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EXPERIMENTAL STUDY ON THE EFFECTIVENESS OF CFRP STRENGTHENING OF SHEAR-DEFICIENT REINFORCED CONCRETE BEAMS UNDER IMPACT LOADING

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ABSTRACT

The paper focuses on understanding the importance of shear mechanisms on reinforced concrete (RC) beams and comparing with CFRP externally reinforced beams under static and impact loading. A total of six RC beams were tested in two groups: shear-deficient (A) and externally reinforced beams (B) with carbon fibre reinforced polymer (CFRP). All beams designed had identical reinforcement properties with the intent to investigate the influences of composite materials on the overall results. Emphasis was placed on crack propagation, experimental failure modes and prevention methods. Experimental results confirm that increases in the shear reinforcement decreases the overall impact displacement, indicating that the shear properties influence the performance of the beams under impact loading. The outcomes also reveal significant improvements in the performance of the RC beams with CFRP external reinforcement in terms of their impact resistance and energy absorption.

KEYWORDS

Impact tests, RC beams, CFRP external reinforcement, energy absorption.

INTRODUCTION

With advancing technology and the risk of man-made disasters, RC structures are subjected to severe blast and impact loadings, especially buildings of historical significance. In recent years, significant emphasis has been placed for the design of blast-resistant structures to improve the safety and decrease the risk of fatality, with the aim of developing a design standard for structures under extreme loading (Remennikov and Rose 2007). Although extensive experimental and analytical research were conducted within the field of RC structures subjected to extreme loading, Bhatti et al. (2009) and Saatci et al. (2009) acknowldged that only a little amount of information is available on shear deficient beams and the relationship between impact loading and the percentage of transverse reinforcement. (Saatci and Vecchio 2009) performed experiments by varying the amount of transverse reinforcement to test shear deficient beams. However, they did not investigate the influence of shear reinforcement under impact loading. Kishi et al (2001) investigated the effect of no shear reinforcement for impact loading. The results showed severe diagonal cracking, deformations and the formation of "shear plugs" in the concrete beams as the velocity of the loading increased. Previous experimental investigations underline and highlight the importance of shear strengthening as a crucial component for the design of impact resistant structures.

Various strengthening techniques for RC beams have been developed in recent years, including composite materials such as CFRP for external reinforcement. Stress distribution around the edge of the CFRP, strain deformation, type of failure (brittle, plastic) and delamination of the fabric from the concrete beam were studied, (Rabinovitch and Frostig 2003). The studies concluded that the changes and decrease in shear reinforcement influence the performance of the RC beams, with flexural shear cracking occurring including delamination of the fibres. Experimental investigations on real life scenario structures which suggested that the CFRP jackets made a considerable difference by changing the failure mode to a ductile manner, with a significant increase in the loading capacity of the retrofitted structures, (Rodriguez-Nikl, Lee et al. 2011).

