PERFORMANCE OF PLAIN AND FIBER REINFORCED CONCRETE PANELS SUBJECTED TO LOW VELOCITY IMPACT LOADING

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Abstract

A centrally loaded round panel test was used to characterize the fracture energy of FRC under low velocity impact loading. The specimens, with a diameter of 650 mm and a thickness of 60 mm, were cast using plain high strength concrete (HSC, f'c = ~80 MPa), steel fiber reinforced HSC and a synthetic fiber reinforced HSC. These panels were subject to impact loading at their centers using a large instrumented drop-weight impact machine. The mass of the drop weight was 578 kg, with an impact velocity 1.9 m/s. Direct measurement of the central deflection at the bottom of the panel was made using a laser transducer.

No significant changes in the failure mode were observed between static and low velocity impact loading, but the peak loads under impact loading were higher. Toughness evaluations were carried out to with central deflections ranging from 30~50 mm, for both static and impact loading. The fracture toughness could be related to the fiber type and volume. It was found that under low velocity impact loading, the toughness of steel reinforced concrete (SFRC), unlike that of synthetic fiber reinforced concrete (PPNFRC), was higher than under static loading at the same central deflection. It was concluded that this test method appears to be promising for impact studies.

1 Introduction

The deformability, toughness and energy absorption of fiber reinforced concrete (FRC) are of great interest. To characterize these parameters, tests carried out concrete beams have most commonly been used. However, it has been found that standard test methods such as ASTMC1018 [1] and ASTM C1399 [2] have various shortcomings [3,4]. A recently approved ASTM standard test method (ASTM C1550)[5] for the flexural toughness of FRC using a centrally loaded, round panel supported on three points (based on a test method developed by Bernard [6]), is now available as an alternative method.

It has been found that the round determinate panel test is able to sort out the relative behavior amongst various concretes essentially the same way as the larger (more representative of field performance) South African water bed test [7]. Similar conclusions have been drawn by other researchers [8,9]. These features, together with the inherently low variability of the test, has led to this test method being specified for quality control purposes on fiber reinforced shotcrete projects in Western Canada in the past several years. [10]

These favorable results under static loading were sufficiently promising to warrant a further study to determine whether this method would have similar advantages in characterizing the performance of FRC under impact loading. The present work is focused on the performance of plain and fiber reinforced concrete panels subjected to low velocity impact loading: steel fibers and synthetic fibers were evaluated and compared with plain high strength concrete (HSC). There has been no research to date on the evaluation of the impact behaviour of FRC using the round determine panel method. The results of the present work may be used to explore the feasibility of test method itself, and to evaluate the effectiveness of fibers in high strength (70-80MPa) concrete matrices under low velocity impact loading.

2 Test setup

A centrally loaded round panel, with a diameter of 635 mm, a thickness (D) of 60 mm and an overhang length (a) of 19.5mm (a modified version of ASTM C1550, in which the size is 800-mm-diameter by 75-mm-thick) was used to characterize the fracture energy of FRC. For static tests, the panels were supported at three points and loaded at the center. Direct measurement of the central deflection was obtained using a potential meter (similar to an LVDT), with a maximum range of displacement of 76mm. The toughness was then characterized by determining the absorbed energy at a specified central deflection, obtained from the load-central deflection curve.

For the round panels subject to impact loading, a bolt load cell attached to the 578 kg falling mass of an instrumented drop-weight impact machine was used to impact the specimen. The capacity of the load cell was 120 kN. Based on a previous study [11], the static calibration for the cell could be extended to the impact condition, even though the bolt was then stressed dynamically. The impact velocity was 1.9 m/s (150mm drop height) for most of the tests. Direct measurement of the central deflection at the bottom of the panel was made using a laser transducer. A flexible rubber sheet was attached to the bottom of the specimen to avoid having the laser “target” lost in one of the cracks that developed. The deflection values obtained were checked using information from two accelerometers located midway between the supports and the centre of the specimen. A PC-based data acquisition system was used to record the signals for load, central displacement, and acceleration with time.

3 Inertial load derivation

A generalized inertial load at the centre of the specimen, Pi(t), can be obtained by using the principle of virtual work. Previous research carried out on beam specimens [12] showed that the distribution of acceleration along the beam length was essentially linear for both FRC and plain concrete. For the round panel system, it was also assumed that the acceleration distribution was linear between the supports and the center of the panel. No data were available for the acceleration distribution along the shaded arc shown in Fig. 1. Thus, to simplify the computations, it was assumed as a first approximation that the acceleration ü(r, χ, t) was constant along the arc, which means that the distribution of ü can be written simply as ü(r, t).

