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Punching behavior of FRC slabs under drop-weight impact loading

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ABSTRACT

As the threat of terrorism has been increased all around the world, a demand for a structure which can withstand the extreme loadings, such as impact and blast, has been increased. Consequently, there have been many researches on the protective design and a simplified design approach using support rotation and damage criteria was developed. However, current damage criterion has its weaknesses in some aspects. As it was developed based on the experimental study on traditional RC components, the damage criteria might not be valid for other construction materials, such as steel fiber reinforced concrete. Also, it cannot provide sufficient information on the post-event structural performance since the limit values of damage criteria were established using the empirical correlations between observed damage and support rotations. In order to develop more reasonable damage assessment procedure, twelve two-way RC slabs were tested under low-velocity impact and static loading conditions. From the test results of low-velocity impact testing, the damage level of specimens was estimated using the current approach. After that, the damage was investigated using another approach, residual load-carrying capacity testing. The test results showed that the former, current approach, could not tell the difference in the damage of each specimens because the damage level of specimens was shown to be identical for all specimens. Whereas, the latter, residual load-carrying capacity testing, was proven to be more effective and was able to quantify the damage of each specimen.

1. INTRODUCTION

As the threat of terrorism has been increased all around the world, a demand for a structure which can withstand the extreme loadings, such as impact and blast, has

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been increased. Consequently, there have been many researches to figure out the impact and blast response of structures (Jang 2015). As a result of those numerous results from various analytical and experimental researches, great strides have been made in the past several decades with respect to the development of the guidelines for impact and blast resistant design. Most of those guidelines were developed for military facilities and to ensure a certain level of protection they present highly conservative provisions, such as larger cross section of the structural members and dense reinforcement layout. However, according to the statistics, the major targets of the terrorist attacks are civil infrastructures and commercial buildings rather than military facilities. In order to ensure the adequate protection level of those civil structures, it might not be desirable to apply the traditional approach. First of all, larger cross section of the members would results in the smaller space of use. Second of all, highly dense reinforcement layout may cause severe difficulties in construction stage, not to mention the financial problems. For this reason, it is required to come up with a better alternative which can meet the requirement of protection level and the limitation of space and cost at the same time. In this regard, the use of fiber reinforced concrete (FRC) can be one of the most effective alternatives applicable for civil protective structures. Fiber reinforcements, randomly distributed in the concrete mix, act as crack arrestors and carry the load between the crack surface until they are pulled out completely. During the pulling out process, FRC can absorbs a large amount of energy, resulting in a substantial increase in toughness and deformability. Nevertheless, there are several challenges remain before the use of FRC in the practical protective design. Most of protective design guidelines provide response parameters and damage levels to simplify the design process. One representative protective design guideline, TM 5-1300, defines the damage level of concrete structures based on a response parameter, support rotation θ. However, this approach has its weakness in some aspects. Briefly, Support rotation θ can not explain the difference of material properties as it has been developed based on experimental results from the traditional RC structural components. Moreover, it does not provide sufficient information on the post-event state of the structure. More detailed statement on these limitations are described in the next chapter. Therefore, a modified experimental approach is required to develop more reasonable damage levels considering the difference of material properties and to explain the post-event state of the damaged structural components.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens

In total, twelve 1,600 × 1,600 × 140 mm two-way RC slab specimens were constructed. Eight of the slabs were cast using a conventional concrete mix design and the others were cast using SFRC mix with 1% of steel fiber volume fraction. The details and the notations of specimens are followed.

As shown in Table 1, there were two variables for tested specimens in this experimental program. First of all, different types of concrete mix were used. For normal concrete (NC), the target concrete compressive strength was 40 MPa. In case of steel fiber reinforced concrete (SFRC), 1% of steel fiber reinforcement was added to the normal concrete mixture. The mix proportion of these concrete materials are shown in Table 2. Also, the material properties of steel fiber reinforcement are described in Table 3.