EXPERIMENTAL PROGRAM

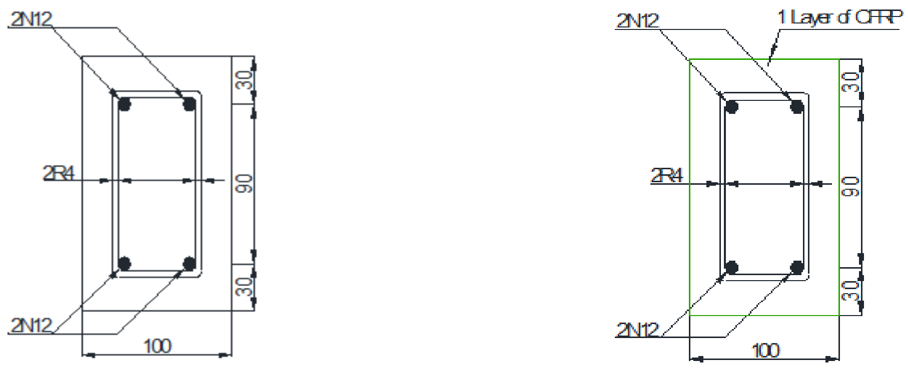
Design of Test Specimens

This section includes the examination of two sets of RC beams with varying shear reinforcement denoted by Group's A and B, see Figure 1. Description of each beam is shown in Table 1. Type A beams were designed to be under-reinforced with varying percentage of shear reinforcement and similar longitudinal reinforcement. They were designed to fail in shear. Group B beams were similar to Type A beams, having identical properties but were continuously wrapped with one layer of CFRP. One of the limitations associated with this type of wrapping is the impracticable and unrealistic approach in engineering applications. This is because in engineering structures, the beam is supported on top by a concrete slab, and thus only a U- configuration or side wrapping is achievable. This type of wrapping is more suitable for other concrete structures, such as circular columns. The corners of the beams were grinded down, for a smooth finish before wrapping. This was to prevent stress concentrations at the edges. The fibres were positioned perpendicular to the longitudinal reinforcement to enhance the shear strength. Group A were the controlled specimens for Group B's beams. Also, beams A1 and B1 were tested under static conditions in a three point loading method, with the four remaining beams tested under the drop hammer to allow for comparisons to be established between the two loading systems.

Table 1**.** Dimensions and reinforcement details of test specimens

Beam	b x d x L (mm)	Stirrup Spacing (mm)	Transverse Reinforcement Ratio (%)	Longitudinal Reinforcement Ratio (%)	Tensile Reinforcement Bars
A1	100 x 150 x 1200	275	0.1	1.8	2N12
A2	100 x 150 x 1200	275	0.1	1.8	2N12
A3	100 x 150 x 1200	375	0.07	1.8	2N12
B1	100 x 150 x 1200	275	0.1	1.8	2N12
B2	100 x 150 x 1200	275	0.1	1.8	2N12
B3	100 x 150 x 1200	375	0.07	1.8	2N12

According to the Australian Standards for concrete structures, AS 3600 (2009), the maximum shear reinforcement spacing is the effective depth of the cross section. With the specimens experimentally tested, this spacing doesn't satisfy code requirement. This was achieved to ensure group A beams were shear deficient and to show that this requirement is not critical for RC beams enhanced with CFRP external reinforcement.

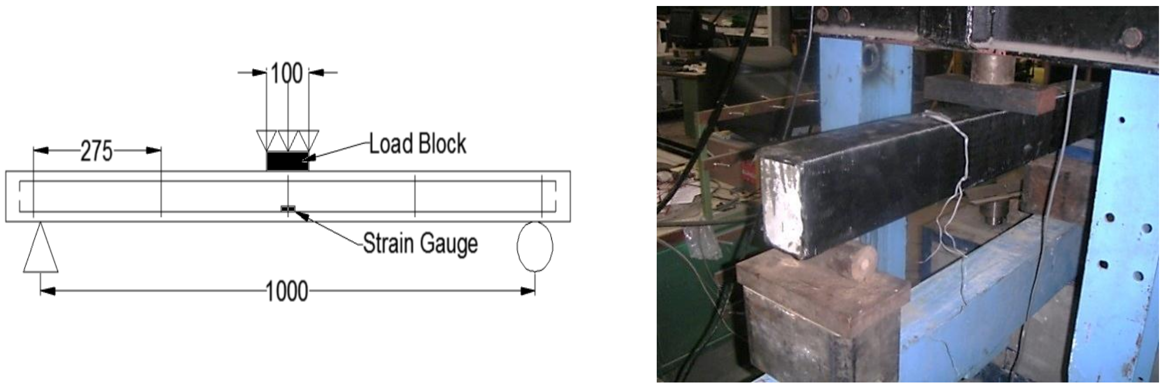


(a) Type A Beams (No CFRP) (b) Type B Beams (With CFRP)

