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Evaluation and Improvement of Performance of Concrete Beams against Impact Loading

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ABSTRACT: This paper presents the results of repeated impact drop-weight test with gradually increasing drop-height on prestressed concrete (PC) beams reinforced with short steel-fibers. In addition, the concrete beam with a buffer layer made of a cement-based material with micro-fibers has been developed for improving the impact resistance. Not only global response (drop-height and load-displacement relations) but also the size of local damaged zone in concrete (cracks, spalling of concrete portions and so forth) was investigated. The prestressing and reinforcing with short steel-fibers impart the impact resistance to concrete beams. This paper also reports that the relationship between the steel-fiber content and the amount of prestress is important to improve the impact resistance of concrete members.

1 INTRODUCTION

In concrete structures such as road facilities, harbor facilities, sediment control dams, and others, impact loads sometimes act directly on members. Load bearing capacity, toughness and displacement recovery properties are important, and should be evaluated appropriately. Simplest of the impact tests is "repeated impact drop-weight test" (ACI 1988), in which the number of blows necessary to cause prescribed levels of distress in the test specimen is the main parameter and the drop-height is kept constant. Relative impact resistance of different materials can be evaluated by using this testing method. However, this testing method cannot be applied to the evaluation of relative impact resistance of different structural types.

Most papers (Hughes 1981, Hughes 1984 and Shah 1986) discussed the impact resistance of concrete members by using smaller specimens, which has no buffer layers.

Using a buffer layer is effective method to improve the impact resistance. For the buffer layers, however, it is also important to prevent the spalling of concrete portions. One of the effective approaches to improve this point is the use of cement-based materials with micro-fiber having good mechanical properties, such as strain-hardening.

In this study, drop-weight test with gradually increasing drop-height was adopted to evaluate the impact resistance of reinforced and prestressed concrete beams with short steel-fibers. Not only global response (drop-height and load-displacement relations) but also the size of local damaged concrete (cracks, spalling of concrete portions) was investigated. In addition, the effect of buffer layer was also studied.

2 OUTLINE OF EXPERIMENTS

2.1 *Test conditions*

A repeated impact drop-weight test with increasing drop-height was used in this study. As illustrated in Table 1, four kinds of members were used: reinforced concrete beams (RC), prestressed concrete beams (PC), RC beams reinforced with short steel-fibers (SF-RC), and PC beams reinforced with short steel-fibers (SF-PC). The short steel-fibers used in the fiber reinforced concrete (SFC) had hooks at each end, having the diameter of 0.75mm, and length of 60 mm (aspect ratio: 80). The fiber content in the SFC was about 1.0% of the concrete by volume. The averaged compressive strengths of the plain concrete and steel-fiber concrete (SFC) were 53.8MPa and 64.3MPa, respectively.

Micro-fiber-reinforced mortar, which was based on ECC mixuture (Li 1998), was used as a buffer layer in this study. It is the high performance mortar showing strain-hardening behavior. Mix proportions of the mortar were referred to the previous study (Li 1998). Water to cement ratio was 30%, and the Polyethylene fiber having the diameter of 0.012mm and length of 12mm was used. Fiber content was 1.5% by volume.

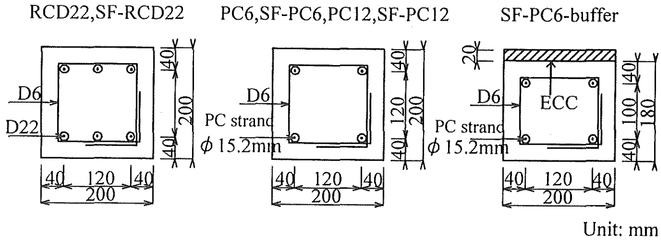

Figure 1. Cross sections

2.2 *Specimen geometry*

The size of specimen was 200 × 200 × 3,000mm (height × width × length). The cross sections of the specimens are shown in Figure 1.

Reinforcements were symmetrically arranged as shown in Figure 1 to resist the tensile stress due to negative deflection after bounding. For prestressed concrete beams, pre-tensioning system was adopted. Two levels of prestressing were prepared: 6MPa and 12MPa. The reinforcements in RC and PC members were determined so that their static bending strength would be almost identical. Table 2 lists the mechanical properties of the reinforcements.

In the case of SF-PC6-buffer, SF-PC beam having the size of 180 × 200mm (height × width) was made, and then the buffer layer (20mm thickness) was placed on the central 1000mm of the beam specimen. The interfacial surface of the substrate concrete was treated to be rough one, in which the aggregates were exposed. The length of loading span was 2,240mm. For shear reinforcement, D6 (SD295A) was arranged in shear span of each specimen, at a pitch of 100 mm.

