EFFECT OF WALL HEIGHT ON EARTHQUAKE RESPONSE OF REINFORCED CONCRETE MULTI-STORY FRAME-WALL STRUCTURES

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SYNOPSIS

A series of four small-scale multi-story reinforced concrete structures were tested, using the University of Illinois Earthquake Simulator. The objective of the tests was to investigate the influence of abrupt changes in building stiffness on earthquake response. This paper contains a description of the test structures and some of the test results.

INTRODUCTION

Stiffness discontinuities in the vertical plane of building structures may be considered to be one of three kinds: (1) a relatively stiff element (such as a wall or a truss working in parallel with frames) in the upper stories of a building discontinued before reaching the foundation level, (2) a stiff element interrupted at an intermediate level resulting in a "gap" of one or more story heights, and (3) a stiff element connected to the foundation but discontinued at an intermediate level of the building.

The first two kinds of stiffness discontinuity, usually introduced by functional requirement, are generally difficult to handle properly and avoided wherever possible. This paper is concerned with stiffness discontinuities of the third kind.

An exploratory study, using the substitute-structure model (1), of structures comprising frames and "cut-off" walls, working in parallel to resist lateral forces, indicated that there would be no serious problems related to detailing such structures for satisfactory earthquake response. As a check of this conclusion, a series of experimental tests was conducted on small-scale structures. This paper provides a brief description of the experimental investigation and its results.

EXPERIMENTAL OUTLINE

Four small-scale test structures were tested with strong base motions simulating one horizontal component of the record obtained at El Centro, California during the Imperial Valley earthquake of 1940. As shown in Fig. 1, each test structure included two nine-story frames. The main experimental variable was the height of the centrally-located wall. For structure FFW, the wall extended through the height of the structure. For FHW and FSW it was terminated at levels four and one (Fig. 1b). Structure FNW did not have a wall.

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THE TEST STRUCTURES

The overall dimensions of the test structures are summarized in Fig. 1a. The first-story height was selected to be large in order to simulate a frequently occurring design condition. The first-story columns and the wall framed into heavy girders at the base level. The girders were bolted to the platform of the earthquake simulator resulting in a nearly fixed-base condition. A mass of 470 kg was supported vertically by the two frames at each story level. The wall was connected to each story mass so that lateral displacements of the frames and the wall would be identical at each level. Hinge-connected plates or "bellows" were attached to the story masses to prevent damage to the test structures resulting from accidental forces transverse to the frames. The bellows permitted relative movement of the stories in the plane of the frames but restrained distortion transverse to that plane.

The distribution of longitudinal reinforcement used in the frames and the walls is summarized in Table 1. As indicated in that table, the distribution of reinforcement was the same for the three structures with walls. Sufficient transverse reinforcement was provided in all elements to minimize the probability of shear failure. Frame joints had special details to avoid local distress (2). Anchorage problems at frame exterior joints were alleviated by extending the beams out as short cantilevers (Fig. 1a). Frames and walls were cast horizontally and monolithically with the stiff foundation girders. Measured mean material properties of the test structures are listed in Table 2.

TESTING AND INSTRUMENTATION

The primary test for each structure was a "design earthquake simulation," a test in which the test platform was driven to develop an acceleration record patterned after the north component of the 1940 El Centro record (3). Additional tests for each structure were conducted in the following order: (1) Free-vibration test to determine frequency at very low amplitudes; (2) Earthquake-Simulation Test; (3) Free-Vibration test; (4) Test with steady-state "sinusoidal" base motions at different frequencies, with maximum response amplitude approximately one half of values obtained in the design earthquake-simulation test; and (5) Static test (horizontal load applied successively at all levels) to obtain a measure of the initial stiffness of the structure. This set of five tests was repeated three times for each structure, with the intensity of the earthquake simulation increasing progressively. This paper includes data from the first set only.

