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論　文

[2219] Analytical Study on the Seismic Behavior of Reinforced Concrete Slabs

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1. INTRODUCTION

In current design practices, floor slabs are frequently assumed to be perfectly rigid in their own planes. Under this assumption, lateral loads are distributed to vertical structural elements in proportion to the story stiffness of each element.

Experience and research, however, have revealed more or less large variation in actual distributions of loads from those calculated based on this assumption. The deviation notably can occur in buildings having long and narrow floor plans; where the in-plane shear stiffness of the floor slabs is critical to the structural safety due to the force redistribution as their stiffness is decreased by cracking.

To date, there have been only a few studies on the effect of slabs as diaphragms on the building response [2,6,7], and even fewer [3,4] on the slab behavior under both the in-plane and out-of-plane forces, as is the case with any building structure.

However, one of these studies [3] deals only with the case of pure bending and the majority of the analyses so far proposed of such slab behavior treat the in-plane problem ignoring the out-of-plane loading which might change the in-plane resisting mechanism of the structure.

This paper proposes a finite element analytical system capable of describing the slab behavior under the combined loading by utilizing the layered Mindlin plate bending element and the membrane element and verifies it against the test results of eight test specimens subjected to combined loading conditions.

2. EXPERIMENTS OUTLINE

2.1 TEST SPECIMENS AND MATERIAL PROPERTIES

The genaeral view and cross sections of a test specimen are introduced in Fig. 1. The test specimen was developed as a one-fifth scale model of a floor system in a building designed according to the corresponding Japanese Code [1].

Each specimen consists of two rectangular panels of the beam-supported slab type. Its

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edge beams are 60 mm wide by 120 mm deep, reinforced longitudinally with eight $\phi 6$ bars or eight $\phi 4.4$ bars. Shear reinforcement comprises of $\phi 2.6$ closed stirrups set 40 mm spaces apart. Both slab panels are 30 mm thick, and are reinforced with $\phi 2.6$ spaced at 40 mm and at 80 mm.

One slab panel was subjected to the lateral load in parallel with the interior beam, while the other was used to ensure edge fixity of the specimen.

The test specimens are divided into two groups different in the slab aspect ratio (defined as the dimension of the specimen orthogonal to the lateral loading direction to the dimension parallel to it); i.e. comprising four of L-type with spans of 1200x800 mm (aspect ratio=*3/2*), and the other four of S-type with spans of 800x1200 mm (aspect ratio=*2/3*).

Table 1 Test Specimen Configuration

Test Specimen	Out-of-plane Force (ton)	Configuration	Beam Reinforcement (bars)
L-6-1	0.4	L-type	8 ϕ 6
L-6-2	1.0		
L-6-3	3.0		
L-4-1	1.0		8 ϕ 4.4
S-6-1	0.4	S-type	8 ϕ 6
S-6-2	1.0		
S-6-3	3.0		
S-4-1	1.0		8 ϕ 4.4

Arrows denote the lateral load direction

Table 1 gives the scheme of elemental working concepts of the current experiment and the load conditions. Within their respective groups, test specimens are identical in dimensions but different in magnitude of applied constant vertical load (to investigate the effect of vertical load level on the in-plane resisting mechanism), and the beam main reinforcement ratio.

Measured mechanical properties of both reinforcement and concrete used in the experiments are shown in table 2.

The structural mortar (of Portland Cement) was cast to be leveled, steam-cured for a day, and then was exposed to the air till its natural hardening.

2.2 TEST SETUP AND INSTRUMENTATION

A general view of the test setup is

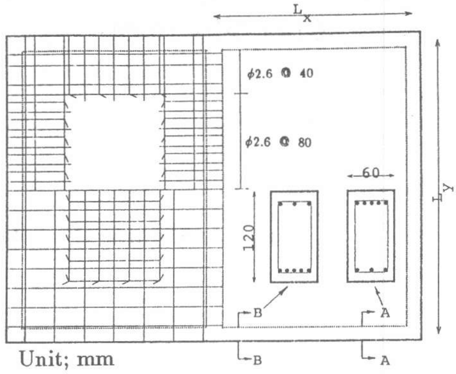


Fig. 1 Test Specimen

Table 2 Mechanical Properties of Materials

Test Specimen	Concrete f'_c kg/cm^2	Concrete E_c kg/cm^2	Reinforcement $\phi 2.6$ f_y kg/cm^2	Reinforcement $\phi 2.6$ E_s kg/cm^2
L-6-1	234	227000	4316	2000000
L-6-2	282	249000		
L-6-3	217	219000		
L-4-1	226	223000	4453	2300000
S-6-1	271	244000	4316	2000000
S-6-2	205	213000		
S-6-3	217	219000		
S-4-1	226	223000	4453	2300000

