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# Impact resistance of ultra-high strength concrete beams with FRP reinforcement

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# Impact resistance of ultra-high strength concrete beams with FRP reinforcement

## **Abstract**

Composite materials, including Fibre Reinforced Polymer (FRP) bars, have been used for decades in the structural and civil engineering sectors over traditional steel reinforcement. The main reasons for this are that FRP composites possess a number of advantages. They are non-corrosive, non-conductive, and lightweight and possess high longitudinal tensile strength. This paper presents the results of an experimental investigation into the effects of the use of glass FRP (GFRP) bars as internal reinforcement on the behaviour of concrete beams with high strength concrete (HSC) and ultra-high strength concrete (UHSC). Both static and dynamic (impact) behaviours of the beam have been investigated. Twelve GFRP reinforced concrete (RC) beams were designed, cast and tested. Six GFRP RC beams were tested under static loading (three point bending) to examine the failure modes, load carrying capacity, deflection and energy absorption capacities. The other six GFRP RC beams were tested under impact loading using a drop hammer apparatus at various levels of impact energy. It was found that the use of UHSC in conjunction with larger amounts of tensile reinforcement showed higher levels of post-cracking bending stiffness. GFRP RC beams under static loading displayed a flexural response at failure. The GFRP RC beams under impact loading displayed a dynamic punching shear failure response at various levels of impact energy.

## **Keywords**

concrete, beams, strength, frp, ultra-high, reinforcement, resistance, impact

## **Disciplines**

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# IMPACT RESISTANCE OF ULTRA-HIGH STRENGTH CONCRETE BEAMS WITH FRP REINFORCEMENT

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## ABSTRACT

Composite materials, including Fibre Reinforced Polymer (FRP) bars, have been used for decades in the structural and civil engineering sectors over traditional steel reinforcement. The main reasons for this are that FRP composites possess a number of advantages. They are non-corrosive, non-conductive, and lightweight and possess high longitudinal tensile strength. This paper presents the results of an experimental investigation into the effects of the use of glass FRP (GFRP) bars as internal reinforcement on the behaviour of concrete beams with high strength concrete (HSC) and ultra-high strength concrete (UHSC). Both static and dynamic (impact) behaviours of the beam have been investigated. Twelve GFRP reinforced concrete (RC) beams were designed, cast and tested. Six GFRP RC beams were tested under static loading (three point bending) to examine the failure modes, load carrying capacity, deflection and energy absorption capacities. The other six GFRP RC beams were tested under impact loading using a drop hammer apparatus at various levels of impact energy. It was found that the use of UHSC in conjunction with larger amounts of tensile reinforcement showed higher levels of post-cracking bending stiffness. GFRP RC beams under static loading displayed a flexural response at failure. The GFRP RC beams under impact loading displayed a dynamic punching shear failure response at various levels of impact energy.

## KEYWORDS

FRP, RC beams, High strength concrete, Flexure, Impact.

