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Research Article

Flexural Assessment of Blast-Damaged RC Beams Retrofitted with CFRP Sheet and Steel Fiber

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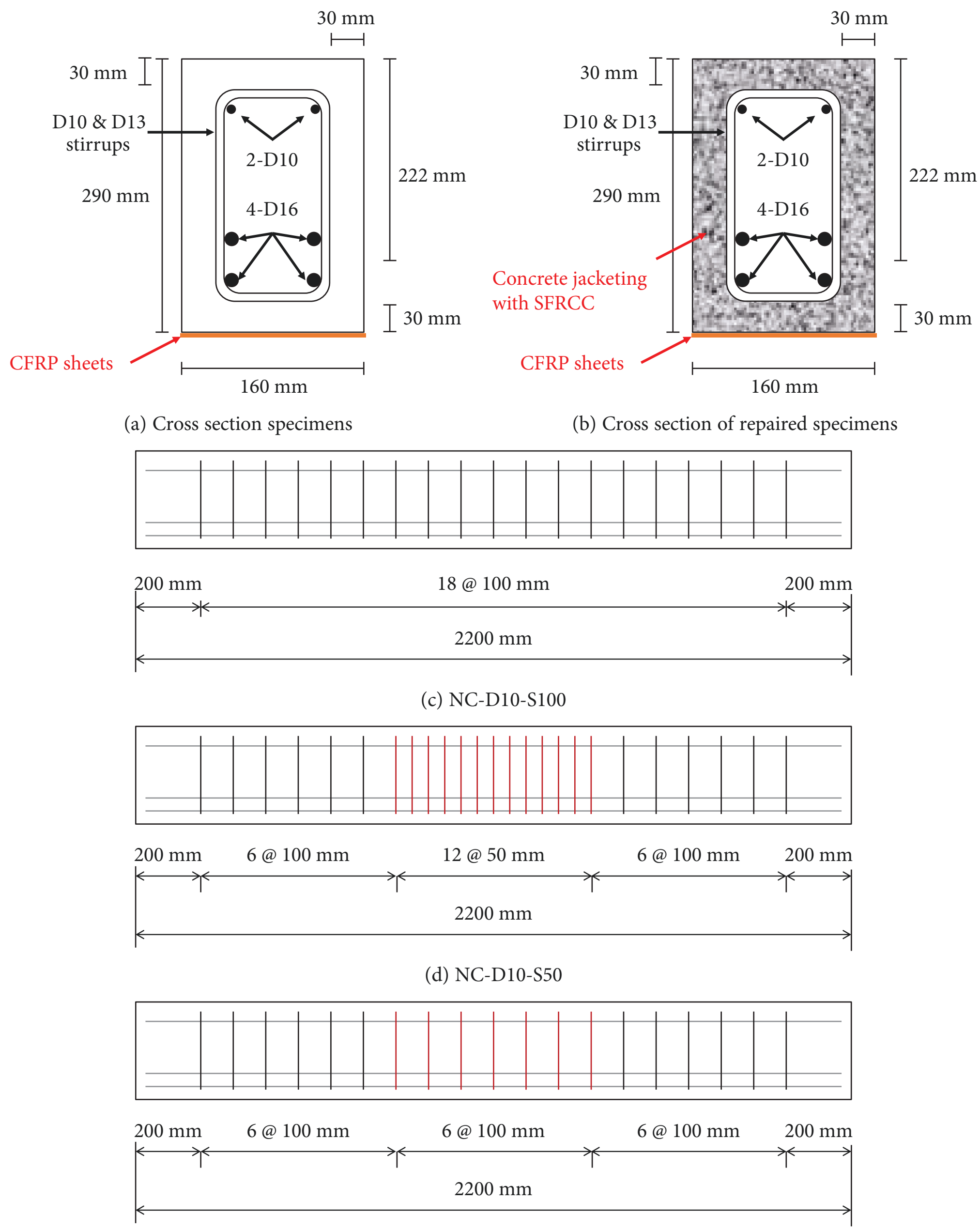
This study presents the effects of blast-induced local damages on the flexural strength of blast-damaged and repaired specimens. In the experimental program, blast-damaged specimens were repaired with steel fiber reinforced cementitious composite (SFRCC) as well as carbon fiber-reinforced polymer (CFRP) sheets and tested for flexural strength measurements. The test parameters included shear reinforcement (amount and spacing), steel fiber content (0, 1.0 vol%), and retrofitting with CFRP sheets. The test results indicated that the use of higher amounts of stirrups demonstrated insignificant benefits in preventing local damages. However, it was shown that the use of small-diameter steel bars for stirrups with small spacing could decrease the local damages more effectively compared to the large-diameter steel reinforcement. For the residual strength of the damaged specimens, the specimens using more stirrups could resist over 60% of their original flexural strength. CFRP retrofitting showed insignificant enhancement in ductility of intact, damaged, and repaired specimens. However, it distributed the blast load and protected debris scattering. The addition of steel fibers results in increased ductility and enhanced blast resistance against local damages. All specimens, excluding control specimen, that repaired with SFRCC showed higher flexural strength to their original strength. Therefore, it can be concluded that replacing damaged concrete cover with SFRCC is adequate for repairing the blast-damaged RC members.

