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# Enhancing impact resistance of concrete beams strengthened with high strength high ductility concrete

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## ABSTRACT

In this study, the effect of the strengthening method type on the flexural response of normal concrete (45MPa) beams (NC-NN) strengthened with high strength, high ductility concrete (HSDC) under impact load was investigated. Therefore, the effectiveness and efficiency of four various techniques for strengthening of reinforced concrete beams using HSDC (NC-B40, NC-TB, NC-3D, NC-4D) were prepared. And in order to compare the flexural capacities with those of strengthening RC beams, the minimum shear reinforcement RC beam (NC-SR) was fabricated. Results of the impact test, the NC-NN, NC-B40 and NC-TB shatter failure mode was observed in the first impact loading, and NC-SR also exhibited havoc spalling in the top surface of test beam in the first impact. Whereas, the other specimens strengthened with HSDC (NC-3D, NC-4D) exhibited flexural failure mode, in the fifth and tenth impact loading, respectively. Furthermore, the maximum reaction force and energy dissipation capacity increased as the HSDC strengthened area increased, moreover, strengthened reinforcement enhances impact resistance in terms of reaction force. Thus, the increase strengthened dimension by HSDC can effectively increase the stiffness and damping capacity of RC beams against impact load.

## 1. INTRODUCTION

The technique of bonding steel plate and FRP to the soffits of reinforced concrete beams can be used to improve the flexural performance of existing structures as it increases the strength and rigidity (Oehlers 1992). A more recent material developed and applied for both repair and strengthening of reinforced concrete structures is the high performance fiber reinforced concrete (Kim 2003). Research work conducted on both its durability and structural performance has so far shown promising results in References (Kim 2003, Tai 2011).

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The main objective of the present study is to evaluating enhancing impact resistance of concrete beams strengthened with high strength, high ductility concrete. Thus, the effectiveness and efficiency of four different techniques for strengthening of reinforced concrete beams using HSDC was investigated.

## 2. EXPERIMENTAL PROGRAM

### *2.1 Mixing proportions and test specimens*

The cementitious materials of normal concrete (NC) and high strength, high ductility concrete (HSDC) in this study were Type I Portland cement. Crushed aggregate was adopted as the sand, and coarse aggregate of maximum size 20 mm was used in NC. Silica fume produced in Norway, silica sand grain size was smaller than 0.5 mm, and 10 μm diameter filler including 99% $SiO_2$ was used in the HSDC. The liquid polycarboxylate superplasticizer (SP) was used to provide suitable workability, as described in Table 1. Table 2 shows the chemical and physical properties of these materials. The high strength polyethylene fiber and high strength straight steel fiber were used in HSDC. And the physical and geometric properties of the fibers are separately listed in Table 3.

The details designation of test specimens are listed in Table 4. All specimens were 125 mm in width, 250 mm in height, and 2,222 mm in length, and longitudinal reinforcements, which consisted of two deformed steel reinforcing bars of diameter of 19.1 mm. The specimen of test series incorporated shear stirrups that were designed according to the minimum shear requirements of ACI 318-14 and were composed of 10 mm undeformed steel bar. They were conventional U-shaped open stirrups and spaced at 100 mm along the shear span of the specimens. Furthermore, the specimens were cured after casting and demolding for 24 hours in a room with steady temperature and humidity until the testing date (28 days), at a temperature of 20 ± 1°C and a relative humidity of 60 ± 5%.

### *2.2 Details of the Mechanical and structural test*

The compressive strength tests were carried out according to ASTM C39 for NC and HSDC. The cylindrical specimens with a diameter of 100mm and height of 200mmwere used and tested at 28 days after casting. The test used a universal testing machine (UTM) with a maximum capacity of 250 tons under the monotonic rate of 0.2 mm/min. And for the HSDC, the three prismatic specimens for each variable were fabricated and tested under four-point flexure according to ASTM C1609, and the direct tensile test used dog-bone-shaped specimens based on the Japan Society of Civil Engineer (JSCE) recommendation. The cross-section of the dog-bone-shaped specimens was 30 mm x 25 mm and two LVDTs with a maximum capacity of 10 mm were used to measure the elongation. A similar UTM as stated above was used under a displacement control rate of 0.2 mm/min.

The test setup for the drop-weight impact test is similar with previous research (Lee 2018). The test setup consists of several parts: guide H-beams, drop steel hammer, and supports. The supports were fixed on the strong floor of the laboratory and designed to prevent rebounding of the test beams under impact load. Two load cells of capacity 490 kN were placed on the supports to evaluate the reaction forces, and a load cell of capacity 1,960 kN was placed in the drop tup of drop-weight to evaluate the impact force. In this study, the mass of the hammer was set to 100 kg, and the magnitude of the applied impact load was adjusted by varying the drop height. The test beams were subjected to multiple impacts. The drop height was 1,600 mm.