The failure pattern observed under impact loading generally consisted of three symmetrical cracks, at angles of about 120 degrees. Thus, one may consider one segment of the panel for analysis using the coordinates shown in Fig. 1.

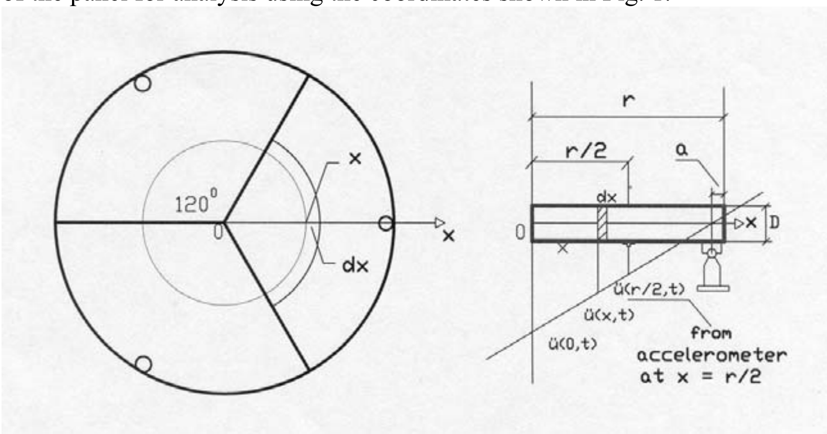


Fig. 1 Schematic description for round panel analysis

The internal load dI, for a 1/3 panel segment with width dx, with an acceleration ü(x,t) distributed on the arc shaped area is given by:

$$dI = \ddot{u}(x,t)\,\psi dV = \ddot{u}(x,t)\,\{\psi(2\phi x\, D)\,dx\,\}/3 \quad (1)$$

$$\ddot{u}(x,t) = \ddot{u}(o,t)\,(r\text{-}a\text{-}x)/(r\text{-}a) = 2\,\{(r\text{-}a\text{-}x)/(r\text{-}2a)\}^{*}\,\ddot{u}(r/2,t) \quad (2)$$

where,

ψ = density of concrete, dV = volume of the segment, D= thickness of panel
r = radius of panel, a = length of overhang
ü(o,t) = acceleration at the center
ü(r/2,t) = measured acceleration of the panel at half of the radius along the support to the centre, at time t.

The virtual work done by the distributed inertial load acting over the distributed virtual displacement should be equal to that done by the generalized inertial load.

$$Pi(t)\ \iota u(0,t) = 3 \int dI \iota u(x,t) \qquad (3)$$

where, due to the linear assumption, the virtual displacement of the selected segment $\iota u(x,t)$ and the virtual displacement at the center $\iota u(0, t)$ have the following relationship:

$$\iota u(x,t) = \iota u(0, t) \cdot (r-a-x)/(r-a) \qquad (4)$$

Substituting Eqs. (1), (2) and (4) into Eq. (3), we have

$$Pi(t) = 3 \int_0^r \{(r-a-x)/(r-a)\}\ \{2\ (r-a-x)/(r-2a)\ \ddot{u}(r/2,t)\ \} \cdot \{\psi(2\phi x\ D)\ dx\ \}/3$$

$$= \frac{4\phi D\psi}{(r\ 4\ a)(r\ 4\ 2a)}\ \ddot{u}(r/2,t) \int_0^r (r\ 4\ a\ 4\ x)^2 x dx$$

$$= \frac{\phi r^2 (r^2\ 4\ 4ar\ 2\ 6a^2) D\psi}{3(r\ 4\ a)(r\ 4\ 2a)}\ \ddot{u}(r/2,t) \qquad (5)$$

Once the generalized inertial load Pi(t) is calculated, the true load $P_{true}(t)$ can be determined as following:

$$P_{true}(t) = P_{total}(t) - Pi(t) \qquad (6)$$

where, $P_{total}(t)$ = the total load recorded by the bolt load cell.

3 Materials and test program

The round panel specimens were cast using normal CSA Type 10 (ASTM Type I) Portland cement, a commercially available silica fume and natural aggregates with a maximum size of 12 mm. Two types of macro-fibers were used, at volume percentages of 0.5% and 1.0%: steel fibers and a synthetic fiber manufactured with a blend of polypropylene and polyethylene. All the fibers were 50 mm long.

