

EARTHQUAKE ENGINEERING RESEARCH AT THE PORTLAND  
CEMENT ASSOCIATION - A PROGRESS REPORT

by

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SUMMARY

This report summarizes past and current earthquake engineering research at the Portland Cement Association (PCA). Programs described include analytical and experimental research on beam-column joints, slab column connections, structural walls, coupling beams, lap splices, and concrete confinement. Work on post-earthquake damage investigations and development of design provisions is also described. This research has led to development of design methods that provide safe, economical, and efficient reinforced concrete structures.

INTRODUCTION

The Portland Cement Association has long maintained an active interest and involvement in earthquake-resistant design of reinforced concrete structures. PCA recognizes the need to continually review the basic philosophy underlying methods for design against earthquakes in the light of newly developed information and experience gained from actual earthquakes. The major objective of past and current work has been the development of a design philosophy for earthquake-resistant structures that takes full advantage of properties inherent in materials and forms.

RESEARCH ON FRAMES

An experimental program to develop data for design of reinforced concrete frame structures was initiated in 1965. Tests of beam-column joints were planned and executed in cooperation with the Structural Engineers Association of California (SEAOC) Seismology Committee. In a separate program, flat-plate structures with "integral beams" or shearheads contained within the slab thickness were evaluated.

Tests of Beam-Column Joints

Three series of tests were run to determine design details necessary for cast-in-place reinforced concrete frames that will resist moderate earthquakes without damage and severe earthquakes without significant loss of strength. Specimens were tested as shown in Fig. 1.(1.1). Axial load was applied to the column. Beams were then subjected to fully reversed cycles of bending.

The first test series included seven isolated exterior joints reinforced with Grade 40 steel.(1.2). A second series of tests on four specimens provided data on corner, interior, and side edge joints(1.5). These

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tests showed that well detailed joints maintained their strength as large inelastic deformations developed under reported reversed bending of the beam. Required ductile behavior could be provided in the beam at the hinging section next to the column as long as the joint retained its shear strength and stiffness. To resist shear forces, hoop reinforcement is required in the joints connecting beams and columns.

Anchorage of beam reinforcing bars continuous through the joint, as in interior and edge joints, was critical because the required anchorage length was not available within the width of the column. However, the continuing bar on the far side of the column provided anchorage in a short length of embedment into the compression zone of the beam. Therefore, when adequate anchorage length cannot be provided within the width of the column, anchorage should be assumed to start at the far face of the column.

Information from the eleven tests provided background for a guide to design (1.3). To verify applicability of the results for joints with Grade 60 reinforcement, five additional specimens were tested (1.4). Results indicated that design equations and details developed for Grade 40 reinforcement were applicable to Grade 60 steel.

#### Tests of Flat Plate-Column Connections

Five full-size portions of a flat-plate structure were tested under a realistic service load combined with reversed applications of unbalanced moment (1.6). The test setup is shown in Fig. 2. Results indicated that considerable deformation capacity is available in flat plates designed with "integral beams" within the slab thickness.

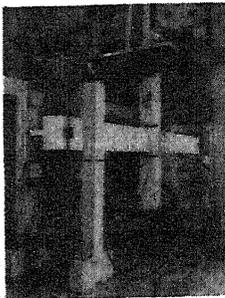


Fig. 1  
Beam-Column Joint



Fig. 2  
Flat Plate-Column

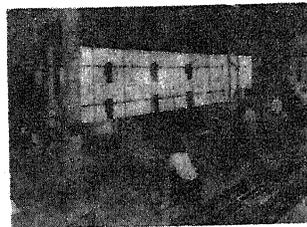


Fig. 3  
High-Rise Wall

Information from the tests provided background for a design procedure for earthquake-resistant flat-plate structures without structural walls (1.6). A "ductile frame" structure is made up of columns and "integral beams". The flat plate is reinforced to avoid shear and torsion distress at the slab-column junction. Existing procedures are used for calculating stiffness for evaluating  $P-\Delta$  effects and for detailing reinforcement. Although frames and flat-plate structures can be designed to withstand severe earthquakes, structural walls may be required to provide drift control and limit nonstructural damage.

