IMPACT RESISTANCE OF UHPFRC PLATES

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Abstract

An experimental investigation has been conducted to address the advantage of using UHPFRC for impact resistance applications. Five identical reinforced concrete (RC) plates, with exception of concrete materials, are tested under repeated impacts by dropping a 475 kg steel weight from a height of 4.15 m. Two reference specimens are constructed using plain normal- (NSC) and high-strength concrete (HSC) mixes, while the other three are constructed using UHPFRC with varying steel fibre volume contents of 1, 2, and 3%. Impact resistance characteristics have been evaluated based on visual inspection, and imparted energy. Test results show that UHPFRC exhibit superior impact resistance characteristics in comparison to traditional concrete. The use of a fibre content of 3% is more effective in enhancing the dynamic performance and damage control properties of UHPFRC structural members. The total impact energy of UHPFRC plate containing 3% fibres was found to be double the capacity of UHPFRC plate containing 2% fibres and 18 times the capacity of NSC plate.

Résumé

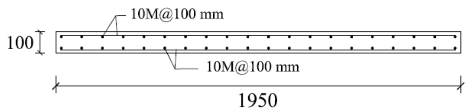
Une recherche expérimentale a été menée pour étudier l'avantage d'utiliser le BFUP dans des applications valorisant la résistance à l'impact. Cinq plaques de béton armé identiques, à l'exception du matériau béton, ont été testées avec des impacts répétés en faisant chuter un poids en acier de 475 kg d'une hauteur de 4,15 m. Deux éléments témoins ont été réalisés avec du béton ordinaire et du béton à hautes performances, tandis que les 3 autres ont été réalisés en BFUP avec des teneurs volumiques en fibres d'acier valant 1, 2, et 3 %. Les caractéristiques de la résistance à l'impact ont été évaluées par une inspection visuelle et estimation de l'énergie transmise. Les résultats des essais montrent que le BFUP présente des caractéristiques de résistance à l'impact supérieures à celles du béton traditionnel. L'utilisation des fibres à hauteur de 3 % conduit à l'amélioration la plus efficace des performances dynamiques et du contrôle de l'endommagement des composants structurels en BFUP. L'énergie totale d'impact d'une plaque de BFUP contenant 3 % de fibres s'est avérée deux fois plus importante que celle d'une plaque de BFUP contenant 2 % de fibres et 18 fois celle d'une plaque en béton ordinaire.

1. INTRODUCTION

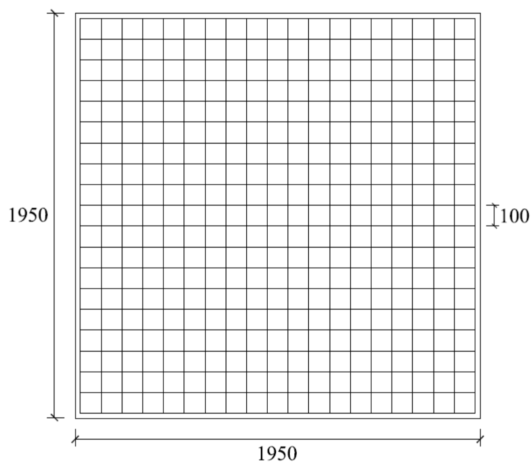
UHPFRC is a relatively new type of concrete that has been developed to obtain a significantly higher material performance than other concrete classes. UHPFRC exhibits outstanding mechanical and durability properties. Several experimental investigations at material level have demonstrated that UHPFRC exhibits excellent impact resistance characteristics [1–3]. Available experimental investigations on UHPFRC structural members under dynamic loading conditions have confirmed that UHPFRC has superior dynamic performance compared to conventional concrete (e.g. [4–7]). However, there is no available data about the effect of fibre content on the impact capacity of UHPFRC structural members. Additionally, there is a lack of sufficient test data showing the impact capacity of UHPFRC in comparison to NSC and HSC structural members. Therefore, this research is a stepping stone in order to address the advantage of using UHPFRC for impact resistance structures.