Table 1. Summary of specimen details

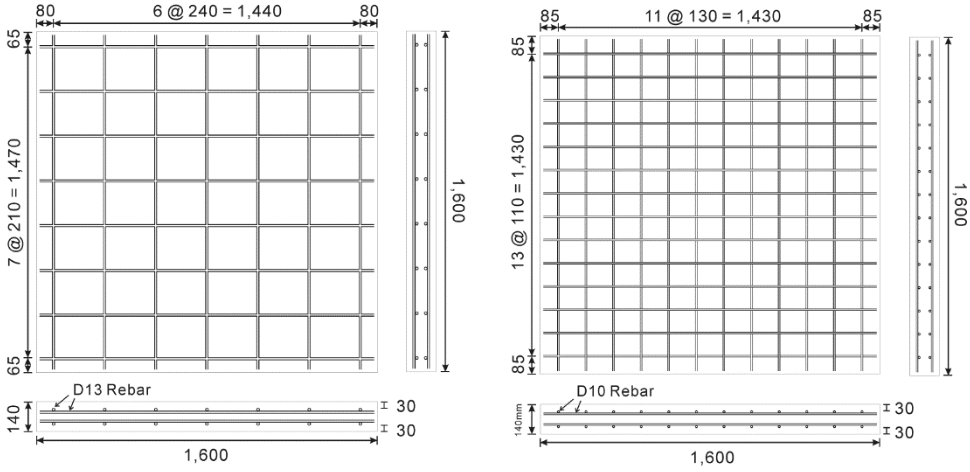
Nomenclature	Concrete mix		Reinforcement layout	
	f_{ck} (MPa)	V_f (%)	Reinforcement ratio	Reinforcement spacing (mm)
NC-D13	40	-	$\rho_x = 0.0038$ $\rho_y = 0.0043$	x direction; D13 bar at 240mm y direction; D13 bar at 210mm
NC-D10			$\rho_x = 0.0039$ $\rho_y = 0.0046$	x direction; D10 bar at 130mm y direction; D10 bar at 110mm
SFRC-D13	40	1.0	$\rho_x = 0.0038$ $\rho_y = 0.0043$	x direction; D13 bar at 240mm y direction; D13 bar at 210mm

Table 2. Mix proportions for NC and SFRC specimens

Nomenclature	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Steel fiber (%)
NC	173	526	750	896	-
SFRC	173	526	750	896	1.0

Table 3. Material properties of steel fiber reinforcement

Type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)
End-Hooked	60	0.75	80	1,196



(a) D13 specimens (b) D10 specimens

Fig. 1 Reinforcement layouts (dimensions in millimeters)

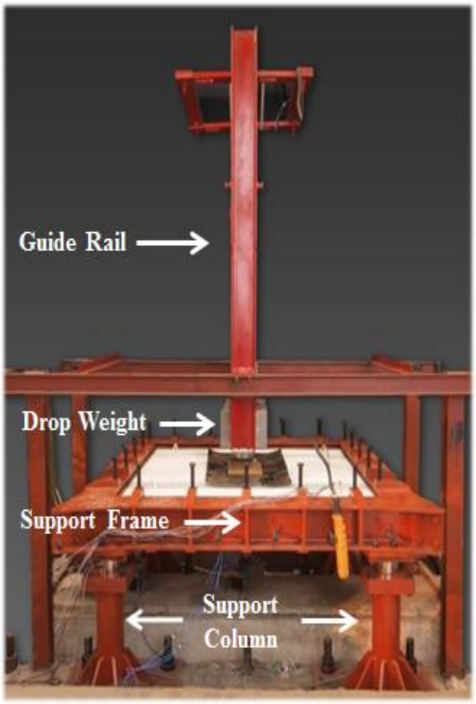
The reinforcement layout was varied (see Fig. 1). All slabs were doubly reinforced with equal amounts of reinforcement in the top and bottom layers. To investigate the effect of reinforcement spacing on the impact response, two types of reinforcing bars were used: KS standard D13 bar (A_s = 126.7 mm2, d_b = 12.7 mm) and D10 bar (A_s = 71.3 mm2, d_b = 9.53 mm). By using different rebar spacing (i.e., 240/210 mm for D13 specimens and 130/110 mm for D10 specimens), the flexural strength of each specimens were kept the same. Also, the spacing of planar directions were adjusted in order to obtain the same flexural strength of both direction (e.g., in case of D13 specimens, 240 mm for x-direction and 210 mm for y-direction).