## INTRODUCTION

Experimental studies carried out have investigated the impact behaviour of RC beams reinforced with conventional steel reinforcement (Chen and May 2009, Fujukake *et al.* 2009, Saatci and Vecchio 2009). There are three types of responses that a RC beam can be subjected to – local response, global response or a combination of both. Localised failure modes of RC beams under impact have been described as being scabbing, which results in spalling and detachment of the tensile concrete cover, penetration, diagonal shear cracking around contact zone. This type of response is typically referred to as a shear “plug” type, even for flexural-critical RC beams (Saatci and Vecchio 2009) or localised dynamic punching shear failure (Kishi *et al.* 2002, Zhang *et al.* 2005) which has shown to occur at higher velocities of impact (Ohnuma *et al.* 1985). This type of response results in the majority of energy from the impact being dissipated around the impact area. A global response represents the bending and deformation response of the RC beams under impact. The behaviour of RC beams under impact loading has been described as a combination of both local and global response (bending and deformation). However, the global response has been documented as the main concern for RC beams subjected to impact loading (Hughes and Beeby 1982). The influence of different parameters including shear mechanisms, impact velocity, cracking response, impact energy and comparisons between static and impact failure modes were investigated in the literature. Also, most of the previous studies were limited to normal strength concrete (NSC). Only a limited number of studies have examined the impact response of high strength concrete beams reinforced with conventional steel reinforcement (Ågårdh *et al.* 1999). Although the behaviour of steel RC beams under impact loading were extensively studied, limited attention has been focused on experimentally investigating the impact response of concrete beams reinforced with GFRP reinforcement bars (Goldston *et al.* 2016). Goldston *et al.* (2016) reported that flexural-critical GFRP RC beams under impact loading displayed a shear “plug” type of failure, indicating the importance of shear mechanisms. Also, higher strength concrete and larger amounts of reinforcement, fewer inclined shear cracks were present along the surface of the GFRP RC beams (Goldston *et al.* 2016). However, there have not been any studies so far addressing the impact behaviour of ultra-high strength concrete (UHSC) beams reinforced with GFRP bars.

## EXPERIMENTAL PROGRAM

### Details of GFRP RC Beams

A total of twelve simply supported GFRP RC beams (2400 mm long, 100 mm wide and 150 mm deep) were constructed and experimentally tested under static loading and impact loading. The experimental program was divided into two series. The first series consisted of six GFRP RC beams tested under static loading (S) (three-point bending) to further investigate the influence of GFRP reinforcement bars on the flexural behaviour of beams. The test variables were the longitudinal reinforcement ratio and concrete strength. Three beams were cast with concrete of 80 MPa nominal concrete compressive strength with three beams cast with concrete of 120 MPa nominal compressive strength. At time of testing, concrete strength was measured as 97 MPa and 116 MPa. The parameters investigated were load-deflection behaviour, failure mode, energy absorption and strain in the concrete and GFRP reinforcement bars. The second series consisted of six beams tested under impact loading to investigate the dynamic response of UHSC GFRP RC beams. The six GFRP RC beams under impact loading (I) were cast with 120 MPa nominal compressive strength. Three beams had a reinforcement ratio of 1.0% and three with a reinforcement ratio of 2.0%. The GFRP RC beams were subjected to three different heights for specimens with reinforcement ratios of 1.0% and 2.0%. The height of the drop hammer was calculated based on the energy absorption capacity (50%, 75% and 100% energy absorption capacity) from static testing results. For the three beams with a reinforcement ratio of 1.0%, beams were subjected to heights of 355 mm, 533 mm and 710 mm. The three beams with a reinforcement ratio of 2.0% were subjected to heights of 550 mm, 825 mm and 1100 mm. Test parameters investigated included dynamic mid-span deflection, dynamic bending resistance, dynamic strain in GFRP reinforcement bars, failure mode and crack patterns. The GFRP RC beams were labelled according to the series, nominal concrete strength, longitudinal reinforcement type, reinforcement ratio and type of loading. The arrangement is in the form of A–B–C–D where A is the nominal concrete strength (80 or 120 MPa), B is the GFRP reinforcement bar type (#2S, #3HM or #4HM), C is the GFRP reinforcement ratio and D is for the type of loading, static (S) or impact loading (I). For GFRP RC beams under impact loading, the subscript <sub>1</sub> represents the height of the drop hammer in metres. For example, GFRP RC beam 80–#3HM–1.0–S was designed with concrete compressive strength of 80 MPa with #3HM GFRP reinforcement bars, a longitudinal GFRP reinforcement ratio of 1.0% and tested under static loading. For GFRP RC beam 120–#4HM–2.0–I<sub>1.1</sub>, nominal concrete compressive strength was 120 MPa, with #4HM GFRP reinforcement bars, a reinforcement ratio of 2.0% and subjected to a 1.1 m height under impact loading.