## RESEARCH ON STRUCTURAL WALLS

Behavior of multistory reinforced concrete buildings during recent earthquakes has demonstrated that both safety and damage control can be obtained in buildings stiffened by properly proportioned and detailed structural walls. Because of a need for information on strength and deformation capacity of walls, a considerable amount of analytical and experimental research has been performed at PCA.

### Tests of Isolated Walls

A laboratory investigation of isolated structural walls was started in 1967. Thirteen walls were tested in the initial program(2.5, 2.36, 7.3). Figure 3 shows one of the walls, which were tested in a horizontal position, ready for loading. Variables in this program included height-to-horizontal length ratio, level of axial load, and amount and distribution of wall reinforcement.

The tests demonstrated that strength of reinforced concrete "shear walls" with height-to-horizontal length ratios of 2.0 or more is predominately governed by flexure rather than shear. Walls with vertical reinforcement concentrated near the ends attained higher rotations for equivalent moment capacities. Axial compression on the walls increased moment capacities, but reduced ultimate rotations. Only one of the walls in this initial program was subjected to reversing loads. Results from this program served as a basis for design provisions for walls in the 1971 Building Code Requirements of the American Concrete Institute(7.3).

Subsequent to the initial program, tests were conducted on eight specimens representing low-rise walls with boundary elements(2.1,2.2,2.14). A photograph of the test setup is shown in Fig. 4. Principal variables included amount of flexural reinforcement, amount of horizontal wall reinforcement, amount of vertical wall reinforcement, and height-to-horizontal length ratio. The test program was designed to determine effects of load reversals. One specimen was repaired and retested. Walls were designed such that their shear capacity was reached prior to flexural yielding. Results of these tests showed that current design procedures underestimate strength of low-rise walls, and a revised design procedure was suggested(2.14).

Since 1974, staff at PCA's Laboratories have been conducting a combined analytical and experimental investigation of structural walls with support from the National Science Foundation(2.7). The overall objective of this investigation is to develop practical design procedures for structural walls and wall systems.

Estimates of strength and deformation requirements in critical regions of walls and wall systems are being established through dynamic inelastic analyses of representative models. Available strength and deformation capacities are being determined from laboratory tests on approximately 1/3-scale models. The laboratory tests also provide data for establishment of proper detailing practices.

Sixteen reinforced concrete isolated structural walls have been subjected to in-plane horizontal reversing loads(2.9,2.13,2.17,2.19,2.20, 2.21,2.25,2.27,2.29,2.35,2.47,2.48,2.49,2.50). Each specimen was tested under combinations of axial load, bending, and shear as shown in Fig. 5. Controlled variables included shape of cross-section, amount of flexural

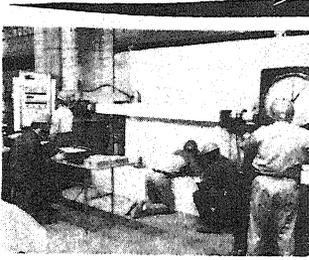


Fig. 4  
Low-Rise Wall

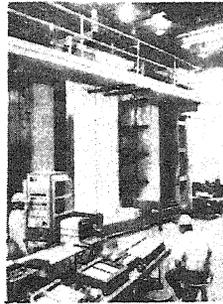


Fig. 5  
Isolated Wall

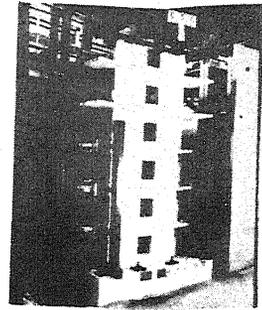


Fig. 6  
Pierced Wall

and shear reinforcement, confinement reinforcement in the boundary elements, concrete strength, vertical load, and lateral load history. In addition, two repaired specimens were tested. Effects of variables on overall behavior, strength, and deformation capacity were evaluated.

