry. Diagonal tension failure of unreinforced and reinforced masonry can be generally assumed to be equivalent (Ref. 3). Failure of zones stressed by principally bending tension in unreinforced masonry may have a common relationship to diagonal tension failure (Ref. 10) but this relationship may be significantly affected by the quality of the bond of mortar to the unit and flaws in this interface. Further, this reference indicates small test specimens are much more sensitive to flaws than large size elements such as walls. Large variation in the material properties of mortar and unit strength affect anisotropy. Estimates of relative mortar and unit strengths for structures in the California Pacific Coast show wide variation. The field survey made throughout the United States indicates this wide variation may be common in all seismic zones for pre-1940 construction.

Prism testing by methods that are commonly referred to as diagonal compression, (Ref. 3), can be made on specimens cut from larger specimens (Ref. 10) oriented to cause tension failure along lines of anticipated least strength. These tests which are considered to establish tensile failure strengths can then be corrolated to the usual orientation of prism tests, (@ 45° to unit orientations), and lower cost sampling methods. Current low cost sampling methods of existing masonry, includes coring of walls and testing of a mortar joint centered in the retrieved core. Practical limits of testing fixtures require orientation of the mortar joint at 15° with the axis of the testing machine. This does not directly provide a relationship of failure load and principal tension on this mortar joint. Further research is needed to confirm that correlation to the prism test exists, and for interpretation of expected scatter of test results of the simpler test method.

Other failure methods of unreinforced masonry walls for in-plane and out-of-plane forces will include displacement on a horizontal plane through mortar joints. This shear failure must be correlated with the axial load on the surface that will occur concurrently. This class of failure has not been investigated by prior research and testing but may be ascertained from the proposed out-of-plane dynamic testing of unreinforced masonry walls. Specimens constructed for out-of-plane testing may, upon completion of proposed tests, provide smaller scale samples for previously discussed prism and core testing.

Identification of material properties that are related to structural response has been discussed in Section 2.3. This testing generally assumes that deterioration in stiffness will not cause vertical load collapse. Post dynamic testing can confirm this expectation by increasing displacement and observing distress.

3.0 CONCLUSIONS

This research, performed in close collaboration with associated research by Agbabian Associates and Steve B. Barnes and Associates, has indicated that mitigation of seismic hazards in existing unreinforced masonry buildings may be accomplished by design methods other than currently utilized. Analysis of undesigned elements or minimally modified existing elements is proposed and feasible. Utilization of undesigned elements and modified elements and modified elements to control displacement within determined bounds is cost effective in comparison to current rehabilitation programs. Current techniques for modification or retrofitting structural elements are applicable to this class of building when determined to be necessary.

Field survey of the inventory of existing unreinforced masonry buildings indicate that commonality of structural characteristics exist in all seismic zones. Methodology for mitigation of seismic hazards can be developed for representative structures. Guidelines describing the limits of application of the proposed methodology can be developed.

This research did indicate that response of this class of structure to ground motion is over estimated by current seismic design recommendations (Ref. 1) that have provision for elastic response. This research confirmed that seismic design recommendations that implicitly require a minimum ductile performance are not applicable.

Dynamic analysis of computer models of flexible horizontal elements such as floors and roofs indicates response is overestimated by current seismic design recommendations, if element properties as determined by prior monotonic load tests, are utilized. However, evaluation of prior dynamic testing of complete structures at small displacements indicate that use of a structural model utilizing only the bare structure will probably be unconservative for estimating response. Test data is need to determine response, displacement, and performance of existing systems. Very minimal pertinent data now exists, and test data generated by the proposed research will be applicable to design of new construction as well as for analysis of existing construction. This data may be directly utilized for preparation of design standards and revisions to applicable regional building codes.

This research utilizing greatly simplified dynamic models did not adequately predict the structural response of stiff cantilevers founded on soils. Additional research with more sophisticated models is required.

Research into simplified models of masonry walls founded on soils indicate that static analysis models neglecting rotational inertial forces will not reasonably predict material stresses. More complex finite element models must be developed to give guidance for development of simple analysis rules.