2. TEST SPECIMENS

Five RC plates with identical dimensions and steel reinforcement ratio are constructed and tested under repeated drop-weight impact. The plates are 1950 mm square with a thickness of 100 mm. All plates are doubly reinforced with equal top and bottom steel reinforcement. 10M CSA standard deformed steel bars of Grade 400 with a spacing of 100 mm are used as longitudinal reinforcement in all plates. Typical dimensions, reinforcement layout of test specimens are shown in Figure 1. As summarized in Table 1, two parameters are considered, namely: concrete class (NSC, HSC and UHPFRC); and fibre volume content of UHPFRC mixes (1, 2 and 3%). The UHPFRC plates are cast using a commercially proprietary product specified by Lafarge North America. The UHPFRC mixes have identical mix proportions with the exception of the fibre volume content. Short steel fibres are used in all UHPFRC mixes, these fibres have a diameter of 0.2 mm and are 13 mm long.



(a) Typical cross-section of reinforced concrete specimen



(b) Typical layout of steel reinforcement

Figure 1: Details of test specimens (dimensions in mm)

Table 1: Details of test specimens

Specimen ID	Concrete material	Fibre content (%)	Steel reinforcement Diameter/spacing (mm)
NSC	NSC	---	10M/100
HSC	HSC	---	10M/100
UH-F_1	UHPFRC	1.00	10M/100
UH-F_2	UHPFRC	2.00	10M/100
UH-F_3	UHPFRC	3.00	10M/100

Measured mechanical properties of concrete materials are summarized in Table 2. Compression and splitting tensile tests are conducted on cylinders with dimensions of 100×200 mm. On the other hand, three-point bending tests are conducted on 100×100×400 mm prisms with a clear span of 300 mm. It is evident from Table 2 that the contribution of fibres is more pronounced in splitting and flexural strength values (i.e. tensile strength) than in compressive strength and elastic modulus values. The effect of increasing the fibre content on the compressive strength is found to be insignificant. Several researches have reported similar observation (e.g. [3, 4]).

Table 2: Mechanical properties of concrete materials

Concrete mix	Compressive strength f_c', (MPa)	Elastic modulus E_c, (GPa)	Flexural strength f_r, (MPa)	Splitting strength f_{tsp}, (MPa)
NSC	34.3	23.8	6.8	3.95
HSC	83.1	30.2	8.0	4.5
UH-F_1	154.8	47.0	8.5	7.3
UH-F_2	162.4	48.8	19.2	11.1
UH-F_3	158.7	49.3	28.3	14.0

3. REPEATED DROP-WEIGHT IMPACT TESTING

Figure 2 shows the drop-weight impact testing setup. During the test, the drop-weight is elevated to the required height above the specimen using an electromagnetic hoist and then the drop-weight is released to hit the specimen at midpoint. The specimens are supported at the four corners. The uplift of each corner is prevented by special tie-down frames. The midpoint displacement is measured using a contact-less laser sensor. A digital camera with a framing rate of 240 fps is used to evaluate the impact velocity. The complete description of impact testing setup, instrumentation, experimental data processing is described in previous publications [8, 9].

The impact resistance of different materials is generally assessed through repeated impact testing techniques. ACI Committee 544 [10] proposed a repeated drop-weight impact technique for evaluating the damage resistance of fibre concrete materials, in which, a steel ball is dropped consecutively from a constant height onto the concrete specimen and the number of blows is the main parameter. Relative impact resistance of specimens with identical dimensions cast using different materials can be evaluated using this technique. Therefore, the same procedures are followed in this investigation. Repeated impact tests with the same energy have been conducted to assess the impact resistance of UHPFRC in comparison with traditional concrete. All specimens are subjected to multi-impacts by dropping a steel mass of 475 kg from a constant height of 4.15 m. The repeated impact testing has been terminated when the cumulative permanent (i.e. plastic) deflection under repeated impacts reached 65 mm or severe punching damage took place with a high probability of instrumentation damage. Accumulated kinetic energy, cumulative permanent displacement and crack pattern during multiple impacts are assessed to determine the resistance of tested specimens.