1. Introduction

The most effective method to protect a structure from a blast risk is to maintain an adequate stand-off distance from the source of the blast. In other words, a structural member is extremely vulnerable from a close-in blast. If such a blast causes a local damage on the structure, it may lead to a progressive collapse. Therefore, vehicles are not allowed near important structures in the United States in order to prevent the structures from damage by close-in blasts [1]. When maintaining a stand-off distance is difficult, the structures should be constructed by using the reinforcing method that can protect themselves from blasts. Therefore, numerous researchers [2–21] have conducted studies to suggest the enhanced reinforcing method against a blast and evaluate the blast resistance of the suggested method. The conventional method to increase the blast resistance is to use a considerable amount of shear reinforcement. Fujikake and Aemlaor [9] experimentally and numerically analyzed the blast resistance of the RC (reinforced concrete) columns by considering not only the shear reinforcement ratio but also the concrete strength and reported that the shear-reinforcing bars confining the core concretes of the RC columns significantly affect the damage of the specimens. Burrell et al. [5] also reported that seismic detailing improves blast performance of RC columns. Despite the results of the abovementioned research, considerably little experimental studies have been devoted to examining the role of shear reinforcement in RC beams under blast load. Therefore, in this study, the blast test on RC beams considering the



(a) Cross section specimens
(b) Cross section of repaired specimens
(c) NC-D10-S100
(d) NC-D10-S50
(e) NC-D13-S100

FIGURE 1: Details of test specimens.

TABLE 1: Test variables.

Notation	Concrete	Shear reinforcement	A_v (mm^2)	FRP
NC-D10-S100	Normal concrete	D10, $s = 100$ mm	998	Not retrofitted
NC-D10-S50		D10, $s = 50$ mm	1854	
NC-D13-S100		D13, $s = 100$ mm	1774	
NC-D10-S100-F		D10, $s = 100$ mm	998	CFRP sheet
SFRC-D10-S100	SFRC with 60 mm steel fiber	D10, $s = 100$ mm	998	Not retrofitted

amount and spacing of shear reinforcements as variables was conducted. A better understanding of the mechanics associated with the effects of shear reinforcement on the local damages and residual strength could allow the designer to determine the shear reinforcement that is most desirable for the blast-resistant structures.

Table 2: Mix proportions of NC, SFRC, and SFRCC [12].

Type of concrete	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Steel fiber (%)[a]
NC[b]	140	350	792	1015	0.0
SFRC[b]	140	350	792	1015	1.0
SFRCC	140	350	1807	0	1.0

[a]Volume fraction of fibers. [b]Data cited from [12].

Table 3: Strength of NC, SFRC, and SFRCC [12].

Concrete	Compressive strength (MPa)	Flexural strength (MPa)
NC[a]	38.7	4.7
SFRC[a]	31.0	6.4
SFRCC	42.3	6.2

[a]Data cited from [12].

Table 4: Properties of steel fibers.

