STUDY ON IMPACT RESISTANCE OF PC BEAMS WITH BUFFER LAYER MADE OF DUCTILE FIBER REINFORCED CEMENTITIOUS COMPOSITES

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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. Recently, to prevent the spalling of concrete portions is also one of the important requirements for concrete structures.

There are many papers [1-5] discussed the impact resistance of concrete members by using smaller specimens. Simplest impact test is "repeated impact drop-weight test [6]". In this test, 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 this testing method. However, this testing method cannot be applied to the evaluation of relative impact resistance of different structural types.

Using a buffer layer is effective method to improve the impact resistance. For instance, there are three requirements of buffer layers as follows;

- Ductility to prevent the spalling of portions
- Bond properties to prevent the delamination of buffer layers itself
- Compatibility with the substrate concrete

One of the effective approaches to satisfy the above requirements is the use of cement-based materials with micro-fiber having higher performance in ductility.

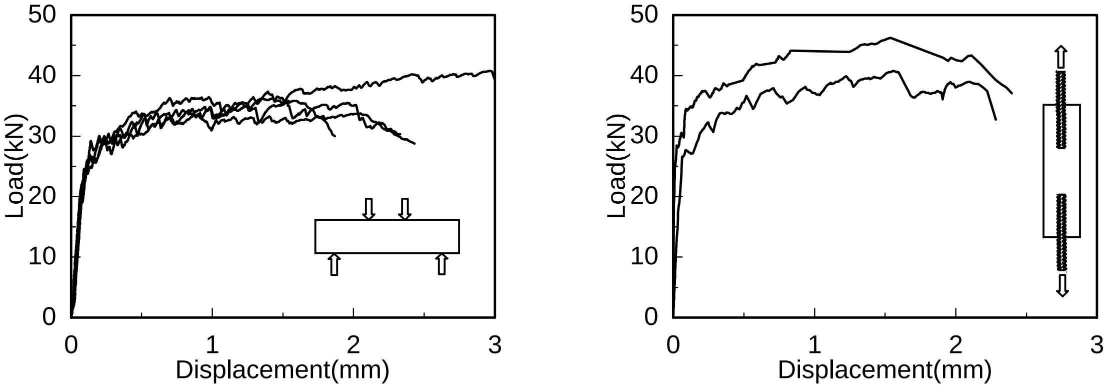
In this study, drop-weight test with gradually increasing drop-height was adopted to evaluate the impact resistance of steel fiber reinforced concrete PC beams. The specimens with buffer layer made of Ductile Fiber Reinforced Cementitious Composites (DFRCC) were also investigated through the fracture behavior focusing on the size of local damaged concrete (i.e. cracks, spalling of concrete portions).

2 PROPERTIES OF DUCTILE FIBER REINFORCED CEMENTITIOUS COMPOSITES

In this study, one of DFRCC named Engineered Cementitious Composites (ECC) was applied for the buffer layer of PC beams subjected to impact loads. ECC designed with micromechanical principles has been developed by Prof. V.C. Li [7, 8] and exhibits strain hardening and multiple cracking behaviors in tension. ECC has much higher performance in ductility, fracture energy, and deformation capacity than conventional fiber reinforced cementitious composites.

Micromechanical parameters associated with fiber, matrix and interface are combined to satisfy a pair of criteria, the first crack stress criterion and steady state cracking criterion [9] to achieve the strain hardening behavior. Micromechanics allows optimization of the composite for high performance while minimizing the amount of reinforcing fibers (generally less than 2-3%).

ECC has a tensile strain capacity of up to 6% and exhibits pseudo-strain hardening behavior accompanied by multiple cracking. It also has high ultimate tensile strength (5-10MPa), modulus of rupture (8-25MPa), fracture toughness (25-30kJ/m^2), and compressive strength (up to 80 MPa) and strain (0.6%). Typical tensile and flexural behaviors are shown in Fig. 1. And also, the example of multiple crack pattern in flexural test is shown in Fig. 2.



(a) Flexural behavior (b) Tensile behavior

Fig. 1 Load-displacement curves of ECC specimens(100×100×400mm)

Fig. 2 Multiple cracks on side surface of beam specimen (100×100×400mm)

Table 1 Test conditions

Specimen name	Specimen type	Prestress level (MPa)	Fiber content (%)
PC6	PC	6	0
SF-PC6	SF-PC	6	1
PC12	PC	12	0
SF-PC12	SF-PC	12	1
SF-PC6-buffer (placing)	SF-PC-buffer	6	1
SF-PC6-buffer (pre-cast)	SF-PC-buffer	6	1

The use of ECC for a variety of applications has been proposed [10, 11]. The application and evaluation of DFRC are now investigated in JCI (Japan Concrete Institute) technical committee on DRFC. An anti-impact member seems to be one of promising applications of ECC.