2.3 *Test setup*

Figure 2 shows the test setup for the impact drop-weight test. The drop-weight of 250kg, which produced by assembling the steel plates, was lifted using a hoist, and released by controlling electromagnetic force in the loading. The striking part of the drop-weight was processed in the sphere with a radius of 75mm.

To prevent the specimen from bouncing out, two springs were installed at each support point on the supporting rack (spring constant: 392N/mm). The constraining force on each point was 15.7kN (total: 62.8kN). As shown in the figure, pins were used as supporting jigs to allow the member to rotate. Rollers were inserted on the movable side of the support point to allow lateral movement of the support. A load cell was inserted on one of the support points.

The drop-height was initially set at 100mm, and increment of 100mm was given at each impact. In this study, acceleration of drop-weight, reaction force at supporting point and displacement at the point of 200mm from the span center as shown in Figure 2 were measured at intervals of 50 μsec using a dynamic strain gauge and a waveform recorder.

When the displacement of the beam specimen after striking of the drop-weight (residual displacement) exceeds the value of 20mm, the loading was terminated.

Table 1. Test Conditions

Specimen name	Member type	Rein-forcements	Prestress level	Fiber content
			MPa	%
RCD22	RC	D22	0	0
SF-RCD22	SF-RC	D22	0	1
PC6	PC	PC cable*	6	0
SF-PC6	SF-PC	PC cable*	6	1
SF-PC6-buffer	SF-PC	PC cable*	6	0
PC12	PC	PC cable*	12	0
SF-PC12	SF-PC	PC cable*	12	1

*7-strand cable with nominal diameter of 15.2mm

Table 2. Properties of reinforcements

Name	Spec.	Nominal diameter	Nominal section area	Tension load	Yield load
		mm	mm^2	kN	kN
D22	SD295A	22.2	387.1	209	149
7-strand cable	SWPR 7BN	15.18	140.2	275	257*

* Yield load of cable having residual strain of 0.2%.

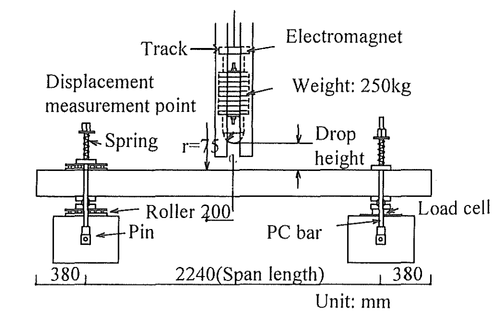

Figure 2. Test setup for impact tests

2.4 *Measurements of global response*

Figure 3 shows the examples of the global response in each time step, such as impact force, total support-point reaction force (impact reaction force) and displacement.

The impact force was calculated by the mass of drop-weight times the measured acceleration of drop-weight. The impact reaction force was equal to the double of the reaction force measured at one of the supports. In addition, the relationships between maximum impact reaction force in each impact and drop-height are shown in Figure 4, with the values of impact force. The values of maximum impact reaction force at each striking were approximately one-fourth as well as those of maximum impact force. It seems that the inertia of the beam specimens produces the difference in the obtained values.

As illustrated in Figure 3, the time of the maximum impact force was different from those of the maximum impact reaction force or displacement. On the other hand, the time of the maximum impact reaction force was similar to that of maximum displacement. In order to investigate the energy consumption of concrete beams, the measured impact reaction force and displacement were used (in Figure 6).

3 TEST RESULTS AND DISCUSSIONS

3.1 *Failure mode and maximum drop-height*

The values of maximum drop-height in the failure of the specimens, where the residual displacement exceeds the value of 20mm, are tabulated in Table 3. For PC12 specimen, the damage was localized in concrete, and loading was terminated at the drop-height of 1.2m.

Impact resistance of the prestressed concrete members (PC, SF-PC) represented by these values was higher than those of RC ones (RC, SF-RC). Figure 5 shows the crack patterns of specimens: RCD22, PC6 and SF-PC6 after impacts from the heights of 0.5m, 1.0m and 1.5m. In the case of RCD22, the number of the cracks was the largest in all series, and the size of local damaged zone, which is indicated with the amount of spalled concrete, was also the largest in all series, as shown in Figure 5. For the crack patterns of PC6, three or four cracks were observed at lower drop-height, and one of the cracks enlarged as the drop-height became higher. The size of local damaged zone is similar to that of RCD22. For the crack pattern of SF-PC6, three or four cracks were observed at lower drop-height. However, the each crack did not open quickly as drop-height became higher. The addition of steel-fibers reduced the damage in the concrete members.

