# EXPERIMENTAL STUDY OF REINFORCED CONCRETE FRAME-WALL STRUCTURES SUBJECTED TO STRONG EARTHQUAKE MOTIONS

by

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## SYNOPSIS

Results of an experimental study of frame-wall interaction in reinforced concrete structures subjected to strong earthquake motions are presented. Design of the ten-story model structures and the experimental program are described briefly. Implications suggested by selected features of observed response of the models are discussed in terms of relevance to earthquake-resistant design of full-scale structures.

## INTRODUCTION

The overall objective of the experimental study was to develop a better understanding of the interaction of walls and frames in reinforced concrete structures subjected to strong earthquake motions. An incidental objective of the research was to investigate improved methods of analysis for design of structures in linear and nonlinear ranges of response.

The study consisted of tests of small-scale (approximately one-twelfth scale) reinforced concrete model structures subjected to simulated earthquake motions [2]. Experimental parameters of the four-structure series were the strength of structure and the base motion. Each ten-story structure (Fig. 1) comprised two frames resisting lateral inertial loads in parallel with one slender structural wall. The test structures were not models of a particular prototype but physical representations of an engineer's concept of lateral-load resistance in a multistory building.

## DESIGN OF THE TEST STRUCTURES

Geometry of each of the four structures was the same, however reinforcement was varied according to different concepts of intended behavior. Strength of members was establsihed according to a design method that recognized energy-dissipation capabilities of reinforced concrete structures in the nonlienar range of response [4]. A linear analytical model with arbitrarily softened members was used to estimate maximum response and to proportion reinforcement throughout the structures. Two concepts of response resulted in structure types with radically different wall reinforcement. Walls intended to respond

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nonlinearly, as a result of dividing cracked stiffnesses by three, were reinforced at base with one-fourth as much reinforcement as walls intended to respond linearly.

Beams of each structure type were reinforced lightly (as low as 0.7 percent) as a result of choosing stiffnesses equal to one-sixth of cracked-section values. Column stiffnesses were chosen equal to cracked-section values so that yield of reinforcement would occur at the ends of beams rather than in the columns. Despite the large difference in wall reinforcement for the two structure types, frame reinforcement for each structure was approximately the same. Differences in relative strengths of wall and frames for each structure type were complemented by differences in lateral accelerations. Lightly reinforced structures were expected to accelerate less than more heavily reinforced structures because of lower natural frequencies and larger amounts of damping.

Story weights were designed as stiff diaphragms so that lateral displacements of frames and wall would be nearly equal. Connections were provided that transferred lateral and vertical forces from each story weight to the frames and wall without eccentricities and with negligible resistances to rotation about each principal axis.

Combinations of amounts of mass and base-motion intensities were selected to result in yield of reinforcement of a reasonable diameter during design-basis earthquake simulations. According to a preliminary analysis, story weights at each level equal to 4.6 KN and base motions with maximum accelerations equal to 0.4 g would provide the desired amplitude of lateral inertial load. Base motions were tailored also with respect to duration. Actual time of recorded ground motions was shortened uniformity along the duration by a factor of 2.5 so that the test structures would be excited in the fundamental mode and accelerate less with increasing damage.

## EXPERIMENTAL PROGRAM

Each of the four structures tested were subjected to three simulated earthquake motions of progressively increasing intensity. Initial test runs consisted of design-basis motions. Second and third test runs were planned to be two and three times as intense as initial test runs. After each simulation, structures were subjected to a range of low-amplitude harmonic vibrations within the neighborhood of fundamental frequencies. To examine variations in dynamic characteristics with successive damage, structures were excited in free vibration at a low amplitude before and after each earthquake simulation.

Measurements at each of the ten levels consisted of acceleration, displacement and force resisted by the wall. Transverse and vertical accelerations were also measured to verify response as intended. Response was recorded on forty-eight channels in analog form which was then digitized and stored on magnetic tape for further reduction.