3 OUTLINE OF IMPACT TESTS

3.1 Test conditions

A repeated impact drop-weight test with increasing drop-height was used in this study. As illustrated in Table 1, three kinds of specimens were used: prestressed concrete beams (PC), PC beams reinforced with short steel-fibers (SF-PC), and SF-PC with buffer layer made of ECC. 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

Table 2 Mix proportions of ECC

Water to cement ratio (%)	Fiber content* (Vol. %)	Water	Cement	Fine aggregate	Admixture1**	Admixture2***
30	1.5	0.3	1	0.31	0.0007	0.03

* Polyethylene fiber, length:12mm, diameter: 0.012mm

** Cellulose ether

***Superplasticizer (poly-carboxylic acid type)

Table 3 Properties of reinforcement

Name	Spec.	Nominal diameter (mm)	Nominal section area (mm^2)	Tension load (kN)	Yield load (kN)
7-strand cable	SWPR 7BN	15.18	140.2	275	257*

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

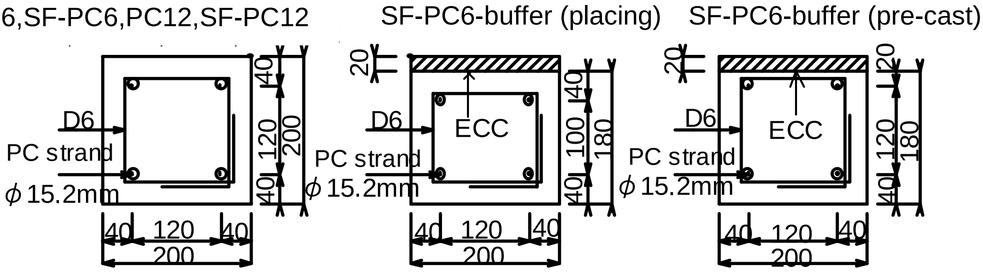


Fig. 3 Cross sections of specimens

concrete by volume. The averaged compressive strengths of the plain concrete and steel-fiber concrete (SFC) were 53.8MPa and 64.3MPa, respectively.

Mix proportions of ECC used for buffer layer are shown in Table 2. 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.

3.2 Specimen geometry

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

Reinforcements were symmetrically arranged as shown in Fig. 3 to resist the tensile stress due to not only positive deflection but also negative one after bounding. The reinforcement was seven-strand cable with nominal diameter of 15.2mm. Pre-tensioning system was adopted. Two levels of prestressing in concrete were prepared: 6MPa and 12MPa. Table 3 lists the mechanical properties of the reinforcement.

In the case of SF-PC6-buffer (placing), 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. For the SF-PC6-buffer (pre-cast), the buffer layer (size: 20×200×1000mm) treated by artificial rough surface (air-cap shape) was made. The substrate concrete was placed on the pre-cast buffer layer.

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.

3.3 Test setup

Figure 4 shows the test setup for the impact drop-weight test. The drop-weight of 250kg, which was

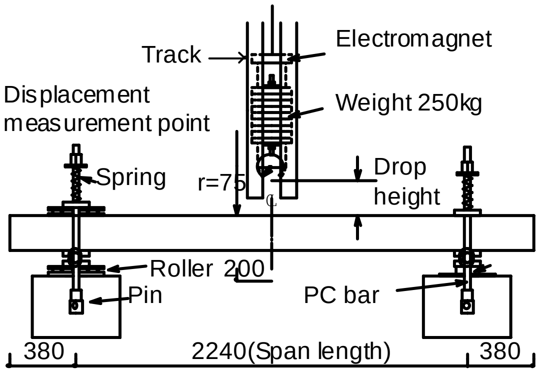
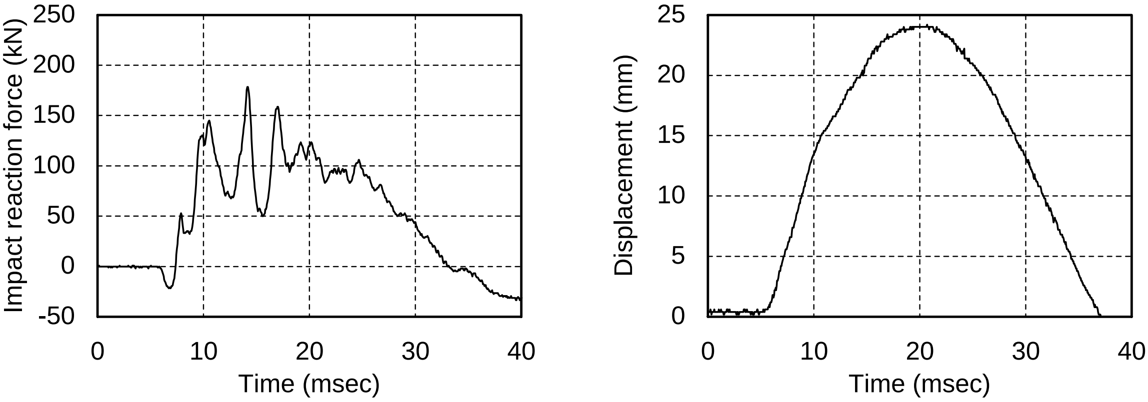


