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Abstract

This paper investigates the overload capabilities and damage mechanisms of Glass Fiber Reinforced Polymer (GFRP) bar reinforced concrete beams subject to high-intensity low-velocity impact loads. The overload condition of the beam is defined as the capability of the beam to sustain input impact energy exceeding its quasi-static energy absorption capacity. Nine GFRP bar reinforced concrete (GFRP-RC) beams were tested under three levels of increasing input impact energy. The shear capacities of the beams were varied by using three spacings of the shear reinforcement. The midspan deflection histories, impact loads, reaction forces, and accelerations of the beams were measured. The crack patterns and failure modes were recorded and analyzed using a high-speed video camera. It was found that the beam shear capacity significantly influenced the type of cracks and the development of cracks under increasing levels of impact energy. Flexural and flexure-shear cracks were observed in the beams with higher shear capacities whereas shear cracks were observed in the beams with lower shear capacities. It was also found that higher beam shear capacities led to reduced residual midspan deflections and higher residual load carrying capacities of the beams. Design recommendations are provided for GFRP-RC beams subjected to high-intensity low-velocity impact events.

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Overload Damage Mechanisms of GFRP-RC Beams Subjected to High-intensity Low-velocity Impact Loads

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ABSTRACT

This paper investigates the overload capabilities and damage mechanisms of Glass Fiber Reinforced Polymer (GFRP) bar reinforced concrete beams subject to high-intensity low-velocity impact loads. The overload condition of the beam is defined as the capability of the beam to sustain input impact energy exceeding its quasi-static energy absorption capacity. Nine GFRP bar reinforced concrete (GFRP-RC) beams were tested under three levels of increasing input impact energy. The shear capacities of the beams were varied by using three spacings of the shear reinforcement. The midspan deflection histories, impact loads, reaction forces, and accelerations of the beams were measured. The crack patterns and failure modes were recorded and analyzed using a high-speed video camera. It was found that the beam shear capacity significantly influenced the type of cracks and the development of cracks under increasing levels of impact energy. Flexural and flexure-shear cracks were observed in the beams with higher shear capacities whereas shear cracks were observed in the beams with

lower shear capacities. It was also found that higher beam shear capacities led to reduced residual midspan deflections and higher residual load carrying capacities of the beams. Design recommendations are provided for GFRP-RC beams subjected to high-intensity low-velocity impact events.

keywords: Reinforced concrete beam; GFRP; design guidelines; shear; failure mode; impact

1. Introduction

Reinforced Concrete (RC) structures may be subjected to sudden dynamic loads including impact loads during the lifetime of the structures. Impact loads are characterized by a high intensity load over a short period of time, which include fall of heavy objects, rock fall, impact of debris carried by tornadoes, accidental impact of vehicles, and terrorist attacks. With the increase in the terrorist attacks and vehicle accidents globally, impact loads need to be considered in the design phase of the critical infrastructure for protecting the critical infrastructure from catastrophic failure [1].

Several studies investigated the impact response of traditional steel bar reinforced concrete (Steel-RC) beams [2-12]. Fujikake et al. [2] developed a correlation between the maximum midspan deflection of Steel-RC beams and the degree of the flexural damage under impact loads. Fujikake et al. [13] proposed a model to predict the maximum midspan deflection for Steel-RC beams failing in flexure under impact loads and evaluated the damage of the beams using the correlation developed in Fujikake et al. [2]. Yi et al. [14] assessed the likelihood of Steel-RC beams to fail in shear under impact loads. The influence of the impact velocity on the failure mode and crack profile of Steel-RC beams was extensively investigated in the literature. Saatci and Vecchio [4] reported that regardless of the impact velocity, severe diagonal cracks appeared at the impact area of the beam forming shear plugs. Kishi et al. [15] reported that Steel-RC beams failed in flexure under low-velocity impact loads. However, the failure mode of steel-RC beams changed from flexure to shear when the impact velocity increased. Zhao et al. [9] also reported that an increase in the impact velocity led to shear failure of Steel-RC beam. Moreover, several experimental and numerical studies were carried out to investigate

the influence of the loading rate and the residual resistance of Steel-RC beams [5, 6, 16-18]. The available studies in the literature focused mainly on the flexural and shear responses of Steel-RC beams under low-velocity impact loads where low-velocity impact loads are considered to have an impact velocity up to 10 m/s.

Glass Fiber Reinforced Polymer (GFRP) bars have emerged as suitable replacements to the steel reinforcing bars in RC structures [19, 20]. GFRP bars have many advantages over steel bars including higher tensile strength and strength-to-weight ratio. In addition, GFRP bars do not corrode and they are electromagnetic neutral. The GFRP bar reinforced concrete (GFRP-RC) structures are mostly desirable in corrosive and marine environments. However, the modulus of elasticity of the GFRP bars is lower than the modulus of elasticity of steel bars, which leads to larger deformations of the GFRP-RC structures compared to Steel-RC structures. Moreover, the bond strength of the GFRP bars in the GFRP-RC structures is weaker than the bond strength of steel bars in Steel-RC structures. The bond characteristics of GFRP-RC beams have been thoroughly investigated in the literature [21-29]. Moreover, since GFRP bars do not have a clear yield point, a different design approach needs to be considered for the design of GFRP-RC beams [30-34]. The flexural behavior of GFRP-RC beams under quasi-static and impact loads was investigated in the literature. Most studies in the literature focused mainly on the flexural behavior of GFRP-RC beams under quasi-static loads [26, 27, 35-40]. A few recent studies investigated the behavior of GFRP-RC beams under impact loads [41-43]. Goldston et al. [41] tested GFRP-RC beams under impact loads with an input impact energy equal to the quasi-static energy absorption capacity. However, no studies in the literature investigated the behavior of GFRP-RC beams under an input impact energy higher than the quasi-static energy absorption capacity of that beam.

