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BEHAVIOR OF FLAT PLATE FLOOR SYSTEMS UNDER IN-PLANE SEISMIC LOADING

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SUMMARY

As part of a comprehensive investigation of the contribution of floor systems to the earthquake resistance of building structures, a series of in-plane shear tests were performed on reinforced concrete flat plates. The tests were designed to study the effects of (1) cyclic loading, (2) shear span variation, and (3) live gravity load on the behavior and strength of the plates. The effectiveness of repairing damaged plates by epoxy injection is also examined. The paper describes the test specimens, setup and techniques, and the behavior observed during the tests. Also included is a summary of the major test results.

INTRODUCTION

The dynamic response of a building subjected to earthquake ground motions depends not only on the characteristics of its vertical load-resisting elements, such as shear walls and frames, but also on those of its horizontal elements. The latter are normally represented by floor slabs which interconnect the vertical elements and make the building to behave as a three-dimensional structure. The floor slabs also act as diaphragms in transmitting and distributing the inertia forces to the vertical elements. Knowledge of the strength and stiffness of the slab and its dynamic properties are essential in determining the overall behavior of a building and the forces which the individual vertical elements are required to resist.

A research program is being carried out to study both experimentally and analytically the behavior of various types of reinforced concrete and metal deck reinforced composite floor systems subjected to in-plane loading. So far, two types of reinforced concrete floor systems have been studied in detail: flat plate and slab on beam. The results of the experimental study on flat plates are presented in this paper.

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Papers presented at
conferences based on
Nakashima
dissertation

RESEARCH OBJECTIVES AND TEST SPECIMENS

The main objective of the experiments is to study the strength and stiffness characteristics of the floor systems, as influenced by: (1) loading condition--monotonic vs. cyclic loading, (2) length of shear span or, equivalently, the moment-to-shear ratio, and (3) live gravity load . Other problems investigated are: the free vibration characteristics, the effectiveness of repair by epoxy injection, the interaction between floor slab and its supporting columns, and the behavior of slab-wall connections.

The test specimen was developed as a scaled model of a portion of the floor in a rectangular multi-story, multi-bay building, whose earthquake resistance is provided by shear walls located in selected bents. The seismic forces at various floor levels are transmitted to the walls through the diaphragm action of the floors. The columns in the building are spaced at 24 ft. on centers in two directions and are 24 in. x 24 in. with no capitals. The floor system selected for study represents an interior panel which is supported on one side by a shear wall and on the other side by columns. The prototype floor was designed for the gravity load condition according to the current ACI code with a required design strength of U = 1.4 D + 1.7 L. A working live load of 80 psf was adopted. The concrete strengths assumed were: 4000 psi for the floor slab and 5000 psi for the shear wall and columns. The yield stress of the reinforcing bars was assumed to be 60 ksi. The direct design method, as described in Section 13.6 of the Code, was employed in calculating the design moments, and sufficient reinforcements were provided to resist these moments. The columns were designed for the combined axial force and bending moment due to the gravity loads. A scale factor of 4.5 was then used to arrive at the test specimen dimensions.

In order to study effectively the variables mentioned above, the actual test specimen consists of three panels supported on two shear walls and four columns. Fig. 1 shows the test specimen and the various types of support conditions that can be provided by the test setup. The basic panel is 64 in. x 64 in. and is 2.22 in. thick. Overhangs, equal to one quarter of the panel dimension, are provided on three sides to represent portions of the floors of the adjacent bays in the prototype building. Fig. 2 shows the reinforcements (both positive and negative) used in the test panels.

Two identical specimens, designated as F-1 and F-2, were fabricated, using materials whose strength properties matched closely with those assumed in prototype design. The following tests were carried out on these specimens:

Specimen F-1:	Panel 1	monotonic test, with no live load
	Panel 2	cyclic test, with no live load
	Panel 3	monotonic test, larger shear span, with no live load

Specimen F-2: Panel 1 monotonic test, with live load

Panel 2 cyclic test, with live load

Panel 3 cyclic test, larger shear span, with no live load

The shear span is 64 in. for Panels 1 and 2 and 128 in. for Panel 3. The live load applied was maintained at the working level.

TEST SETUP, TECHNIQUES, AND SEQUENCE

A special setup was developed to perform the test. The three-panel structure was supported on four heavily reinforced concrete pedestals which were anchored to the laboratory test floor (Fig. 3). The fixtures connecting the shear walls to the pedestals were so designed that the support conditions for the walls could be easily changed. With the help of a set of heavy steel braces, the walls could be effectively fixed against rotation and translation in the plane of the test specimen. The walls could also rotate about an axis perpendicular to the same plane or slide freely with the test panels (Figs. 4 and 5). The columns could either slide freely on a metal surface 11 in. below the center line of the slab or rotate about a horizontal axis 16 in. below the slab. The latter was used in the column interaction studies.