Figure 1. Cross sectional dimensions and reinforcement details of tested beams

Static Testing Procedure

The static test setup involved testing two beams A1 and B1 and measuring their responses to a monotonically increasing load as seen in Figure 2. The reasons for testing beams A1 and B1 under these conditions included: collecting data involving the load-deformation behaviour, analysis of energy absorption capacities at failure and use as control specimens for the RC beams subjected to impact loading. The beams were simply supported in a three point loading configuration using a roller and pin, producing an effective span of 1000 mm. The steel plate with dimensions 100 mm x 280 mm x 50 mm was placed at the midspan of each beam to distribute the applied concentrated load. The beams were tested using a hydraulic jack to deflect the beams at a constant rate. The loading rate was initially 1 mm/min and was gradually modified to a rate of 2 mm/min for each beam. This was done to provide the sufficient time for the beams to deflect before failing. Strain measurements of the tensile reinforcement were recorded through the data logger and program Strain Smart 5000.



(a) FBD of Static Beams (b) Experimental Static Testing

Figure 2. Static Testing of CFRP Strengthened Beam B1

Impact Testing Procedure

The specimens for impact testing in this research program were designed as detailed in Table 1 and tested using the High Capacity Impact Testing Machine, see Figure 3. The impact height was calculated using energy principles, by equating the area under the load – deflection graph from the static results to the potential energy of the drop hammer. One drop-weight was utilised in this test program: weight of 590 kg. The load was measured via the load cell attached to the drop hammer with the strain recorded by the data logger from the tensile reinforcement. Deflection was analysed using a high speed camera situated within the cage with the footage being examined using computer software Image Pro Plus. The data logger recorded results at a rate of 50,000/sec with the high speed camera measuring 1000 frames/sec.

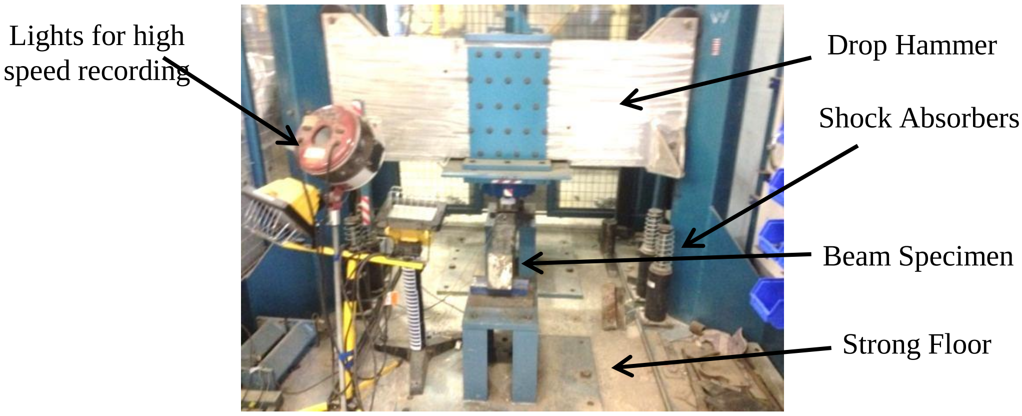


Figure 3. Impact testing of CFRP Strengthened Beam in Drop Hammer Facility

EXPERIMENTAL RESULTS

Static Tests

Specimen A1 initially exhibited a linear elastic response, showing signs of residual strength and integrity as the load increased. This linear response began to deteriorate around 30 kN load capacity, where the beam began to show signs of minor cracks. The initial formation of shear cracks occurred at a peak load of 41.0 kN with critical diagonal shear cracks at 45° propagating from the supports to the midspan of the RC beam, see Figure 5(a). This indicated the beam had an insufficient amount of shear reinforcement to resist shear forces. The secondary peak as seen in Figure 4 indicated critical shear cracks, ultimately causing shear failure of the RC beam at a load of 39.5 kN and deflection of 11.5 mm. This resulted in a major reduction in the load carrying capacity of the RC beam. Additional web shear cracks formed, causing large sections of the concrete to separate from the compression fibres.