This paper investigates experimentally the overload damage mechanisms of GFRP-RC beams under high-intensity low-velocity impact loads. In total, nine GFRP-RC beams were tested under impact loads using the high-capacity impact testing facility at the University of Wollongong. Significant influences of the shear reinforcement and impact velocity on the dynamic shear behavior

of the GFRP-RC beams were observed. The results of this study will help in understanding the shear behavior of GFRP-RC beams under high-intensity low-velocity impact loads including failure modes, midspan deflections, and dynamic forces.

2. Experimental program

2.1 Details of the tested beams

The experimental program comprised nine GFRP-RC beams tested under low-velocity impact loads. In addition, one GFRP-RC control beam was tested under quasi-static loads. As shown in **Fig. 1**, all the beams were 200 mm in width, 300 mm in height, and 2400 mm in length. The clear concrete cover on the top, bottom, and sides was 25 mm. The GFRP-RC beams were longitudinally reinforced with 16 mm diameter GFRP bars. Two bars were placed at the tension side and two bars were placed at the compression side. **Fig. 1** shows the reinforcement details and the dimensions of the tested beams. All beams were designed as over-reinforced beams according to ACI [30] and Australia [32]. The GFRP shear reinforcement was calculated according to ACI [30] and Australia [32]. The GFRP stirrups had a diameter of 12 mm. In this study, according to Australia [32], the maximum spacing of transverse reinforcement shall not exceed $0.6d_v$ or 400 mm, where d_v is the effective shear depth. According to ACI [30], the maximum spacing of transverse reinforcement shall not exceed the smaller of $d_{eff}/2$ or 600 mm, where d_{eff} is the effective depth of the beam. Therefore, the maximum spacing of transverse reinforcement was chosen as 150 mm. In order to study the influence of the shear capacities on the damage mechanisms, the center-to-center spacing of the stirrups varied for the three different groups of tested beams. The stirrup spacing of 150 mm, 100 mm, and 75 mm were used in the tested beams which corresponded to the spacing of $D/2$, $D/3$ and $D/4$, where D is the beam depth. The details of the GFRP-RC beams were been reported in **Table 1**. Moreover, six accelerometers were mounted to the side of the GFRP-RC beams to capture the accelerations across the beams during impact.

2.2 *Material properties*

To determine the compressive strengths of concrete, nine concrete cylinders were tested on 28 days of concrete casting, on the first day of testing (day 78), and the last day of testing (day 138). The MATEST Servo-Plus Evolution machine was used to test the concrete cylinders. For the nine tested beams and the control beam, the target compressive strength of concrete was 50 MPa. The average compressive strength of concrete at 28 days was 52.5 MPa. The average compressive strength of concrete between the first day of testing and last day of testing was 59.3 MPa. To determine the ultimate strength and modulus of elasticity of the GFRP bars used, tensile tests were carried out on five GFRP bar specimens of diameter 16 mm. An INSTRON tensile machine was used for the tensile testing of the GFRP bars. Strain gauges were attached to the GFRP bars to measure the strains during the tests. The average ultimate strength of the GFRP bars was 957 MPa and the average modulus of elasticity of the GFRP bars was 47.1 GPa.

2.3 *Experimental program*

One GFRP-RC beam was tested under a quasi-static three-point bending load as a control beam. A pin support and a roller support were at a distance of 200 mm from the beam ends. Monotonically increasing loads were applied at the midspan of the control beam at a rate of 1 mm/min. The applied load was recorded using a load cell. The midspan deflection of the control beam was recorded using a laser displacement transducer ACUITY AR550-250. Fifty millimeter square grids were marked across the beam to track the development and position of cracks on the beams. The energy absorption capacity of the control beam was calculated as the area under the load-midspan deflection curve [44, 45]. The three impact velocities were then chosen based on the energy absorption capacity of the control beam to deliver the impact energy as a multiple of the quasi-static energy absorption capacity of the control beam. A detailed explanation of the choice of impact velocities is presented in the following sections.

Nine GFRP-RC beams were tested under low-velocity impact loads using the high-capacity impact testing facility at the University of Wollongong. The mass of the drop hammer was 600 kg. The

impact load and dynamic beam reactions were measured using high-capacity load cells attached to the impact hammer and supports, respectively. The flat round impactor plate with a diameter of 300 mm was attached to the drop hammer load cell. **Fig. 2** presents the beam setup in the impact testing facility. Rebound frames were used at the beam ends to prevent the uplift of the beams during the impact. A 5 mm rubber pad was placed on top of the beam at the impact zone to protect it from crushing by the impactor. A MEMRECAM HX-7 high-speed video camera was used to record the impact and the propagation of cracks at 5000 frames/sec. Six accelerometers were mounted to each beam along the length to measure the accelerations and derive the dynamic shear forces.

To investigate the effects of shear capacity on the impact behavior of the GFRP-RC beams, the nine beams were divided into three groups according to the shear reinforcement spacing. Each group included one beam with the maximum spacing of stirrups of 150 mm or $D/2$, according to ACI design provisions for shear design [30]. Other common spacing of $D/4$ (75 mm) and $D/3$ (100 mm) were also used for designing the beams. The beams in each group were subjected to the same impact velocity that was selected based on the quasi-static energy absorption capacity of the control beam. The beams were referred to as a series of numbers indicating the spacing of shear reinforcement and the corresponding impact velocity. For example, Beam 150-6.5 represents a GFRP-RC beam with a spacing of stirrups of 150 mm and tested under an impact load with a velocity of 6.5 m/s. All experimental data were recorded at a sampling rate of 100 kHz. The test set-up ensured that each group of beams had three different shear reinforcement spacing and was subjected to the same impact velocity.