## EXPERIMENTAL SETUP

### Static Testing

The beams were simply supported, with a pin support at one end and a roller support at the other end as shown in Figure 1. The simply supported conditions allowed for the GFRP RC beams to deflect under static loading. A 600 kN hydraulic actuator anchored to an independent steel frame was used to apply a monotonic increasing load on a steel circular plate positioned at the mid-span. The hydraulic actuator was also used to measure mid-span deflection. GFRP RC beams were tested under displacement controlled loading at a rate of 1 mm/min until failure. Two electrical resistance strain gauges were attached at the top on each side of the GFRP RC beams, directly underneath the position of the load cell for measurement of concrete strain. One strain gauge was attached to each of tensile GFRP reinforcement bars, at the centre for measurement of tensile strain. All data including load, mid-span deflection and strain were recorded using the high speed data acquisition system,



Figure 1 Experimental Set-up for GFRP RC Beams under Static Loading

## Impact Testing

Six GFRP RC beams were subjected to a 580 kg high capacity free falling drop weight apparatus used to apply impact load as shown in Figure 2. The setup procedure involved fixing two steel blocks to the floor to allow for the GFRP RC beams to have a clear span of 2000 mm with 200 mm overhang on each side. All impact GFRP RC beams were simply supported and positioned on a steel pin and steel roller. For the prevention of rebound during impact, steel frame rollers were connected to the steel blocks, which allowed the GFRP RC beams to roll during impact. The drop hammer was mechanically lifted to the required drop height using an automotive control system and released using an electronic quick release system. Dynamic mid-span deflections were determined by image processing technique using high-speed video camera recordings. Dynamic concrete strain was not measured due to the extensive damage in the impact area caused by the drop hammer. However, dynamic tensile strain was measured from the strain gauges located in the middle of each GFRP tensile reinforcement bar. This allowed for an average reading of dynamic tensile strain at the mid-span to be obtained. The recording rate of the high speed camera was 1000 frames per second.

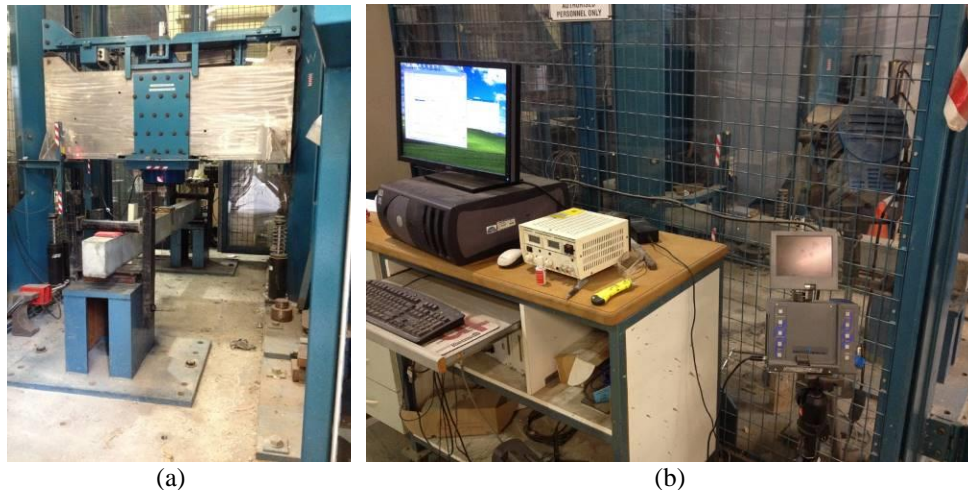


Figure 2 (a) Experimental Set-up for GFRP RC Beams under Impact Loading; (b) Data acquisition system and high speed camera used in impact tests.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Static Testing