Type of fiber	Length (mm)	Diameter (mm)	Aspect ratio (L/D)	Tensile strength (MPa)
End-hooked steel fiber	60	0.75	80	1196

Table 5: Properties of reinforcement.

Deformed bar	Nominal diameter (mm)	Area (mm^2)	Yield strength (MPa)	Ultimate strength (MPa)
D10	9.53	71.3		
D13	12.7	126.7	508.5	605.3
D16	15.9	198.6		

Table 6: Typical mechanical properties of FRP composite [11].

	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Ultimate strain (%)
CRFP sheet	1.4	2400	131	1.87

Recent research has shown that using SFRC and retrofitting with FRP composites can improve the strength and ductility of RC members [22–28]. The effectiveness of using FRP sheet to improve blast behavior of RC members has been demonstrated experimentally and numerically by Saatcioglu et al. [21]. Ross et al. [14] also reported that FRP retrofitting is effective in increasing blast resistance. In case of SFRC, some limited research has been conducted on RC members under blast load. Lan et al. [29] conducted a field blast test on RC slabs and noted that SFRC panels demonstrated improved damage tolerance. However, most previous studies focused on the blast resistance at the moment; the blast load was imparted on the specimens without considering the structural behavior after the blast. In this context, few studies were performed to evaluate residual strength of blast-damaged specimens, although the effect of local damages on the structural strength of the specimens is an important factor that could lead to progressive collapse. Moreover, limited research has been conducted on the repaired RC beams using steel fiber-reinforced cementitious composite (SFRCC) and carbon fiber-reinforced polymer (CFRP) sheet.

Accordingly, in this study, blast-induced local damages and static flexural strength of intact, damaged, and repaired specimens were examined. The test data of the flexural test on intact specimens and blast test was cited from previous studies [11, 12]. The amount and spacing of shear reinforcements, the addition of steel fiber, and FRP retrofitting were considered as test variables to investigate the effect of the various reinforcing methods on blast-local damages. For the flexural test on repaired specimens, the specimens were fabricated by using SFRCC, CFRP sheet, and blast-damaged specimens that were tested in the previous study and tested to investigate the effect of repairing materials on flexural strength of repaired specimens.

2. Experimental Program

2.1. Details of Test Specimens. The experimental program consisted of four phases: (1) static tests on intact specimens, (2) blast tests on intact specimens, (3) static tests on blast-damaged specimens, and (4) static tests on repaired specimens. Five reinforced RC beams were tested, and the test data of ten specimens were cited to investigate the effect of CFRP sheet, steel fibers, and shear reinforcement in RC beams under blast load [11, 12]. The details of the specimens are shown in Figure 1 and Table 1.

The types of concrete (NC, SFRC), CFRP retrofitting, and details of shear reinforcement were considered as variables. As illustrated in Figure 1, all specimens were 160 mm in width, 290 mm in height, and 2200 mm in length. In addition, longitudinal reinforcements consisted of four 15.26 mm diameter-deformed steel-reinforcing bars (denoted as D16). NC-D10-S100 (control specimen), NC-D10-S100-F, and SFRC-D10-S100 were designed according to the minimum shear requirements of ACI 318-14 [30] and composed of 10 mm deformed reinforcing bars (denoted as D10). They were conventional rectangular stirrups and spaced at 100 mm along the middle zone of the beams. In case of NC-D10-S50 and NC-D13-S100, the stirrups, composed of D10 and D13 rebars, were spaced at 50 and 100 mm, respectively. For the FRP retrofitting, two layers of CFRC sheets were bonded with epoxy on the bottom of the beam. After the blast test, blast-damaged specimens were repaired with SFRCC. The details of the repaired specimens are presented in Figure 1(b). A 30 mm thick SFRCC layer was used to wrap

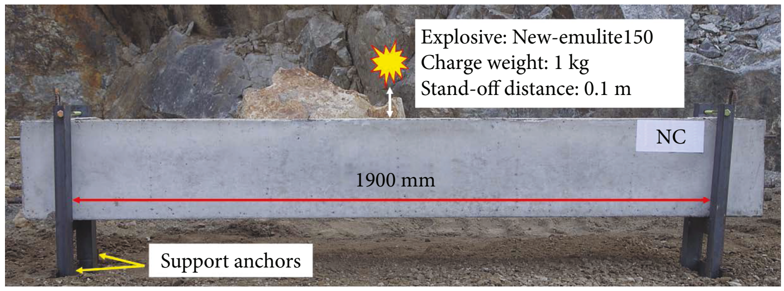


Figure 2: Test set-up of a blast test.