The in-plane load was applied either by a hydraulic jack or a mechanical jack and was distributed to five points along the column line through a loading arm (Fig. 5). The cyclic test was conducted statically by applying repeated and reversed displacements of increasing amplitude to the slab until failure (excessive cracking) occurred. The live load was applied as a series of concentrated loads by a specially designed "gravity load simulator".

All the in-plane displacements and rotations were measured by LVDT's mounted on a fixed reference frame. The strains in the reinforcements and on the surface of the slab were measured by either single element strain gages or rosettes. A data acquisition system was used to record automatically all the LVDT and strain gage readings.

The actual test sequence varied somewhat for the two specimens. The following general sequence was adopted for Panels 1 and 2: (1) free vibration test using the hammer-impact or the drop weight method; (2) stiffness test by applying small symmetrical and anti-symmetrical loads to the edge of the panels, as shown in Fig. 4; (3) ultimate strength test with either monotonic or cyclic loading; (4) epoxy injection repair of the test specimen and repeating 3 above; and (5) column interaction test. Additional vibration tests were also performed during the course of testing. Panel 3 was not repaired and retested.

BEHAVIOR OF PANELS IN ULTIMATE STRENGTH TESTS

Specimen F-1, Panels 1 and 2   The general behavior and crack pattern of these two panels were very similar, although one was subjected to monotonic loading and the other to cyclic loading. Panel 1 was the first panel tested in the series and some difficulty was experienced in measuring the applied load. This problem did not appear again in the subsequent tests. In Panel 2, flexural cracks first formed near the wall (Section 1-1, Fig. 5(b)). When the load was increased to about 29 kips, a major crack of the flexural-shear type developed at a location near Section 2-2 where the negative reinforcements were terminated. This crack is illustrated in Fig. 5(b). (A similar crack forming at the opposite edge of the panel when the load was reversed is not shown). This crack grew rapidly in length and in width during the subsequent cycles of load application ($\delta_3 \pm 0.04$ in.). The test was stopped when a maximum δ_3 of 0.25 in. was reached. At that time, several reinforcing bars in the slab were broken. Fig. 6 shows the crack pattern of this panel after reaching an ultimate load of about 35 kips. The repaired panels behaved very similarly to the virgin panels.

Specimen F-1, Panel 3 and Specimen F-2, Panel 3   These panels were tested with a shear span of 128 in., as shown in Fig. 5(c). Their strength and crack pattern were essentially controlled by flexture. The general behavior of the two panels was again very similar except that the ultimate strength of the panel in F-2 (cyclically loaded) was noticeably less than that of F-1 (monotonically loaded). Flexural cracks developed initially between Sections 3-3 and 4-4 at a displacement of $\delta_5 = 0.04$ in., but these cracks did not affect the behavior significantly. A major flexural crack formed subsequently at a location about 10 in. beyond Section 4-4. The maximum load reached was 18.6 kips and the corresponding displacement was 0.13 in. in the monotonic test.

Specimen F-2, Panels 1 and 2   The test programs for these panels were similar to those for Panels 1 and 2 in Specimen F-1, except that live load, equal to the working value, was also applied. The live load caused several cracks near the wall and at the mid-span. The subsequent application of the in-plane load led to very extensive cracking of the panels, especially in the central portions. The in-plane load-carrying capacity was reduced about 20% because of the live load.

TEST RESULTS

In-plane stiffness tests   The results of the tests employing the symmetrical and anti-symmetrical edge loading as shown in Fig. 4, can be analyzed to yield a set of in-plane stiffnesses for the basic test panel (64 in. x 96 in.). These stiffnesses, denoted as K_{11} and K_{12}, are useful in performing three-dimensional analyses of building structures, when the effect of floor deformation is to be taken into account. These tests also permit experimental determination of the bending rigidity, EI, and the shear rigidity, GF, of the panels. The symmetrical test gives the values of θ_s, δ_{θ_s}, and the total edge displacement $\delta_{\theta_s} + (\delta_b + \delta_s)$. θ_s is obtained from the readings of LVDT #11 and #12, and δ_{θ_s} is equal to $\theta_s \times \frac{5}{4}L$. LVDT #1 (or #5) measures the total edge displacement which, after subtracting out δ_{θ_s}, gives the combined displacement $\delta_b + \delta_s$ due to bending and shear. When the results of the anti-symmetrical tests are analyzed by a similar procedure, the rotation θ_a can be obtained. Proper combinations of θ_s and θ_a corresponding to a given value of P give the desired stiffness properties of the test panel. The experimentally determined values for the panels of Specimen F-2 are $K_{11} = 10.9 \times 10^6$ kip-in and $K_{12} = 4.22 \times 10^6$ kip-in. They compare closely with the calculated values (based on experimental material properties) of 10.7×10^6 and 4.18×10^6 based on the simple beam theory but modified for the effect of shear.