The "design earthquake" had an effective peak acceleration of approximately 0.4g. The time-scale of the original acceleration record was compressed by a factor of 2.5. A typical acceleration record obtained on the test platform is shown in Fig. 2a. Acceleration response spectra calculated at a damping factor of 0.1 for the first earthquake simulation test of each structure are shown in Fig. 2b. At periods between 0.2 and 1.0 sec., which represented the range of interest for the test structures, the four spectra indicated comparable acceleration responses.

Instrumentation of the test structures included sensors for measuring relative displacements and absolute accelerations in the direction of the base motion. The connection at each story between the mass and the wall was instrumented with electric strain gages and calibrated to indicate the force at the connection. All measurements were recorded continuously. After each earthquake-simulation test, crack patterns, crack-widths, and any local crushing of concrete were recorded.

DISPLACEMENT RESPONSE

A measure of the behavior of a structure during strong base motion is its displacement history, which is especially convenient because displacement responses at different levels tend to be in phase. Examination of the displacement history at a given level, coupled with information about the deformed shape at peak deflection times, provides a fairly complete perspective of behavior. Figure 3 shows the measured displacement histories and Fig. 4 contains the deformed shapes at the time of maximum displacement for the four test structures.

A feature most apparent in Fig. 3 is not the different but the similarity of the four records. The curves for structures FFW and FHW were virtually identical. For all three structures with walls (FFW, FHW, FSW) the maximum displacement was attained at the same instant and in the same direction. However, for FFW and FHW the rebound from the maximum was not as strong as for FSW. This is reflected consequently in larger permanent displacement at the end of the test for FFW and FHW. Close comparison of the records indicates a slightly larger effective period for FNW and also that the waveform for FNW is perceptibly different from the others at approximately three and seven seconds. Otherwise, the displacement record for FNW was not markedly different from those of the structures with walls. Using the top-level displacement as the only criterion, then, it would be difficult to differentiate among the four structures and even more difficult to identify especially unsatisfactory response in any one of the four.

The displacement distributions shown in Fig. 4 suggest that the story drifts, as would be expected, were moderately higher for FNW and FSW. The more significant information in Fig. 4 is the indication that the displacement distribution for FHW appeared more favorable than that for FFW. Story drifts were comparable with those for FFW in lower stories but considerably less in upper stories.

It should be noted that for a lateral force distribution corresponding to the deformed shape, initiation of structural yielding would occur at a top-level displacement of approximately 10mm. That limit was exceeded for all test structures during the first seconds of the "earthquake" duration so that response observations refer to structures responding beyond initial yielding.

BASE FORCES

Shear and moment response at the base, calculated from acceleration measurements, are shown in Fig. 5 and 6 for the four test structures. It is seen from those figures that the maximum base shears and moments were comparable for the four structures. It is, therefore, of interest to reconcile the observed responses of FFW and FNW, systems which are clearly different from each other, in the light of their observed dynamic properties. Measured apparent lowest frequencies in the first set of tests for each structure were as follows:

	FFW Hz	FHW Hz	FSW Hz	FNW Hz
Free Vibration	4.9	5.2	4.9	4.0
Earthquake Simulation	2.2	2.2	2.2	1.8
Free Vibration	2.8	3.2	2.9	2.4
Steady-State	2.0	2.1	2.0	1.8
Free Vibration	2.7	2.9	2.8	2.2

The initial free-vibration frequencies represent reasonably closely the corresponding frequencies calculated on the basis of uncracked section. Clearly those frequencies are of little significance in determining the force response of the structures during strong base motion when the structure is driven well into the nonlinear range of response. The apparent frequencies in the earthquake simulation test were 2.2 and 1.8 Hz for the lowest effective mode of structures FFW and FNW. Entering Fig. 2 with periods based on these measurements (0.45 and 0.56 sec.), it follows that the base shear and moment maxima would not be expected to be too far apart. The differences in lowest effective periods indicate a fifty percent difference in stiffness between the two structures both prior and during the earthquake simulation. However, judgments about response based on gross-section properties would be misleading because of the large change in response acceleration (in that frequency range) for a small frequency change. During the earthquake simulation test (with an apparent stiffness reduction ratio of over four) spectral accelerations were nearly equal.