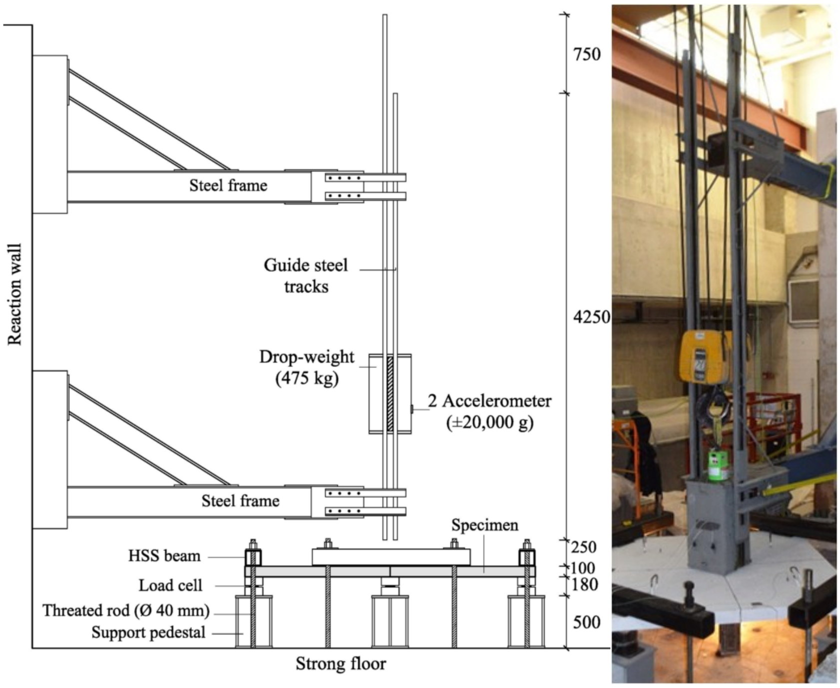


Figure 2: Drop-weight impact setup (dimensions in mm) [8]

4. RESULTS AND DISCUSSIONS

4.1 Impact capacity

In this investigation, the total kinetic energy ($E_k = \Sigma 1/2\ mV_i^2$) imparted to each specimen is used to estimate the impact capacity. The impact velocity (V_i) is calculated using image analysis of the recorded videos and the mass of drop-weight (m) is 475 kg. The impact capacities of RC specimens are summarized in Figure 3. The number between brackets is the total number of impact tests that were applied to each specimen until reaching one of the two testing termination criteria. It is evident from Figure 3 that the use of UHPFRC material enhances the impact capacity significantly. Comparing the capacity of UHPFRCs to NSC and HSC plates that were constructed using the same steel reinforcement ratio, the total imparted kinetic energy of UHPFRC plates is in the range of 7 to 18 times the capacity of the NSC plate. The increased capacities of UHPFRC plates are correlated to the steel fibre content. However, increasing of fibre content from 1 to 2 % has only a limited effect on the impact capacity compared to increasing the fibre content from 2 to 3 %.