Ultimate strength tests Fig. 8 shows the load-deflection ($P - \delta_3$) hysteresis relationships of Panel 2, Specimen F-1. The hysteresis loops do not resemble those normally obtained from testing reinforced concrete structural elements, such as beams, columns and shear walls. The test panel contains relatively small amounts of reinforcing steel ($\rho = 0.0048$ for Section 1-1 and 0.0023 for Section 2-2) and, unlike some of the ductile shear walls, it has no "boundary members". Table 1 summarizes the maximum loads of all the panels tested. The predicted maximum load for the case of monotonic loading and without live load is 39.4 kips based on bending strength of Section 1-1 and is 30.2 kips based on Section 2-2. In the monotonic test, the panel was always "pushed" (+P) first and the extent of damage caused by the initial push affects the maximum load that could be attained when the panel was "pulled" in the reverse direction. The maximum loads reported in Table 1 can be used to evaluate the significance of the major variables included in the test program. (See the section on "Research Objectives and Test Specimens"). Cyclic loading causes only a slight reduction of the ultimate load for Panel 2. This reduction, however, becomes 14% for Panel 3. An increase of the shear span from 64 in. to 128 in. decreases the maximum load by about 50%. The working live load acting on Panels 1 and 2 causes a reduction of the in-plane strength by about 20%. Epoxy injection repair recovers substantially the original strength of Panels 1 and 2.

CONCLUSIONS

A program of tests of six reinforced concrete flat plates subjected to in-plane loading has been described. The following tentative conclusions may be reached based on the results of these limited tests.

1. The ordinary beam theory, with modification for the effect of shear deformation, can be employed to determine the elastic in-plane stiffness of flat plates whose aspect ratios (length-to-depth ratios) may be as low as 0.64.

2. The behavior of flat plates under cyclic loading is very similar to the behavior under monotonic loading. A small reduction in ultimate load due to cyclic loading is likely.

3. The strength and failure mode of flat plates are affected significantly by a change of the length of the shear span (or the

moment-to-shear ratio). Both flexural and flexural-shear modes are possible.

4. The presence of working live load reduces the in-plane strength by about 20%.

5. The original strength of damaged plates may be recovered substantially by epoxy injection repair.

ACKNOWLEDGMENTS

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TABLE 1 SUMMARY OF ULTIMATE LOADS

Specimen and Panel Nos.	State of Test Panel	Ultimate Load (kips)	
		Push +P	Pull -P
F-1, Panel 1	Virgin	24.5*	12.9*
Monotonic	Repaired	36.0	13.2
F-1, Panel 2	Virgin	35.5	32.0
Cyclic	Repaired	34.4	32.8
F-1, Panel 3	Virgin	18.6	7.9
Monotonic			
F-2, Panel 3	Virgin	15.9	14.2
Cyclic			
F-2, Panel 1	Virgin	29.5	22.8
Monotonic	Repaired	28.8	20.5
F-2, Panel 2	Virgin	33.2**	28.9**
Cyclic	Repaired	28.1	20.5

*These loads are being further checked. For the case of +P, the maximum load is probably more than 36 kips.