GFRP RC beams under static loading were designed to have two distinct failure modes: GFRP reinforcement rupture and concrete crushing. During testing, the beams designed as under-reinforced displayed vertical flexural cracking, initially forming around the mid-span. Flexural cracks began forming at around 3 kN. At higher loading levels, new vertical cracks began propagating closer towards the supports. Already formed cracks around the mid-span continued to propagate further, vertically. The under-reinforced GFRP RC beams failed due to rupture of the GFRP reinforcement bars as shown in Figure 3, whereas the GFRP RC beams defined as over-reinforced failed by concrete crushing as shown in Figure 4. However, the over-reinforced GFRP RC beams showed signs of continually sustaining load, indicating signs of reserve capacity or an amount of pseudo “ductility”. At higher loading stages, concrete cover continued to crush prior to total failure. At total failure, the over-reinforced GFRP RC beams failed by rupture of the GFRP reinforcement bars. Figure 5 shows the experimental load-deflection graphs for the GFRP RC beams under static loading. All GFRP RC beams displayed a bi-linear relationship. Initially, prior to cracking, beams had high bending stiffness. Once cracking occurred, bending stiffness reduced, especially for the GFRP RC beams with the lowest amount of reinforcement. Concrete strength was shown to be more influential for GFRP RC beams with tensile longitudinal reinforcement ratios of 1.0% and 2.0% in increasing the load carrying capacity, due to the failure being governed by the strength of the concrete (crushing of concrete cover). For reinforcement ratios of 1.0% and 2.0% load increased by 27% (from 33 kN to 41.8 kN) and 13% (from 46.1 kN to 52.2 kN), respectively by increasing concrete from 95 MPa to 116 MPa. At higher reinforcement ratios, higher concrete strength (UHSC) did not show to improve post-cracking bending stiffness. Table 1 reports the experimental load carrying capacity and mid-span deflection of the GFRP RC beams under static loading.





Figure 3 GFRP Reinforcement Rupture of Under-Reinforced GFRP RC Beam



Figure 4 Concrete Crushing of Over-Reinforced GFRP RC Beam

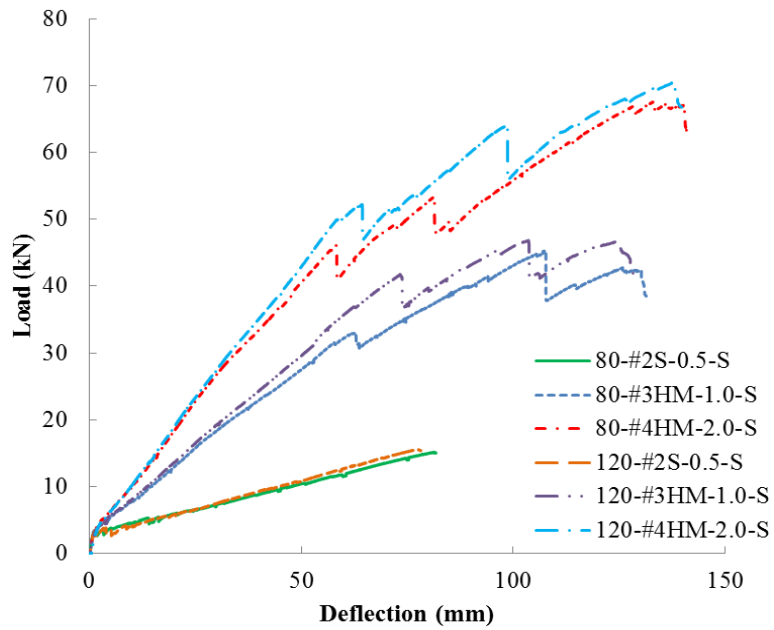


Figure 5 Load-Deflection of GFRP RC Beams under Static Loading

Table 1 Experimental Results for GFRP RC Beams under Static Loading

GFRP RC Beam (Failure Mode)	Experimental Load (kN)	Mid-Span Deflection(mm)
<b>80-#2-0.5</b> (GFRP Rupture)	15.0	81.8
<b>80-#3-1.0</b> (Concrete Crushing)	33.0	62.6
<b>80-#4-2.0</b> (Concrete Crushing)	46.1	58.3
<b>120-#2-0.5</b> (GFRP Rupture)	16.2	77.5
<b>120-#3-1.0</b> (Concrete Crushing)	41.8	73.3
<b>120-#4-2.0</b> (Concrete Crushing)	52.2	64.3