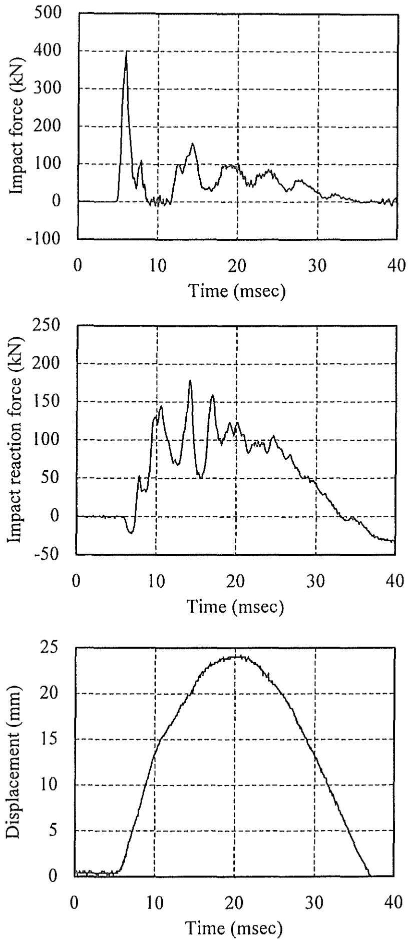

Figure 3. Example of global response (SF-PC6, h=1.0m)

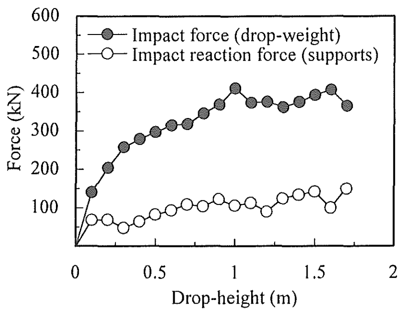

Figure 4. Impact force and impact reaction force

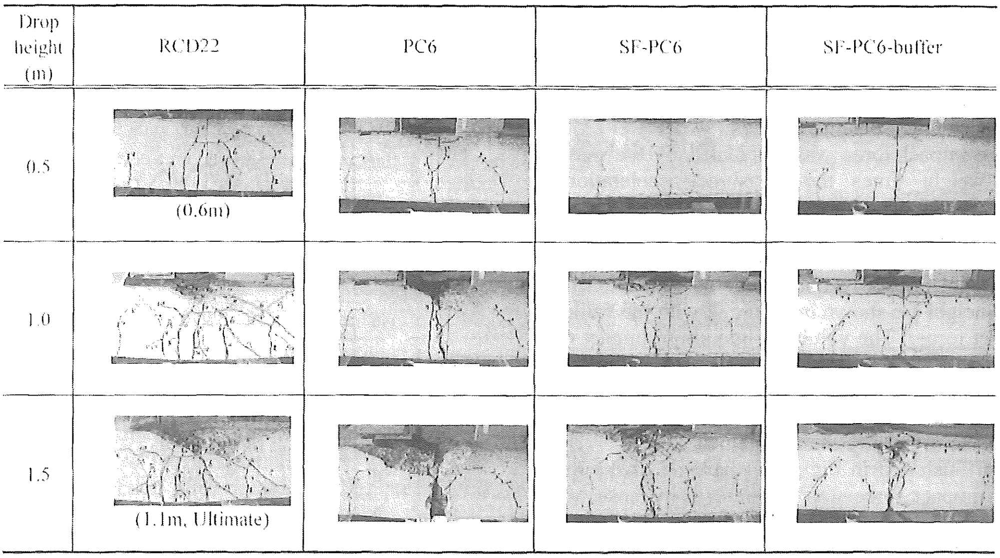

Figure 5. Crack patterns at each impact

Table 3. Test results in impact and static tests

Specimen name	Maximum drop height	Maximum impact reaction force*	Impact reaction force in ultimate*	R value	Maximum load in static tests
	m	kN	kN		kN
RCD22	1.1	141.1	61.7	0.56	111.95
SF-RCD22	0.9	105.8	75.5	0.29	117.51
PC6	1.4	87.2	78.4	0.10	99.37
SF-PC6	1.6	142.1	100.0	0.30	110.97
PC12	1.2	95.1	72.5**	0.24	112.12
SF-PC12	1.5	113.7	97.0	0.17	116.37

* Value at the time having maximum displacement

** Loading was terminated

3.2 *Impact reaction force and displacement relationship*

Figure 6 shows the relationships between impact reaction force and maximum displacement at each impact. The displacement at impact force of zero means the residual displacement after impacts. The measured values were connected each other. Figure 6 shows a sort of fracture process of the concrete members under impact loading. In addition, the incline of the connected lines indicates the performance for the restoration of deflection of concrete members.