2.2 Impact Testing Apparatus

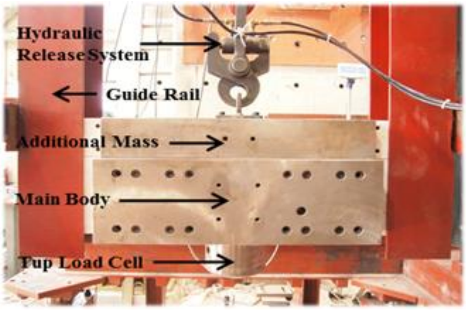
In this study, an impact testing apparatus was devised to investigate the behavior of two-way RC slabs under impact and assess the damage level induced by low-velocity impact loadings (see Fig. 2).

First of all, the impact load was applied to the mid-point of the specimens by dropping a steel weight at a certain drop-hight. The drop-weight was designed to vary from 300 kg to 500 kg by attaching the additional mass of 100 kg. The diameter of tup was ϕ150 mm with a flat contact surface. Also, two H-beam were installed to guide the weight during the fall. On the top of the steel weight, a hook was made to hang it to a hydraulic release system. and the maximum drop-height was 2,000 mm. The maximum impact velocity was expected to 6.3 m/s and the maximum impact energy was calculated as 9.8 kJ.

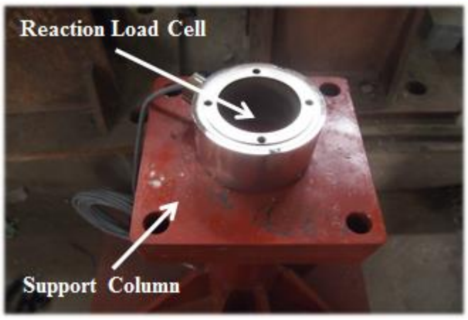
Second of all, to prevent bouncing when the impact load is applied, the fixed support boundary condition was applied. Support frame was made of 200$\times$ 200 mm H-beam strengthened with equally spaced stiffeners at all side of the beam so that the support frame had enough stiffness. The clear span of the slab specimens was 1,500 mm.



(a) Impact testing apparatus



(b) Drop-weight



(c) Support column

Fig. 2 Devised impact testing apparatus

Second of all, to prevent bouncing when the impact load is applied, the fixed support boundary condition was applied. Support frame was made of 200 × 200 mm H-beam strengthened with equally spaced stiffeners at all side of the beam so that the support frame had enough stiffness. The clear span of the slab specimens was 1,500 mm.

Lastly, in order to record the force variation during the impact phenomena, load cells were installed at the tup of the drop-weight and each support column. The load cell for impact tests must have a sufficient sensitivity to provide adequate resolution and have a sufficient capacity greater than the maximum expected load (Zineddine and Krauthammer, 2007). Based on the previous experimental research (Bentur et al., 1986; Saatci et al., 2009; Kishi et al., 2012; Hrynk, 2013) where the impact conditions were similar to that of this research, the capacity of each load cell was chosen. Impact load cell and each reaction load cell were manufactured with a static capacity of 1960 kN and 490 kN, respectively.

2.3 Testing procedure

Three specimens for each variable were tested in the main test program. First of all, a single impact loading was applied to specimens (group #1 and #2) in order to induce the damage. After that, the residual load-carrying capacity was evaluated from the quasi-static loading test and compared to that of undamaged specimen (group #0).

In the single impact testing, as presented in Table 4, two different loading conditions were applied. The drop-height was set as 2,000 mm and the drop-weight was 300 and 400 kg for specimen group #1 and #2, respectively. During the single impact testing, deflection-time history of each specimen was measured and corresponding damage level was evaluated using conventional damage assessment approach based on support rotation θ.

Table 4. Applied impact loadings of main test

Group	Drop-weight (kg)	Drop-height (mm)	Imparted energy (kJ)
Group #0	-	-	-
Group #1	300	2,000	5.9
Group #2	400	2,000	7.8

In the residual load-carrying capacity testing, quasi-static loading condition with 0.025 mm/sec constant deflection rate was applied. The clear span was 1,500 mm and fixed support boundary condition was adopted, identical to that of impact testing. To measure the mid-point deflection, LVDTs were installed beneath the center of the specimens.