**The live gravity load applied was about 1/3 of the working value.

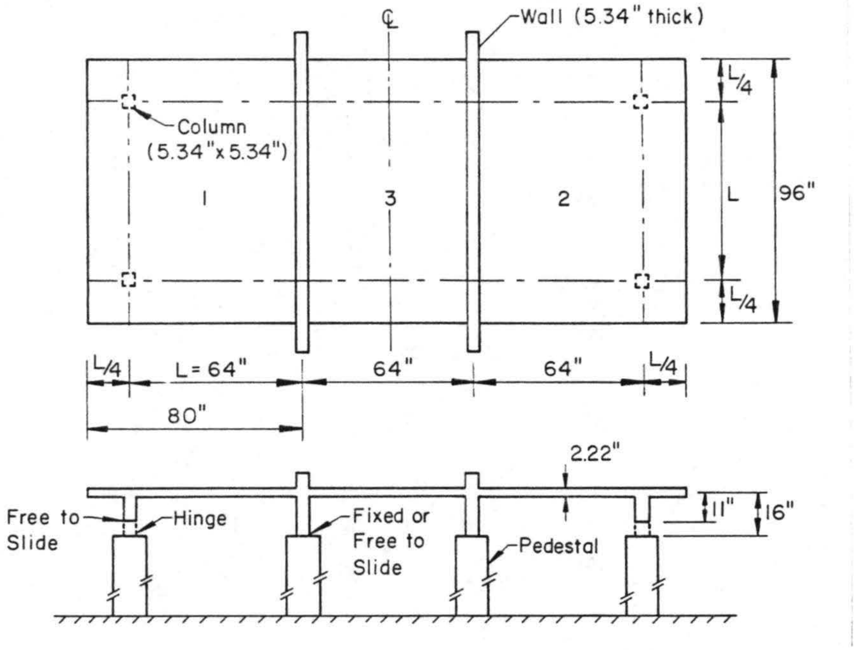


Fig. 1 Test Specimen and Support Conditions

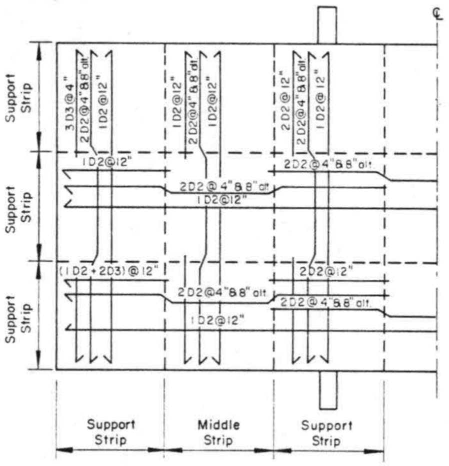


Fig. 2 Reinforcement Details

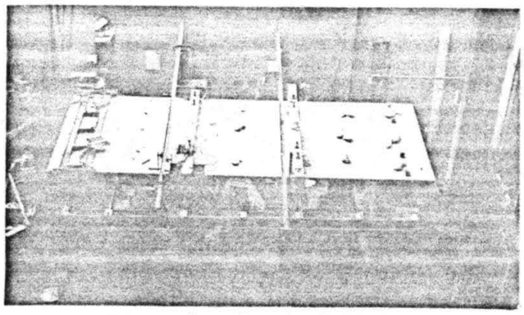
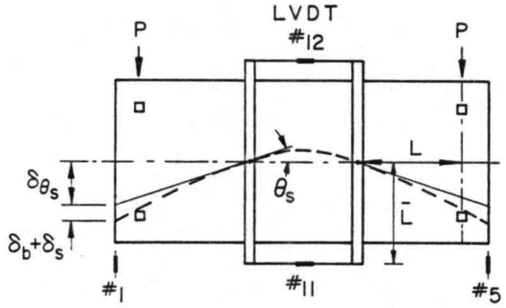
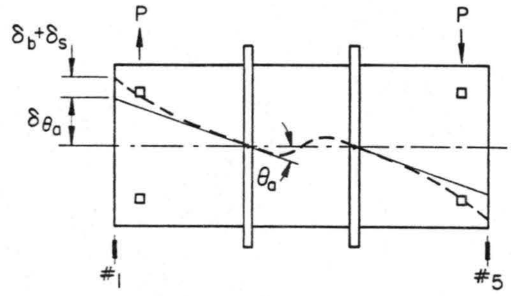