For the PC beams (PC6, PC12, SF-PC6 and SF-PC12), the increment of residual displacement at each impact was smaller than that of RC ones (RCD22 and SF-RCD22). Damaged concrete in RC beams, in which cracks propagated and spalling of concrete occurred due to the repeated impact loading, imparted the decreasing in the stiffness to concrete members, and gave the reduction of impact force after maximum one, as shown in Figure 6. Prestressing, however, reduced the size of damaged concrete zone.

The impact force reducing ratio, R value, was defined by the equation as follows and given in Table 3.

$$R = 1 - (IF_u / IF_{max}) \quad (1)$$

where R= impact force reducing ratio; IF_{max}= maximum impact reaction force; IF_u= impact reaction force in ultimate. R value indicates the ductility in softening region for impact loading.

As for the most beam specimens with prestressing or reinforcing with short steel-fibers, the impact resistance represented by the R value became higher than that of RCD22 specimen. In the specimen with

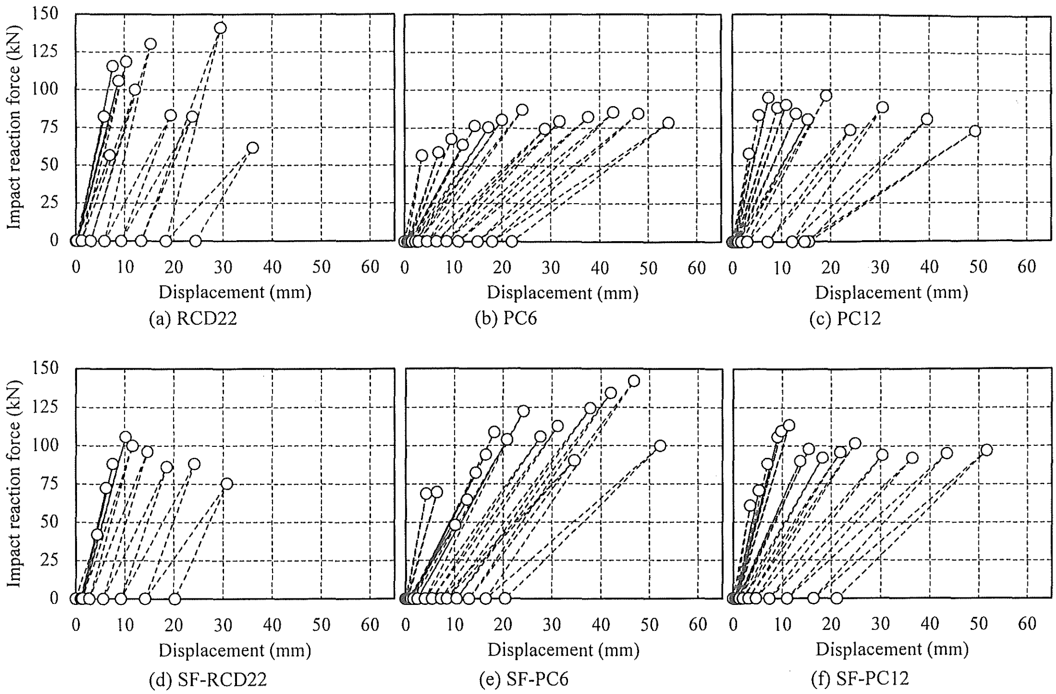

Figure 6. Relationships between impact reaction force and maximum displacement at each impact

no short steel-fibers, prestressing gave only the ductility with higher restoration of deflection. For FRC beams, however, the prestressing gave the higher impact reaction force at each impact as shown in Figure 6. Especially, the maximum impact reaction force in SF-PC6 was highest in all series. For SF-PC12, the reaction force at each impact was little higher than that of PC12, and the effect of prestressing was not evident in this study. It seems that too much prestressing increased the localized damage in concrete. There would be a best combination between the steel-fiber content and the amount of prestress to improve the resistance of concrete beams against impact loading.

3.3 *Comparison with results in static loading tests*

Static bending tests were carried out on the specimens having the same geometory conditions as for the impact tests. The load-displacement relations are shown in Figure 7. The values of maximum load are also tabulated in Table 3. Maximum load or ductility in each specimen was similar to each other, except for PC12. These results indicate that the addition of steel-fibers gave higher resistance.