The water/cement ratio for all mixes was maintained at 0.28. To improve the workability, superplasticizing and air entraining admixtures were used to make plain high strength concrete (HSC), steel fiber reinforced HSC and synthetic fiber reinforced HSC. The fiber addition rates and the properties of the resulting mixtures are shown in Table 1. The raw materials were batched in a pan mixer and then placed in oiled plastic forms and vibrated on a vibrating table until fully compacted. The specimens were stored under plastic sheets for one day, then were de-molded and cured in water until the time of testing, at an age of 28 days.

Table 1 Fiber additions and properties of resulting mixtures

Concrete type	Plain	SFRC*		SynFRC**	
Fiber volume (Vf), %	0	SF 0.5	SF 1.0	PPN 0.5	PPN1.0
Slump, mm	70	75	50	55	45
Air content, %	3.6	4.0	4.1	3.9	4.4
Compressive strength, (MPa)	83.2	85.0	88.0	71.3	69.6

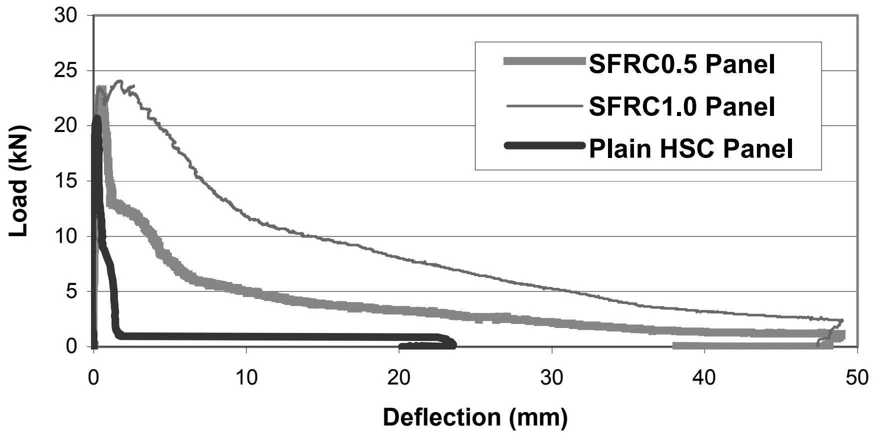
* Optimet 7550, produced by Optimet Inc. ** Structural fiber, produced by W.R. Grace

4 Experimental results and discussion

4.1 Static tests

As the panel was loaded, cracks first appeared at the bottom of the panel at its central point, radiated to the edges, and then opened upwards. The typical crack (failure) pattern of each round panel was three cracks at angles about 120^o, with the panel breaking into 3 pie-shaped wedges at large deflections. The load vs. deflection curves (an average of two specimens) for different kinds of fiber reinforcement, together with the curves for plain HSC panels, are shown in Fig. 2.

Typically, the load vs. deflection curves of the panels were almost linear up to the peak load. The central deflections at first crack load for both steel fiber reinforced concrete (SFRC) panels were similar, 0.523 mm, and 0.596 mm for SFRC0.5 and SFRC1.0, respectively, much larger than for the plain concrete, 0.242 mm. The increase in peak load due to steel fiber reinforcement was not significant. However, the toughness increased to 11 times that of plain panels for SFRC 0.5, and to 22 times for SFRC1.0. When PPN fiber was added, the peak load also showed a slight increase. However, beyond the peak a sharp load drop occurred, and there was a clearly defined second peak. Due to the fiber additions, the panels could still maintain a considerable post-peak load. Consequently, the toughness increased to 12 times that of plain concrete panel for PPN-FRC0.5, and 19 times for PPN-FRC1.0. In short, the SFRC panels exhibited higher residual load capacity immediately after cracking, while the PPNFRC panels had higher residual load capacity when the cracks had opened at larger deflections.