Fig. 4 Test setup



(a) Impact reaction force (b) Displacement

Fig. 5 Examples of global response (SF-PC6, h=100cm)

produced by assembling the steel plates, was lifted using a hoist, and then 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 Fig. 4, 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 Fig. 4 were measured at intervals of 50μsec 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.

Figure 5 shows the examples of the global response in each time step, such as total support-point reaction force (impact reaction force) and displacement. The impact reaction force was equal to the double of the reaction force measured at one of the supports.

4 TEST RESULTS AND DISCUSSIONS

4.1 Fundamental mechanical properties in impact tests

Figure 6 shows the crack patterns of specimens: PC6, SF-PC6, PC12, SF-PC12 after impacts from the heights of 0.5m, 1.0m and 1.5m. 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. For the crack pattern of SF-PC6, three or four cracks were observed at lower drop-height. However, the

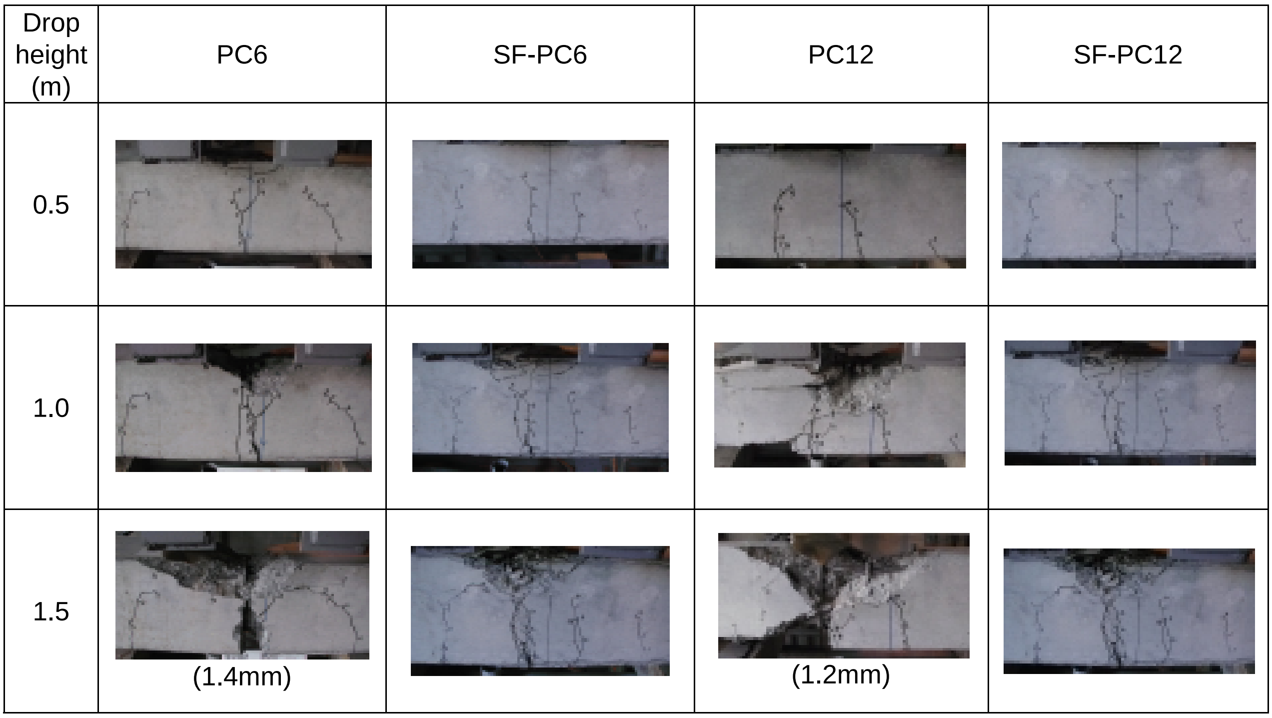


Fig. 6 Crack patterns of specimens

Table 4 Test results in impact tests

Specimen name	Maximum drop height up to ultimate (m)	Maximum impact reaction force* (kN)
PC6	1.4	87.2
SF-PC6	1.6	142.
PC12	1.2**	95.1
SF-PC12	1.5	114.
SF-PC6-buffer (placing)	1.5	124.
SF-PC6-buffer (pre-cast)	1.4	113.