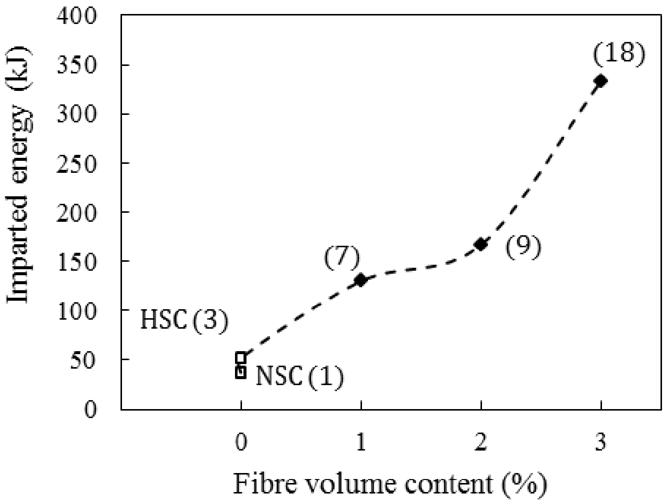


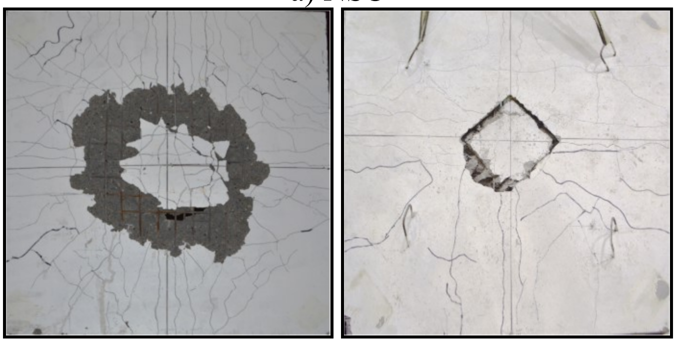
Figure 3: Influence of concrete material and fibre content on impact capacity

4.2 Crack patterns and damage characteristics

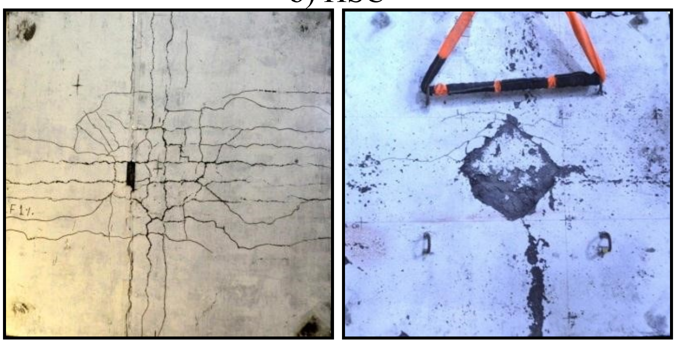
The final crack patterns of tested specimens are shown in Figure 4. NSC and HSC plates failed in punching shear mode (Figures 4-a, and b). The NSC plate terminated after the first impact due to concrete ejection with high probability of instrumentation damage under additional impact tests. The HSC specimen sustained two more impacts, the HSC plate test was terminated after the third impact for the same reason. On the other hand, all UHPFRC specimens completed the multi-impact test course with pronounced ductility. Typically, all UHPFRC plates exhibited similar flexural multi-crack pattern. Bending cracks aligned with steel reinforcement developed in both directions (Figure 4-c). All UHPFRC specimens showed enhanced damage control properties compared to NSC and HSC specimens. No spalling, scabbing, or significant large concrete fragmentations are observed during repeated impact tests. The fragments of damaged UHPFRC plates were in form of fine powder.

A comparison between damage progression under repeated impact loads for the HSC specimen and the UHPFRC specimen containing 1 % fibres (UH-F_1) is shown in Figure 5. The UHPFRC plates show a high capability to limit the damage progression under repeated impact loading. UHPFRC plate is able to absorb more impact energies with less damage. It should be emphasized that in the previous two figures the UHPFRC plate containing 1% steel fibres is the lower-bound and the UHPFRC plates that contain 2 or 3 % steel fibres show higher damage control properties. Increasing the fibre content has led to an increase in the number of cracks and a reduction in the width of cracks.

a) NSC



b) HSC



c) UH-F_1 (fibre volume content of 1%)

Figure 4: Final crack pattern of RC specimens (left: bottom surface; right: top surface)

Table 3 summarizes the damage characteristics of the tested RC specimens. It is evident from Table 3 and Figures 3 and 4 that the use of UHPFRC instead of traditional concrete enhances the impact performance significantly. UHPFRC structural elements are able to sustain more impact energy with less damage. The fibre content contribution is shown up clearly in the assessed damage characteristics (Table 3). The midpoint residual displacement is decreased with the increase of fibre volume content.

