Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Loading tests and analyses of various types of reinforced concrete slabs under different deformation speeds

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ABSTRACT: In reinforced-concrete structures, the characteristic of their hysteresis curve, expressed by the relationship between the load and the response deformation, greatly differs depending on the deformation speeds. By using a high-speed loading apparatus and four types of approximately 1/7.5 scale model specimens of reinforced-concrete plates for industrial facilities, the authors applied concentrated loads to the surface at 3 loading speed: static, low, and high to obtain the degree of deformation and failure behavior. In this way, the authors clarified the relationship between the deformation speed and load, and the degree of deformation. We also analyzed the behavior of typical specimens by applying the finite element method and we noted how the characteristic of hysteresis curve is affected by the deformation speed of the reinforced concrete. We also found that the analyzed results could explain the experimental results until the occurrence of punching shear failure.

1 EXPERIMENTAL METHOD AND SPECIMEN

Using a high-speed loading apparatus (Figure 1), the test specimen was loaded (Tsujimoto 1989) with the loadingplate, first being placed in contact with the center of the test specimen. Then it was moved by dislocating the actuator. The loading speed could be set to the desired value within a range of 0 to 4 m/s. The setting speed during the test was 3 m/s for high-speed loading and 0.03 m/s for low-speed loading. The displacement of the loading plate could be set to the desired value within a range of 0 to 15 cm. In this test, we set the displacement to 15 cm, the maximum value of the apparatus capacity. The loading plate used was a square steel plate with dimensions of 15 cm×15 cm (5 cm in thickness).

Table 1 shows the basic conditions of the four types of test specimens. Figure 2 and Figure 3 show the shapes of the flat plate and the cylindrical wall. The flat-plate test specimens, in three different thicknesses and the ratio of reinforcement bar, each being a square plate with the dimensions of 120 cm×120 cm was simply supported on all four sides at 100-cm span positions. The cylindrical wall test specimen, a curved plate measuring 150 cm×100 cm in the shape of a part of a cylindrical wall, was simply supported on two sides at the 120-cm span positions. To prevent deformation from expanding as a curvature, the two sides of the curved plate were constrained by PC steel bars. Reinforcing bar, D6 or D10, made of SD295 material was used as the main reinforcement of the test specimens.

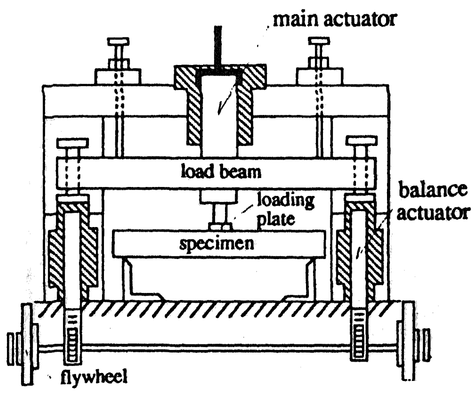


Figure 1. Loading apparatus

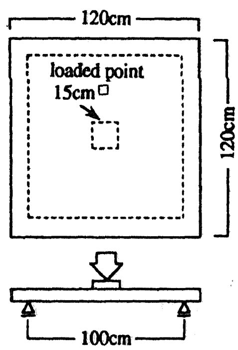


Figure 2. Flat plate type specimen

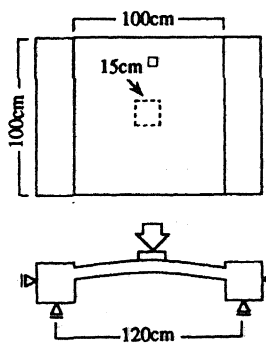


Figure 3. Cylindrical wall type specimen

Table 1. Test specimens and bar arrangements

	Plate thickness	Ratio of reinforcement
Flat plate (A)	12cm	0.5%
Flat plate (B)	12cm	0.2%
Flat plate (C)	7cm	0.5%
Cylindrical	9cm	0.4%

2 MATERIAL TEST

To assess the mechanical properties of the material constituting the test specimens, material tests were conducted at static, low, and high loading speeds. Table 2 shows the test results on the compressive strength and tensile strength of the concrete material. The test was conducted with 10 cm-diameter cylinders.