3. TEST RESULTS AND DISCUSSION

3.*1 Material properties*

Table 5. Summary of quasi-static test results

Specimens	Mechanical properties under quasi-static loading					
	Compressive strength (MPa)		Flexural strength (MPa)			
			At first crack		At peak load	
NC	41.2	40.7 (avg.)	4.01	4.24 (avg.)	4.01	4.24 (avg.)
	40.4		4.64		4.64	
	40.6		4.07		4.07	
SFRC	32.8	31.2 (avg.)	6.45	5.35 (avg.)	7.81	7.49 (avg.)
	30.3		4.87		6.58	
	30.6		4.72		8.09	

Companion tests, consisting of compression tests in accordance with ASTM C 39 and third-point flexure tests according to ASTM C 1609 were performed under quasi-static loading condition. For compression test, cylinderical specimens with a dimension of ϕ100× 200 mm were used. Compression tests were performed using a universal testing machine (UTM) and a compressometer with three LVDTs was used to obtain the average compressive strain. In flexure tests, three prism specimens with a dimension of 100× 100× 400 mm were used. Also, two LVDTs were installed on both side of the specimen to measure deflection at the center. The Summary of quasi-static test results are shown in Table 5.

3.*1 Results of impact testing*

Three specimens for each variable were tested in the main test program. First of all, a single impact loading was applied to specimens (group #1 and #2) in order to induce a certain level of damage. After that, the residual load-carrying capacity was evaluated from the quasi-static loading test and compared to that of undamaged specimen (group #0).

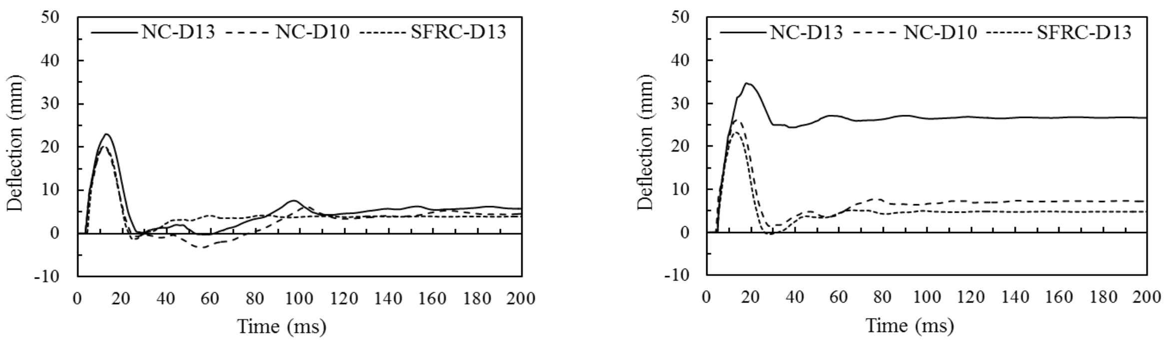
Two different impact loading conditions were applied. The drop-height was set as 2,000 mm and the drop-weight was 300 and 400 kg for specimen group #1 and #2, respectively.

In this section, the impact damage was evaluated using conventional approach based on support rotation θ. And then, it was compared to the damage assessment results from the residual load-carrying capacity test.

3.1.1 Damage Assessment Based on Support Rotation

The value of support rotation θhave traditionally used as a response parameter in protective design. This parameter based on the maximum dynamic deflection of structural components, which is relatively easy to measure in the test.

During the single impact loading test, deflection-time history (see Fig. 3) exhibited by each specimen was recorded and used to calculate support rotation values. And then, corresponding damage level was evaluated according to the design criteria provided by TM 5-1300, the most representative protective design manual.



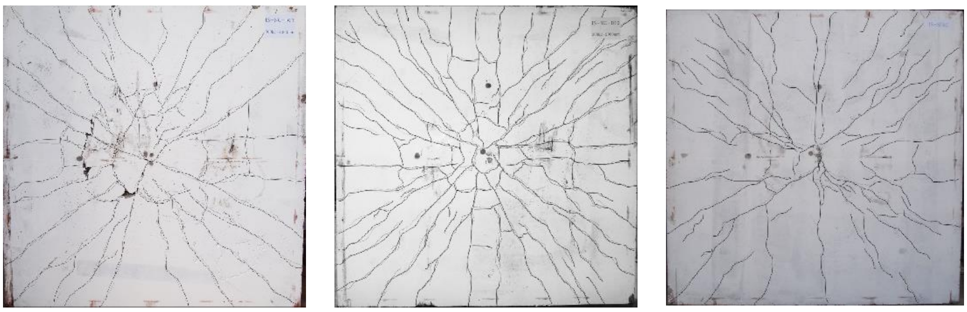
(a) Group #1 specimens (300kg, 2,000mm) (b)Group #2 specimens(400kg, 2,000mm)