CONCLUDING REMARKS

Without detailed quantitative discussion of the experimental results and without supporting data for different types of base motions, it would be unjustified to make broad generalizations from the test results described. But the tests have provided evidence demonstrating that the actual and inferred problems of the first two kinds of stiffness discontinuities should not be assumed to apply generally and without analysis to structures having stiffness discontinuities of the third kind discussed in this report. To the contrary, the overall performance of structure FHW, with the wall terminated at approximately half way up the building, suggests that "cutting off" a relatively stiff element at some intermediate level of the building may provide a satisfactory option in structural planning of earthquake-resistant buildings.

ACKNOWLEDGMENT

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Table 1. Reinforcement Ratios (x 100)

	Frame Structure			Frame-Wall Structures		
Level	Exterior Columns	Interior Columns	Beams	Columns	Beams	Wall
9	0.88	0.88	0.74	0.88	0.74	0.90
8	0.88	0.88	0.74	0.88	0.74	0.90
7	0.88	0.88	0.74	0.88	0.74	0.90
6	0.88	0.88	0.74	0.88	0.74	0.90
5	0.88	0.88	0.74	0.88	0.74	0.90
4	0.88	0.88	0.74	0.88	0.74	0.90
3	0.88	0.88	1.10	0.88	0.74	0.90
2	0.88	1.75	1.10	0.88	0.74	0.90
1	1.75	1.75	1.10	0.88	0.74	0.90

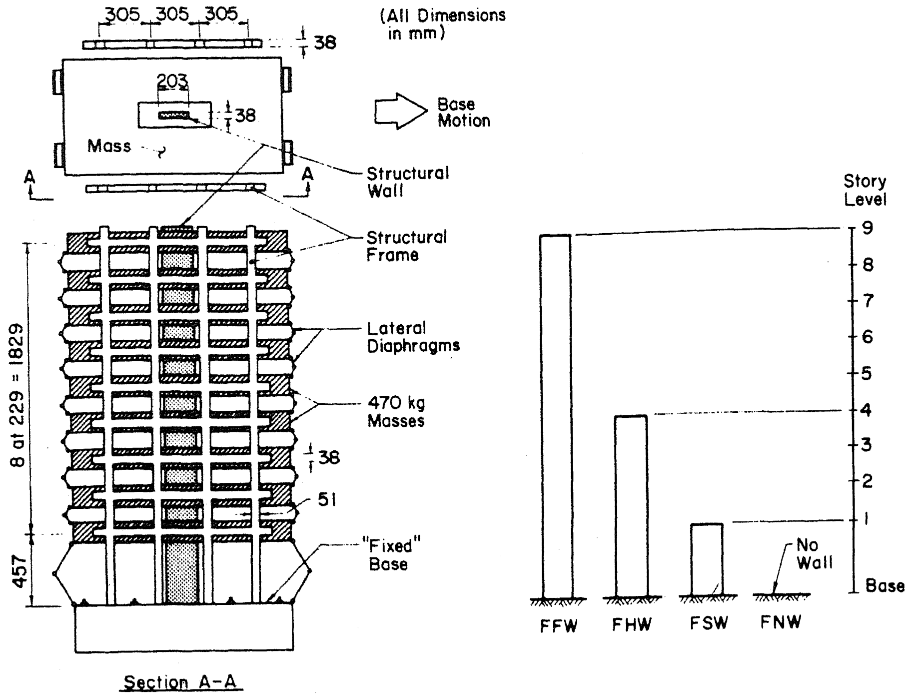
Note: Reinforcement ratio = A_s/bd

for columns and wall:
A_s = total steel area
b = width of section
d = depth of section

for beams:
A_s = top or bottom steel area
b = width of section
d = effective depth

Table 2. Mean Material Properties

Structure	Concrete Properties		Steel Properties	
	Strength (MPa)	Modulus (MPa)	Frame Yield (MPa)	Wall Yield (MPa)
FFW	37.1	18700	399	339
FHW	35.9	19000	399	339
FSW	34.5	18000	399	339
FNW	39.9	20300	399	339