Fig. 3 Test Setup



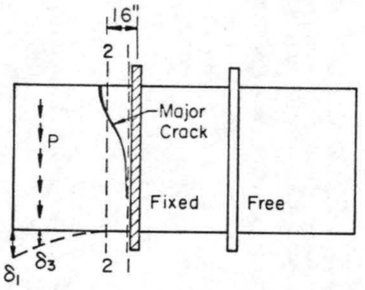
(a) Symmetrical Loading



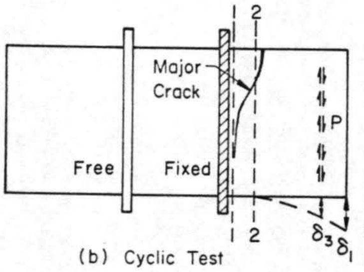
(b) Anti-symmetrical Loading

Walls Allowed to Rotate, Columns Free to Slide

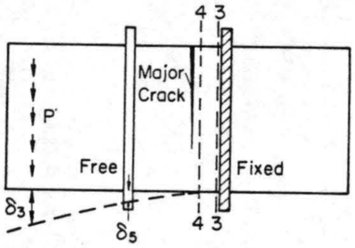
Fig. 4 Stiffness Tests



Columns Free to Slide
(a) Monotonic Test



(b) Cyclic Test



Monotonic: F-1, Cyclic: F-2
(c) Monotonic and Cyclic Tests of Panel 3

Fig. 5 Ultimate Strength Tests

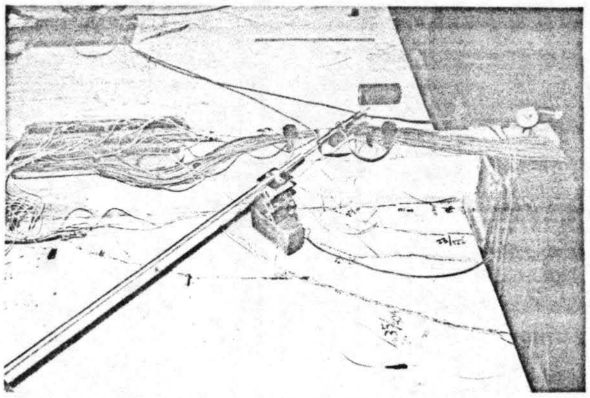


Fig. 6 Crack Pattern of Panel 2
Specimen F-1

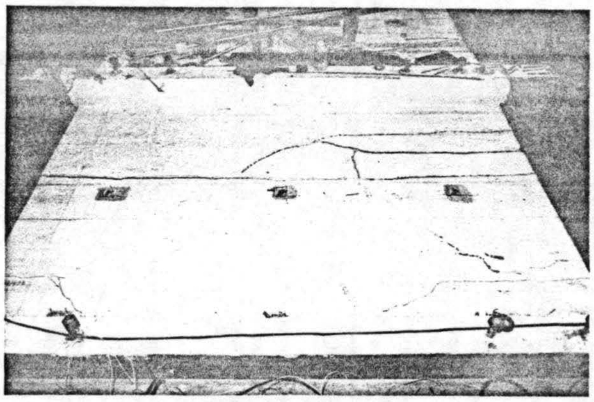


Fig. 7 Crack Pattern of Panel 3
Specimen F-2

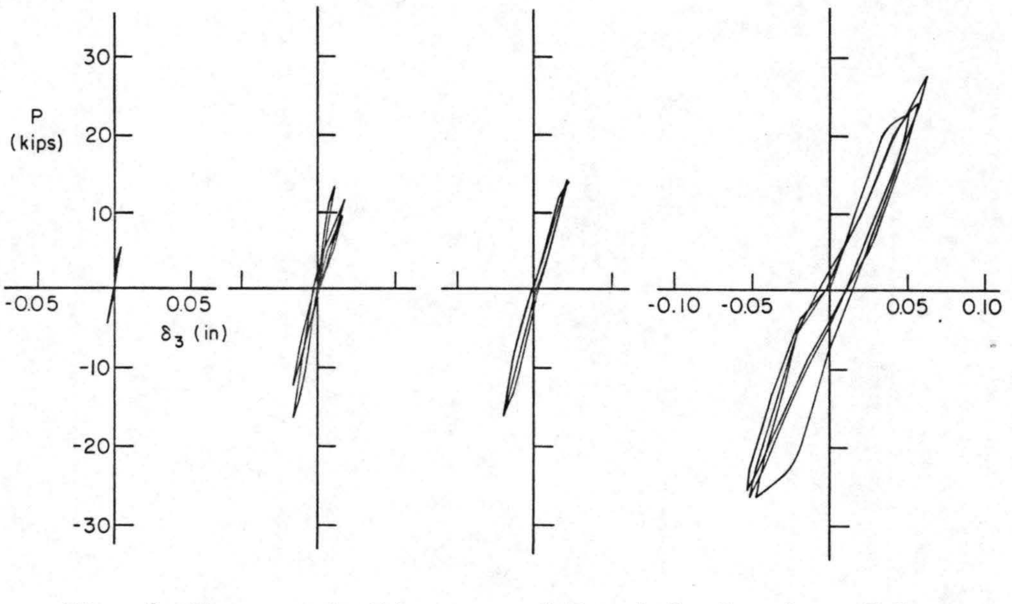


Fig. 8 Hysteresis Diagrams of Panel 2, Specimen F-1