Analysis of an unreinforced masonry wall for forces normal to its surface cannot be satisfactorily performed by usual static methods unless the wall has adequate tensile strength (or axial compression) to equal dynamic stresses. Quality of materials used in pre-1934 building walls and their performance cannot be rationalized with probable dynamic stress ranges. Dynamic behavior of this element in each seismic zone must be researched by computer models. All mathematical models must be confirmed by dynamic testing. Dynamic testing for full scale wall models is necessary to determine deterioration of masonry subject to dynamic excursions on cracked surfaces.

Methods of determining strength of existing masonry have received little attention in the past. Extensive testing has been made on new materials and general conclusions thereby obtained, as to strength relationships, can be utilized. Sampling methods using equipment readily available to the construction industry throughout the United States must be devised. Test procedures for retrieved samples must be within the capability of available testing facilities. Properties determined by these simple tests must be linked to the multiplicity of stresses, tensile, compressive and shear, that need be compared with analytically derived stresses.

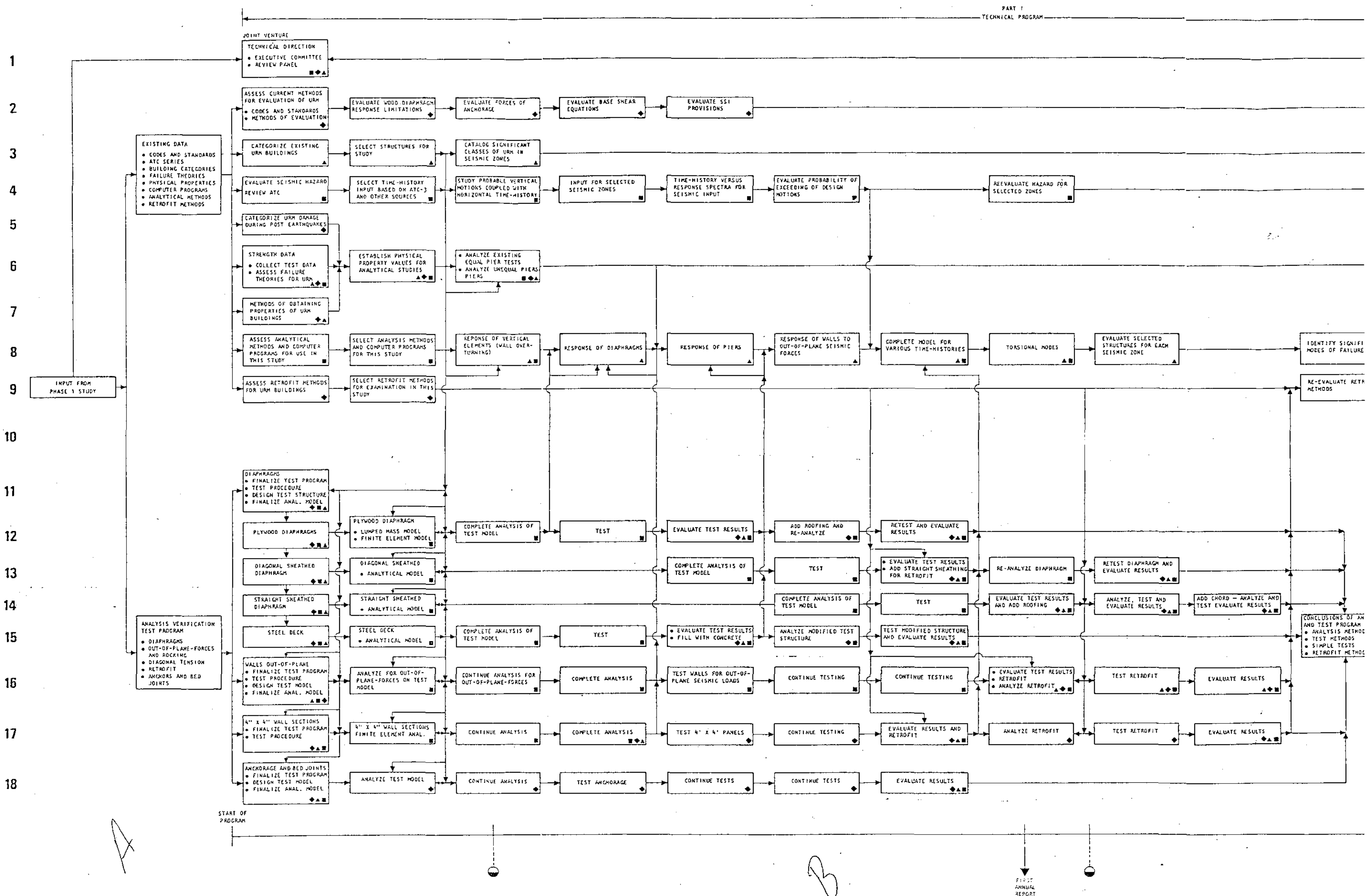
4.0 PROPOSED RESEARCH

This Phase I research project was conducted in close collaboration with two other structural engineering firms, Agbabian Associates and Steve B. Barnes and Associates. The three Phase I projects were interlinked by the original proposal and each investigated subdivisions of the general topic – Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings. The three firms will jointly propose carry-on research. Therefore, this discussion of proposed research relates to the joint effort. The total research program is shown in the accompanying task chart.

This proposed research will adopt seismic zoning for ground motion developed by the Applied Technology Council, Palo Alto, California under the sponsorship of the National Science Foundation RANN Program and National Bureau of Standards.

Concurrent and recent research into strength relationships of unit masonry sponsored by the National Science Foundation will provide information that can be related to existing masonry. This research program then will concentrate on determining the specific properties that are unique to unreinforced masonry.

The developed methodology will be directed toward the design professional familiar with the design of building structures. The methodology will be evaluated during the proposed research program by its application to representative structures.