Young's modulus was evaluated with a secant elastic modulus at the 1/3 point of the stress level in the compressive strength.

Table 3 shows the tensile test results of the reinforcement bar (D10) used as the main reinforcement for the test specimens.

Table 2. Physical properties of concrete

Unit : MPa

	Static	Low speed	High speed
Flat plate			
compression	24.1	30.5	43.9
tention	2.0	2.8	5.9
Young's modulus	21000	32100	42400
Cylindrical wall			
compression	33.0		51.0
tention	2.7		6.4
Young's modulus	21300		43200

Table 3. Physical properties of reinforcement bar

Unit : MPa

Yield stress			Tensile stress		
Static	Low speed	High speed	Static	Low speed	High speed
367	423	445	577	607	646

3 TEST RESULTS

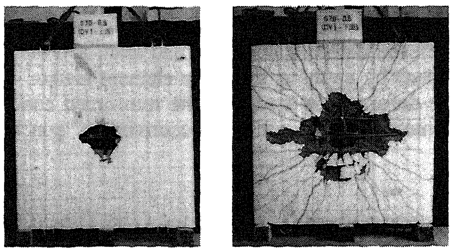
Figure 4 and Figure 5 respectively show the final failure conditions of the flat plate (C) and the cylindrical wall test specimens after high-speed loading tests.

In the flat plate (C), bending deformation occurred during the initial stage of loading in all the loading tests, and in final stage punching shear failure resulted. The final failure modes were nearly the same for all the loading speeds. That is, no cracks occurred at the front surface of the specimens except for the hole drilled with the loading plate; however, radiating cracks occurred at the rear surface as indicated in Figure 4.

In the cylindrical wall, the failure modes were greatly affected by the loading speeds. During static loading, punching shear failure occurred, and at the rear surface, the concrete lacked a circular shape when the loading plate was at the center. During high-speed loading, however, bending compression failure occurred, and the specimen cracked at the center. At the rear surface, punching shear failure was observed, as indicated in Figure 5.

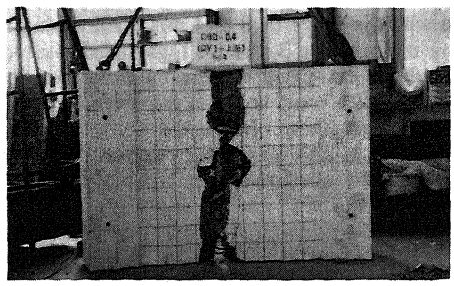
Figures 6 to 9 show the relationship between the load and the displacement of the loaded point at the center of the test specimen. Table 4 shows the maximum strength of each specimen.

In every test specimen, the maximum strength increased in the order of static, low-speed, and high-speed load-



front surface rear surface

Figure 4. Final failure of flat plate (C) after high-speed loading test



front surface

rear surface

Figure 5. Final failure of cylindrical wall after high-speed loading test

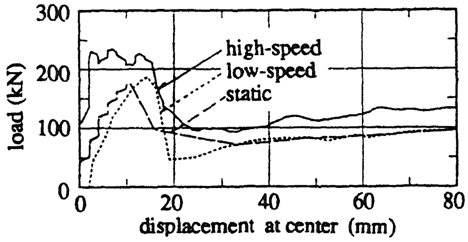


Figure 6. Load-dispacement Curve (Flat plate A)

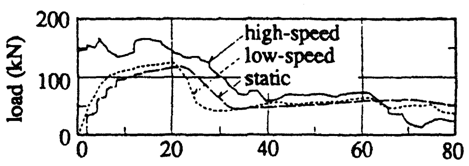


Figure 7. Load-dispacement Curve (Flat plate B)