Table 7: Properties of explosive [12].

Detonation velocity (m/s)	Volume density (g/cc)	Energy of explosion (kcal/kg)	Drop sensitivity (cm)	Amount of gas (L/kg)
5900	1.18 ~ 1.50	1140	100	820

Table 8: Anticipated blast load.

Charge weight (kg)	Stand-off distance (m)	Peak pressure (MPa)	Peak impulse (MPa/ms)	Duration for positive phase (ms)
1.0	0.1	38.6	1.42	0.07

the damaged specimens after eliminating a damaged concrete cover. In the case of NC-D10-S100-F, the repaired specimen was retrofitted with CFRP sheet again.

2.2. Material Properties. The concrete properties and mix proportions are summarized in Tables 2 and 3. All specimens were fabricated with an identical mixture that had a water-to-cement ratio of 0.4 and maximum aggregate size of 20 mm. However, in the case of SFRCC, coarse aggregate was not used in order to gain better structural performance under static and blast loadings. For SFRC and SFRCC, 60 mm hooked-end steel fibers were used in the cement paste and the fiber content was 1.0 vol%. The properties of steel fiber are shown in Table 4. The compressive and flexural strengths were measured based on ASTM C39 and C1609 [31, 32], on cylinders with a diameter of 100 mm and height of 200 mm and beams with a cross section of 100 × 100 mm and a length of 400 mm. The compressive strength of NC, SFRC, and SFRCC was approximately 39, 31, and 42 MPa, respectively. In case of flexural strength, NC exhibited an average strength of 4.7 MPa, while the SFRC and SFRCC exhibited an average strength of approximately 6.3 MPa. For steel reinforcements, Grade 400 Korean Standard (KS) deformed reinforcing bars were used. The properties are presented in Table 5. Woven carbon fiber sheets were used for FRP retrofitting, and typical properties of FRP composite are shown in Table 6.

2.3. Test Procedure

2.3.1. Static Test. Static three-point flexural tests were carried out on five repaired specimens with a quasi-static loading rate of 0.02 mm/s using a universal testing machine (UTM) with maximum load capacity of 2800 kN. The mid-span deflection, excluding the support settlement, was measured by linear variable differential transducers (LVDTs). The specimens were simply supported, and clear span was 1900 mm. The steel bearing plates were placed at the loading and support points to prevent local crushing of the concrete.

Static flexural tests on the intact and damaged specimens were performed by Lee et al. [11, 12], and the test results were cited to evaluate the effect of CFRP sheet, steel fibers, and shear reinforcement in RC beams. All of the tests on intact, damaged, and repaired specimens were conducted using identical instrumentation.

2.3.2. Close-In Blast Test. Close-in blast tests on specimens were carried out by Lee et al. [11, 12]. The local damages and effect of CFRP sheet, steel fibers, and shear reinforcement were investigated by analyzing the test results. After the blast tests, the residual strength of blast-damaged specimens and flexural strength of repaired specimens were measured. Test set-up of the blast test is presented in Figure 2. For the blast tests, New-emulite150, emulsion explosive, was used to impart the blast load on the specimens. The TNT equivalent factor of this explosive is 1.01, and the properties of explosive are presented in Table 7. Charge weight of explosive was 1 kg, and stand-off distance was 0.1 m. The imparted blast pressure was calculated by AT-Blast software and shown in Table 8.