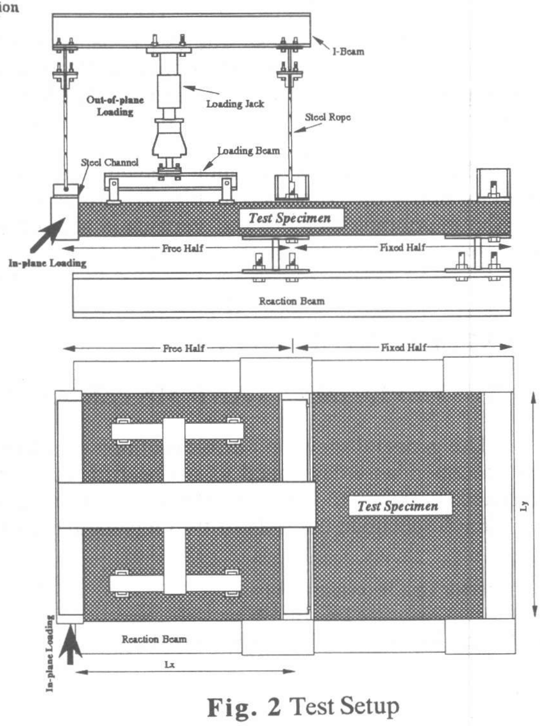


Fig. 2 Test Setup

shown in Fig. 2. The specimen was fixed to the reaction beams using steel channel pieces with bolts. The free-end beam was covered by steel channel through vertical bolts.

Cyclic lateral (in-plane) load was applied to the specimen along its free end through the covering steel channel. In this case the bolts to fix the channel side by side to the exterior beam were designed to distribute the lateral load along the beam.

At first, vertical loading was increased at several successive stages up to the designed level, to be followed by cyclic loading.

The nominal deflection levels represent the in-plane deflections of the free end amounting to 0.05% (by one cycle), 0.1% (by 2 cycles), 0.2% (by 1 cycle), 0.4% (by 2 cycles) and 1.6% (by half cycle).

Slab and longitudinal beam reinforcing bars were mounted by electrical resistance strain gages at different critical sections. Linear variable displacement transducers were installed at some critical location on the slab whereby to monitor its displacement.

3. FINITE ELEMENT MODEL

To represent the behavior of such slab panel, two ingredients are required in a finite element system. First, the element should be capable of describing both the vertical and lateral deflections. For this purpose, two basic elements were superimposed, namely the layered Mindlin plate bending element for the out-of-plane case, and the membrane element for the in-plane case. Second, the material model should describe adequately the reinforced concrete behavior.

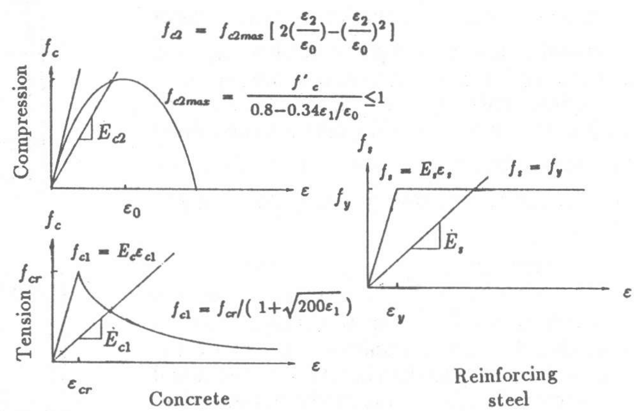


Fig. 3 Constitutive Relationships

3.1 GENERAL ASSUMPTIONS AND CONSTITUTIVE RELATIONS

The concrete is assumed to be isotropic up to either cracking or crushing, and the model allows for strain softening after cracking or crushing.

A smeared crack approach is adopted and rotating cracks are assumed to form following the principal strains' orientation. Cracked reinforced concrete is treated as an orthotropic material with its principal axes correspond to the direction of the principal average strain and average compressive strain. Poisson effect is ignored after cracking.

The strain hardening of reinforcement steel is also ignored. The constitutive relations contained in the modified compression field theory [8] have been adopted and are summarized in Fig. 3.

3.2 ANALYSIS PROCEDURE

The slab floor is divided into elements and layers. Each layer may have different material properties, but these properties are assumed to be constant over the layer thickness. This allows a discretized variation of material properties and stress states through the thickness as loading progresses yet retains the limited degrees of freedom of the two-dimensional approach. A further advantage is that only a biaxial yield criterion for concrete need be known, because each layer is assumed to be in a state of plane stress.

Moreover, since there are two states of loading (out-of-plane and in-plane), this discretization would provide a good presentation of the strain and internal forces occurring in any state at each layer. This would make such variables and states easier to update and deal with.

The element selected for use is rectangular and has eight nodes. A 3x3 Gaussian integration over the element layer plane is adopted.