Table. 1 The proportion of materials in the cement composites mixture

| | *w/b* (%) | Cement | Water | Sand | Corse aggregate | Silica fume | Filler | Steel fiber | PE fiber |
|---|---|---|---|---|---|---|---|---|---|
| NC | 43.0 | 1.00 | 0.43 | 2.15 | 2.42 | - | - | - | - |
| HSDC | 17.2 | 1.00 | 0.172 | 1.10 | - | 0.25 | 0.30 | 1.0 | 0.5 |

[Note] NC: normal concrete; HSDC: high strength, high ductility concrete; *w/b*: water to binder ratio; PE fiber: Polyethylene fiber.

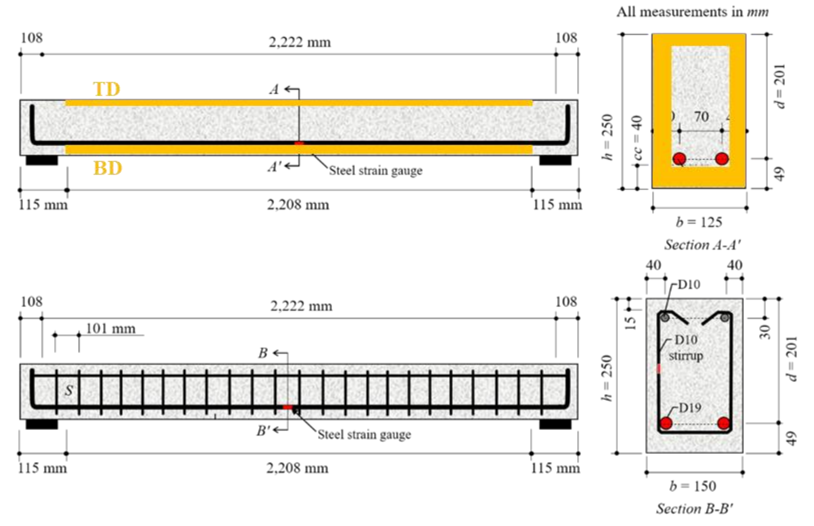
Table. 2 Chemical composites and physical properties of cementitious materials

| | Surface area ($cm^2/g$) | Density ($g/cm^3$) | Chemical composition (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Ns_2O$ | $K_2O$ |
| Cement | 3,492 | 3.15 | 21.16 | 4.65 | 3.14 | 62.79 | 2.81 | 2.13 | - | - |
| Silica fume | 200,000 | 2.20 | 96.00 | 0.25 | 0.12 | 0.38 | 0.10 | < 0.2 | - | - |
| Filler | 2.65 | 0.75 | 99.60 | 0.31 | 0.025 | 0.010 | 0.006 | - | 0.009 | 0.004 |

Table. 3 Properties of polyethylene and steel fiber

| | Diameter, $d_f$ | Length, $l_f$ (mm) | Aspect ratio ($l_f/d_f$) | Density ($g/cm^3$) | Tensile strength (MPa) | Elastic modulus (GPa) |
|---|---|---|---|---|---|---|
| Polyethylene fiber | 31 µm | 12 | 387 | 0.97 | 2,900 | 100 |
| Steel fiber | 0.2 mm | 19.5 | 97.5 | 7.80 | 2,650 | 200 |

Table. 4 Designation of test specimens

| | Stirrup (mm) | HSDC (mm) | | |  |
|---|---|---|---|---|---|
| | | TD | BD | SD | |
| NC-NN | - | - | - | - | |
| NC-SR | 101 | - | - | - | |
| NC-B40 | - | - | 40 | - | |
| NC-TB | - | 20 | 40 | - | |
| NC-3D | - | - | 40 | 20 | |
| NC-4D | - | 20 | 40 | 20 | |

## 3. EXPERIMENTAL REULTS AND DISCUSSION

### 3.1 *Results of Mechanical test*

The compressive strength of NC was occurred 46.2 MPa, and the HSDC exhibited a great tensile strength and strain resistance capacity. And compressive strength and flexural strength of HSDC was occurred 123.4 MPa and 21.9 MPA at 28-day, respectively. Based on the flexural load-deflection curve, the different toughness indices $I_5$, $I_{10}$, $I_{30}$ of the HSDC were calculated and exhibited 5.4, 12.2, 58.8, respectively (Yuan 2019). According to recent research (Naaman 1995), the fiber-reinforced concrete with toughness indices $I_5$>5, $I_{10}$>10, $I_{30}$>30 can be defined as strain-hardening composites. Thus, HSDC can be defined as strain-hardening materials base on its great toughness indices. The post-crack tensile stress and tensile strain capacity were 9.6 MPa and 2.78%, respectively.