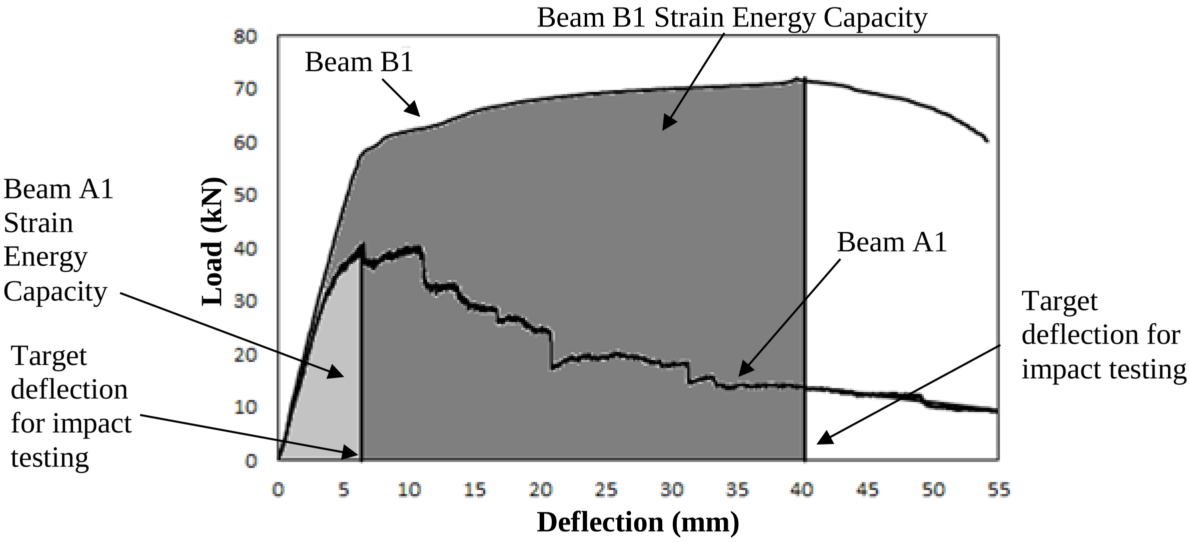


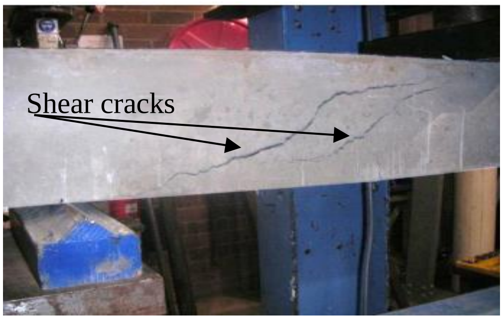
Figure 4. Load-deformation behaviour of test specimens A1 and B1 under quasi-static loading

Specimen B1 showed that the strengthening process of the CFRP significantly increased the load carrying capacity and shear capacity of the beam, with a maximum load of 72.0 kN being measured at a deflection of 42.0 mm. The beam initially performed up to a load of approximately 55 kN before starting to yield and plastically deform, showing signs of ductility based on the curvature (Sheikh et al. 2010) as seen in Figure 4. By positioning the carbon fibres parallel to the transverse reinforcement, the RC beam failed in a flexural response, completely resisting shear cracks. The fibre assisted in carrying the load by the static weight, thus preventing shear cracks propagating from the supports. There was one major flexural crack localised under the loading plate which propagated from the tensile fibres vertically. This crack caused the composite material to separate and debond from the concrete surface under the loading as seen in Figure 5(b).