3. Experimental Results and Discussion

3.1. Evaluation of Blast-Induced Local Damages

3.1.1. Effect of Shear Reinforcement on Local Damages. When a blast occurs, the main types of local damage on concrete specimen can be classified into three types: crater, spall, and breach. As shown in Figure 3, crater occurs at the front side of the specimen when the specimen is directly exposed to the blast pressure, while the spall is a rear side damage induced by tensile stress. Breach occurs when the specimen is totally penetrated [33]. In addition, shear plug also occurs when the impact or blast load is imparted on the concrete beams because the velocity of the crack propagation is higher than the load transfer velocity. After the close-in blast test, the fracture behaviors of the specimens were observed. Diameter and depth of local damages, angle of shear crack,

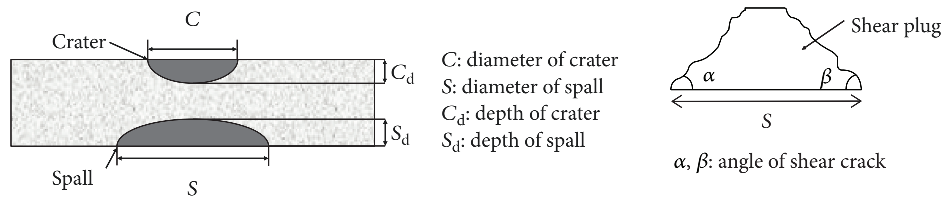


Figure 3: Blast-induced local damages.

Table 9: Local damages of specimens [11, 12].

Variables	Local damages					
	C (cm)	C_d (cm)	S (cm)	S_d (cm)	α (°)	β (°)
NC-D10-S100	77	14	89	6	26	29
NC-D10-S50	72	16	74	7	23	32
NC-D13-S100	70	14	88	9	26	28
NC-D10-S100-F	79	15	103	5	30	25
SFRC-D10-S100	48	12	0	0	34	25

and weight loss were measured. These are presented in Table 9 and Figure 4. The average crack angle was 25° in blast-damaged specimens. In the case of NC series, there were no significant differences in size of crater and spall, because most of the fracture occurred at the concrete cover. However, for the weight loss, NC-D10-S50 showed the smallest weight loss among the NC series except NC-D10-S100-F. On the other hand, NC-D13-S100 showed same weight loss with NC-D10-S100, even though it had 1.8 times of shear reinforcement compared with NC-D10-S100. From the above results, it was confirmed that the space of stirrups is a more important factor in protecting the concrete core than the amount of shear reinforcements.

3.1.2. Effect of FRP and Steel Fiber on Local Damages. As presented in Table 9 and Figure 4, retrofitting with CFRP sheets and adding fibers enhance the blast resistance against local damages. Particularly, spalling did not occur in SFRC specimen because of a fiber bridging capacity at the rear side of the specimen. Moreover, the smallest amounts of crater and weight loss were observed. Therefore, it was verified through the experimental tests that the addition of steel fibers can be an effective method to enhance blast resistance against local damages. In case of NC-D10-S100-F, weight loss was reduced compared to control beam, NC-D10-S100, even though there were no significant differences in size of crater and spall. In addition, CFRP sheet distributed the blast load and protected debris scattering before bonding failure between CFRP sheet and concrete.

3.2. Static Response of Intact Specimens. The load-displacement curves and summary of test results obtained from the static tests on intact, blast-damaged, and repaired specimens are presented in Figure 5 and Table 10. In the static flexural test, all of the intact specimens failed in flexure-critical mode, because every specimen had identical details in longitudinal reinforcement. NC series except NC-D10-S100-F sustained an average flexural strength of 183.1 kN·m. The addition of fibers and retrofitting with CFRP sheet resulted in an increase of 13% and 8% in the flexural strength, respectively, compared to the average strength of NC series. Although these specimens failed at similar maximum loads, SFRC-D10-S100, which was reinforced with steel fibers, exhibited the highest ductility index calculated as follows:

$$\text{Ductility index} = \frac{\Phi_u}{\Phi_y}. \tag{1}$$

In case of NC-D10-S100-F, the brittle bonding failure between CFRP sheet and concrete occurred, while it showed the highest flexural strength. In addition, it exhibited the lowest ductility index. Therefore, it is recommended to use FRP sheet on RC members with caution.