The strains are evaluated from the displacement field at each integration point within each layer and are used in the constitutive relationships to form the stiffness matrix and to evaluate the stress state at each level where plane stress conditions are assumed.

Following the order of the loading history, the structure is analyzed under the constant vertical loads then under the lateral ones. Under the vertical loads, out-of-plane strains ε_{out} are calculated and crack occurrences are marked. Then while carrying out the next step of analyzing the structure under lateral loads, these out-of-plane strains ε_{out} are added to the in-plane strains ε_{in} resulting from the in-plane analysis.

$\varepsilon=\varepsilon_{out}+\varepsilon_{in}$ Eq.1

The internal forces vector $F_{internal}$ resulting from the first step is compensated for and modified at each iteration because of the stiffness changes, and then is added to the nodal forces vector $F_{external}$, this can be expressed as

$F=F_{external}+F_{internal}$ Eq.2

Cracks formed already in the out-of-plane analysis process are assumed incapable of contributing to the element lateral resistance, therefore the stiffness at such a point is zeroed out.

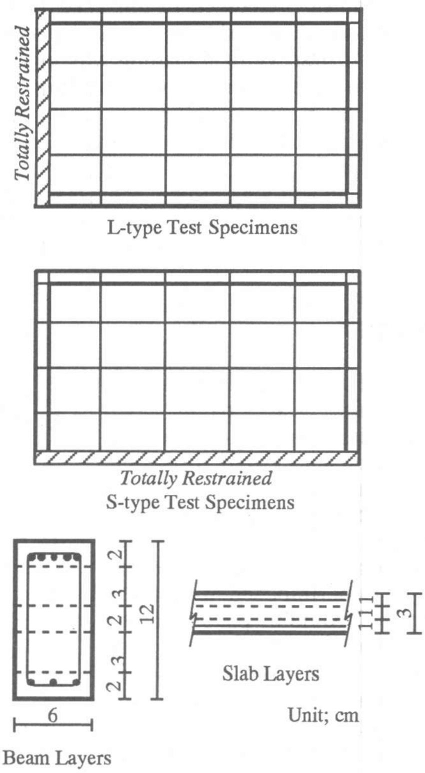


Fig. 4 Mesh and Layers

4. COMPARISON BETWEEN THE EXPERIMENTAL AND ANALYTICAL RESPONSE

4.1 PREDICTION OF LATERAL LOAD-DEFLECTION CURVES

The described procedure was implemented in analyzing the response of the eight test specimens. Each test specimen was divided into elements according to both the overall geometry and reinforcement arrangement. As a result, a 6x6 and a 5x6 mesh were generated for L-type and S-type test specimens respectively.

Each element was divided into layers; beam element into 5 and slab elements into 3. Fig. 4 shows the mesh and layers of both types of test specimens.

The modeled free half of the test specimen was assumed to be fully restrained to the middle beam and restrained only vertically at the free edge. Materials parameters (f_{cr}, ε_0) were assumed as in [8].

The test results for some specimens are plotted in Fig. 5. A close agreement is obvious between the predicted and observed results for L-type test specimens. However, in S-type test specimens, the predicted failure force value was about 15% to 20% less than the observed