From Figure 4, a target deflection was chosen for each specimen, defined as the point in where the beams began to shown signs of failure under the load. This target deflection was chosen based on how the beam behaved under a monotonically increased load. Thus for the purposes of being able to compare the results with the beams under impact loading, the deflection was chosen for Beam A1 when the specimen had begun to show signs of structural deficiency and experience its first critical shear crack (Peak 1) in Figure 4. This resulted in a target deflection of 6 mm chosen for this beam. A target deflection limit was chosen to be 42.0 mm for Beam B1 because this is when the RC beam began to fail under the static loading and it was the specimen's maximum deformation capacity before failure. An energy absorption capacity was calculated as 296 J by estimating the area under the load-deflection curve for Beam A1 and 2422J for Beam B2. The carbon fibre external reinforcement enhanced the energy capacity of the RC by approximately 8 times compared to the controlled specimen. See Table 2 for a summary of the static results and energy absorption capacities of the test specimens.

Table 2. Static Results of Test Specimens

Beam	Static Peak Load (kN)	Target Deflection (mm)	Static Strain Energy Capacity (J)	Static Experimental Failure Mode
A1	41.0	6.0	296	Shear
B1	72.0	42.0	2422	Flexural



(a) Beam A1


(b) Beam B1

Figure 5. Damage patterns of tested specimens under static loading

Impact Tests

Beams A2 and A3 were tested twice due to malfunctions with the data acquisition equipment. The initial drop for beam A2 displayed two distinct shear cracks propagating from the roller and pin supports to the midspan as shown in Figure 6 by 1. Minor tensile cracks were observed within the shear span of the beam. The second drop caused the beam to sustain more damage, with the critical shear crack expanding in width from the pin support as seen in Figure 6. Smaller shear cracks also extended from the left support (pin) with additional tensile cracks being developed as shown by 2.The high increase in the tensile cracks expanding from the tensile face suggested some flexural behaviour occurring despite the beam failing in shear. The second drop didn't cause any major shear cracks within the beam.

Beam A3 experienced severe shear cracking from the pin support after the initial drop as shown by 1 in Figure 7. A minor web shear crack developed at the roller support with a few hair width tensile fractures centralised around the left support. The additional drop showed minor differences in the pattern of the cracks throughout the beam. The changes observed between the two drops are identified with the critical shear crack from the pin support, depicted by 2. The change in width of this crack expanded considerably with severe buckling of the compressive reinforcement. This caused the top cover concrete to separate and break off following the impact produced by the drop hammer. Extra tensile cracks formed due to the large deformation as a result of the extensive shear failure. The initial and secondary impact placed beam A3 in a more structural deficient state than beam A2, with the concrete being displaced from the compressive fibres under the loading plate with more distinct cracking.

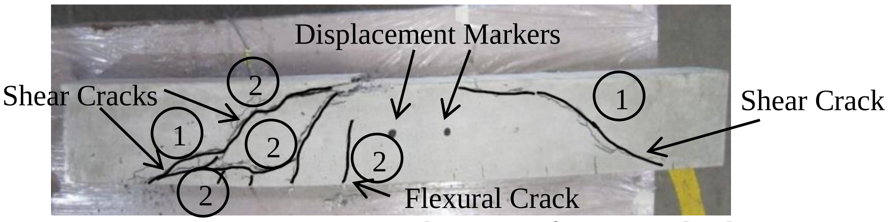


Figure 6. Beam A2 Test 2 crack pattern after impact loading

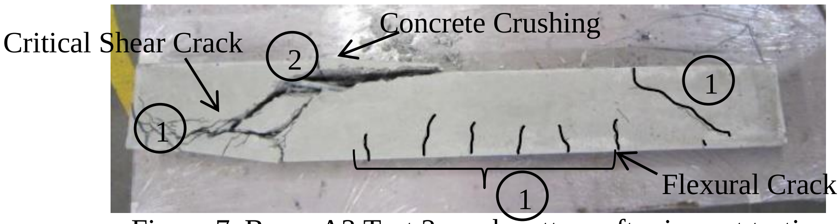


Figure 7. Beam A3 Test 2 crack pattern after impact testing

Comparing crack propagation between the static and impact loading, similar patterns were observed. Regardless of how the force was applied, the beams were predominately shear-deficient, indicating the static test was a valid benchmark of their performance. The impact tested beams displayed similarities in the maximum deflection compared to the theoretically predicted deflection value of 6 mm. The maximum deflection results of 7 mm and 9.2 mm for beams A2 and A3 respectively were slightly higher and the reasons for this include energy losses associated with the beams inertia, transverse steel reinforcement ratios, concrete compressive strength and the friction at the supports.