Results of tests conducted to date have led to the following conclusions regarding use of structural walls in earthquake-resistant buildings:

1. Structural walls designed according to the 1977 American Concrete Institute Building Code will attain their design strength in both flexure and shear. However, the designer must be aware that present provisions underestimate flexural capacity because strain hardening of reinforcement is neglected. For inertia loadings, shear forces developed are related to actual flexural capacity, not design flexural capacity. Thus, the level of shear can be significantly higher than anticipated if inelastic response occurs.
2. Properly detailed structural walls will behave in a ductile manner. Deformation capacity is dependent on the level of shear stress applied to the wall. For lower levels of shear, higher deformation capacities are attainable.
3. Maximum shear stress that can be developed in a wall with vertical boundary elements is limited by web crushing capacity. Addition of horizontal shear reinforcement to resist the total applied shear force does not significantly improve strength or ductility for this mode of failure.
4. Presence of confined boundary elements significantly improves inelastic behavior. Confinement reinforcement is only necessary in anticipated hinging regions. Stiff boundary elements help to limit shear distortions and construction joint slip.
5. Construction joints in structural walls will perform adequately if made following standard practice of roughening and cleaning the surface to remove laitance and loose particles.
6. Displacements caused by shear distortions are a significant portion of the total lateral inelastic displacements in structural walls subjected to reversing loads.
7. Structural wall performance under load reversals is a function of load history. The previous level of maximum deformation is critical.

In addition to tests of solid isolated walls, PCA's current program includes evaluation of walls pierced by openings and coupled walls.

### Tests of Walls Pierced by Openings

To evaluate effects of openings on performance of walls under load reversals, two companion specimens were tested. One was solid and the other was pierced by openings. The structures were six-story models with floor slabs simulated at each story level. Vertical reinforcement was concentrated at each end of the walls in the form of confined boundary elements concealed within the wall thickness.

The pierced wall, shown in Fig. 6, had openings that represented about 20% of the horizontal cross-sectional area of the wall. In designing the pierced wall a simple approach was used. Horizontal and vertical reinforcement interrupted by the openings were placed to either side of the openings so that the same total area of steel was available. Lintels were designed to resist a shear corresponding to that which would occur when the wall yielded. Both walls were subjected to an increasing number of inelastic load reversals.

Capacity of the solid wall was limited by "sliding shear". This occurred under increasing load cycles as the interface shear transfer mechanism along cracks in the wall deteriorated. Eventually shear could no longer be transferred and the upper portion of the wall slid over the lower portion without increase in load resistance. This mode of response is very much a function of the number of reversals as well as the level of axial load and the crack pattern that develops in the wall.

The presence of openings changed the failure mode from sliding shear to crushing in the compression zone. However, load-deformation response for the pierced wall was nearly identical to that for the solid wall. The openings had very little effect on strength and deformation capacity.

### Tests of Coupled Walls

Reinforced concrete structural walls most often occur in combination with frames or coupled to other walls by beams. A major advantage of coupled walls and frame-wall systems, as compared to isolated walls, is their structural redundancy. This redundancy permits engineers to design inelastic energy dissipation capacity into elements that are not critical to overall structural stability. As is the case for PCA's isolated wall research, both analytical and experimental investigations of wall systems are being conducted. The tests are to determine strength and deformation capacity of wall systems under loads simulating seismic conditions. To date, two coupled wall systems have been tested(2.46).

Objectives of the tests were to evaluate: (1) effects of axial load induced by coupling beams on behavior of the individual walls and (2) effects of coupling beams on crack development, general behavior, and sequence of yielding. The six-story models were tested as shown in Fig. 7. First, a system with light coupling was tested. Following this test, beams were replaced to provide stronger coupling.

The following conclusions were obtained from the tests:

1. The amount of axial load in the walls created by accumulation of shear forces in the coupling beams significantly influenced behavior and ductility of individual walls.
2. The lightly coupled wall system behaved as a frame, with most of the inelastic action occurring in the coupling beams before the walls yielded.

