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Abstract

This paper numerically investigates the behavior of glass fiber-reinforced polymer (GFRP) bar-reinforced concrete beams (GFRP-RC beams) under low-velocity impact loads. A finite element model has been developed and calibrated against the experimental investigation results of six GFRP-RC beams. The results of the numerical analysis have been found in very good agreement with the experimental investigation results. The finite element model captured the failure modes, crack profiles, midspan deflection, impact and reaction forces, and dynamic strain of the GFRP-RC beams. Moreover, a parametric study has been carried out to investigate the influence of the reinforcement ratio, compressive strength of concrete, drop mass, drop velocity, and impact energy on the response of GFRP-RC beams under low-velocity impact loads. It was found that the drop mass and velocity significantly influenced the damage profiles of the beams, and the reinforcement ratio significantly influenced the midspan deflection and reactions at the support.

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NUMERICAL ANALYSIS ON THE BEHAVIOR OF GFRP-RC BEAMS UNDER
IMPACT LOADS

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ABSTRACT

This paper investigates numerically the behavior of Glass Fibre Reinforced Polymer (GFRP) bar reinforced concrete beams (GFRP-RC beams) under low-velocity impact loads. A finite element model has been developed and calibrated against the experimental investigation results of six GFRP-RC beams. The results of the numerical analysis have been found in very good agreement with the experimental investigation results. The finite element model captured the failure modes, crack profiles, midspan deflection, impact and reaction forces, and dynamic strain of the GFRP-RC beams. Moreover, a parametric study has been carried out to investigate the influence of the reinforcement ratio, compressive strength of concrete, drop mass, drop velocity, and impact energy on the response of GFRP-RC beams under low-velocity impact loads. It was found that the drop mass and velocity significantly influenced the damage profiles of the beams and the reinforcement ratio significantly influenced the midspan deflection and reactions at the support.

Keywords: Reinforced concrete, Beam, GFRP, Impact, Modelling

INTRODUCTION

Fibre Reinforced Polymer (FRP) bars have emerged as one of the most suitable replacements for steel bars in Reinforced Concrete (RC) structures, especially in aggressive and corrosive environments. Glass FRP (GFRP) bars, in particular, have been popular and suitable for replacing steel bars in RC structures due to their availability, relatively low cost, and high ultimate strength. Recently, impact loads on structures and structural components have been receiving increasing research attention due to the increase in terrorist attacks worldwide. The response of Glass Fibre Reinforced Polymer bar Reinforced Concrete (GFRP-RC) beams under impact loads varies significantly from the response under static loads. Several studies investigated the response of GFRP-RC beams under static loads¹⁻⁴ and Steel-RC beams under

impact loads⁵⁻¹⁰. However, the response of GFRP-RC beams under impact loads has not been adequately investigated^{11,12}. The key parameters (e.g. reinforcement ratio, concrete compressive strength, velocity of impact, and mass of the drop hammer) influencing the response of GFRP-RC beams under impact loads have not been thoroughly investigated.

Experiments carried out to investigate the response of GFRP-RC beams under impact loads are expensive. The finite element method has been widely used to model the behavior of RC beams under low-velocity (velocity less than 10 m/sec [32.81 ft/sec]) impact loads¹³⁻¹⁸. The finite element method is both cost and time efficient and is reliable in modelling the behavior of GFRP-RC beams under impact loads. There have been no numerical studies in the literature that investigated the response of GFRP-RC beams under low-velocity impact loads. The finite element program LS-DYNA^{19, 20} has been one of the most popular codes to model the response of RC beams under low-velocity impact loads due to its comprehensive material library and ability to capture the non-linear response of RC beams under low-velocity impact loads. Hence, a comprehensive numerical investigation is carried out in this paper to understand the complex behavior of GFRP-RC beams under low-velocity impact loads.