### Impact Testing

Three GFRP RC beams with reinforcement ratios of 1.0% and 2.0% were subjected to various levels of impact energy. For GFRP RC beam 120<sub>II</sub>-#3HM-1.0-S, static energy absorption capacities were calculated as 2029 J, 3043 J and 4057 J, at 50%, 75% and 100%, respectively. Hence, three impact heights were calculated as 355 mm, 533 mm and 710 mm, respectively. For GFRP RC beam 120<sub>II</sub>-#4HM-2.0-S, static energy absorption capacities were calculated as 3189 J, 4783 J and 6377 J, at 50%, 75% and 100%, respectively. Hence, the impact heights were calculated as 550 mm, 825 mm and 1100 mm, respectively. Overall, the experimental failure mode and general behaviour including crack patterns was relatively similar for all six GFRP RC beams subjected to various impact heights. The experimental failure mode, defined as a “dynamic punching failure” was given, which can be defined as the GFRP RC beams being subjected to a moving punch (from the drop hammer) in the mid-span. This resulted in localised concrete crushing on the top surface with the majority of damage (crack propagation) occurring in the impact area.

For the GFRP RC beams with a reinforcement ratio of 1.0%, GFRP RC beam 120-#3HM-1.0-I-0.355 experienced a dynamic punching failure response, with minor crushing of the concrete cover on the top surface, at impact point. During impact, cracks, predominately observed as a combination flexure, flexure-shear and minor shear cracks propagated from the tensile region throughout the height of the GFRP RC beam. Majority of these cracks were observed to be localised around the impact zone, with a few flexure-shear cracks closer towards the supports. No permanent deformation was observed when subjected to an impact energy of 2029 J. GFRP RC beam 120-#3HM-1.0-I-0.533 showed signs of further additional concrete cover crushing, with the exposure of the compressive GFRP reinforcement bars. Crushing of cover was not symmetric under impact, with localisation to one side of the impact point. Under an impact height of 533 mm, a small amount of rupture of the bottom concrete cover occurred, also exposing the GFRP tensile reinforcement bars around the impact zone. This caused a few cracks around the midspan to significantly widen. Cracks were predominately flexure cracks throughout the span of the GFRP RC beam, with the inclusion of a few flexure-shear and minor inclined shear cracks present. GFRP RC beam 120-#3HM-1.0-I-0.710 showed extreme localised concrete cover crushing and rupture of the tensile concrete cover occurred, causing the concrete to spall off as shown in Figure 6. The spalling off of the concrete was shown to be more symmetrical under the impact point, causing exposure of the compressive and tensile GFRP reinforcement bars. Again, a predominant flexural crack pattern was observed around the impact zone, with a very few signs of flexure-shear cracks and minor inclined shear cracking. This GFRP RC beam showed the least number of cracks during impact. By close inspection, some signs of splitting of fibres from GFRP tensile reinforcement bars were observed.



Figure 6 Dynamic Punching Failure and Crack Propagation of GFRP RC Beam 120<sub>II</sub>-#3HM-1.0-I-0.710

## CONCLUSIONS

An experimental study of twelve simply supported GFRP RC beams subjected to static loading and impact loading has been conducted, highlighting the effectiveness of HSC and UHSC. Observations from the experimental testing have led to the following conclusions being made:

- 1) Failure mode of GFRP RC beams under static loading can be determined using sectional analysis used for beams reinforced with steel reinforcement. It was found that the ratio of the reinforcement ratio to the balanced reinforcement ratio held true for the governing failure. For the GFRP RC beams with more than balanced reinforcement, failure was shown to be caused by crushing of concrete cover. For the GFRP RC beams with less than balanced reinforcement ratio, failure was shown to be caused by GFRP reinforcement rupture.
- 2) Load-deflection behaviour of GFRP RC beams under static loading showed a bi-linear response. The first section represented an uncracked section, followed by a crack section, resulting in a reduction in bending stiffness. The GFRP RC beams with more reinforcement than balanced reinforcement displayed signs of pseudo “ductility”, where the beams were able to resist load before total collapse. As opposed to the under-reinforced GFRP RC beams which failed suddenly by rupture of GFRP reinforcement, resulting in no reserve capacity.
- 3) Effect of HSC and UHSC on the GFRP RC beams under static loading were shown to be more influence load carrying capacity, deflection and post-cracking bending stiffness. For the GFRP RC beams with a reinforcement ratio of 0.5%, increasing the concrete strength from 95 MPa to 116 MPa, load increased by 8% (from 15 kN to 16.2 kN). The reason for this is because these GFRP RC beams are designed as under-reinforced and thus their failure is governed by the tensile strength of the GFRP reinforcement bars. For GFRP RC beams with a reinforcement ratio of 1.0% and 2.0%, load increased by 27% (from 33 kN to 41.8 kN) and 13% (from 46.1 kN to 52.2 kN), respectively by increasing concrete from 95 MPa to 116 MPa. However, increasing concrete strength showed to increase mid-span deflection for a reinforcement ratio of 1.0% and 2.0% by 17% and 10%, respectively. In terms of post-cracking bending stiffness, for a reinforcement ratio of 1.0%, stiffness increased 10% for a change in concrete strength. However, for a reinforcement ratio of 2.0%, a reduction in 0.07% in post-cracking bending stiffness was observed. At higher reinforcement ratios, higher concrete strength doesn't seem to improve post-cracking bending stiffness.
- 4) Under impact loading, regardless of the shear capacity of the GFRP RC beams, the GFRP RC beams displayed a dynamic punching shear failure response. Minor shear cracking around the impact area with crushing of concrete cover was observed. However, the GFRP RC beams under static loading were shown to failure in a flexural response. Thus, the shear behaviour of flexure-critical GFRP RC beams must be considered when designing structures subjected to impact loads.

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## REFERENCES

- Ågårdh, L., Magnusson, J. and Hansson, H. (1999). “High Strength Concrete Beams Subjected to Impact Loading - An Experimental Study”. *FOA Defence Research Establishment Report*, FOA-R--99-01187-311-SE, Stockholm, Sweden.
- Chen, Y. and May, I. M. (2009). "Reinforced Concrete Members under Drop-Weight Impacts". *Proceedings of the Institution of Civil Engineers - Structures & Buildings*, 162(1), 45-56.
- Fujikake, K., Li, B. and Soeun, S. (2009). "Impact Response of Reinforced Concrete Beam and Its Analytical Evaluation". *Journal of Structural Engineering*, 135(8), 938-950.
- Goldston, M., Remennikov, A. and Sheikh, M. N. (2016). "Experimental Investigation of the Behaviour of Concrete Beams Reinforced with GFRP Bars under Static and Impact Loading". *Engineering Structures*, 113, 220-232.
- Hughes, G. and Beeby, A.W. (1982). “Investigations of the Effect of Impact Loading on Concrete Beams”. *The Structural Engineer*, 60B(3), 45-52.
- Kishi, N., Mikami, H., Matsuoka, K. G. and Ando, T. (2002). "Impact Behavior of Shear-Failure-Type RC Beams without Shear Rebar". *International Journal of Impact Engineering*, 27(9), 955-968.



- Ohnuma, H., Ito, C. and Nomachi, S. G. (1985). "Dynamic Response and Local Rupture of Reinforced Concrete Beam and Slab Under Impact Loading". *Transactions of the 8th International Conference on Structural Mechanics in Reactor Technology*, Brussels, Belgium, 19-23 August.
- Saatci, S. and Vecchio, F. J. (2009). "Effects of Shear Mechanisms on Impact Behavior of Reinforced Concrete Beams". *ACI Structural Journal*, 106(1), 78-86.