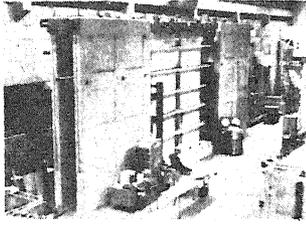


Fig. 7  
Coupled Wall

3. Repair by replacing coupling beams with stronger elements was simple and effective.
4. In the repaired system, inelastic action occurred in the coupling beams and walls. Axial load in the walls significantly affected their performance. The repaired specimen lost its load carrying capacity by crushing of the wall under compression. This wall showed significantly less ductility than an identical wall subjected to zero axial load. It was apparent from the observed behavior that the wall under compression carried most of the shear forces applied to the system.
5. Conventionally reinforced beams effectively coupled the two walls. Vertical shear reinforcement provided in the beams was effective for the design shear.
6. Design of coupled wall systems should relate the amount of coupling to strength and ductility of beams and walls. Ductility of coupling beams will be critical in a design requiring early yielding of the beams. Strength and ductility of the walls will be critical in a design requiring beam and wall yielding at approximately the same level.

#### Analytical Investigation of Isolated Walls

The analytical investigation consisted of four phases: (1) input motions, (2) dynamic inelastic analyses-parametric studies, (3) development of design procedure-design force levels, and (4) representative loading history. These phases are briefly summarized below.

Input Motions. To minimize the number of input motions that need to be considered in establishing "critical" structural response, an examination was made of the major parameters characterizing strong motions (2.8, 2.16, 2.23, 2.30). The three major parameters were intensity, duration, and frequency content. Major emphasis was placed on the effects of frequency characteristics of input motions on dynamic inelastic response. Accelerograms were classified into two broad categories: peaking spectrum and broad band spectrum.

Because the extent of yielding in a structure is influenced by yield level of the structure as well as intensity of the input motion, both parameters have to be taken into account when selecting the appropriate type of motion to use as input. This applies particularly to the frequency content of the input motion.

Dynamic Inelastic Analyses of Structures - Parametric Studies. A major step in the development of a design procedure for earthquake resistant isolated structural walls was the evaluation of the relative influence of various structural and ground motion parameters on dynamic inelastic response (2.10, 2.15, 2.24, 2.26, 2.28, 2.31, 2.33, 2.40). Parametric studies serve to identify the most significant variables affecting dynamic response. All subsequent development can then be carried out in terms of major variables.

Models of isolated walls were investigated to obtain dynamic response data on the basic element of interest and to establish a reference from which results for more complex structural wall systems could be compared. The basic structure considered in the parametric studies was a hypothetical twenty story building consisting mainly of a series of parallel structural walls. Parameters considered in the parametric study were fundamental period, yield level, yield stiffness ratio, hysteretic force displacement relationship, damping, stiffness taper, strength taper, and degree of base fixity. Of major interest was the influence of these parameters on the force and deformation requirements in the hinging region near the base of the wall. The dynamic analyses were made using the DRAIN-2D program developed at the University of California, Berkeley.

The most important parameters affecting force and deformation demands were intensity, and frequency content of the ground motion and fundamental period and yield level of the structure. Other parameters investigated appeared to be of minor significance, at least for the range of variables considered.

Shear at the base of an isolated structural wall was found to be more sensitive to higher mode response. Base shears generally underwent a greater number of reversals than moments or deformations. The major effect of the duration of ground motion was to increase the cumulative deformation in the hinging region. Deformation requirements increased almost proportionately with an increase in the intensity of ground motion. For the same yield level, ductility requirements generally increased with decreasing fundamental period. The magnitude of the deformation requirements in hinging regions, in terms of ductility ratios and cumulative plastic hinge rotations, generally decreased with increasing values of the yield level.