3. Experimental results and discussion

3.1 Quasi-static loading

The quasi-static load testing was carried out by loading the control beam until failure at a rate of 1 mm/min. The load-midspan deflection behavior was nearly bilinear until failure (**Fig. 3**). Afterwards, there were fluctuations in the peak loads as the beam continued deflecting. The first part

of the bilinear behavior represents the stiffness of the uncracked response of the beam. At a load of 22 kN, concrete under tension cracked and the stiffness of the beam dropped. The second part of the behavior represents the post-cracking behavior. The load increased until the first peak of 170 kN. The deflection corresponding to the first peak load was 45.4 mm. At the first peak load, the cracks in the beam were flexural cracks, starting from the tension side and propagating vertically upwards. Also, the cracks in the concrete cover in the compression zone were visible. After the first peak load, the load dropped to 148 kN. The load then increased until it reached the second peak at 178 kN. The deflection corresponding to the second peak load was 59.3 mm. At the second peak load, concrete in compression crushed and the load dropped to 164 kN. The load increased again until it reached the third peak at an ultimate load of 180 kN. The deflection corresponding to the ultimate load was 65.8 mm. At the ultimate load, the GFRP bars in tension ruptured and the beam collapsed. The control beam failed in flexure and the cracks observed were predominantly flexural cracks. The quasi-static energy absorption capacity “ E ” of the control beam was calculated as the area under the load-midspan deflection curve in **Fig. 3**. A similar approach was adopted in the studies relating the quasi-static energy absorption capacity of the beam to the input impact energy [41, 46]. The energy absorption capacity was equal to 8684 Joules. Using this energy absorption capacity, the three impact velocities applied on the three groups of beams were chosen as 5.5 m/s, 6.5 m/s, and 7.5 m/s.

Nine beams were tested under impact loads. After the impact loads test, the beams were tested under quasi-static three-point bending to measure their residual capacities. The residual load-carrying capacities (residual capacities hereafter) of the beams were considered to be the ultimate load-carrying capacities of the damaged beams recorded under the quasi-static three-point bending. These residual capacities were then compared to the ultimate load-carrying capacity of the control beam (180 kN). Based on the observed behavior of the tested beams, when the residual capacity of the beam was over 90% (meaning the residual load-carrying capacity was over 162 kN), the damage was considered to be minor. If the residual capacity of the beam was between 80% and 90% (residual

load-carrying capacity between 144 kN and 162 kN), the damage was considered to be medium. If the residual capacity of the beam was lower than 80%, the damage was considered to be severe.

3.2 Impact loading

The impact energy was calculated from the evaluation of the kinetic energy (impact energy = $\frac{1}{2}mv^2$), where $m = 600$ kg is the mass of the impactor and v is the impact velocity. Impact velocities for Groups 1-3 were estimated from the energy balance between the impactor kinetic energy and multiples (1.0, 1.5, and 2.0) of the quasi-static energy absorption capacity of the control beam. Therefore, the three impact velocities chosen were 5.5 m/s, 6.5 m/s, and 7.5 m/s. Impact tests were carried out to determine the failure modes, crack propagation, midspan deflections, residual midspan deflections, and dynamic forces of the GFRP-RC beams tested under impact loads.

3.2.1 Effect of inertia on beams under impact loads

The impact load is generated when the drop hammer impacts the beam [4]. This impact load is resisted by the stiffness of the beam while the beam accelerates downwards. The inertia load is produced by the beam acceleration. The magnitude of this inertia load is discussed in the sections below. The inertia load acts in the opposite direction to the acceleration of the beam. Therefore, since the beam accelerates downward, the inertia load acts upwards along the span of the beam. The dynamic bending moments and shear forces are different in shape and magnitude from the quasi-static bending moments and shear forces. At the initial stage of the impact loading, the inertia load had a significant influence on the response of the beam. This was explained in details in the “dynamic equilibrium of applied forces” section.

3.2.2 Analysis of damage mechanisms

Group 1 beams

Analysis of damage mechanisms of the tested beams was performed by conducting a frame-by-frame analysis of the high-speed video recordings for each beam. **Fig. 4** presents the damage progression of the beams belonging to Group 1 at the three time instances. The first row presents the

effect of beam inertia resistance (at $t = 1$ ms). The second row presents the beam damage at the maximum midspan deflection (at $t = 22 - 23$ ms). The third row presents the post-impact damage of the beams. The first column presents the damage of progression of Beam 150-5.5. The other two columns present the beams with higher shear capacities (Beam 100-5.5 and Beam 75-5.5).

The first impact loads test was carried out for Beam 150-5.5 (spacing of stirrups of $D/2$, impact velocity of 5.5 m/s). During the first millisecond of impact loading, two inclined shear cracks (cracks 1 and 2) originating from the impact zone appeared along with flexural cracks (crack 3) (**Fig. 4**). The shear cracks propagated at 45 degrees. As the beam continued deflecting, the shear cracks (cracks 1, 2, and 8) widened and additional flexural cracks appeared (cracks 4-7). At $t = 23$ ms, Beam 150-5.5 reached its maximum midspan deflection. The shear cracks dominated the damage response of Beam 150-5.5 and were wider than the flexural cracks. In addition to that, local damage of concrete was observed at the impact zone. As the beam rebounded to its initial position, the impactor bounced a few times on the beam before resting on it. The bouncing of the impactor caused additional local damage at the impact zone. However, the reinforcement was not exposed. The maximum midspan deflection of Beam 150-5.5 was 61.4 mm and the residual deflection was 10 mm (**Table 2**). The residual deflection of Beam 150-5.5 was 16% of the maximum midspan deflection. Three-point quasi-static loads test was carried out after the impact on Beam 150-5.5 to determine the residual capacity of the beam. It was found that the residual capacity of Beam 150-5.5 was 153 kN, which was 85% of the load-carrying capacity of the control beam. This meant that the damage of Beam 150-5.5 could be considered as medium.

