HIGHLIGHTS OF AN EXPERIMENTAL INVESTIGATION OF THE SEISMIC PERFORMANCE OF STRUCTURAL WALLS

by

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Design criteria are developed for reinforced concrete structural walls used as lateral bracing in earthquake-resistant buildings. Primary items of interest include the ductility, energy dissipation capacity, and strength of structural walls. This paper describes the highlights of the experimental investigation which consists of four parts: isolated walls are subjected to reversing in-plane loads; structural wall systems are subjected to proof tests of coupled walls and frame-wall structures; an investigation is conducted of the stress versus strain characteristics of confined concrete; and an investigation is conducted of the behavior of coupling beams subjected to reversed loading.

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INTRODUCTION

The behavior of multi-story buildings in recent earthquakes has indicated that buildings stiffened with properly proportioned reinforced concrete structural walls can provide both safety and damage control.(1) However, a lack of information on the deformation capability of structural walls has limited their use.

Because of this lack of information, a combined experimental and analytical investigation of structural walls was undertaken at the Portland Cement Association. The overall objective of this investigation is to develop design criteria for reinforced concrete structural walls used as lateral bracing in earthquake-resistant buildings. Primary items of interest include the ductility, energy dissipation capacity and strength of structural walls. The investigation is sponsored in part by National Science Foundation Grant No. GI-43880.

The experimental portion of the investigation consists of four parts. In Part I, isolated walls are being investigated. These walls are subjected to reversing in-plane loads. Part II is an investigation of structural wall systems. The systems investigation consists of proof tests of coupled walls and frame-wall structures. In Part III, an investigation of the stress versus strain characteristics of confined concrete is being carried out. Part IV is an investigation of the behavior of coupling beams subjected to reversed loading.

This paper describes the highlights of the experimental investigation.

OBJECTIVES

The objectives of the experimental investigation are:

1. To determine the load-deformation characteristics for a wide range of configurations of structural walls.

2. To determine the ductility and energy dissipation capacity of walls and wall systems subjected to reversing loads.

3. To determine the flexural and shear strengths of walls and wall systems subjected to reversing loads, and to compare these strengths with the strengths under monotonic loading.

4. To determine means of increasing the energy dissipation capacity of walls where required.

5. To develop design procedures for walls of adequate strength and energy dissipation capacity.

6. To evaluate the effects of rectangular hoops as confinement reinforcement for large cross sections and to determine the effective stress versus strain relationship of confined concrete.

7. To develop test data for elements of systems such as coupling beams.

PART I - ISOLATED WALLS

The isolated wall test specimens are approximately 1/3-scale models of full-size walls, although no specific prototype walls are modeled. The model walls are 15-ft (4.57m) high and 6-ft 3-in. (1.91m) wide. Wall thicknesses are 4 in. (102mm). The specimens are subjected to in-plane lateral reversing loads. A specimen and the testing apparatus are shown in Fig. 1.

Controlled variables in the program have been the shape of the wall cross section, the amout of main flexural reinforcement, the amount of hoop reinforcement around the main flexural reinforcement, and the concrete strength. In addition, several walls are being subjected to monotonic loading.

In general, two types of behavior were observed in tests of the first five walls. These types were distinguished by the magnitude of the applied shear stresses. All specimens were provided with horizontal shear reinforcement so that the calculated moment capacity would be developed.