Beam B2 underwent extensive deflection during the first 0.03 seconds after the impact as seen in Figure 8, compared to the controlled specimens. This was due to the increased shear capacity of the beam by the CFRP confinement, resulting in flexure-based failure rather than shear failure. A peak deflection of 30 mm was recorded with a residual displacement of 25 mm. This peak displacement was slightly lower than the 40mm predicted from the static tests. The reason for the differences in deformation was due to the assumption that the kinetic energy of the drop hammer is fully absorbed by the beam to cause its flexural deformation. Other energy dissipation mechanisms include friction at the supports, friction between the CFRP and concrete, contributing to the lower peak displacement. The energy based analysis ignores contribution of damping, which in the case of CFRP-wrapped concrete beams could be quite sustained.

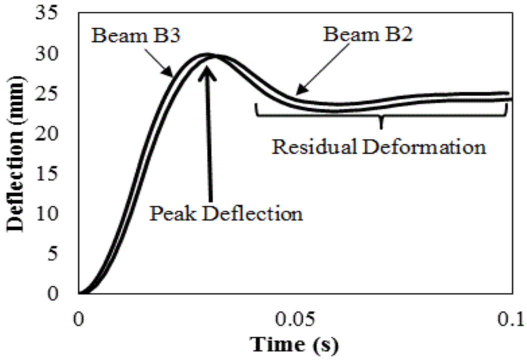


Figure 8. Deflection-time behaviour of strengthened beams under impact loading

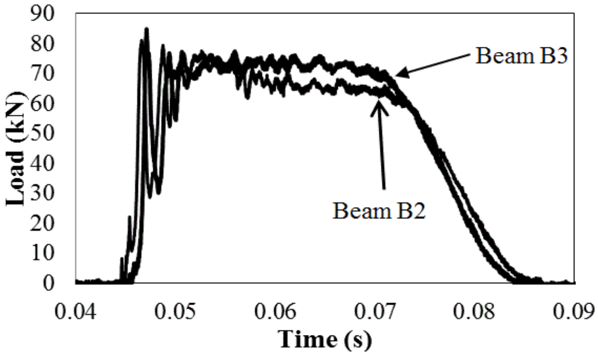
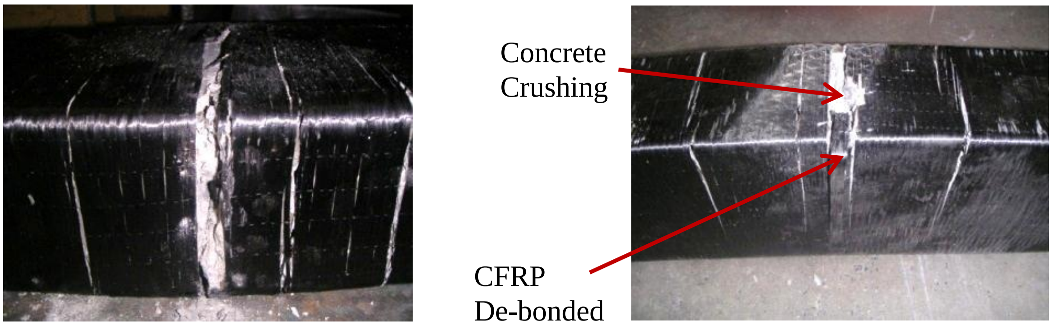


Figure 9. Load – time behaviour of strengthened beams under impact loading

The impact deflection response of beams B2 and B3 was similar as shown in Figure 8, regardless of the extra shear reinforcement in B2, thus indicating that the external CFRP confinement played the dominant role in providing concrete confinement with the contribution of the internal shear links significantly diminished. The deformed shape of both beams was identical to beam B1 and this was expected since all variables except for the stirrups were kept constant. The peak deformation for beam B3 was recorded as 30mm, with a residual deformation of 24mm.