Next, impact loading test was carried out for Beam 100-5.5 (spacing of stirrups of $D/3$). During the first millisecond of impact loading, a flexural crack (crack 1) at the midspan of the beam was observed as the beam started deflecting (**Fig. 4**). As Beam 100-5.5 continued deflecting, additional flexural cracks (cracks 2-4, 8), flexure-shear cracks (cracks 5 and 6), and shear cracks (crack 7) were observed. This behavior showed a transition in the damage mechanism from shear-plug under the

impact point to flexure-shear upon increasing the shear capacity of the beam. Also, it was observed that the shear cracks appeared after the flexural cracks in Beam 100-5.5. At $t = 23$ ms, Beam 100-5.5 reached its maximum midspan deflection and the cracks reached their maximum widths. Local failure of the concrete at the impact zone was clearly observed. The diagonal shear cracks (i.e., crack 7) were the dominant cracks. The shear cracks were wider than the flexural cracks. As the beam returned to its initial position, most of the flexural cracks closed. However, the shear cracks were still visible. The post-impact damage of Beam 100-5.5 is presented in **Fig. 4**. It can be observed that the damage at the impact zone did not expose the GFRP reinforcement bars. The measured maximum midspan deflection and residual deflection were 60.9 mm, and 6 mm, respectively. The residual deflection of Beam 100-5.5 was 9% of the maximum midspan deflection. The residual capacity of Beam 100-5.5 was 166 kN, which was 92% of the load-carrying capacity of the control beam. This indicated that the damage of Beam 100-5.5 could be considered as minor.

The final impact loading test for Group 1 beams was carried out for Beam 75-5.5 with a spacing of stirrups 75 mm, or $D/4$. As the beam started deflecting, it was observed that during the first millisecond of impact loading the first flexural cracks appeared (cracks 1 and 2) (**Fig. 4**). As Beam 75-5.5 continued deflecting, additional flexural (cracks 3, 7, 8, and 9), shear (cracks 5 and 6), and flexure-shear (cracks 4 and 10) cracks started appearing. The inclined shear cracks originated from the impact zone and propagated at an angle of 45 degrees. It was observed that the shear cracks appeared after the flexural cracks. The cracks appearing during the first millisecond of impact were due to the inertia effect of the beam. Beam 75-5.5 reached the maximum midspan deflection at $t = 22$ ms where the cracks reached the maximum widths. It was observed that at $t = 22$ ms, when the beam was at its maximum midspan deflection, the shear cracks were not dominant in the damage mechanism. The widths of the flexural cracks and the shear cracks were similar. The higher shear capacity of Beam 75-5.5, in comparison to Beam 100-5.5, prevented the development of severe shear cracks. The failure mode of Beam 75-5.5 was observed to be dominated by the flexural response. Local damage and post-impact cracks at the impact zone were observed. However, the GFRP

reinforcing bars were not exposed. The maximum midspan and residual deflections were 59.2 mm and 4 mm, respectively. The residual deflection was 7% of the maximum midspan deflection. The residual capacity of Beam 75-5.5 was 175 kN, which was 97% of the load-carrying capacity of the control beam. This could be considered as minor damage of Beam 75-5.5.

It was observed for Group 1 beams that the width of cracks was influenced by their shear capacities. An increase in the shear capacity led to a decrease in the width of cracks. Moreover, diagonal shear cracks of shear-plug type were observed for beams with a larger spacing of stirrups and a lower shear capacity (Beam 150-5.5), whereas flexural cracks were observed for beams with a higher shear capacity (Beam 75-5.5). This also shows that during the beam inertia resistance stage, the shear capacity significantly influences the damage mechanism in a beam. Flexural damage mechanisms started developing during the initial inertia stage of impact loading in Beam 75-5.5, whereas shear-plug damage mechanisms started developing within the duration of inertia load in Beam 150-5.5. In addition to that, the beam shear capacity significantly affected the residual load-carrying capacities of the beams. Beams with a higher shear capacity demonstrated a higher post-impact load-carrying capacity.

Group 2 beams

The impact velocity was increased for Group 2 beams to 6.5 m/s. This impact velocity transferred 13026 Joules of impact energy into Group 2 beams which is 50% higher than the impact energy used for Group 1 beams. The beam 150-6.5 (spacing of stirrups of $D/2$) was tested first in this group. During the inertia loading stage, shear crack (crack 3) and flexural cracks (cracks 1 and 2) appeared in the beam (**Fig. 5**). The shear crack was more dominant than the flexural cracks. As Beam 150-6.5 continued deflecting, some of the flexural cracks became flexure-shear cracks (crack 2). Moreover, additional shear cracks were formed (crack 5). Some of the initial flexural cracks (crack 1) did not increase significantly in width due to the presence of a dominant adjacent flexure-shear crack (crack 2). At $t = 26$ ms, Beam 150-6.5 reached its maximum midspan deflection and the cracks reached their

maximum widths. The dominant cracks were the flexure-shear cracks (crack 2) and shear cracks (crack 3). Local damage was observed and the GFRP stirrups and longitudinal bars were exposed, (**Fig. 5**). The residual deflection was 20% of the maximum midspan deflection. The residual load-carrying capacity of Beam 150-6.5 was 132 kN, which was 73% of the load-carrying capacity of the control beam. This indicated that the damage of Beam 150-6.5 could be classified as severe.

For the second impact loading test in Group 2, Beam 100-6.5 (spacing of stirrups of $D/3$) was tested. Two flexural cracks (cracks 1 and 2) appeared at the midspan of the beam (**Fig. 5**). As Beam 100-6.5 continued deflecting, additional shear cracks (cracks 6 and 7) and flexure-shear cracks (cracks 3-5) appeared in the beam. It was observed that the flexure-shear cracks appeared after the shear cracks in Beam 100-6.5. At $t = 25$ ms, the beam reached its maximum midspan deflection and the cracks reached the maximum widths. Therefore, the failure mode for this beam was considered as flexure-shear. The post-impact damage of Beam 100-6.5 is presented in **Fig. 5**. It can be observed that the damage at the impact zone exposed the GFRP stirrups and longitudinal bars at some locations. The residual load-carrying capacity of Beam 100-6.5 was found to be 144 kN, which was 80% of the load-carrying capacity of the control beam. This indicates that the damage of Beam 100-6.5 could be considered as medium.