Fig. 3 Deflection-time history under single impact

Table 6 presents the damage level evaluated using conventional approach based on support rotation θ. Support rotation values for all groups and all specimens were in the range of moderate damage level, from 2 degree to 5 degree. Hence, this damage assessment results could not provide sufficient information to make a detailed comparison. The crack patterns are shown in fig.5 and 6.

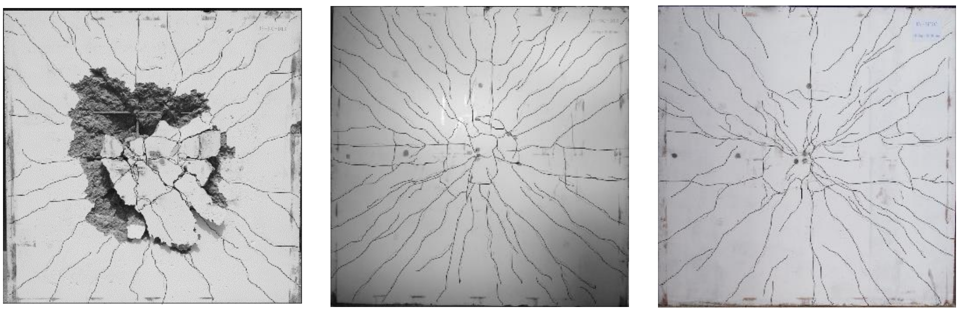
Table 6 Damage assessment using conventional approach

Group	Specimens	Maximum deflection (mm)	Support rotation (degree)	Damage level (TM 5-1300)
Group #1	NC-D13	23.0	3.07	Moderate
	NC-D10	19.8	2.64	Moderate
	SFRC-D13	20.2	2.69	Moderate
Group #2	NC-D13	34.7	4.62	Moderate
	NC-D10	26.2	3.49	Moderate
	SFRC-D13	23.3	3.11	Moderate



(a) NC-D13 (b) NC-D10 (c) SFRC-D13

Fig. 4 Observed damage after single impact (group #1 specimens)



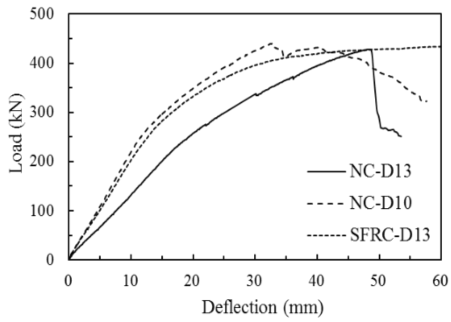
(a) NC-D13 (b) NC-D10 (c) SFRC-D13

Fig. 5 Observed damage after single impact (group #2 specimens)

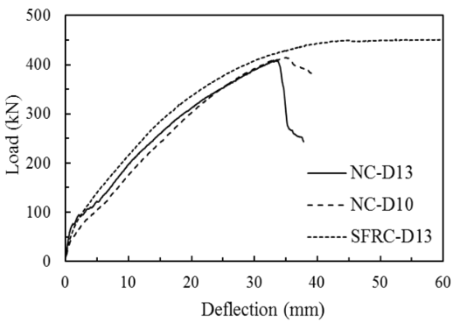
3.1.2 Damage Assessment Based on Residual Strength

In order to make a more detailed comparison of impact damage, a residual load-carrying capacity test was also carried out under quasi-static loading condition.

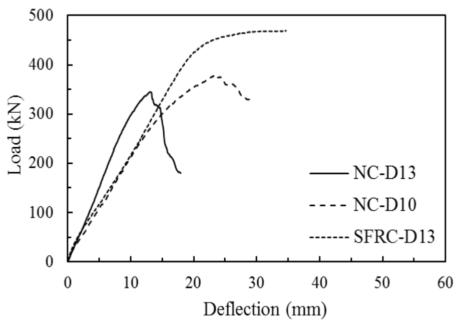
The load-deflection curves obtained from residual load-carrying capacity test are presented in Fig. 6. Using the test results, the variation of strength before and after impact phenomena was investigated.