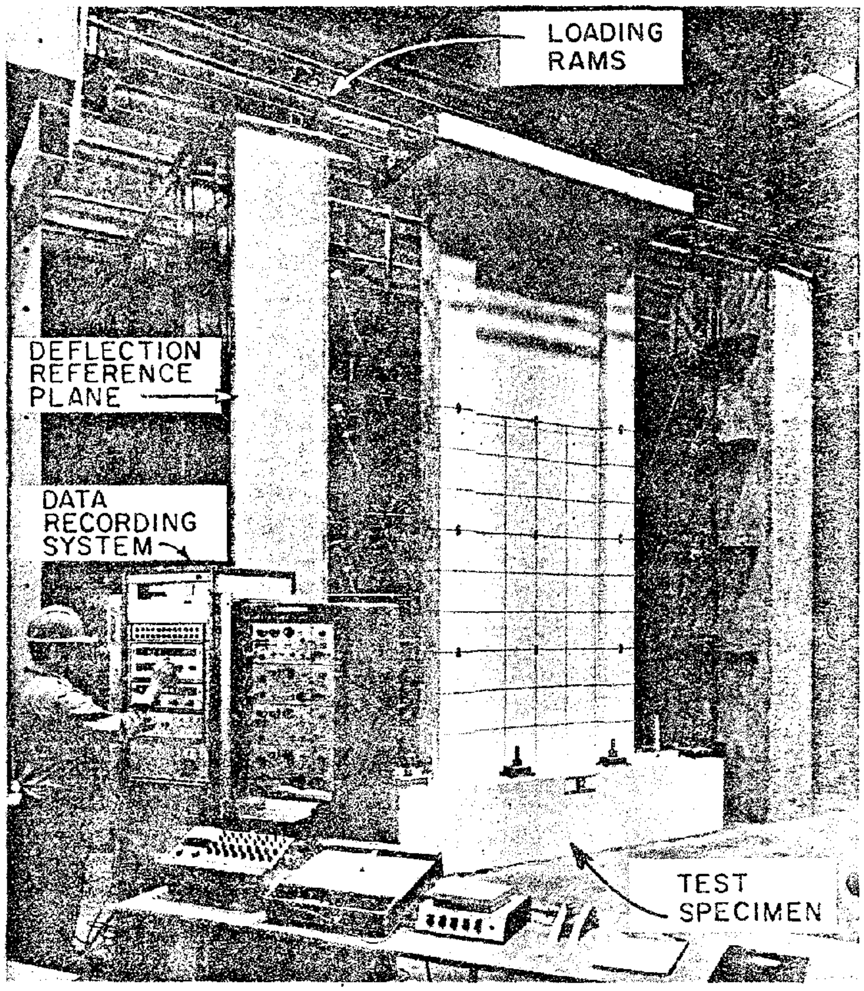

Fig. 1 Isolated Wall Test

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Two specimens were subjected to high nominal shear stresses $v_{max} > 7.2\sqrt{f'_c}$. The failure mode for these specimens was associated with web shear distress.

Three specimens were loaded to produce low nominal shear stresses $v_{max} < 3.1\sqrt{f'_c}$. Two of these had ordinary column ties. One had lateral confinement reinforcement around the main flexural reinforcement in the boundary elements. Capacities of these specimens were governed by damage to the boundary elements as alternate tensile yielding and compressive buckling of the main flexural reinforcement occurred.

Lateral confinement reinforcement in the boundary elements helped to limit bar buckling and to contain cracked concrete within the core. Confinement provided a wall with somewhat greater ductility, but no significant increase in strength.

In conjunction with the lateral load tests, a series of free vibration tests are being carried out. Free vibration characteristics of the specimens are measured at several stages as the lateral load tests progress. The tests are performed at two amplitude levels. For the smaller displacement amplitudes, the walls are struck with a hammer. For the larger amplitudes, a prestressing wire is attached to the top of the wall. The wire is pulled to a predetermined force and then suddenly cut.

The output of the free vibration tests is the top displacement of the specimen plotted versus time. The curves obtained are used to calculate the frequency and damping characteristics of the walls. Test results indicate a significant decrease in frequency and increase in damping as the walls crack during the lateral load tests.

PART II - SYSTEMS

A structural wall system is defined as a group of interacting structural elements, at least one of which is a structural wall.

Presently four systems are scheduled for testing. These represent a wide range of structural combinations encountered in practice. Systems scheduled for testing include walls coupled by deep beams, walls coupled by slender beams, walls pierced with openings, and a wall coupled to a frame. The testing arrangement is shown in Fig. 2.

Specimens will be constructed at approximately 1/3 scale. Individual walls will have a height of 18 ft (5.49m), a horizontal length of 6 ft 3 in. (1.91m), and a thickness of 4 in. (102mm). The overall length-to-depth ratio will be 2.5 for the deep coupling beams and 5.0 for the slender coupling beams. For the wall with