For the last test of Group 2 beams, Beam 75-6.5 (spacing of stirrups of $D/4$) was tested. **Fig. 5** presents the flexural cracks (cracks 1 and 2) and shear cracks (crack 3) in Beam 75-6.5 during the initial inertia response of the beam. As Beam 75-6.5 continued deflecting, additional shear cracks (crack 5) and flexure-shear cracks (cracks 4 and 6) appeared. It was observed that the flexure-shear cracks appeared after the shear cracks in Beam 75-6.5. This shows that Beam 75-6.5 with higher shear capacity than Beams 100-6.5 and 150-6.5 was capable of resisting the development of shear-plug damage mechanism. At $t = 25$ ms, the beam reached its maximum midspan deflection and the cracks reached their maximum widths. The flexural cracks were more dominant than the shear cracks and had larger widths. The GFRP stirrups and longitudinal bars were exposed after the impact. The

residual capacity of Beam 75-6.5 was measured by conducting a three-point quasi-static loads test on the beam after impact. The residual load-carrying capacity of Beam 75-6.5 was 164 kN which is 91% of the load-carrying capacity of the control beam which could be considered as minor damage.

It was observed for Group 2 beams that an increase in the shear capacity led to the transition of the damage mechanisms from shear to flexure-shear which was consistent with the observed damage mechanisms of Group 1 beams. Large shear cracks were observed in beams with lower shear capacity (Beam 150-6.5), whereas Beam 75-6.5 with higher shear capacity did not experience severe shear cracking. The post-impact damage of the Beam 150-6.5 (spacing of stirrups of $D/2$) was severe, whereas the damage of Beams 100-6.5 (stirrup spacing $D/3$) and 75-6.5 (stirrup spacing $D/4$) was medium and minor, respectively.

Group 3 beams

The impact energy was doubled for Group 3 beams compared to Group 1 beams which produced an impact velocity of 7.5 m/s. Similar to Groups 1 and 2, the first test was carried out for a beam with a spacing of stirrups $D/2$, Beam 150-7.5, followed by Beam 100-7.5 (stirrup spacing $D/3$), and then Beam 75-7.5 (stirrup spacing $D/4$). During the inertia stage of impact loading for Beam 150-7.5, minor flexural cracks (crack 1) appeared at the midspan of the beam (**Fig. 6**). As Beam 150-7.5 continued deflecting, some of the flexural cracks transitioned into flexure-shear cracks (crack 3). Moreover, additional flexural cracks (crack 2) and large shear cracks (cracks 4-7) were formed. Beam 150-7.5 continued deflecting until the GFRP bars ruptured in tension. The beam did not rebound. The image of Beam 150-7.5 at $t = 26$ ms is presented although Beam 150-7.5 did not experience a maximum midspan deflection. The local damage of Beam 150-7.5 exposed the stirrups and the GFRP bars. The residual capacity of Beam 150-7.5 was assumed as zero due to rupture of the GFRP bars.

Due to technical difficulties, the high-speed video of Beam 100-7.5 was not captured. Upon analyzing the impact load and midspan deflection data, it was observed that Beam 100-7.5 reached the maximum midspan deflection after 26 ms of the impact. The value of the maximum midspan

deflection was 90.6 mm. The beam then rebounded to its initial position at $t = 58$ ms. The concrete cover was damaged and the GFRP stirrups and longitudinal bars were exposed. The residual deflection measured in Beam 100-7.5 was 19 mm which was 21% of the maximum midspan deflection. The residual capacity of Beam 100-7.5 was assumed as zero due to the partial rupture of the GFRP bars in tension and the high residual deflection.

The final impact loading test was carried out for Beam 75-7.5 (spacing of stirrups of $D/4$). During the inertia loading phase, a shear crack (crack 1) appeared on Beam 75-7.5 (**Fig. 6**). As the beam continued deflecting, several flexure-shear cracks (cracks 4, 6, and 7), flexural cracks (cracks 2 and 3), and shear cracks (crack 5) appeared in the beam. At $t = 26$ ms, the beam reached its maximum midspan deflection. The flexural and shear cracks were not as dominant as the flexure-shear cracks (cracks 4 and 7). This can be attributed to the large shear capacity of Beam 75-7.5 that resisted the development of the shear-plug mechanism in the beam. Moreover, it was observed that although the first crack to appear (crack 1) was a shear crack, the width of this crack did not significantly increase and was minor compared to the flexure-shear cracks. Beam 75-7.5 then rebounded to its initial position and the impactor bounced on the beam a few times which caused one of the GFRP bars in tension to fully rupture (**Fig. 6**). The residual capacity of Beam 75-7.5 was assumed to zero due to the rupture of the GFRP bar.

It was observed that all beams belonging to Group 3 experienced catastrophic failure due to GFRP bar rupture. Beams with lower shear capacities (Beam 150-7.5) failed without the beam rebounding to its initial position. Beams with higher shear capacities (Beams 100-7.5 and 75-7.5) failed after the impactor bounced on the beams. Moreover, dominant shear cracks were observed in beams with lower shear capacity (Beam 150-7.5), whereas Beam 75-7.5 with higher shear capacity experienced a flexure-shear failure.

Under impact loads, the majority of the input impact energy is transformed into kinetic energy during the vibration [4]. The remaining energy is dissipated by concrete cracking, damage, and

permanent deformation [4, 6, 13]. In this study, the residual midspan deflection of GFRP-RC beams subjected to high-intensity low-velocity impact loads was relatively small (under 20%) when the GFRP bars did not rupture. However, the GFRP-RC beams that experienced severe local damage (Group 2 and Group 3 beams) may not be repairable.