Table. 5 The results of mechanical test

| | Compressive strength (MPa) | Flexural strength | | | | Direct tensile strength | |
|---|---|---|---|---|---|---|---|
| | | Stress (MPa) | $I_5$ | $I_{10}$ | $I_{30}$ | Stress (MPa) | Strain (%) |
| NC | 46.2 | - | - | - | - | - | - |
| HSDC | 123.4 | 21.9 | 5.4 | 12.2 | 58.8 | 9.6 | 2.78 |

### 3.2 *Results of impact test*

The impact capacity of each specimen is measured in terms of total imparted energy until final failure. The results of the impact test are summarized in Table 6. The impact load was evaluated by a load cell placed in the drop tup, and the reaction load was evaluated by adding the calculated support reactions. The variation of the maximum reaction load was defined as the failure criteria.

In the case of NC-NN (control specimen) and NC-TB (top and bottom side strengthening), shatter failure mode was observed in the first impact as shown in Table 6. And minimum shear reinforced concrete specimen NC-SR exhibited havoc spalling in the top surface of test beam in the first impact. Whereas, the other specimens strengthened with NSHSDC (three sides strengthening, and four side strengthening) exhibited flexural failure mode, in the fifth and tenth impact, respectively. The maximum reaction force increased as the NSHSDC strengthened area increased; moreover, strengthened reinforcement enhances impact resistance in terms of reaction force. In order to evaluate the dissipated energy, the impact loads were imparted repeatedly until the specimen failed with severe damage. The specimen NC-NN, NC-TB cannot calculate impact energy because shatter failure mode was observed in the first impact, which has not reinforced shear capacity to resist the impact load. Hence, the deflection of those specimens cannot be measured using current apparatus.

On the other hand, the specimen NC-SR, NC-3D, and NC-4D occurred ductile behavior and dissipated 21.4, 108.7, 370.2 kJ of imparted energy until the final impact. Thus, it was verified that impact resistance can be enhanced by using shear reinforcement and over 3 dimensions strengthened by NSHSDC, as compared with conventional RC beams without reinforcement (NC-NN). The final crack profiles of impact test specimens are presented in Table 6. The specimens without shear reinforcement (NC-NN, NC-TB) exhibited shatter failure with severe diagonal cracks, and those reinforced with stirrups and strengthened by NSHSDC over 3 dimensions exhibited vertical flexural cracks. The number of cracks increased with increase in the strengthened dimensions by NSHSDC. In all repeated impact load specimens, local damages occurred at the surface where the large impact load was imparted rapidly owing to the load concentration. In the case of NC-NN, NC-SR, spalling occurred at the rear side of the beam. However, in the case of NC-3D and NC-4D, spalling was not observed as the fibers effectively resisted it.

Table. 6 Impact test results of beams

| | Blow No. | Max. mid-span displacement (mm) | Residual mid-span displacement (mm) | Max. reaction force (kN) | Dissipated energy (kJ) |
|---|---|---|---|---|---|
| NC-NN | 1 | - | - | 104.5 | 1.18 |
| NC-SR | 1 | - | - | 90.9 | 1.12 |
| NC-B40 | 1 | 17.6 | 4.99 | 66.2 | 1.17 |
| NC-TB | 1 | 42.4 | - | 126.6 | - |
| NC-3D | 1 | 10.6 | -0.63 | 66.0 | 2.43 |
| | 2 | 12.2 | -1.37 | 103.4 | |
| | 3 | 13.4 | -0.17 | 90.5 | |
| | 4 | 13.5 | 0.37 | 82.2 | |
| | 5 | 14.7 | 0.40 | 77.3 | |
| NC-4D | 1 | 12.8 | -1.71 | 138.7 | 9.26 |
| | 2 | 13.5 | -1.84 | 133.1 | |
| | 3 | 14.8 | -1.52 | 122.6 | |
| | 4 | 15.6 | -1.20 | 112.9 | |
| | 5 | 16.2 | -1.21 | 113.2 | |
| | 6 | 17.0 | 1.96 | 115.0 | |
| | 7 | 17.9 | 1.94 | 120.3 | |
| | 8 | 19.3 | 3.09 | 100.7 | |
| | 9 | 20.6 | 4.73 | 83.1 | |
| | 10 | 22.1 | 5.75 | 78.0 | |

## 3. CONCLUSIONS

This research investigated the enhancing impact resistance of concrete beams strengthened with high strength, high ductility concrete. From this investigation, the following concluding remarks can be drawn:

In all repeated impact load specimens, local damages occurred at the surface where the large impact load was imparted rapidly owing to the load concentration. In case of NC-NN, NC-SR, spalling occurred at the rear side of the beam. However, in the case of

NC-3D and NC-4D, spalling was not observed as the fibers effectively resisted it. Thus, the increase strengthened dimension by NSHSDC can effectively increase the stiffness and damping capacity of normal concrete beams against impact loads.

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