(a)

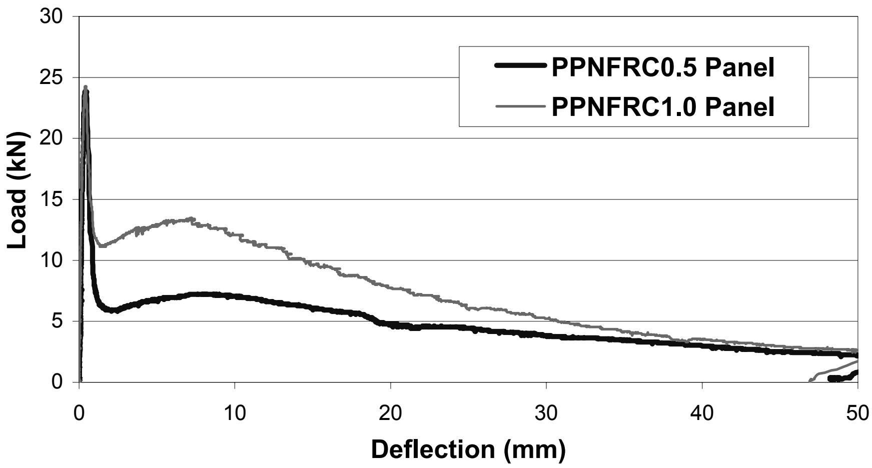


Fig. 2 Load-deflection curves of panels under static loading (a) SFRC and plain (b) PPN-FRC and plain

4.2 Impact tests

When the panels were subjected to impact loading, a similar failure pattern was observed. However, the three cracks seemed to be more irregular or less evenly distributed. The load-deflection curves for SFRC panels and PPN-FRC panels are shown in Fig. 3 and Fig. 4, respectively.

Because of the low flexural toughness of the plain concrete panels under static loading and the large weight of the hammer (about 575 kg), the drop height for the plain concrete specimens was set at 120 mm, in order to avoid catastrophic failure (instead of 150 mm drop height for other specimens). Although there are some differences in toughness due to these different drop heights, this should not significantly affect the comparisons between FRC panels and plain HSC panels.

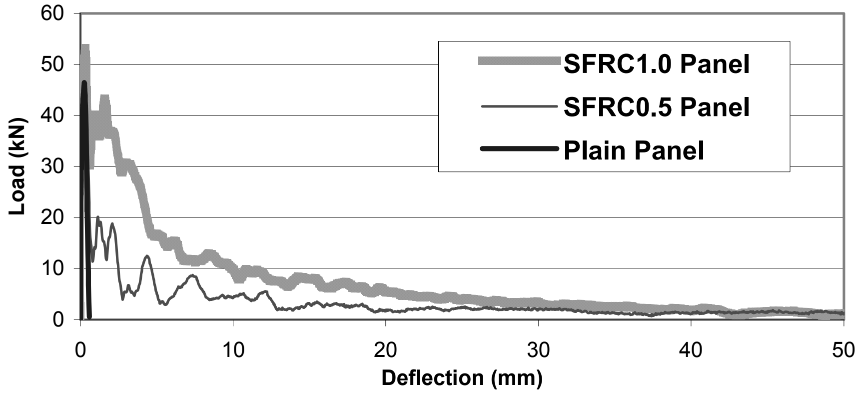


Fig. 3 Load-deflection curves of SFRC panels under impact loading

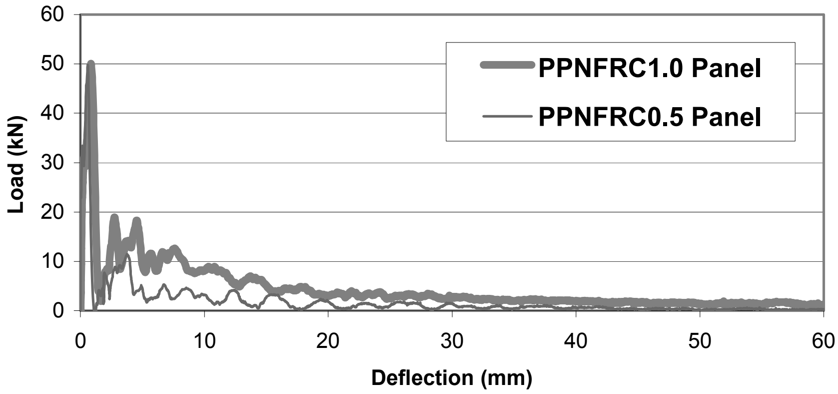


Fig. 4 Load-deflection curves of PPNFRC panels under impact loading

5 Discussion

5.1 Peak load and post-peak loading-capacity of panels under impact

As expected, the peak load of the round panels under impact loading increased.

The average peak load under impact ranged from 50.74 to 55.53 kN (after the inertial effect had been considered), approximately 2.2 to 2.7 times of those obtained from static tests (Table 2). The synthetic fiber reinforced concrete (PPNFRC) panels appeared to have a slightly lower peak load than the SFRC panels. The inertial effect at peak load was about 10% of the recorded load.