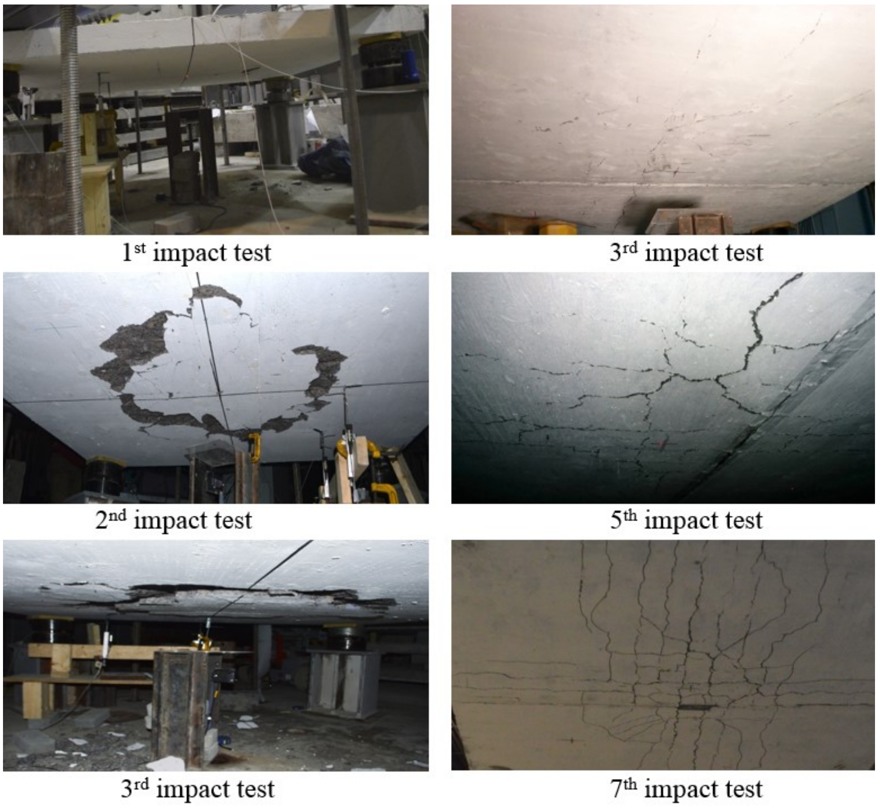


Figure 4: Damage history under repeated impact loads (left: HSC; right: UH-F_1)

Table 3: Damage characteristics of tested RC specimens

Specimen	No. of impacts	Failure mode	Scabbing mass* (kg)	Permanent deflection (mm)
NSC	1	Punching	24.75	29.3
HSC	3	Punching	28.10	47.6
UH-F_1	7	Flexural	---	65.7
UH-F_2	9	Flexural	---	65.3
UH-F_3	18	Flexural	---	65.0

* Ejection of material from back face of the RC specimen (target)

5. CONCLUSIONS

This research enables a better understanding of the advantage of using UHPFRC to produce impact resistance shield structures. The findings of the experimental investigation can be summarized as follows:

– Under repeated impact tests, all UHPFRC plates, regardless of the fibre volume content, sustained higher impact energy and failed in ductile flexural mode. On the other hand, NSC and HSC plates failed suddenly due to punching associated with severe concrete ejection in the impact zone.

- UHPFRC has superior impact resistance characteristics. The impact capacity of UHPFRC plates is in the range of 7 to 18 times the capacity of the NSC plate. The increased capacity of UHPFRC plates is correlated to the steel fibre content.
- Increasing the steel fibre content has a positive effect on damage control properties which is reflected in less residual displacement and a higher impact energy capacity. However, the use of 3% fibre content for impact resistance structures is more effective in enhancing the impact resistance compared to the other used two steel fibre contents of 1 and 2 %. The impact capacity of UHPFRC plate containing 3 % fibres is double the capacity of UHPFRC plate containing 2 % fibres and 2.5 times the capacity of the UHPFRC plate containing 1 % fibres.

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