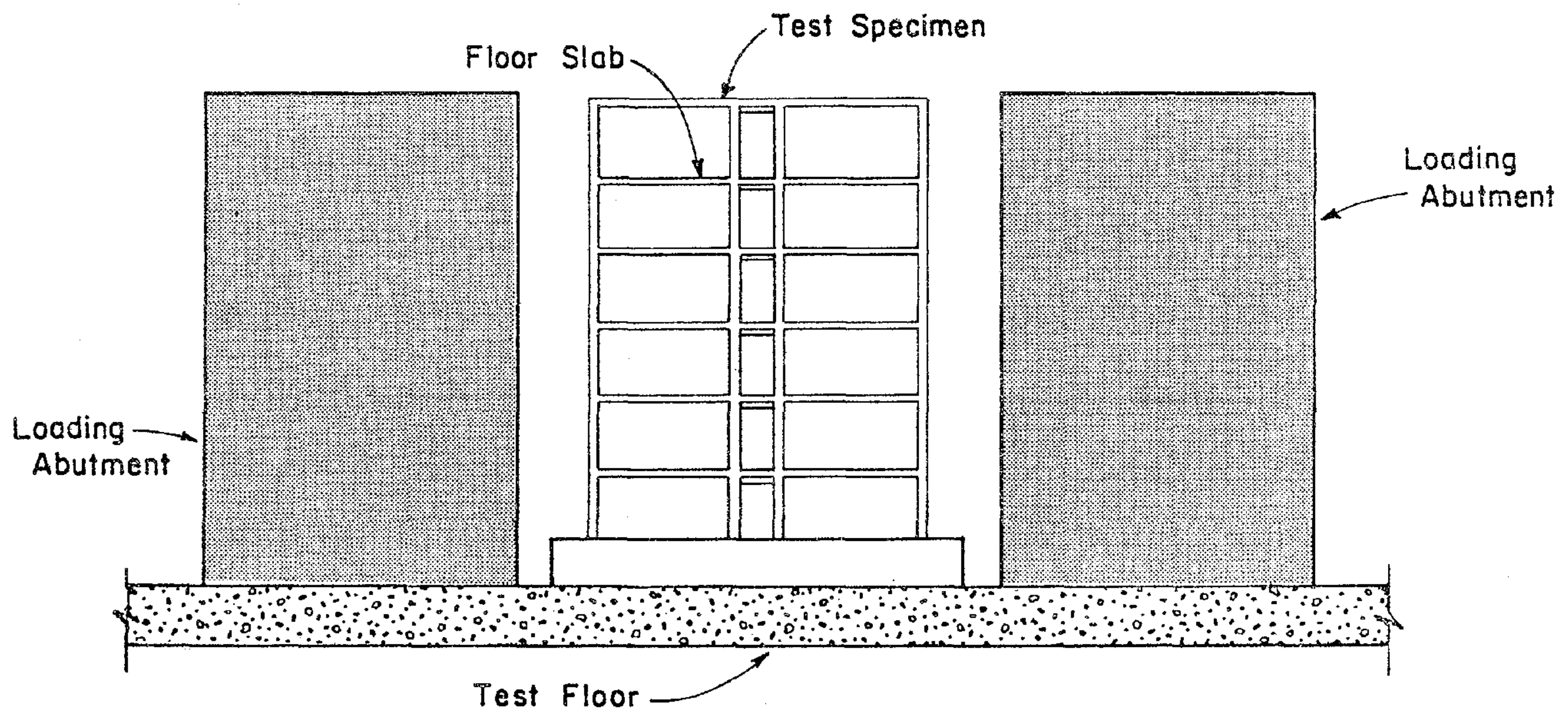

Fig. 2 Setup for Systems Tests

openings, connecting elements above and below the openings will have an overall length-to-depth ratio of 0.4.

The specimens will be cast vertically with construction joints. Grade 60 reinforcement and 3000 psi (20.7 MPa) concrete will be used in all specimens. The loading will consist of reversing in-plane lateral forces. Loads will be applied through floor slab elements.

All systems will be instrumented to measure applied loads, deflections at various intervals of height, rotations in the walls and coupling beams, shearing distortions in the walls and coupling beams, and strains in the reinforcement of the walls and coupling beams.(4)

PART III - CONFINED CONCRETE

In this investigation, tests are being performed on specimens representing full-size compression zones of structural walls. The results are being used to evaluate the effects of rectangular hoops as confienement reinforcement. Stress versus strain relationships of confined concrete are being determined.

The test specimen has been adapted from one developed earlier for determination of the stress versus strain relationship of plain concrete.(2) Figure 3 shows the test specimen and test apparatus. The center vertical region of the specimen represents the confined compression zone of a structural wall. Controlled variables in the test program include hoop size, hoop spacing, amount of longitudinal reinforcement, concrete strength, and size of test specimen.