* Value at the time having maximum displacement

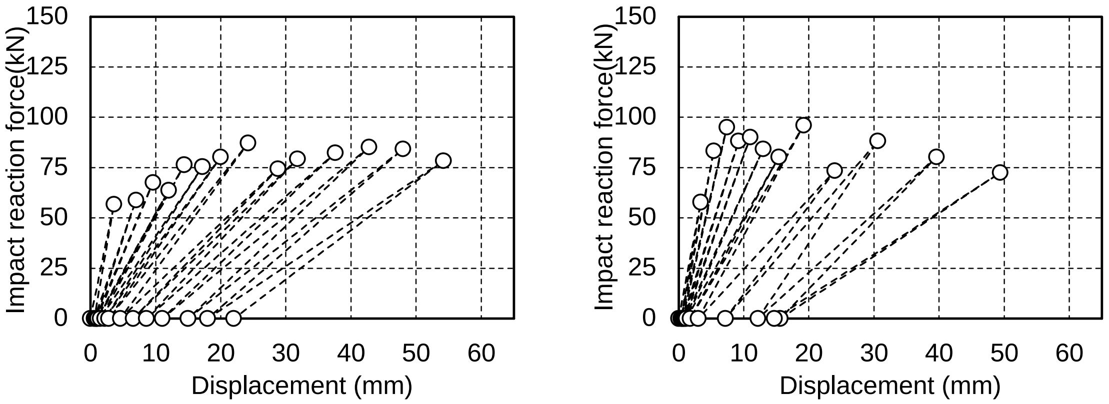
** Loading was terminated

each crack did not open quickly as drop-height became higher. The addition of steel-fibers reduced the damage in the concrete members. Impact resistance of the PC members with steel short-fiber (SF-PC) was higher than that of PC ones with no steel short-fiber.

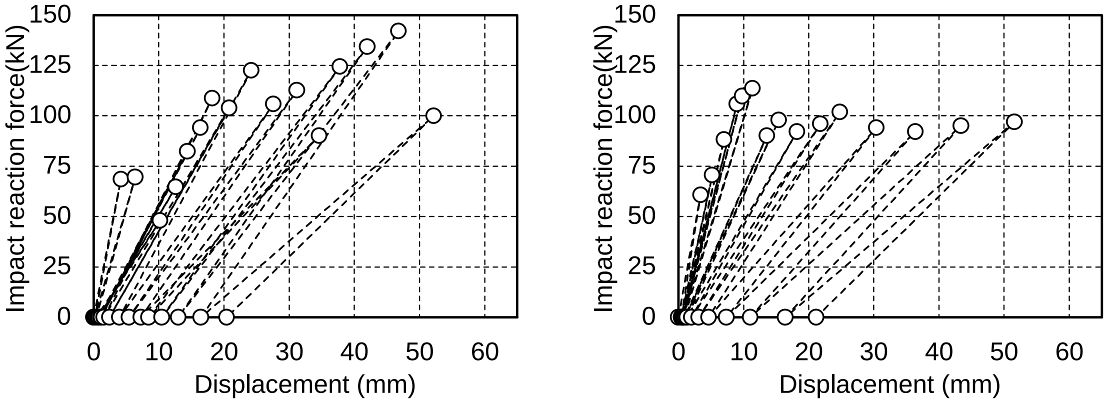
The values of maximum drop-height in the failure of the specimens, where the residual displacement exceeds the value of 20mm, are tabulated in Table 4. For PC12 specimen, the damage was localized in concrete, and loading was terminated at the drop- height of 1.2m.

Figure 7 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 7 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.

As for the most beam specimens reinforced with short steel-fibers, the impact resistance became higher than that of PC6 specimen. In the specimen with 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 Fig. 7. Especially, the maximum impact reaction force in SF-PC6 was highest in all series. For SF-PC12, the reaction force at each impact



(a) PC6 (b) PC12



(c) SF-PC6 (d) SF-PC12

Fig. 7 Relationship between impact reaction force and maximum displacement 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.

It can be concluded from this study that the proposed impact testing method with increasing drop-height at increment of 100mm was efficient for the evaluation of relative impact resistance of PC beams.