In addition to the dynamic testing of the ten-story structures, samples of frame and wall elements were subjected to slowly applied load reversals to investigate behavior in the nonlinear range. Strength, stiffness and energy-dissipation characteristics were examined to substantiate modeling procedures used with small-scale construction and to help interpret internal response of the ten-story structures. Representative hysteresis curves obtained from these tests is presented in Ref. 1.

## RESPONSE OBSERVATIONS

In addition to providing data for testing a numerical model [3], observed response of the test structures suggested the following implications.

(1) The structures responded within the nonlinear range. A softening of the structures resulting from nonlinear behavior may be suggested from an apparent decrease in frequency of the structures with increase in amplitude of motion (Fig. 2b). This observation was corroborated by a reduction in the ratio of base-moment and displacement maxima for cycles of response following successively larger displacement amplitudes (Fig. 4).

Permanent displacements and residual forces applied to wall (Fig. 2c) were another observation identifying the occurrence of nonlinear behavior. As demonstrated by the first displacement wave form of Fig. 2b, structures with lightly reinforced walls were observed to incur larger displacements following an earthquake simulation than structures with heavily reinforced walls implying greater extent of nonlinear behavior for the lighter reinforced structures. The shape of the two displacement waveforms also suggests this tendency. A more erratically shaped response history for the structures intended to respond nonlinearly implies a larger amount of energy dissipation which may be attributable to larger amounts of damping through hysteresis.

(2) Nonlinear behavior occurred at regions selected in the design process. The size of crack widths measured after initial earthquake simulations suggested yield of longitudinal reinforcement at ends of beams and at base of wall. Moreover, response histories of moment at base of the structures determined from lateral accelerations and forces applied to the wall (Fig. 3) suggested the occurrence of nonlinear behavior at base of the lightly reinforced wall (first waveform shown) and linear behavior at base of the heavily reinforced wall. Amplitudes and frequency contents of moments at base of lightly reinforced walls were not consistent with those of moments at base of the combined frame-wall system as were moments at base of heavily reinforced walls.

Yield of reinforcement at ends of beams was also implied by results of tests of beam-column assemblies subjected to displacement histories similar to those measured during earthquake simulations. Measured rotations of the beam-column joints and observations of the width of crack at the beam-column interface indicated yield at ends of beams.

Additionally, the occurrence of nonlinear behavior at ends of beams and base of wall was suggested by the pattern of signs and amplitudes of the residual forces applied to the wall following an earthquake simulation (Fig. 2c). According to a linear numerical analysis, large residuals measured at the first level, particularly for lightly reinforced walls, implied permanent rotations at base of wall. Residual forces at intermediate levels of opposite sign implied permanent rotations at ends of beams at those levels.

(3) Limiting strengths of the structures could be calculated conservatively using conventional procedures of limit design with static strengths of members. Using a mechanism consisting of hinges at ends of beams and base of columns and wall with rotational strengths determined experimentally from tests of components subjected to slowly applied loading reversals resulted in limiting base moments slightly smaller than observed maxima. Additional strengths not included in the calculation may be attributable to strain-rate effects and compressive axial load on wall.

(4) A linear modal analysis using softened member stiffnesses was found acceptable for calculating response maxima of the combined wall-frame system. Apparent fundamental-mode frequencies observed in measured response could be calculated reliably using average slopes of measured hysteresis loops for cycles of maximum displacement. Furthermore, examination of displacement measurements of several amplitudes of motion suggested a nearly constant displaced shape of structure despite the observed nonlinear behavior. Accelerations observed at the eighth level (Fig. 2a) did not include frequencies in the range of expected second-mode apparent frequencies which implied a nearly constant node point for an apparent second-mode shape.