Table 2 Peak load of concrete panels under static and impact loading

Description		Plain	SFRC		PPNFRC	
Fiber volume, %		0	SF 0.5	SF 1.0	PPN 0.5	PPN1.0
Peak load, kN	Static	20.21	22.81	24.33	22.29	23.12
	Impact	46.25	45.52	53.15	49.55	50.09

The FRC panels showed a much more "ductile" behaviour compared with plain high strength concrete panels, as evidenced by the durations of the impact events and the cracked conditions of specimens after test. The entire impact event duration for plain concrete panels was only about 0.005 seconds. However, it increased from 0.045 seconds for SFRC0.5% to 0.060 seconds for SFRC 1.0%; and similarly, from 0.0475 seconds to 0.055 seconds for PPNFRC 0.5% and 1.0%, respectively.

From the load vs. deflection curves of the SFRC panels (Fig.3), it may be seen that for SFRC0.5 under impact, the curve was very similar to that for static loading up to a central deflection of 4 mm; beyond that point, the impact curve displayed a series of fluctuations, showing that some combination of matrix cracking and fiber pull-out was occurring, at least out to a deflection of 20 mm. This phenomenon is quite similar to the findings of Sukontasukkul et al. [13] for simply supported FRC plates under impact loading; they explained the multi-peak phenomenon as a continuous process with the overlap of successive cycles of fiber behavior (fiber bridging, stretching, then strength recovery until the subsequent peak), For the SFRC1.0 panel, a clear second peak was observed at a deflection of about 1.8 mm, an indication of the increased peak-load carrying capacity.

For the PPN-FRC panels (Fig.4), the specimens exhibited a much larger drop in load at low deflections; at larger deflections, the loads fluctuated considerably, suggesting again the combination of fiber pullout, fiber fracture and matrix cracking.

5.2 Toughness of panels under static and impact loading

Results of the toughness tests of the various panels under both static and impact loading are summarized in Table 3. It may be seen that, for plain concrete and SFRC panels, the toughness under impact was higher than that under static loading. For the PPN-FRC panels, however, the toughness under impact was significantly less than that under static loading, which may be explained by the failure patterns and conditions of the fibers bridging the cracks.

Under the low-velocity impact test carried out here, more PPN fibers tended to break instead of pulling out. As a consequence, they contributed less to impact resistance.

For the SFRC panels, more fibers pulled out under impact loading leading to higher impact resistance. This is similar to the findings of Banthia et al. [14]; from FRC beam tests, they reported a higher toughness for SFRC than for polypropylene fiber reinforced concrete (HPP-FRC) at a relatively low drop height (200 mm to 500 mm), although they also reported a totally different trend for SFRC compared to HPP-FRC at higher stress rates (1000 mm drop).

Table 3 Toughness of round panels up to 40mm deflection

Concrete type	**V_f (%)**	**Toughness under impact test**		**Toughness under static test (J)**
		Toughness (J)	**Drop height (mm)**	
Plain HSC	0	57.06*	120	17.81
SFRC	0.5	240.98	150	186.50
SFRC	1.0	458.38	150	378.46
PPN-FRC	0.5	112.95	150	198.12
PPN-FRC	1.0	238.44	150	321.01

* Toughness is the entire area under load vs. deflection curve to failure, which was 0.60 mm.

5.3 Effects of fiber type and volume fraction (V_f) on toughness

The effects of fiber volume fraction on toughness under impact loading were also observed for both SFRC and PPN-FRC panels. The results of fracture toughness vs. V_f at a deflection of 40 mm are re-plotted in Fig. 5. Similar to the static tests, the toughness of all panels under impact loading increased with an increase in fiber volume. Clearly, steel fibers were more effective than PPN fibers in toughening the high strength concrete at the same V_f, although the difference between these two fiber types was not so large under static loading, especially at low fiber volume fractions.