4.2 Applicability of ECC to buffer material against impact loading

As indicated in previous section, SF-PC6 specimen has higher resistance against impact loading in all series. Therefore, the buffer layer system made of ECC was applied to the SF-PC6 specimen as shown in Fig. 3.

Figure 8 shows the crack patterns of each specimen. The global failure

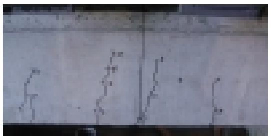
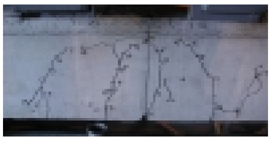
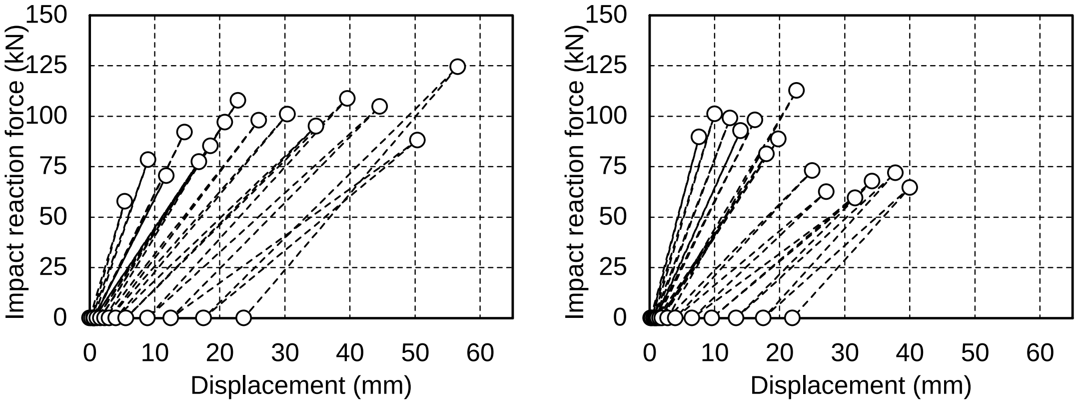
Drop height (m)	SF-PC-buffer (placing)	SF-PC-buffer (pre-cast)
0.5		
1.0		
1.5		 (1.4m)

Fig. 8 Crack patterns of specimens with buffer layer



(a) SF-PC6-buffer(placing) (b) SF-PC6-buffer(pre-cast)

Fig. 9 Relationship between impact reaction force and maximum displacement at each impact

behaviors of both specimens were originated from the delamination of the buffer layer at ultimate stage. Few cracks were observed in the buffer layer itself. And also, the spalling of concrete portions was reduced compared to the specimen with no buffer layer. Using the buffer layer imparts the impact resistance to the specimen through reducing both the local damaged part struck by the drop-weight and tensile cracks due to bouncing out of the specimens.

The difference of crack patterns related to the bond properties at interface could be observed, as shown in Fig. 8. It seems that the bond property in the SF-PC6-buffer (placing) specimen would be better than that in SF-PC6-buffer (pre-cast) specimen. Only the crack located at the center of the specimen propagated after occurring the delamination of the buffer layer in SF-PC6-buffer (pre-cast) specimen. However, SF-PC6-buffer (placing) specimen exhibits many cracks, in which the length of each crack was almost the same, and has large deformation capacity.

In impact reaction force-maximum displacement relations as shown in Fig. 9, the maximum impact load and ultimate displacement of SF-PC6-buffer (placing) became larger than those of SF-PC6-buffer (pre-cast). It became clear from these tests that the bond properties at interface between the buffer layer and substrate was important and should be improved in order to utilize ECC for buffer layers.

5 CONCLUSIONS

The PC beams reinforced with short steel-fibers were developed, and tested through "repeated impact drop-weight test" to evaluate their impact resistance. And also, ductile fiber reinforced cementitious composite (ECC) was applied to the buffer material against impact loading. The following results were obtained:

(1) The reinforcing with short steel-fibers imparted the impact resistance to PC concrete beams. However, 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.

(2) The proposed impact testing method with increasing drop-height at increment of 100mm was efficient for the evaluation of relative impact resistance of PC beams.

(3) Using buffer layer made of ductile fiber reinforced cementitious composite (ECC) was effective method to reduce the spalling of concrete portions.

(4) The failure behaviors of both specimens with buffer layer were originated from the delamination of the buffer layer itself. However, the difference in crack patterns and impact reaction force-displacement curves related to the bond properties at interface could be observed. The bond properties at interface between the buffer layer and substrate was important and should be improved in order to utilize ECC for buffer layers.

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