Two sizes of specimens were tested. The large specimens had a 10x16-in. (254x406mm) cross section, and had longitudinal reinforcement percentages of 0.5 or 3.9. For the large specimens, hoop size and spacing of No. 4 bars at 4 in. (102mm) was found to meet requirements of the Appendix to the 1971 ACI Building Code.(3) The hoop size and spacing were increased and decreased from this combination to determine the influence on the effective stress versus strain relationship. The specimens were constructed with 3000 psi (20.7 MPa) concrete.

The small specimens had a 5x8-in. (127x203mm) cross section, and had longitudinal recinforcement percentages of 0.5 or 4.4. For the small specimens, the confinement reinforcement consisted of No. 2 bars at 2 in. (51mm). Specimens with 3000 psi (20.7 MPa) and 6000 psi (41.4 MPa) concrete strengths were tested.

For correlation with previous work, tests were carried out on both large and small unreinforced concrete specimens.

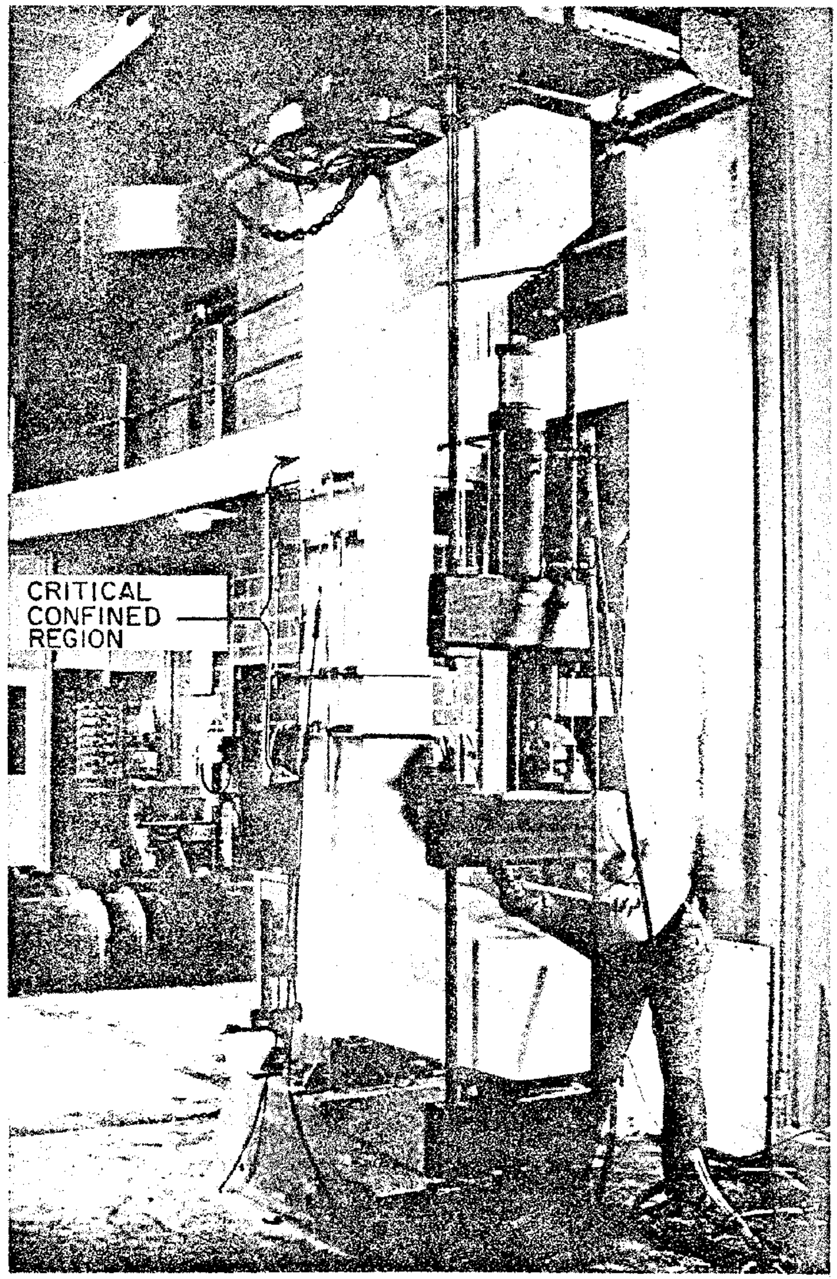

Fig. 3 Confined Concrete Test Specimen

Analysis of the test results showed that all arrangements of rectangular hoops were effective in significantly increasing the limiting concrete strain. For those specimens with hoop reinforcement meeting the requirements of Appendix A of the 1971 ACI Building Code,[3] limiting concrete strains exceeded 0.015.