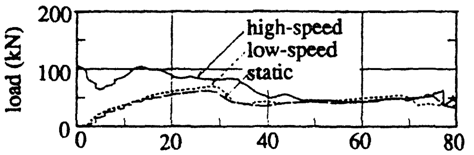


Figure 8. Load-dispacement Curve (Flat plate C)

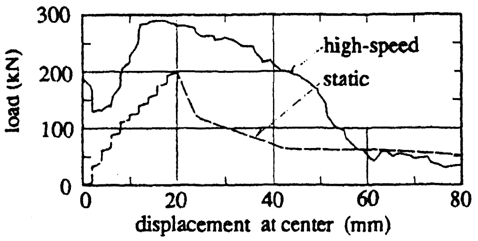


Figure 9. Load-dispacement Curve (Cylindrical wall)

ing, indicating that the greater the loading speed, the greater the load that could be borne by the structural components. This is probably due to the fact that the compressive strength and tensile strength of the concrete and reinforcement bar increase with the increase in the loading speed, as indicated in the results of the material test.

The effect of the parameters on the maximum strength will be described below:

Slab thickness: In the test of flat plate (A), which was 12 cm thick, the maximum strength was 7% greater during low-speed loading and 35% greater during high-speed loading than it was during static loading. Also, in the test of 7 cm thick flat plate (C) with the same ratio of reinforcement bar, the maximum strength was 14% greater during low-speed loading and 71% greater during high-speed loading test that it was during static loading. Thus, it can be concluded that the increased rate of the maximum strength of the flat plate (C) was twice as

Table 4. The maximum strength of specimens

Unit : kN

	Static	Low speed	High speed
Flat plate (A)	174 (1.00)	187 (1.07)	235
Flat plate (B)	118 (1.00)	124 (1.05)	166 (1.41)
Flat plate (C)	61.7 (1.00)	70.2 (1.14)	106 (1.71)
Cylindrical	201 (1.00)		290 (1.44)

The parentheses indicate the ratio of the value to the static loading test results.

great as that of the flat plate (A).

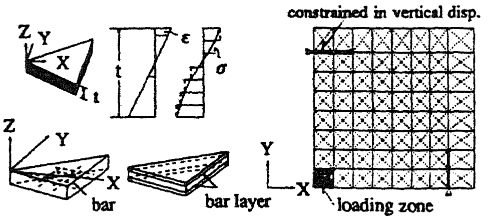
Ratio of reinforcement: A comparison of flat plates (A) and (B), in which only the ratio of reinforcement is different, indicates that the increase in the maximum strength is nearly the same in (A) and (B) both at low-speed and high-speed loading. It may be concluded, therefore, that the ratio of the reinforcement hardly affects the maximum strength when the loading speed increases.

Cylindrical wall test specimen: During the testing of the cylindrical wall specimen, the maximum strength proved to be 44% greater during high-speed loading than during static loading. The experimental conditions for the cylindrical wall specimens were different from the conditions for the flat-plate specimens in that a one-way slab was used and an in-plane axial force was applied. Despite such differences, the increase in the maximum strength was as great as that in the flat-plate specimens.

4 SIMULATION ANALYSES OF TEST RESULTS

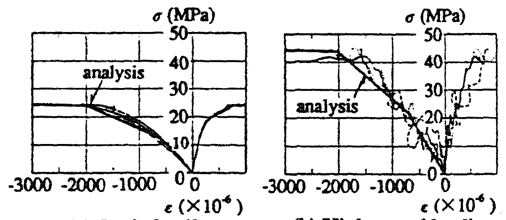
For typical test specimens, we conducted simulation analyses of reinforced-concrete structures with a nonlinear finite element analysis program using the layered shell elements CARC-SHELL-DYN (Uchida 1985). The test specimen was a flat-plate specimen (C) and the analyzed results were compared with the results for the static and high-speed experiments.