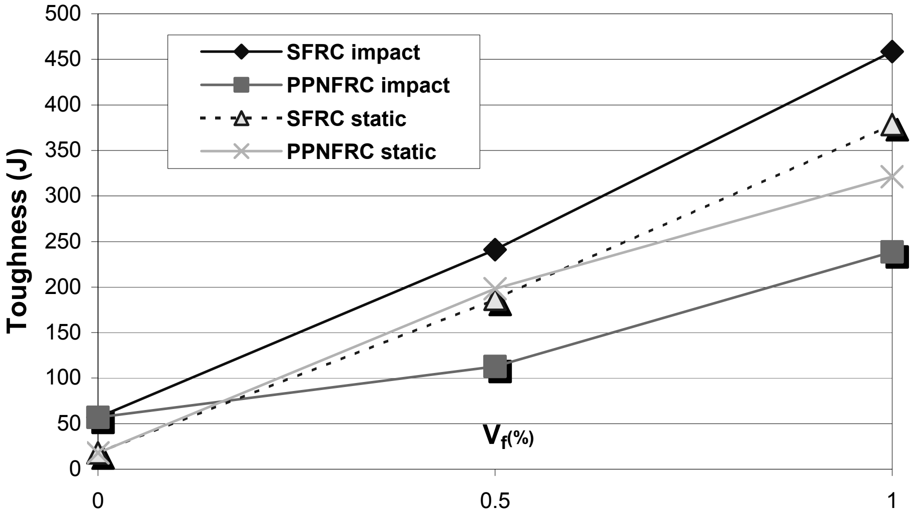


Fig. 5 Effects of fiber type and volume fraction on panel toughness (at a deflection 40mm)

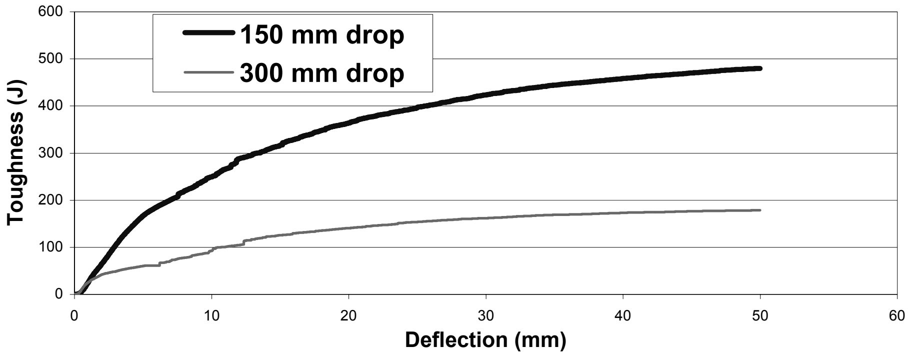


Fig. 6 Toughness of SFRC panel under different loading rates

5.4 Effects of loading rate on toughness

Some SFRC1.0 panels were also tested to study the effects of loading rate (drop height) on the impact behaviour. While the peak load increased from 55.23 kN to 57.87 kN when the drop height was increased from 150 mm to 300 mm, the SFRC panels appeared to be more brittle at the higher drop height. The toughness vs. deflection curves of the panels under the two different drop height are compared in Fig. 6. The panels tested at a drop height of 300 mm showed much less toughness than at 150 mm. This may be mainly due to more fiber fracture as opposed to pullout when the loading rate was increased.

5.5 Evaluation of round panel test method

From the tests reported here, it would appear that the impact tests of the round panels are quite reproducible, and that this method can distinguish amongst different types of concrete: plain, SFRC and PPN-FRC. This suggests that, as a test method, the round panel specimen shows promise to characterize the toughness of FRC under impact loading. However, the following sources of uncertainty still exist:

1. Assumption of acceleration distribution of the panel for inertial loading calculations.
2. Failure mode: if the specimen does not always crack into three similar pieces, the toughness may vary between specimens. Thus, the failure mode should be checked after each test.
3. The rubber sheet must be attached properly to the underside of the panel; otherwise, the changes in deflection will be difficult to detect using a laser transducer.
4. Load-deflection smoothing procedures may lead to some error in toughness calculations.

More FRC panel tests, using different concrete matrices and/or different fibers, are needed to verify these findings in order to ensure that this test method is suitable for characterizing the properties of FRC under impact.

6 Conclusions

1. Increases in toughness for both SFRC and PPN-FRC panels were observed due to increased fiber volume fractions under both static and impact loading. Steel fibers were more effective than PPN fiber in toughening high strength concrete under low velocity impact loading.
2. Plain and SFRC panels were tougher under impact than under static loading, while for PPN-FRC panels, the reverse was true, due to more PPN fibers breaking under impact than pulling out.
3. When the drop height was doubled, the toughness of SFRC panels was reduced considerably.
4. The round panel test was found to be suitable to characterize FRC under impact, and gave reproducible results. However, more theoretical and experimental work in this regard is needed to verify this.

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