Response of the model structures to a particular base motion could be determined using a linear oscillator whose frequency was equal to the measured frequency of the structure. Lateral loads were calculated using measured frequencies and base motions, and assuming linear behavior. Loads were distributed along height of structure using properties of measured displaced shapes. Base moments at time of maximum displacements determined from these loading distributions were in good agreement with measured response maxima (Fig. 4).

(5) Arbitrary softening of the wall in the design process resulted in a more economical structure with no loss of serviceability. Measured response of structures with lightly and heavily reinforced walls (Fig. 5) indicated nearly equal maxima of measured displacements for each structure type. Inertial loads applied to the stronger structure were slightly larger which may be attributable to higher frequencies of the structure and smaller amounts of energy dissipation. Damage incurred by the lightly reinforced wall in the form of diagonal-tension cracking was much less severe than for the more heavily reinforced wall.

(6) Force distributions acting on wall varied considerably with progressive softening at ends of beams and base of wall. As demonstrated by the force reversal at level ten (Fig. 5), the frames resisted

not only the total lateral load at that level, but also restrained the wall from deflecting as it would if it were isolated. Constantly changing stiffnesses of the frames and the wall because of behavior in the nonlinear range of response resulted in a complicated interaction of the wall and the frames. Force response (Fig. 2c) contained large residuals resulting from variable extents of nonlinear behavior between the frames and the wall. Furthermore, frequency contents of wall response varied with story level which made identification of force distributions at a specific instant nearly impossible.

## CONCLUSIONS

Response of four model structures has demonstrated that a physical model may be used to develop a better understanding of the interaction of frames and walls in structures subjected to strong earthquake motions. The experimental study has shown that response maxima of the nonlinearly behaving structures may be estimated with a linear modal analysis using members with reduced stiffnesses. Although internal force distributions applied to the frames and the wall could not be calculated reliably, moments observed at base of wall suggested that the redundant system of frames and wall behaved in accordance with the strengths provided and that the design procedures were appropriate.

## ACKNOWLEDGEMENTS

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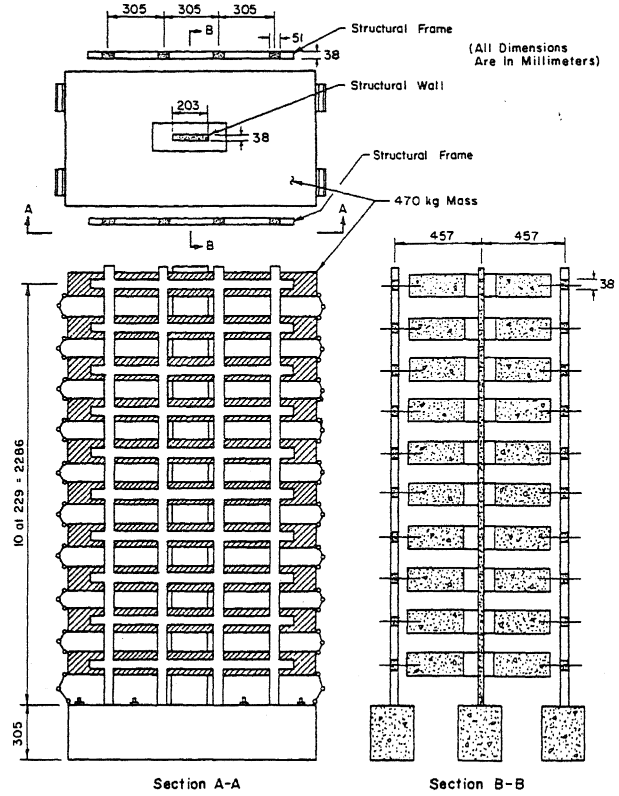