Development of Design Procedure - Design Force Levels. The objectives of this part of the investigation have been:

1. Determination of maximum force and deformation requirements in critical regions of structural walls corresponding to different combinations of significant structural and ground motion parameters
2. Determination of appropriate stiffness ranges for walls to limit overall structural deformations and interstory distortions
3. Determination of an appropriate measure of deformation to enable a meaningful comparison of analytical and experimental results
4. Correlation of data on critical dynamic response with data from the laboratory tests to arrive at recommendations on design force levels.

Critical force and deformation requirements were obtained through an extensive series of analyses(2.12,2.34,2.41). The results were organized in the form of plots to indicate maximum values of top displacement, interstory displacement, bending moment and shear force at the base of the wall corresponding to different input motions and structural parameters. A procedure for determining design force levels based on a correlation of analytically derived response data and test results has been developed.

Representative Loading History. In correlating demand with capacity, an important consideration is the degree to which the laboratory loading represents earthquake response conditions. A valid correlation is possible only if it can be shown that the loading program used in the test is comparable to or more severe than conditions that can be expected under earthquake excitation.

An investigation was made to determine appropriate loading programs for use in quasi-static tests to simulate response to earthquakes (2.32, 2.38). To define a representative loading history in quantitative terms, data were assembled from inelastic dynamic analyses of isolated structural walls. Particular attention was placed on factors that would have significant effects on structural behavior. The loading history is characterized by the maximum amplitude of deformation, the number of large-amplitude cycles of deformation, the sequence of large-amplitude cycles relative to small amplitude cycles, and the associated maximum forces. Based on this investigation a loading history has been suggested for laboratory tests of structural walls (2.32, 2.38).

#### Analytical Investigation of Wall Systems

The objective of the analytical investigation of structural wall systems is the development of rational and practical design procedures (2.39, 2.42, 2.44, 2.45). These procedures will be based on information relating probable strength and deformation demands with available capacities, particularly as these are influenced by the significant design variables.

Basic Models. Compilation of data upon which design values can be based requires a considerable number of analyses. Because these analyses take an appreciable amount of computing time, the basic models were chosen to be as simple as possible while still incorporating essential mechanisms distinguishing each structural type. Thus, for coupled walls, a model consisting of two identical walls connected by coupling beams at every floor level is analyzed, while for frame-wall systems a single wall linked to a two-column rigid frame by inextensional members with nonrigid connections is examined. The model for the frame-wall system is meant to focus attention on primary effects of interaction between the frame and wall.

Analysis Procedure. Three general steps of model testing, parametric studies and design data compilation were adopted for this investigation. This approach is similar to that for the investigation of isolated walls.

Data on force and deformation demands corresponding to a wide range of values of significant parameters are being developed. Relative stiffnesses and strength of coupling beams, relative stiffness and strength of the frame and wall, fundamental period of the structure, and yield level of the wall are being considered. Data are being generated for 10-, 20-, 30-, and 40-story structures subjected to varying ground motion intensities. A number of selected accelerograms are used as input motions.

Parameters Being Examined. The effects of a number of parameters on dynamic response are being evaluated. For coupled wall systems, parameters included are: (1) initial fundamental period of structure (as affected by stiffness), (2) yield level in flexure of walls, (3) yield level in shear of walls, (4) coupling beam-to-wall stiffness ratio, (5) coupling beam-to-wall flexural strength ratio, and (6) foundation rocking (linearly elastic model). For frame-wall systems, parameters are: (1) initial fundamental period of structure (as affected by stiffness), (2) yield level in flexure of wall, (3) yield level in shear of wall, (4) frame-to-wall stiffness ratio, (5) frame-to-wall flexural strength ratio, and (6) foundation rocking at base of wall (linearly elastic model).

The frame in the frame-wall systems is assumed to be designed primarily for gravity loading. The effect of each parameter is examined by varying its value over a practical range while keeping the other parameters constant.