(a) Group #0 - undamaged



(b) Group #1 - 300kg, 2,000mm



(c) Group #2 - 400kg, 2,000mm

Fig. 6 Results of residual load-carrying capacity test

The results of residual load-carrying capacity test are summarized in Table 7.

When it comes to the specimen group #1 and #2, no strength reduction was observed though those specimens exhibited extensive cracking when visually inspected (see Fig. 4 and 5). However, in the case of specimen group #2, a significant strength reduction was observed in NC-D13. Also, NC-10 specimen showed 8.59% of strength reduction, approximately 46% lower than that of NC-D13 specimen. Lastly, no strength reduction was observed in SFRC-D13 specimen. This obviously indicates that impact capacity can significantly increase using dense reinforcement layout and steel reinforcement.

Also, it should be noticed that the damage level evaluated using conventional approach was shown to be identical regardless of specimen type and applied impact loading. However, from the residual load-carrying test results, the strength reduction significantly varied depending on applied impact loading and the type of specimen.

Table 7. Damage assessment using residual strength

Specimens	Group #0 (undamaged)	Group #1 (300kg, 2,000mm)		Group #2 (400kg, 2,000mm)	
	Peak load (kN)	Peak load (kN)	Strength reduction (%)	Peak load (kN)	Strength reduction (%)
NC-D13	410.1	428.2	-	345.3	15.8
NC-D10	414.6	435.5	-	379.0	8.59
SFRC-D13	451.7	433.9	-	471.3	-

3.1.3 Comparison of Approaches for Damage Assessment

Damage assessment procedure using residual load-carrying capacity has its strength in some aspects.

First of all, damage assessment using residual load-carrying capacity provides more quantitative results compared to the conventional approach. The conventional approach provides three damage level, such as light, moderate and severe damage. Each of these damage levels covers a wide range of support rotation, which may not be capable of detailed comparison as presented previously. Whereas, the approach based on residual load-carrying capacity can produce quantitative damage evaluation in term of strength reduction.

Second of all, this approach is more practical compared to the conventional approach. It can provide sufficient information on post-event state of damaged structural component while the conventional one only presents approximated level of damage only.

In this sense, more accurate approach that estimate the damage level of structural components can be developed by adopting residual load-carrying capacity test. It can be a possible solution to correlate the residual strength of damaged components with the corresponding support rotation θso that it can explain the post-event state of the components. And then the damage criteria would become more reasonable and quantitative.

4. CONCLUSIONS

The purpose of this study was to verify the effectiveness of devised impact testing apparatus and also to develop a modified damage assessment procedure that can reasonably measure the impact resistance of two-way RC slabs. The conclusions drawn from this research are followed.

Impact testing apparatus was devised and was shown to have an adequate accuracy to capture impact responses

According to the test results, the estimated coefficient of variation of measured data set was negligibly small, 1.6%, 1.4% and 0.54% for impact forces, reaction forces and deflections, respectively. Also, from the results of FFT analysis using measured data set, adopted sampling rate, 100 kHz was shown to be adequate to capture the rapid varying impact responses.

Dense reinforcement layout and the addition of steel fiber reinforcement can

increase the impact capacity of RC slabs

When subjected to sequential impact loading, total imparted energy of specimens, where the dense reinforcement or steel fiber reinforcement applied, significantly increased. Moreover, from the residual load- carrying capacity test results, the strength reduction due to impact damage enormously decreased. This obviously indicates that dense reinforcement layout and steel reinforcement significantly improves the impact capacity of RC slabs.

More reasonable damage assessment procedure can be developed by adopting the residual load-carrying capacity test

The results of main test showed that current approach, based on support rotation only, could not provide sufficient information on the impact damage of each specimens, resulting in the identical damage level for all specimens. Whereas, residual load-carrying capacity testing, was proven to be more effective and was able to quantify the damage of each specimen. Also, it was capable of explaining the post-event state of damaged specimens after the impact phenomena. In this sense, more reasonable approach that estimates and quantifies the damage level of structural components can be developed by adopting residual load-carrying capacity testing.

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