3.2.3 Dynamic equilibrium of applied forces

The dynamic forces during the impact were the impact force, reaction force, and inertia force. According to Saatci and Vecchio [4], the impact force, at a certain instant, equals the sum of the reaction force and the inertia of the beam. The inertia of the beam is calculated as the integral of the mass per unit length of the beam multiplied by the acceleration of the beam over its length, as shown in Eq. 1:

$$\int_0^L \bar{m}\ddot{u}(x, t)dx + R(t) = I(t) \quad (1)$$

where L is the length of the beam, $\bar{m}$ is the mass per unit length of the beam, $\ddot{u}$ is the acceleration of a particular point on the beam, R is the total reaction force, and I is the impact force. In this experiment, the impact and reaction forces were recorded using load cells, and the accelerations were recorded using accelerometers attached externally to the beams. The change in the acceleration between two adjacent accelerometers was assumed linear. The distributions of the accelerometers and forces are presented in **Fig. 7**. Six accelerometers were used, which were spaced at 200 mm on one half of the beam starting at the midspan and ending at the end of the overhang of the beam. The accelerations at the supports were assumed to be zero. The capacity of the accelerometers used was 1000g, where g is the gravitational acceleration.

It was observed that regardless of the amount of shear reinforcement, the duration of the initial triangular pulse was almost 2 ms. The second pulse started after 5 ms of the impact and fluctuated until the end of the impact. It was also observed that when the impact velocity increased, the maximum impact load increased as well. Therefore, the shear reinforcement had no influence on the impact force for beams belonging to the same group. The reaction force, on the other hand, started

after 5 ms of the impact and fluctuated until the end of the impact. It was observed that the delay between the impact and reaction forces was around 5 milliseconds. This delay is due to the time it took for the stress wave to propagate from the impact zone to the supports.

4. Analysis of the dynamic shear force

The dynamic shear force distribution of a GFRP-RC beam under impact load is different from the shear distribution under quasi-static loads. In order to measure the dynamic shear force in the beams, the data from the accelerometers were analyzed. The dynamic shear force over the duration of the impact was plotted using the static equilibrium of the dynamic forces (inertia, impact, and reaction) and Eq. 1. The maximum measured shear forces for every beam are presented in **Table 3**. It was observed from **Table 3** that when the experimental shear force was significantly larger than the shear capacity predicted by ACI [30], the failure mode was shear.

An analysis was carried out over the first 10 ms of impact to determine the instant at which the dynamic shear force peaked. It was found that the maximum dynamic shear force was recorded after 1 ms of the impact (when the impact force peaked) before the shear force decreased to a minimum after 5 ms (when the reaction force was present). This observation was similar to the findings of Zhao et al. [9]. It was reported in Zhao et al. [9] that the maximum dynamic shear force was recorded after 1 ms (maximum impact force) of the impact and the minimum dynamic shear force was recorded after 5 ms of the impact. This can be explained by the impact force reaching its peak after 1 ms of the impact, where the forces acting during the first millisecond of impact were the impact force and the inertia force. The reaction forces were not activated during the first millisecond of impact due to the stress waves not reaching the support. The maximum dynamic shear force was directly correlated with the maximum impact force. The maximum dynamic shear force increased during the first millisecond of impact similar to the impact force, then decreased with the impact force. After 5 ms of the impact, the reaction force was activated and the forces present were the impact force, inertia force, and reaction force. The dynamic shear force diagram of Beam 75-5.5 over the first 5 ms of

impact is presented in **Fig. 8**. It can be observed that the shape of the shear force was gradually transitioning from dynamic shear to quasi-static shear over the first 5 ms of impact. This showed that the shear cracks were generated within the first 5 ms of impact. The failure mode of the beams was then determined by comparing the shear capacity of the beam calculated as per ACI [30] with the maximum measured shear force. If the maximum shear force measured in the beam was larger than the shear capacity, the failure mode was considered to be shear failure. The dynamic shear force diagrams, for the first millisecond of impact, of the beams tested is presented in **Fig. 9**. The dynamic shear force diagrams after 5 ms of impact are presented in **Fig. 10**. It was also observed after analyzing the shear cracks in the beam that the beams predicted to fail in shear according to ACI [30] failed in shear.

5. Design recommendations based on impact testing of GFRP-RC beams

5.1 Validation of the damage mechanisms based on the code provisions

According to ACI [30], the design of shear reinforcement for a GFRP-RC beam is similar to that of a Steel-RC beam. However, the mechanical properties of the GFRP bars affect the shear strength and should be taken into account. The nominal shear strength at a section (V_n), presented in Eq. 2, is the sum of the nominal shear strength provided by concrete (V_c) and the shear resistance provided by the GFRP shear reinforcement (V_f). The shear capacities for the nine beams calculated by ACI [30] were presented in **Table 3**.

$$V_n = V_c + V_f \quad (2)$$

The nominal shear strength provided by concrete is calculated by Eq. 3 (SI units)

$$V_c = \frac{2}{5} \sqrt{f'_c} b (kd) \quad (3)$$

where f'_c is the compressive strength of concrete (in MPa), b is the width of the beam (in mm), k is the ratio of depth of neutral axis to reinforcement depth presented in Eq. 4, and d is the distance from extreme compression fiber to centroid of tensile longitudinal bars (in mm).

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \quad (4)$$

where ρ_f is the longitudinal reinforcement ratio and n_f is the modular ratio calculated by Eq. 5

$$n_f = \frac{E_f}{E_c} \quad (5)$$

where E_f is the modulus of elasticity of the GFRP bars and E_c is the modulus of elasticity of concrete (calculated as $5700\sqrt{f'_c}$ for f'_c in psi or $4700\sqrt{f'_c}$ for f'_c in MPa).

The contribution of the GFRP shear reinforcement is calculated by Eq. 6

$$V_f = \frac{A_f f_f d}{s} \quad (6)$$

where f_f is the tensile strength of the shear reinforcement (in MPa), s is the center-to-center spacing of shear stirrups (in mm), and A_f is the area of shear reinforcement in the spacing s (in mm²).