PART I
TECHNICAL PROGRAM
1
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17
18
INPUT FROM PHASE 1 STUDY
EXISTING DATA • CODES AND STANDARDS • ATC SERIES • BUILDING CATEGORIES • FAILURE THEORIES • PHYSICAL PROPERTIES • COMPUTER PROGRAMS • ANALYTICAL METHODS • RETROFIT METHODS
ANALYSIS VERIFICATION TEST PROGRAM • DIAPHRAGMS • OUT-OF-PLANE-FORCES AND ROCKING • DIAGONAL TENSION • RETROFIT • ANCHORS AND BED JOINTS
JOINT VENTURE
TECHNICAL DIRECTION • EXECUTIVE COMMITTEE • REVIEW PANEL
ASSESS CURRENT METHODS FOR EVALUATION OF URM • CODES AND STANDARDS • METHODS OF EVALUATION
EVALUATE WOOD DIAPHRAGM RESPONSE LIMITATIONS
EVALUATE FORCES OF ANCHORAGE
EVALUATE BASE SHEAR EQUATIONS
EVALUATE SSI PROVISIONS
CATEGORIZE EXISTING URM BUILDINGS
SELECT STRUCTURES FOR STUDY
CATALOG SIGNIFICANT CLASSES OF URM IN SEISMIC ZONES
EVALUATE SEISMIC HAZARD REVIEW ATC
SELECT TIME-HISTORY INPUT BASED ON ATC-3 AND OTHER SOURCES
STUDY PROBABLE VERTICAL MOTIONS COUPLED WITH HORIZONTAL TIME-HISTORY
INPUT FOR SELECTED SEISMIC ZONES
TIME-HISTORY VERSUS RESPONSE SPECTRA FOR SEISMIC INPUT
EVALUATE PROBABILITY OF EXCEEDING OF DESIGN MOTIONS
REEVALUATE HAZARD FOR SELECTED ZONES
CATEGORIZE URM DAMAGE DURING POST EARTHQUAKES
STRENGTH DATA • COLLECT TEST DATA • ASSESS FAILURE THEORIES FOR URM
ESTABLISH PHYSICAL PROPERTY VALUES FOR ANALYTICAL STUDIES