Beams B2 and B3 displayed similar performances under the impact load. By analysing the high speed data acquisition results, both beams developed the same peak impact resistance of about 80 kN, see Figure 9. This impact resistance is the impact load capacity of the specimen. The impact resistance is defined as the capacity of the beam at failure under impact loading. Regardless of the height of the drop hammer, the beam will fail at the same value of the impact load considering that all other parameters of the beam are kept constant, –i.e., reinforcement ratio, concrete strength and amount of CFRP external reinforcement. Comparing the beams from the two groups, the impact loading capacity varied because of the presence of the layer of external reinforcement. The presence of external CFRP reinforcement significantly increased the the impact height. The CFRP significantly increased the ductility of the specimens which resulted in a larger increase in impact load at failure, as displayed in group B beams. The two beams sustained this resistance over a short period of 0.04 seconds, after the drop hammer struck the beams initially. From Figure 9, the beams showed signs of ductility, with the specimens being able to sustain a constant load over a period of time. The results indicate that the variations in shear reinforcement of the two specimens had minimal influence on the peak impact load.

Beam B2 as shown in Figure 10(a) displayed large, severe flexural cracks propagating from the tensile fibres vertically towards the compressive region. The CFRP debonded and ruptured on the underside of the RC beam due to the impact load applied at the mid-span. The concrete was fractured around the central region, with significant concrete crushing evident based on small particles flaking off. Beam B3 as depicted in Figure 10(b) had a larger percentage of transverse reinforcement and showed similar crack patterns to beam B2 under similar impact loading. By comparison, the carbon fibre ruptured with more damage and separation evident in beam B3.There was a critical flexural crack appearing in the midspan, expanding approximately two thirds up from the tensile fibres. The tensile cracks were more obvious and clear with this beam which was expected because of the extra reinforcement. See Table 3 for a summary of the impact test results for all specimens.



(a) Beam B2 – Concrete crushing (b) Beam B3 – CFRP de-bonding

Figure 10. Failure modes of FRP strengthened beams under impact loading

Table 3. Summary of Impact Test Results

Beam	Drop Hammer Height (mm)	Peak Impact Capacity (kN)	Peak Impact Displacement (mm)
A2 – Test 1	51	N/A*	7.0
A3 – Test 1	51	47.3	9.2
B2 – Test 1	450	85.1	30.0
B3 – Test 1	450	88.7	30.0

* Data not collected due to malfunctions with the acquisition system

CONCLUSIONS

A successful experimental program of six RC beams under static and impact loading has been presented and discussed, providing information on the effectiveness of CFRP strengthening of the shear-deficient RC beams subjected to impact loads. Observations and experimental data analyses have led to the following conclusions:

1. The testing data for group A's beams (no CFRP strengthening) showed that increase in the amount of shear reinforcement significantly decreases the damage and deformation of the shear deficient beams under impact loadings.
2. The use of CFRP as an external reinforcement enhanced the performance of RC beams significantly increasing the energy absorption capacity under quasi-static and impact loading (up to 8 times) compared to the shear deficient beams. The CFRP wrapping transformed the failure mode of the beams from shear failure to flexural failure. The ultimate load capacity of the CFRP strengthened beams under static and impact loading increased 74% and 81% respectively, compared to group A beams with insufficient amount of shear reinforcement for resisting impulsive loading.
3. Further research is needed to investigate the effect of various CFRP configurations (side bonding, u-shape configuration) on the behaviour of shear-deficient beams under static and impact. Such analyses will increase the data and provide more valid outcomes for use of the composite material in civil engineering applications.

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