#### Explicit Inelastic Dynamic Analysis

With the availability of inexpensive, efficient, two-dimensional response history computer programs such as DRAIN-2D, it is practical to carry out explicit inelastic dynamic analyses. In such analyses, mathematical models of wall-frame or coupled wall systems are subjected to carefully selected accelerograms. Designs based on such analyses make it possible to: (1) predetermine the sequence of plastification, (2) provide ductility details only where required, and (3) balance the strength and ductility requirements of members. Efficiency, economy, and desired structural performance are achieved as a result. A number of design examples have been carried out (7.14, 7.15, 7.16, 7.17).

#### RESEARCH ON COUPLING BEAMS

Eight model reinforced concrete coupling beam specimens were tested under reversing loads representing those that would occur in beams of coupled structural walls during a severe earthquake (3.1, 3.2). Effects of selected variables on hysteretic response were determined. These included shear span-to-effective depth ratio of the beams, reinforcement details, and size of the confined concrete core.

The beams had shear span-to-effective depth ratios of either 1.4 or 2.8. Maximum nominal shear stresses on short-span beams ranged from  $7\sqrt{f_c^t}$  psi ( $0.58\sqrt{f_c^t}$  MPa) for beams with conventional reinforcement to  $11\sqrt{f_c^t}$  psi ( $0.91\sqrt{f_c^t}$  MPa) for beams with full-length diagonal reinforcement. Equivalent shear stresses for long-span beams were  $4\sqrt{f_c^t}$  and  $5\sqrt{f_c^t}$  psi ( $0.33\sqrt{f_c^t}$  and  $0.42\sqrt{f_c^t}$  MPa), respectively. Load versus deflection relationships, strength, energy dissipation, and deformation capacity were basic parameters used to evaluate performance.

#### Conventional Longitudinal Reinforcement

Inelastic response of coupling beams with conventional reinforcement was limited by sliding shear deterioration at the beam-wall intersection. This was the case even though transverse hoops were provided to carry the entire shear without yielding. Since sliding shear cracks propagated between transverse reinforcement, the hoops eventually became ineffective. Development of sliding shear is dependent on load history. Deterioration is a function of number of cycles and intensity of applied deformations. As such, any generalization of results must consider load history.

Improved inelastic performance was obtained by increasing the size of the concrete core. The confined core of coupling beams should be made as large as possible within the limits of cover requirements.

#### Diagonal Reinforcement in Hinging Regions

Diagonal reinforcement within hinging regions at the ends of the beams improved performance, but not enough to justify the added complexity and cost. Based on the laboratory tests, it does not appear that this detail would be an economical solution.

#### Full-Length Diagonal Reinforcement

Beams with full-length diagonal reinforcement had the best strength, ductility, and energy dissipation characteristics of any of those tested.

Improvement in hysteretic response using full-length diagonals for long span beams was not as significant as for short-span beams. In addition, gravity loads within the span take on greater significance for longer span beams. These loads cannot be resisted efficiently by diagonal reinforcement. Considering these findings, straight diagonal bars do not appear to be justified for beams with shear span-to-effective depth ratios of 2.8 or more.

If full-length diagonals are used, the diagonal bars must be properly anchored in the adjoining wall. The diagonals must be restrained over their full length to prevent buckling. Since this type of detail effectively develops strain hardening of the reinforcement, the actual capacity of the beams should be considered in designing a structural wall system. A design based on yield level would not properly allow for the forces that can be imparted to the walls by the beams.

Results of the coupling beam tests clearly indicated the relative influence of special reinforcement details on inelastic hysteretic response of coupling beams. This does not, however, justify the use of one system over another for all situations. The response characteristics and energy dissipation capacity attainable in the beams must be matched with that required for the structure and design conditions being considered.

#### RESEARCH ON LAP SPLICES

As part of the investigation of reinforced concrete structural walls, lap splices of reinforcing bars are being evaluated(4.1,4.2). The specific problem considered is the use of tension lap splices in regions where main reinforcement yields under severe stress reversals.