(a) (b)

Figure 1. Dimensions of the Test Structures

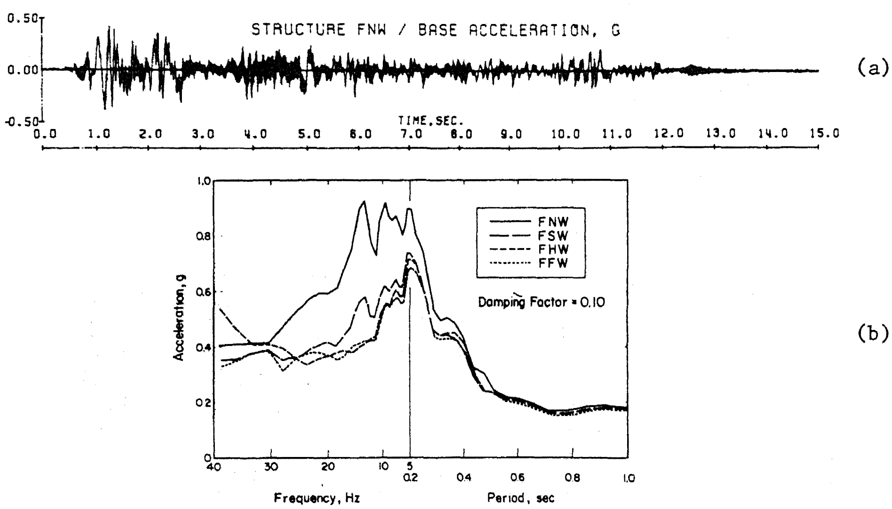


Figure 2. Measured Base Acceleration and Calculated Acceleration Response Spectra