Fig. 1 Test Structure

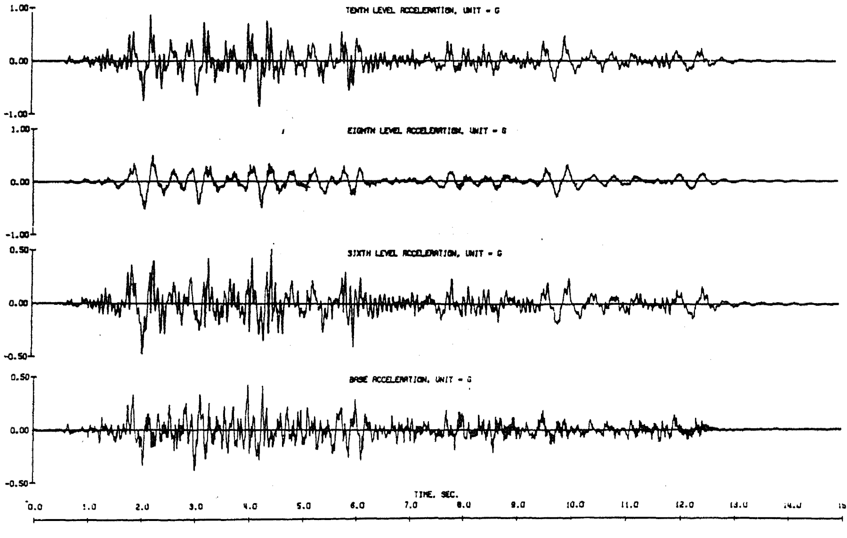

Fig. 2a Measured Accelerations

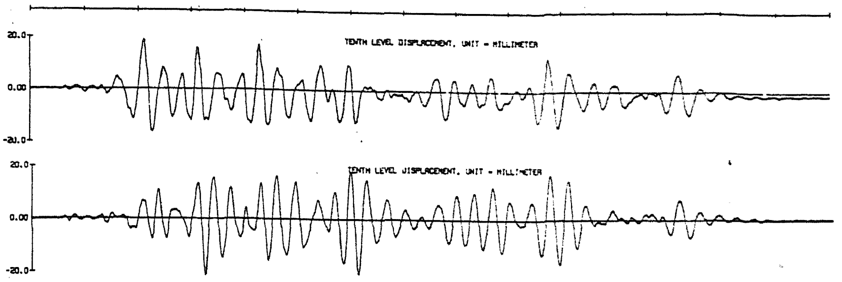

Fig. 2b Measured Displacements

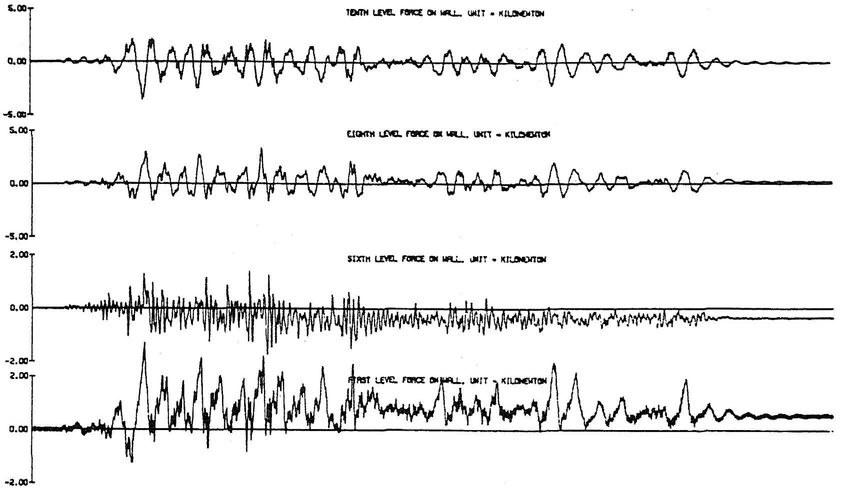

Fig. 2c Measured Forces Applied to Wall

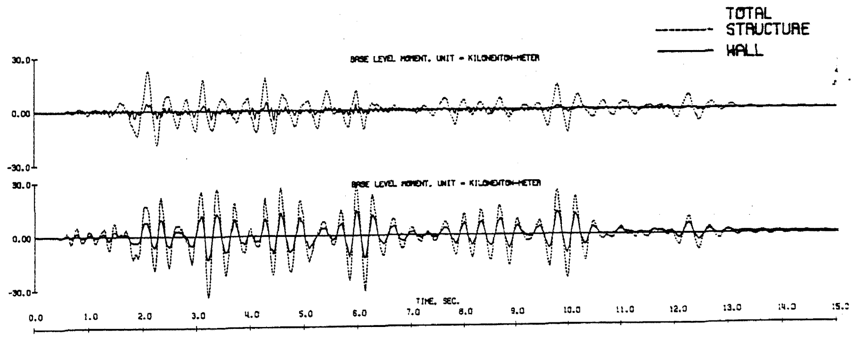