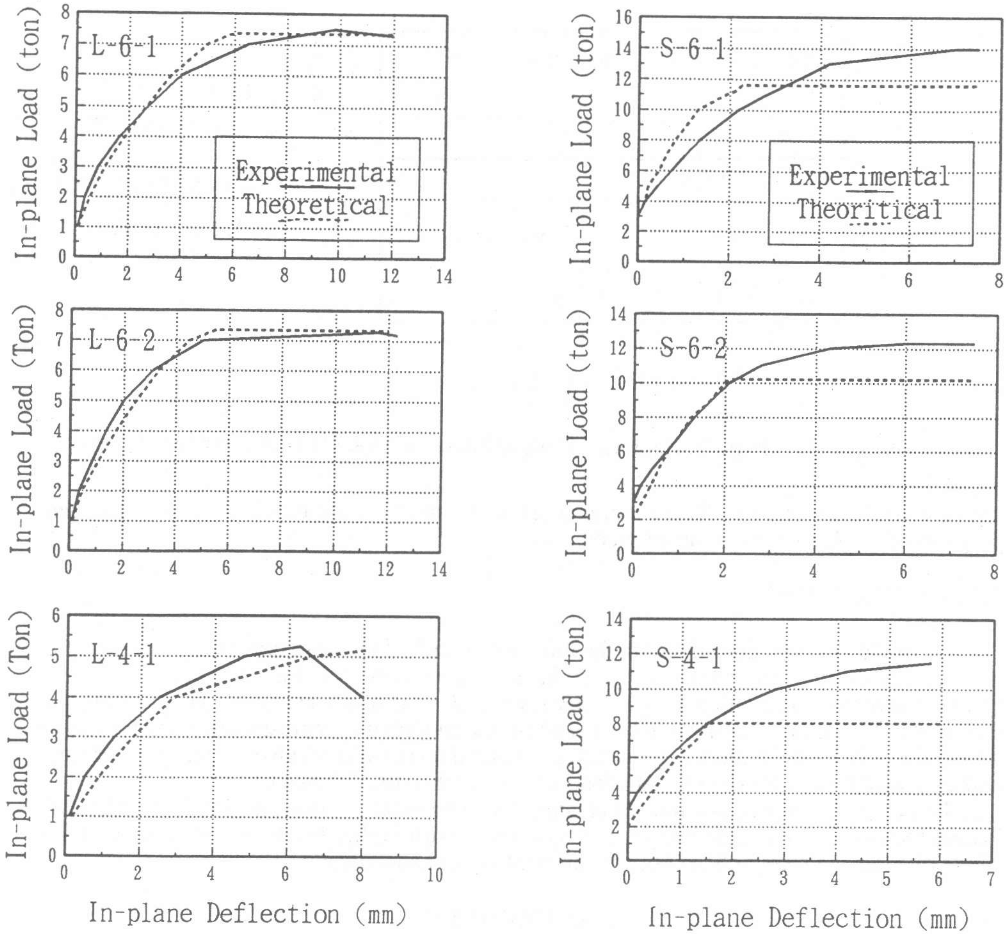
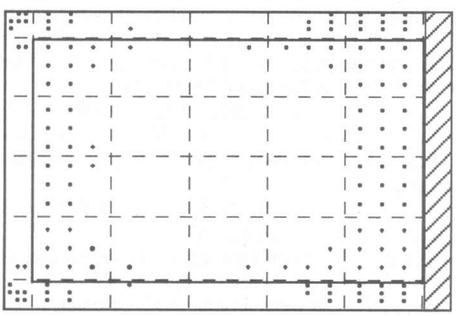


Fig. 5 Comparison of Experimental and Analytical Results

one. As for the specimens subjected to the ultimate vertical load, the analytical values were found not to correspond well with the experimental ones. This can be attributed to the cracks formed by the out-of-plane loading phase, as can be seen in Fig. 6 which shows cracks which occurred in the first analysis phase due to vertical loading for the test specimen L-6-3. Therefore the proposed analytical procedure should further be improved so as to cover such an extreme case.



* Gaussian Point at which a crack or more occured

Fig. 6 Upper Surface Cracks (L-6-3) 'Analytical'

4.2 PREDICTION OF THE OUT-OF-PLANE DEFORMATION

The calculated vertical deformation values are shown in Fig. 7. The analytical results agreed with the observed phenomena that is the out-of-plane deflection increase because of the

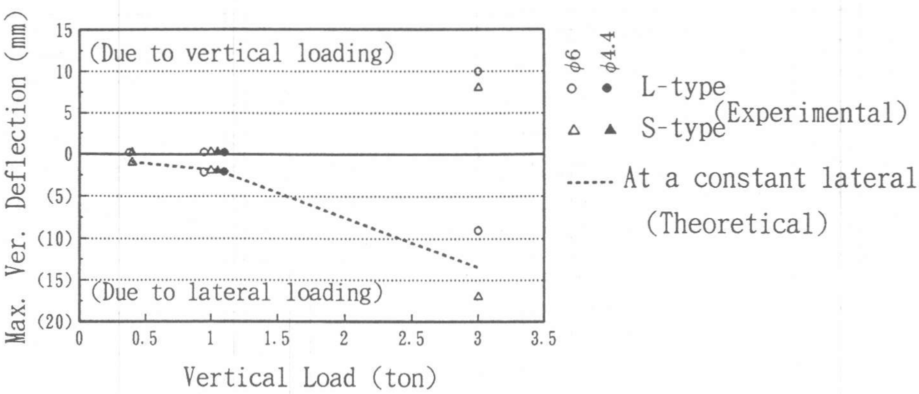


Fig. 7 Maximum Vertical Deflection vs. Vertical Load Level

in-plane loading increase. These deflections were more pronounced for test specimens subjected to higher levels of out-of-plane loads.

5. CONCLUSIONS

From the present investigation, the following conclusions were drawn:

1. A finite element procedure using two basic elements (the Mindlin plate bending element and the membrane element) to analyze floor slabs under out-of-plane and in-plane loading was suggested. The constitutive laws were based on the modified compression field theory, with smeared crack representation. A good agreement could be obtained between both experimental and analytical results for out-of-plane load levels less than the ultimate level.
2. Out-of-plane deflections increased with the increment of in-plane loading. Also this increase was more distinguished for test specimens with higher levels of out-of-plane load. These phenomena were noticed both experimentally and analytically.

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