5.2 Recommendations based on experimental observations

The input parameters of this experimental program were the shear reinforcement and the impact velocity. In this study, a spacing of $D/2$ (150 mm), $D/3$ (100 mm), and $D/4$ (75 mm) were chosen between the stirrups. The three impact energies used were 8684 Joules, 13026 Joules and 17368 Joules which were multiples of the energy absorption capacity of the control beam.

In terms of the residual deflections of the beams impacted with an impact energy equivalent of $1.0E$, it was observed that a decrease in the spacing of the shear reinforcement to $D/3$ led to a 40% decrease in the residual deflection (compared to $D/2$ spacing). Moreover, a decrease in the spacing of the shear reinforcement to $D/4$ led to a 60% decrease in the residual deflection. When the impact energy was increased to $1.5E$, it was observed that a decrease in the spacing of the shear reinforcement

to $D/3$ led to a 6% decrease in the residual deflection. Moreover, a decrease in the spacing of the shear reinforcement to $D/4$ led to an 18% decrease in the residual deflection. When the impact energy was increased to $2.0E$, it was observed that all beams failed by GFRP bar rupture. This observation suggests that GFRP-RC beams may not be able to sustain an overload caused by impact energy exceeding 1.5 times the quasi-static energy absorption capacity without catastrophic collapse.

In terms of the residual capacities of the beams impacted with an impact energy equivalent to $1.0E$, it was observed that when the spacing of the shear reinforcement decreased to $D/3$, the residual capacity of the beam was 92%. Moreover, when the spacing of the shear reinforcement decreased to $D/4$, the residual capacity of the beam was 97%. The residual capacity of the beam with a stirrup spacing of $D/2$ was 85%. When the impact energy was increased to $1.5E$ intensity, it was observed that when the spacing of the shear reinforcement decreased to $D/3$, the residual capacity of the beam was 80%. Moreover, when the spacing of the shear reinforcement decreased to $D/4$, the residual capacity of the beam was 91%. The residual capacity of the beam with a stirrup spacing of $D/2$ was 73%.

Therefore, decreasing the spacing of the shear reinforcement to $D/3$ had a significant influence on GFRP-RC beams in terms of the residual deflection and residual capacities under impact energies close to the quasi-static energy absorption capacity. However, when the impact energy increases up to the level of $2.0E$, decreasing the spacing of the shear reinforcement to $D/4$ had a more significant influence on the residual deflections and residual capacities of the GFRP-RC beams. It is noted that more research is required to study the effect of the decreasing the stirrups spacing in certain locations (in the impact zone only or in the shear span) on the damage behavior of GFRP-RC beams and the residual capacity of the beams under impact loads.

Fig. 11 presents the residual capacities of the beams with different shear capacities. The damage zones were also presented in **Fig. 11**. Based on the discussion above, it is recommended to use shear reinforcement spacing of $D/3$ to transform the shear failure into a flexure-shear failure for beams

under impact energies in the vicinity of their quasi-static energy absorption capacities. However, under higher impact energies (impact energies close to the intensity of $2.0E$), the beams might still fail in shear. Therefore, it is recommended to use shear reinforcement spacing of $D/4$ to resist the shear failure and transform the failure into flexural failure or flexure-shear failure even when the impact energy is twice the quasi-static energy absorption capacity of the beams.

Based on the above results, it is recommended for designers to use the above recommendations to design or check a GFRP-RC beam section under a specified input impact energy. To check if an existing GFRP-RC beam can resist a specified impact load, the section capacity should be calculated first. The section capacity can be calculated using existing design codes [30, 32]. For example, using ACI [30] recommendations, the section capacity can be calculated for an over-reinforced or under-reinforced section using equations 7.2.2a and 7.2.2f, respectively. After the section capacity is calculated, the ultimate load and corresponding midspan deflection (section 7.3.2.3) can be calculated. Therefore, plotting the load-midspan deflection allows for the calculation of the maximum quasi-static energy absorption capacity ($E_{s,max}$) of the beam. If $E_{s,max}$ is larger than 1.5 times the input impact energy E , then the post-impact residual capacity of the beam would be dependent on its shear capacity.

If a new GFRP-RC beam were to be designed, similar steps should be followed. The minimum quasi-static energy absorption capacity ($E_{s,min}$) should be larger than 1.5 times the input impact energy E , or the following design condition should be satisfied, $E_{s,min} \geq 1.5E$. To calculate $E_{s,min}$, both the ultimate load and corresponding midspan deflection need to be calculated. The ultimate load should be assumed first by trial and error and the corresponding midspan deflection should be calculated based on the ultimate load. The quasi-static energy absorption capacity of a GFRP-RC beam can be calculated as per design code recommendations. After several iterations (if required), when the calculated $E_{s,min}$ is found, the ultimate load can then be used to design the section.

Therefore, the section dimensions, compressive strength of concrete, and GFRP bar reinforcement can be designed to resist high-intensity low-velocity impact loads.

6. Conclusions

In this paper, the overload damage mechanisms of nine GFRP-RC beams were investigated by conducting a series of impact loads tests. A well-instrumented experimental program was carried out to investigate the influence of shear capacity and impact velocity on the behavior of GFRP-RC beams under high-intensity low-velocity impact loads. After impact, the beams were tested under quasi-static monotonically increasing loads to determine the residual capacities of these beams. The following conclusions were drawn:

1. The shear capacities of the GFRP beams significantly influenced the failure modes of the beams under high-intensity low-velocity impact loads. Beams with higher shear capacities failed in flexure and flexure-shear, whereas beams with lower shear capacities developed shear-plug type of failure.

2. As the impact velocity increased, all beams regardless of their shear capacities experienced higher levels of local damage and post-impact cracks.