The spacing and amount of transverse reinforcement were the primary variables affecting the stress versus strain relationship of the concrete. The amount of longitudinal reinforcement had little effect.

PART IV - COUPLING BEAMS

This investigation is being undertaken to determine a suitable configuration of reinforcement for the coupling beams in the systems tests. The configuration for the systems tests will be selected based on performance of the beams when subjected to load reversals. Performances will be evaluated from observed ductility, energy dissipation, and strength.

The test specimens are approximately 1/3 scale. Cross-sectional dimensions of the beams are 4x6-5/8 in.(102x169mm). Overall length to depth ratios of 2.5 and 5.0 will be investigated.

A test specimen and the test setup are shown in Fig. 4. As can be seen, coupling beams are tested in a horizontal position. Two beams are connected in parallel by two wall segments. The wall segments also serve to apply in-plane reversing loads to the coupling beams. The applied force is positioned to avoid axial forces in the beams.

Controlled variables include the arrangement of diagonal reinforcement, size and spacing of transverse hoops, use of supplementary ties and concrete strength.

Each test specimen is instrumented to measure applied loads, displacements, rotations, shearing distortions, and steel strains.[4]

SUMMARY

This paper highlights the setup for an experimental investigation of reinforced concrete structural walls for earthquake resistant buildings. Tests of isolated structural walls, structural wall systems, confined concrete elements, and coupling beams are described.

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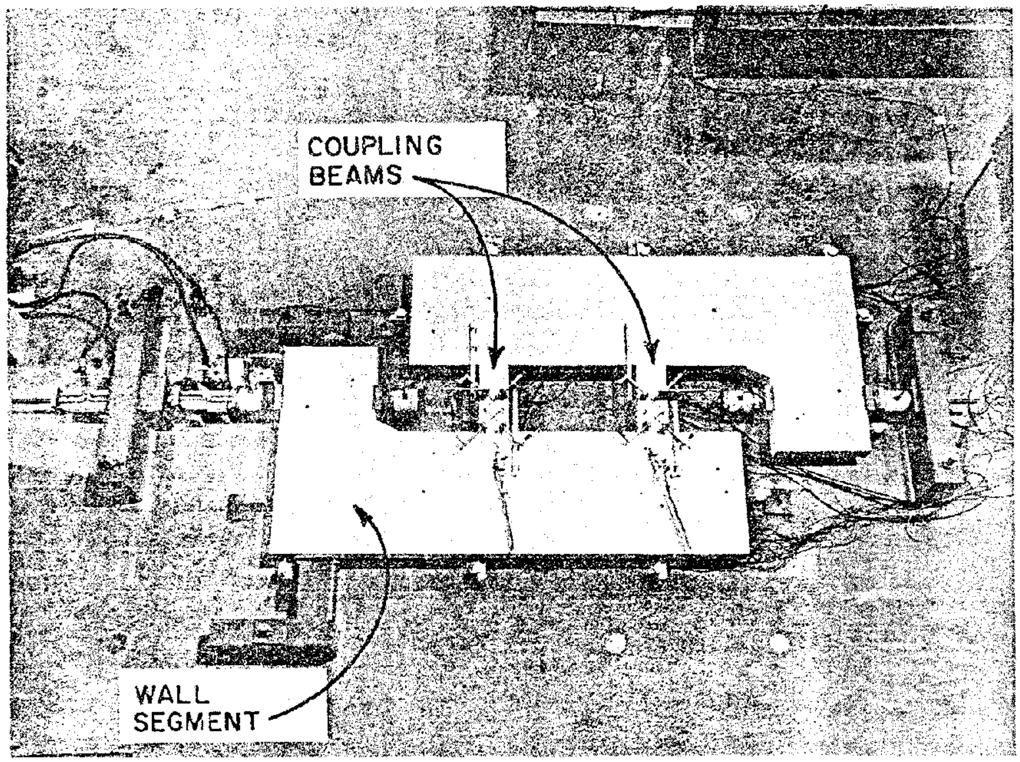

Fig. 4 Coupling Beam Test

tion and testing of the specimens are performed by the Technical Staff of the Section with the assistance of the Staff of the Transportation Development Section.

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NOTATION

f'_c = compressive strength of standard 6x12-in. concrete cylinders
h = wall thickness
ℓ_w = horizontal length of wall
V = shear force
v = nominal shear stress = $\frac{V}{0.8\ \ell_w\ h}$