As Figure 10 (b) shows, as the analysis model we adopted a flat quadrilateral element for a quarter part of the plate for which the symmetry was considered. The concrete was partitioned into 64 elements and 7 layers, and the reinforcement was modeled with equivalent layers (Figure 10 (a)) with rigidity in only the reinforcement direction. For the analyses, the stress-strain relationship of the concrete and reinforcement bar under both static and high-speed conditions were assumed to be as shown in Figure 11 and Figure 12, based on the material test results. The boundary conditions of the test specimen were defined as the simple support of the sides; however, when the contact conditions at the support in the experiment were actually measured, the four corners of the test specimen were observed to float up.



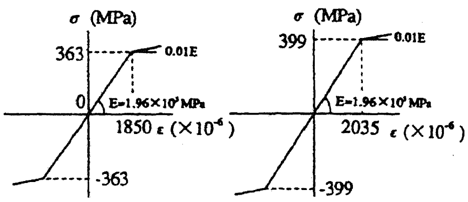
(a) Model in thickness (b) Mesh layout

Figure 10. Analytical model of test specimen (C)



(a) Static loading (b) High-speed loading

Figure 11. Stress-strain curves of concrete



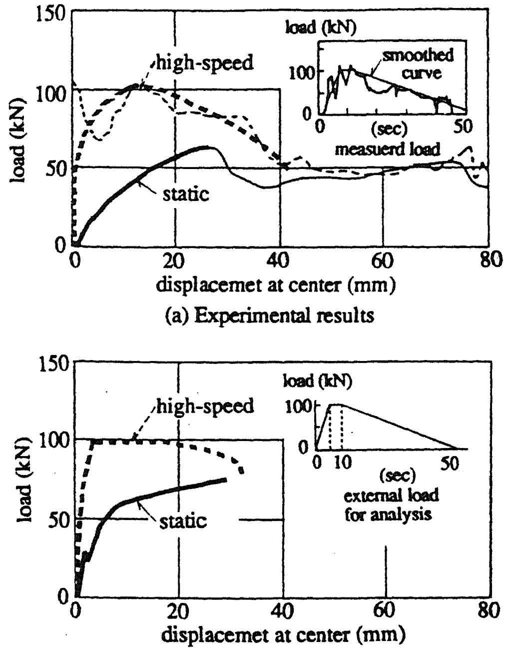
(a) Static loading (b) High-speed loading

Figure 12. Stress-strain curves of reinforcement bar

Therefore, vertical displacement was constrained only at the positions indicated by thick lines in Figure 10 (b). During static loading, the loading plate was assumed to be a rigid body, and was given the same displacement, while its reaction force was taken as the load. During high-speed loading, the load (Figure 13 (a)) measured at the loading plate was smoothed, and taken up as the external load (Figure 13 (b)) for analysis.

Then a nonlinear analysis due to the time-dependent load was performed to calculate the response results.

Figure 13 shows the relationship between the load and the displacement at the center of the test specimen, obtained through the experiments so that the results of both cases could be compared. During the experiment, the load-displacement relationship during high-speed loading was given as a complex, irregular curve, while in the analysis, the load was smoothed. Thus, the experiment results until the occurance of punching shear failure corresponding to the analysis could be, as a whole, expressed by the thick line in Figure 13 (a). Figure 13 shows that the experimental results and the analytical results match well. Thus, in nonlinear finite element analysis of reinforced-concrete structures using layered shell elements, once the material characteristics during both static and high-speed loading are given, it becomes possible to explain the plate-loading experimental results until punching shear failure occures.



(a) Experimental results

(b) Analytical results

Figure 13. Comparison of experimental and analytical results

5 CONCLUSIONS

By applying concentrated loads to the surface of the reinforced-concrete plates at static, low, and high loading speeds, we find that, as the loading speed increases, the slab failure mode changes, and the maximum strength of slab increases.

We also find that the loading test results until the occurrence of punching shear failure can be explained by indicating the material characteristics at static and high-speed loading during nonlinear finite element analysis of the reinforced-concrete structures using layered shell elelments.

This study was carried out as a part of joint research study by 10 electric power companies in Japan (Tokyo, Hokkaido, Tohoku, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu and Japan Atomic).

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