3.4 *Effect of buffer layer*

The impact test results of SF-PC6-buffer are shown in Figure 8. The impact reaction force at each impact is as well as that of SF-PC specimen. The spalling of concrete portions, however, was reduced, and few cracks were observed in the buffer layer. The failure behavior of SF-PC6-buffer, however, originated from the delamination of the buffer layer, as shown in Figure 5. This means that the bond properties at interface between the buffer layer and substrate should be improved in order to utilize the high performance of the buffer layer, e.g. strain-hardening. Then further research is needed in future.

4 CONCLUSIONS

The concrete members with prestressing and reinforcing with short steel-fibers were developed, and tested through "repeated impact drop-weight test" to evaluate their impact resistance. Following results were obtained:

- The prestressing and reinforcing with short steel-fibers imparted the impact resistance to concrete beams.
- Prestressing improved the performance for the restoration of deflection of the members under impact load. In the specimen with no short steel-fibers, prestressing gave only the ductility with

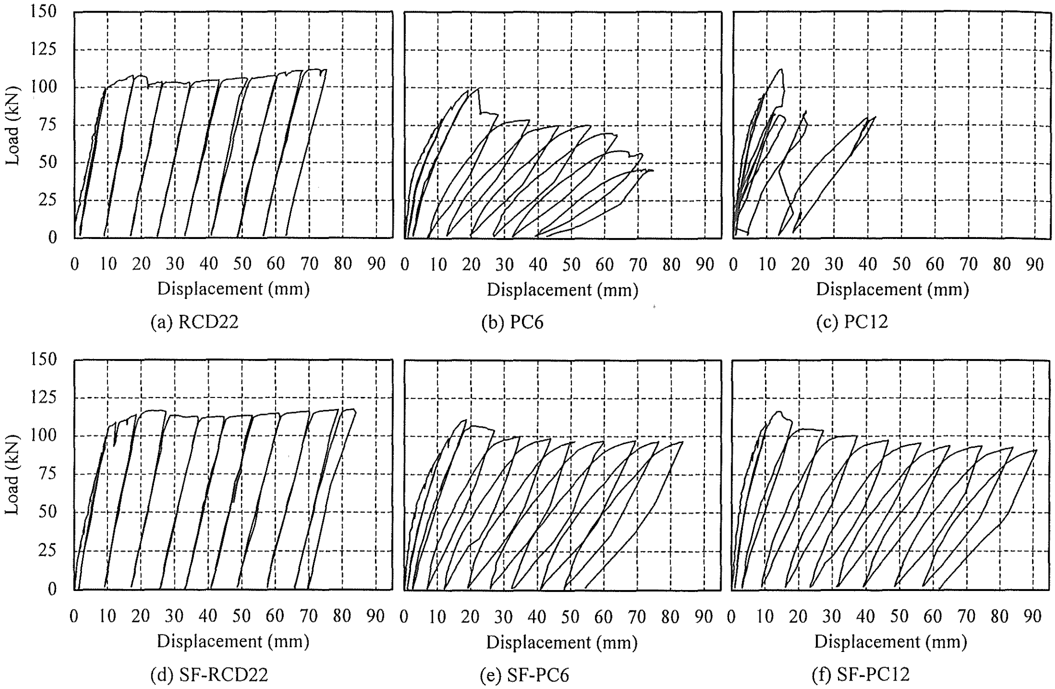

Figure 7. Relationships between load and displacement in static tests

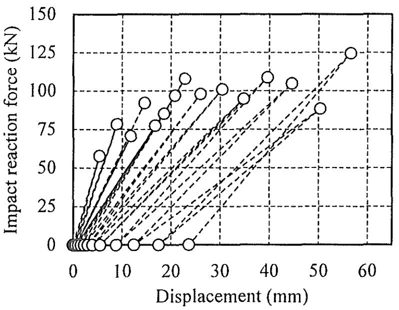

Figure 8. Relationships between impact reaction force and maximum displacement at each impact (SF-PC6-buffer)

higher restoration of deflection. For FRC beams, the prestressing gave the higher impact reaction force at each impact. In the case of SF-PC12, the effect of prestressing was not evident. It seems that too much prestressing increased the localized damage in concrete. There would be a best combination between the steel-fiber content and the amount of prestressing.

- The buffer layer made of cement-based material with micro-fibers improved the impact resistance of concrete beams. The spalling of concrete portions was reduced.

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