3. During the first 5 ms of the impact, the shear force transitioned from a dynamic shear force at the center of the beam to a quasi-static shear force. The shear-plug cracks observed on all beams can be explained using the dynamic shear force diagrams of the beams which are influenced by the inertia resistance of the beams.

4. The maximum input impact energy the beams were able to resist was 1.5 times the quasi-static energy absorption capacity. An input impact energy higher than that led to a catastrophic failure of the beams regardless of the shear capacity.

5. It was observed that increasing the shear capacity of a GFRP-RC beam led to smaller residual deflections and higher residual capacities. To resist impact loads, it is recommended to use a spacing of the shear reinforcement of $D/3$ for beams subjected to impact energies similar to the quasi-static

energy absorption capacity and a spacing of $D/4$ for beams that could be subjected to impact energies up to 1.5 times the quasi-static energy absorption capacity.

6. Based on the experimental observations and existing design codes, design recommendations were provided to design a GFRP-RC section to resist a specified input impact load.

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Tables

Table 1

Details of the tested beams

Beam Group	Beam name	Dimensions of beam (mm)	Compressive strength of concrete (MPa)	Longitudinal reinforcement (mm)	Transverse reinforcement	
					Bar diameter (mm)	Spacing (mm)
C	Control beam	200 (Width)	59.3	Two 16 mm bars (Tension)	12	100
1	75-5.5					75
	100-5.5					100
	150-5.5					150
2	75-6.5	300 (Depth)		Two 16 mm bars (Compression)		75
	100-6.5	2400 (Length)				100
	150-6.5					150
3	75-7.5					75
	100-7.5					100
	150-7.5					150

Table 2

Midspan deflection details of the tested beams

Beam Group	Beam name	Impact velocity (m/s)	Maximum midspan deflection (mm) (Δ_{max})	Time at maximum midspan deflection (sec) ($t_{\Delta_{max}}$)	Time at final position (sec) (t_{final})	Residual midspan deflection (mm) (Δ_{res})
1	75-5.5	5.5	59.2	0.022	0.048	4
	100-5.5		60.9	0.023	0.048	6
	150-5.5		61.4	0.023	0.048	10
2	75-6.5	6.5	72.3	0.025	0.05	14
	100-6.5		73.1	0.025	0.051	16
	150-6.5		85.8	0.026	0.057	17
3	75-7.5	7.5	90.6	0.026	0.058	19
	100-7.5		92.4	0.026	0.058	22
	150-7.5		N/A	N/A	N/A	N/A

*Note: Δ_{max} : maximum midspan deflection, $t_{\Delta_{max}}$: time at maximum midspan deflection, t_{final} : time when

the beam returned to its initial position, Δ_{res} : residual midspan deflection

Table 3

Shear capacity of the tested beams

Beam Group	Beam name	Peak dynamic shear force (kN)	Shear capacity according to ACI [30] (kN)	Failure mode
1	75-5.5	361	374	Flexural failure
	100-5.5	365	286	Shear failure
	150-5.5	371	198	Shear failure
2	75-6.5	402	374	Flexure-shear failure
	100-6.5	401	286	Flexure-shear failure
	150-6.5	410	198	Shear failure
3	75-7.5	457	374	Shear failure
	100-7.5	435	286	Shear failure
	150-7.5	N/A	198	Shear failure

Figures

Fig. 1. Details of the tested GFRP-RC beams

Fig. 2. Impact loads test

Fig. 3. Load-midspan deflection behavior of the control beam

Time	Beam 150-5.5	Beam 100-5.5	Beam 75-5.5
Maximum inertia load
Maximum beam midspan deflection
Post-impact

Fig. 4. Damage progression of Group 1 beams under impact loads

Time	Beam 150-6.5	Beam 100-6.5	Beam 75-6.5
Maximum inertia load	<p>Shear crack 3 1 2 Flexural cracks t = 1 ms</p>	<p>Flexural cracks 1 2 t = 1 ms</p>	<p>Shear crack 3 1 2 Flexural cracks t = 1 ms</p>
Maximum beam midspan deflection	<p>Local failure 5 1 2 3 4 t = 26 ms</p>	<p>Local failure Shear cracks 1 2 3 4 5 6 7 t = 25 ms</p>	<p>Local failure 3 1 2 4 5 6 t = 25 ms</p>
Post-impact	<p>Local damage</p>	<p>Local damage Post-impact cracks</p>	<p>Local damage Post-impact cracks</p>

Fig. 5. Damage progression of Group 2 beams under impact loads (see Table 1)

Time	Beam 150-7.5	Beam 75-7.5
Maximum inertia load	<p>Flexural crack</p> <p>$t = 1 \text{ ms}$</p>	<p>Shear crack</p> <p>$t = 1 \text{ ms}$</p>
Maximum beam midspan deflection	<p>Shear cracks</p> <p>$t = 26 \text{ ms}$</p>	<p>Local failure</p> <p>$t = 26 \text{ ms}$</p>
Post-impact	<p>Local damage</p> <p>GFRP bar rupture</p>	<p>GFRP bar rupture</p>

Fig. 6. Damage progression of Group 3 beams under impact loads (see Table 1)

Fig. 7. Distribution of the accelerometers along the beam

Fig. 8. Dynamic shear force diagram of Beam 75-5.5 over the first 5 ms of the impact

Position from the center of the beam (mm)

(a)

Position from the center of the beam (mm)

(b)

Position from the center of the beam (mm)

(c)

Fig. 9. Dynamic shear force distribution at $t = 1 \text{ ms}$ for: (a) Group 1 beams, (b) Group 2 beams, and (c) Group 3 beams (See Table 1)

(a)

(b)

(c)

Fig. 10. Dynamic shear force distribution at $t = 5 \text{ ms}$ for: (a) Group 1 beams, (b) Group 2 beams, and (c) Group 3 beams (See Table 1)

Fig. 11. Residual load-carrying capacities of the beams with different shear capacities