3.3. Residual Strength of Blast-Damaged Specimens. After the blast test, static flexural test on damaged specimens was carried out to investigate the residual strength of the specimens [11, 12]. From these test results, the effect of local damages on residual strength was examined. In the damaged NC series, flexural strength of NC-D10-S100, NC-D10-S50, and NC-D13-S100 decreased by 59%, 30%, and 39%, respectively, compared to the original strength of intact specimens. The residual strength was significantly decreased because of buckling of compressive reinforcing bars when the concrete cover at compression zone was fractured. On the other hand, NC-D10-S50 and NC-D13-S100, which were the specimens reinforced with more amounts of shear stirrups than the control specimen, showed relatively less decrease in residual strength because of the effect of confinement by stirrups. SFRC specimens showed the highest residual strength because relatively small local damages at the front and rear sides occurred. Thus, it can be concluded that the addition of steel fibers is the most effective method to maintain residual strength of a structural member after blast. In the case of NC-D10-S100-F, flexural strength was decreased by 33%, compared to original strength.

3.4. Flexural Strength of Repaired Specimens. As plotted in Figure 5, all repaired specimens showed ductile behavior and higher flexural strength than the strength of intact specimens. In the case of the control specimen, NC-D10-S100, the flexural strength increased by 11%, while the ductility index decreased by 44%, compared to test results of the intact specimen. These results are because the concrete cover was replaced with SFRCC that had a higher compressive and tensile strength than that of normal concrete, and the longitudinal reinforcements yielded

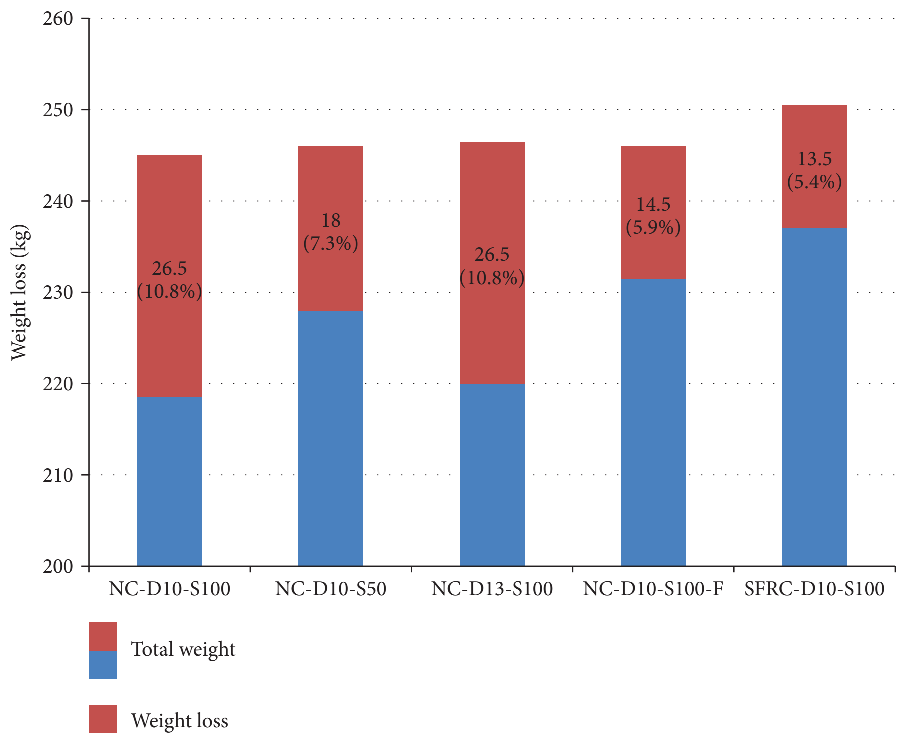


Figure 4: Weight loss of blast-damaged specimens.

during the blast load was imparted on the specimen. For NC-D10-S50 and NC-D13-S100, these two specimens had similar flexural behavior. The flexural strength of these specimens increased by 6% and 14%, respectively. Moreover, these beams showed an increase in the ductility index approximately 27% and 19%, respectively. From these results, it can be concluded that sufficient shear reinforcement can provide considerable blast resistance against local damages and yielding of the longitudinal reinforcement. As a result of the decrease in local damages, the flexural strength of repaired specimens can regain the design-intended structural performance.