• ANALYZE EXISTING EQUAL PIER TESTS • ANALYZE UNEQUAL PIERS PIERS
METHODS OF OBTAINING PROPERTIES OF URM BUILDINGS
ASSESS ANALYTICAL METHODS AND COMPUTER PROGRAMS FOR USE IN THIS STUDY
SELECT ANALYSIS METHODS AND COMPUTER PROGRAMS FOR THIS STUDY
REPONSE OF VERTICAL ELEMENTS (WALL OVER-TURNING)
RESPONSE OF DIAPHRAGMS
RESPONSE OF PIERS
RESPONSE OF WALLS TO OUT-OF-PLANE SEISMIC FORCES
COMPLETE MODEL FOR VARIOUS TIME-HISTORIES
TORSIONAL MODES
EVALUATE SELECTED STRUCTURES FOR EACH SEISMIC ZONE
IDENTIFY SIGNIFI MODES OF FAILURE
ASSESS RETROFIT METHODS FOR URM BUILDINGS
SELECT RETROFIT METHODS FOR EXAMINATION IN THIS STUDY
RE-EVALUATE RETR METHODS
DIAPHRAGMS • FINALIZE TEST PROGRAM • TEST PROCEDURE • DESIGN TEST STRUCTURE • FINALIZE ANAL. MODEL
PLYWOOD DIAPHRAGMS
PLYWOOD DIAPHRAGM • LUMPED MASS MODEL • FINITE ELEMENT MODEL
COMPLETE ANALYSIS OF TEST MODEL
TEST
EVALUATE TEST RESULTS
ADD ROOFING AND RE-ANALYZE
RETEST AND EVALUATE RESULTS
DIAGONAL SHEATHED DIAPHRAGM
DIAGONAL SHEATHED • ANALYTICAL MODEL
COMPLETE ANALYSIS OF TEST MODEL
TEST
• EVALUATE TEST RESULTS • ADD STRAIGHT SHEATHING FOR RETROFIT
RE-ANALYZE DIAPHRAGM
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CONTINUE TESTS
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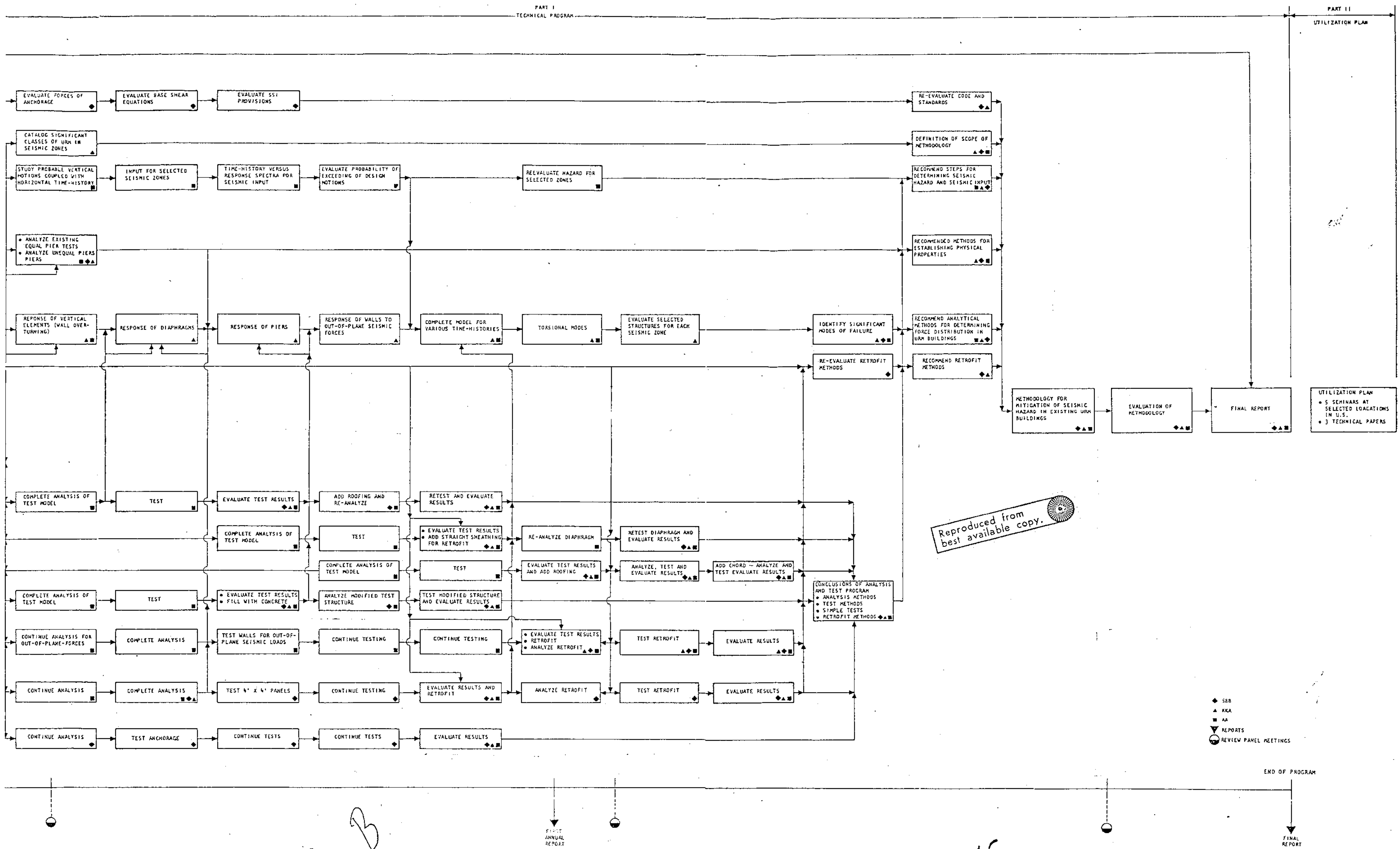
24.