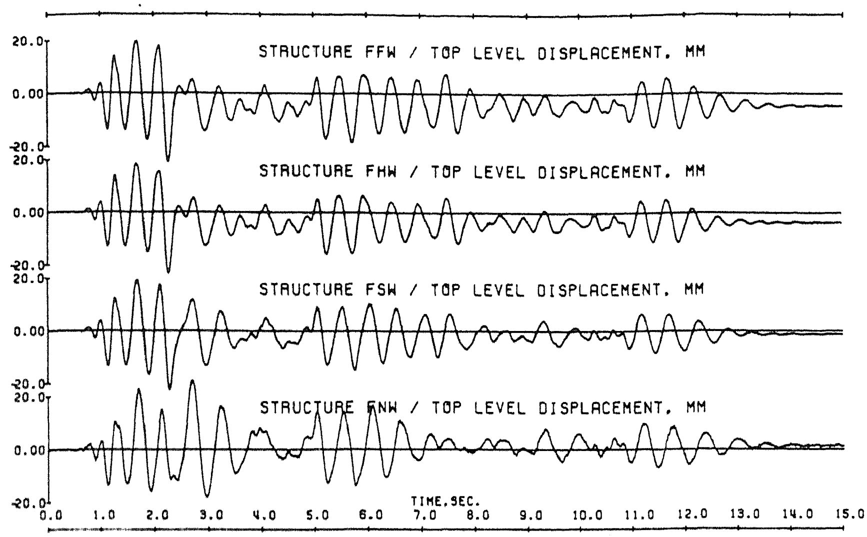


Figure 3. Displacement Measured at Top Level

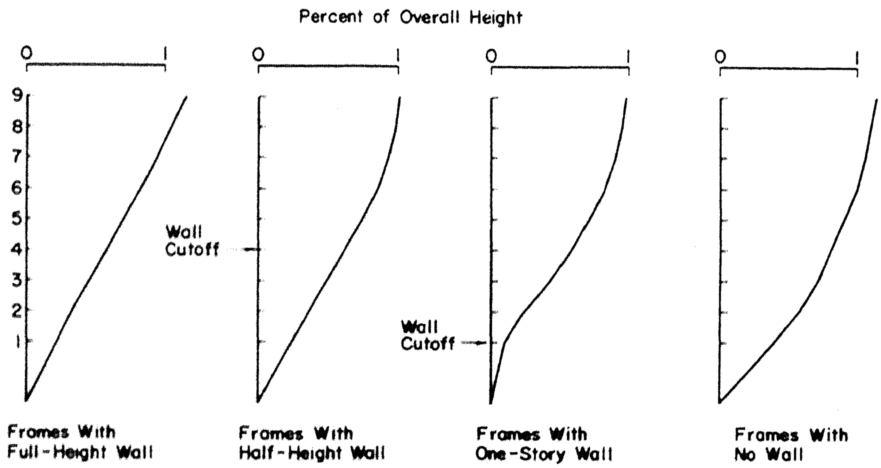


Figure 4. Variation of Displacement over Height of Structure at Time of Maximum Displacement

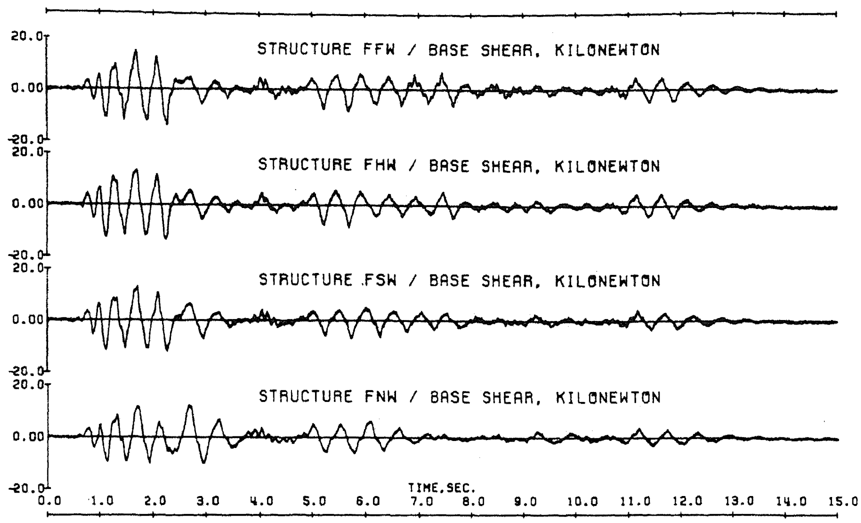


Figure 5. Measured Base Shear Response

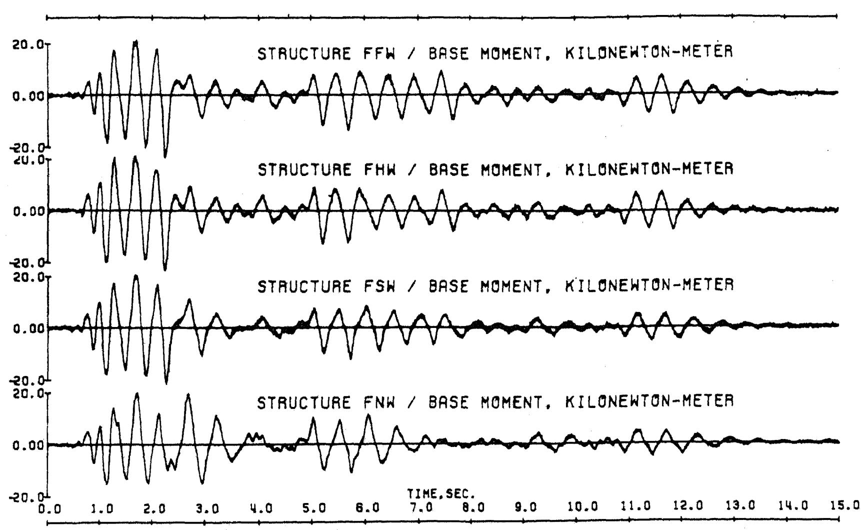


Figure 6. Measured Base Moment Response