The NC-D10-S100-F, CFRP-retrofitted specimen, demonstrated significant increase in flexural strength and ductility. Although bonding failure between CFRP sheet and concrete occurred during the test, the specimen still showed ductile behavior with higher flexural strength than the strength of the intact specimen. However, further research is required to study the bond failure between FRP and concrete under blast-loading condition.

As mentioned previously, adding fibers enhances the blast resistance against local damages under the blast loads. However, it led to an increase in load ratio that was resisted by the longitudinal reinforcement. This was due to the increase in maximum displacement at maximum load of SFRC specimen over the yield point of steel rebars. As a result, the ductility index of repaired specimen decreased because the longitudinal reinforcement was yielded when the blast load was imparted on the specimen, whereas the structural behavior of blast-damaged specimen was relatively ductile. Therefore, there is the need to consider the design goals of structural members when the SFRC is applied on the members.

4. Conclusions

This study investigated the effects of stirrups, FRP retrofitting, and adding steel fibers on intact, blast-damaged, and repaired RC beams. From the above discussions, the following conclusions are drawn:

(1) When blast load was imparted on RC beams by close-in detonation, critical local damages on RC beams occurred even if the charge weight was small. It was verified through the experimental tests that the progressive collapse could have occurred because the residual strength of the damaged control specimen, NC-D10-S100, was below 40% of its original strength. Therefore, it is necessary to apply the protective design using more stirrups and SFRC and retrofitting with FRP on the structural members, if the members are vulnerable to a blast.

(2) The use of higher amounts of stirrups demonstrated insignificant benefits in preventing local damages. However, it was shown that the use of small-diameter steel bars for stirrups with small spacing could decrease the local damages rather than the use of large-diameter steel reinforcements, when the volume of stirrups was fixed. For the residual strength of the damaged specimens, both specimens