Fig. 3 Moments at Base of Structure

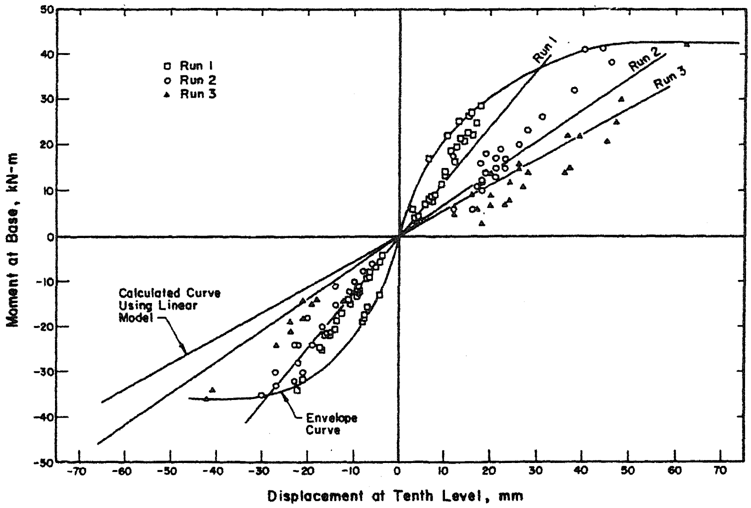

Fig. 4 Base Moment - Displacement Maxima

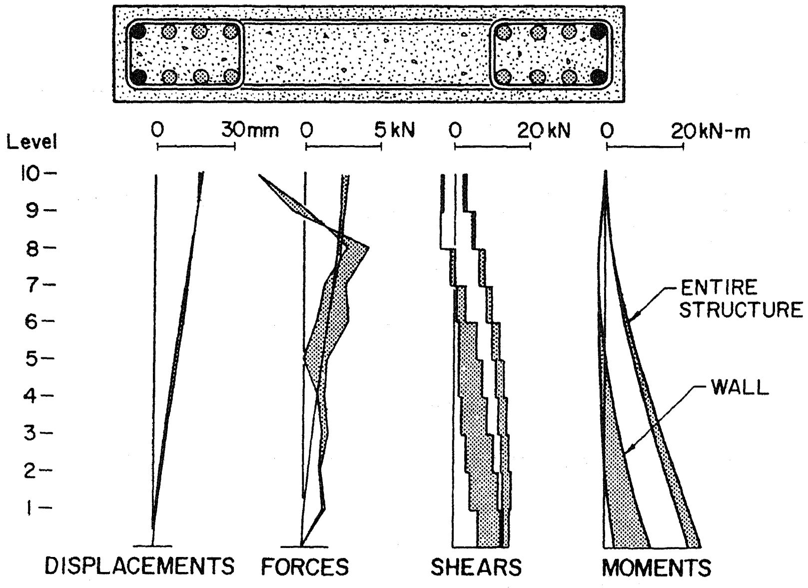

Fig. 5 Comparison of Measured Response for Structures with Heavily and Lightly Reinforced Walls