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6.0 UTILIZATION

Information gained from this preliminary investigation has been communicated to a technical committee actively involved in formulating sesimic design recommendations and advocating revisions of adopted seismic design requirements. The professional group is the Geotechnical Subcommittee of the Seismology Committee of the Structural Engineers Association of Southern California.

Immediate interest of this subcommittee is establishing guidelines for determining allowable dynamic soil bearing values. Structural response of structures subjected to ground motion must be categorized as a first step in formulating guidelines. The information available from this preliminary study is applicable to stiff buildings founded on or near the soil surface. These structures as a class represent one bound of the types of buildings covered by seismic design requirements.

Preliminary information and conclusions obtained from this and the two associated studies of facets of the same general topic will be utilized to review the provisions of a draft ordinance now prepared for the City of Los Angeles. This draft ordinance entitled "Earthquake Hazard Reduction in Existing Buildings" is intended to be applicable to pre-1934 bearing wall masonry buildings. Principal investigators from two of the engineering firms involved in these studies were participants in the development of the ordinance.

Information gained from computer studies of flexible horizontal diaphragms has been shared with designers of and contractors for installation of wood diaphragms and the American Plywood Association. Continuing discussions and exchange of information may result in agreement to participate in the testing process of the proposed research. Data acquired in the proposed research would be directly applicable to formulating improved design recommendations and modifying current code approvals to make these flexible diaphragm systems more cost effective and provide improved earthquake resistance.

Anticipated users of the proposed research would be local public agencies that have indicated an interest in abating a perceived hazard in existing unreinforced masonry buildings. The final methodology would provide a basis for preparation of ordinances such as the draft ordinance now prepared by the City of Los Angeles. Public agencies in the Los Angeles Basin had technical personnel participate in the preparation of the draft ordinance. Request for copies of this draft have been received from additional cities and state agencies.

Building officials throughout the United States contacted during the survey phase of this project expressed interest in this research topic for its applicability to structures of this class that are being recycled into higher occupancy uses.