Tests of eight specimens were performed on reinforced concrete column elements under reversing axial loads. Columns had cross-sectional dimensions of 12x12 in. (305 x 305 mm). Longitudinal reinforcement consisted of either four No. 8 bars or eight No. 6 bars. Variables included load history, amount and configuration of lapped reinforcement, and amount of transverse hoop reinforcement around the lapped bars. Results indicate that distribution of transverse hoop reinforcement significantly influences performance. Offset reinforcing bars also have a significant effect. Specimens with Class C lap splices and special transverse hoop reinforcement performed well under monotonic and reversing loads.

#### RESEARCH ON CONFINED CONCRETE

Tests were performed on 17 specimens to evaluate rectangular hoops as confinement reinforcement(5.1-5.4). The effective stress versus strain relationship of confined concrete was determined. Controlled variables included spacing of confinement reinforcement, size of confinement reinforcement, amount of longitudinal reinforcement, size of test specimen, and concrete strength.

Rectangular hoop reinforcement meeting or exceeding the 1977 ACI Building Code requirement for lateral confinement as specified in Appendix A extended the limiting concrete strain beyond 0.015. This is five times the value of 0.003 assumed for ultimate strain of plain concrete. All specimens tested with hoop reinforcement had significantly greater strains than could be obtained with plain concrete. Spacing and amount of transverse hoop reinforcement were of primary importance. It is

suggested that use of smaller size hoops at smaller spacings is a more efficient method of obtaining the required volumetric ratio because tightly spaced hoops also provide restraint against buckling of longitudinal reinforcement.

Confinement reinforcement for the range tested in this program showed no significant influence on concrete strength. However, tests were limited to four corner longitudinal bars with single rectangular hoops. In practice, the same percentages of longitudinal and transverse reinforcement can be obtained with eight longitudinal bars and with hoops placed diagonally as well as parallel to the sides of the section. Such arrangements are recommended for future test programs to investigate the influence of reinforcement distribution.

#### POST-EARTHQUAKE DAMAGE INVESTIGATIONS

Post-earthquake damage investigations are an extremely valuable aid to understanding effects of earthquakes on structures. Major earthquakes investigated since 1960(6.1-6.9) have dramatically, and sometimes tragically, illustrated flaws in design and detailing practice. The knowledge gained from such "field tests" has led to a number of improvements in design and construction procedures, as well as changes in design concepts and philosophy. For example, in the 1960's the concept was to design buildings for flexibility. However, recent investigations(6.6) have shown that flexible buildings sustain significant nonstructural damage. Non-structural components can account for as much as 80% of the cost of the structure. Therefore, the use of stiffening elements, such as structural walls and diagonal bracing, is being given greater consideration. This will result in stiffer structures with less nonstructural damage.

#### DEVELOPMENT OF DESIGN PROVISIONS

The culmination of investigative and research activity is the development of design codes, regulations, and standards of recommended practice. Translation of research results and field experience into a concise, precise, understandable, and practical code document is always a difficult undertaking. For seismic design the task is even more challenging. To a great extent, this is because most structural engineers have not been educated in the relatively new field of earthquake analysis and design.

The experience of the Portland Cement Association(7.1-7.17) is that code provisions must be based on thorough research combined with sound engineering judgement. Prior to adoption as a legal document, code provisions should be "tested" by having experienced designers and researchers do "trial designs." This should insure that provisions will result in efficient, economical, and "buildable" structures.

#### CONCLUSIONS

This paper has summarized past and current earthquake engineering research at the Portland Cement Association (PCA). Primary emphasis was placed on current research on earthquake resistance of buildings with reinforced concrete structural walls. The major objective of PCA research has been to develop design provisions to produce safe, economical, and efficient reinforced concrete structures.

Work has encompassed experimental and analytical investigations of resistance of structures to earthquakes, experimental investigations of

repair and strengthening of structures, development of recommended construction practices, post-earthquake field investigations, and development and improvement of building code regulations for seismic design.

#### ACKNOWLEDGEMENTS

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PCA R&D Ser. 1638

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