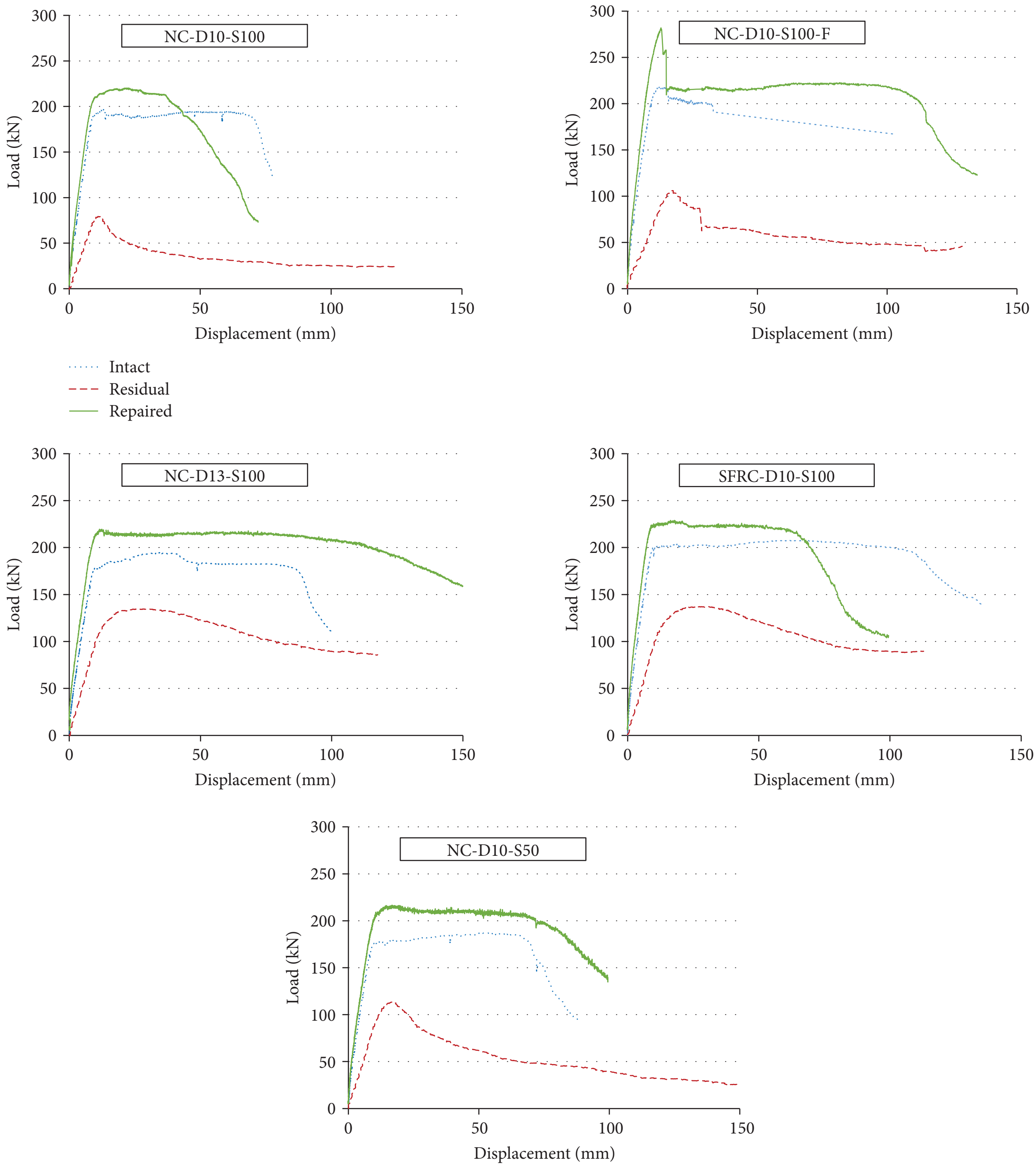


Figure 5: Load-displacement curves of intact, blast-damaged, and repaired specimens.

Table 10: Static flexural test results.

Variables	Max. load (kN)			Flexural strength (kN·m)			Ductility index (Φ_u/Φ_y)		
	Intact	Damaged	Repaired	Intact	Damaged	Repaired	Intact	Damaged	Repaired
NC-D10-S100	196.5	79.3	217.6	186.7	75.3	206.7	7.9	1.3	4.4
NC-D10-S50	194.6	134.6	205.8	184.9	127.9	195.5	4.8	3.1	6.1
NC-D13-S100	186.9	113.3	212.3	177.6	107.6	201.7	7.3	1.4	8.7
NC-D10-S100-F	217.5	105.9	258.4	206.6	100.6	245.5	3.3	1.9	9.1
SFRC-D10-S100	207.5	137.2	225.3	197.1	130.3	225.3	11.5	2.7	5.5

using more stirrups could resist above 60% of the original flexural strength. Therefore, it can be concluded that although the use of higher amounts of stirrups was not adequate to prevent the blast-induced local damages, it can increase the residual strength because of improved confinement.

(3) The addition of steel fibers results in increased ductility and enhanced blast resistance against local damages. However, the ductility index of repaired specimen decreased, because the longitudinal reinforcement experienced flexural yielding when the blast load was imparted on the beam. Therefore, it is recommended to design the steel reinforcements with consideration of the characteristics of SFRC, while designing the structures subjected to extreme loadings. In case of FRP retrofitting, it demonstrated significant increase in flexural strength. Moreover, it showed benefit in protecting debris. However, bonding failure between CFRP sheet and concrete occurred in the intact and repaired specimens. Therefore, further research is needed to increase the bond strength between FRP sheet and concrete.

(4) All specimens that repaired with SFRCC showed higher flexural strength than the original strength, except the control specimen. In the case of ductility, all specimens demonstrated ductile behavior, although the ductility index was slightly decreased in control and SFRC specimens. Therefore, it can be concluded that replacing the damaged concrete cover with SFRCC is adequate to repair the blast-damaged members if the longitudinal reinforcements were not failed.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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