RESEARCH SIGNIFICANCE

This study explores, through numerical analysis, the response of GFRP-RC beams under low-velocity impact loads. An extensive parametric study has been carried out to investigate the effect of longitudinal reinforcement, compressive strength of concrete, drop mass, drop velocity, and impact energy on the response of GFRP-RC beams under impact loads. The results of this study will help in developing guidelines for the design of GFRP-RC beams under impact loads. Moreover, the experimental investigations will provide detailed data that can assist in the validation of future numerical and analytical studies.

NUMERICAL INVESTIGATIONS

The finite element code LS-DYNA has been extensively used in the literature to model the behaviour of Steel-RC beams under impact loads^{14, 16-18, 21-27}. The advantages of using LS-DYNA include the efficient computational capability and the availability of a comprehensive material library.

Structural geometry

To account for the experimental conditions (presented in the next section), a three dimensional (3D) FE model was created. The full 3D FE model presented in **Fig.1** accounts for the boundary conditions (roller and pinned supports) and for the loading conditions (drop hammer). To represent the concrete, supports, and drop hammer, eight-node solid hexahedron elements with single point integration were used. Single point integration produces a less stiff element and saves substantial computational time. However, an overhead of using one-point integration is the need to control the zero energy modes (hourglass modes) for the stability of the solution. In order to control and minimize the hourglass mode, Flanagan-Belytschklo hourglass control was chosen for the solid elements. The hourglass energy is presented in **Fig.2**, where it is calculated to be less than 0.3% of the total energy. To represent the GFRP bar for the reinforcement, 2D Hughes-Liu beam elements with 2x2 Gauss quadrature integration were used. A separate convergence study was carried out to select the appropriate mesh size. Mesh sizes of 20, 15, 10, and 5 mm (0.787, 0.59, 0.393, and 0.197 inch) were modelled and analysed. It was found that a mesh size of 10 mm (0.59 inch and mesh aspect ratio of 1) was the most suitable for this study. The decrease in the mesh size below 10 mm (0.59 inch) increased the computational time significantly with a minor influence on the accuracy of the results.

Contact and boundary condition

While several formulations are available in LS-DYNA to model the contact between the drop hammer beam, and supports, the automatic contact option was found to be sufficient for the

current study. Pin and roller supports were used in order to replicate the boundary conditions of the experiment. The pin support restrained the movement and allowed the rotation about its major axis, whereas the roller support allowed translation and rotation about its major axis. The nodes located above the supports, on the top surface of the beam, were also restrained to prevent the uplift of the beam after the impact. Furthermore, the drop hammer was constrained to vertical movement in order to replicate the movement of the free-falling drop hammer. Moreover, taking the advantage of the symmetry, quarter models were used with appropriate symmetry boundary conditions to model the GFRP-RC beams in this study. In order to replicate the loading conditions, the drop hammer was set at a starting position 1 mm above the beam and was assigned an initial velocity $v_0 = \sqrt{2gh}$ (calculated from the condition of a free-falling body) where g is the gravitational acceleration and h is the drop height. The self-weight of the beam, drop hammer, and gravitational acceleration were taken into account as well to replicate the experimental conditions. To avoid spurious oscillation at the contact surfaces, suitable viscous damping was specified for the model.

Bond-slip model

The bond between the GFRP bars and the concrete was modelled using a one-dimensional bond-slip model. A perfect bond was assumed between the concrete and the steel stirrups using merged nodes. The one-dimensional bond-slip model allows a set of nodes of the reinforcement (slave nodes) to slide along a set of nodes of the concrete (master nodes) via fictitious springs. Modelling the bond between the reinforcement and the concrete using a bond-slip model was used in previous research studies²⁸⁻³¹. This contact model is an elastic-perfect-plastic model that requires input of the bond shear modulus (G_s), maximum elastic slip (s_{max}), damage curve exponential coefficient (h), and damage parameter (D). The relationship of the elastic-perfect-plastic model is given by Equation (1):

$$\tau = \begin{cases} G_s s, & s \leq s_{\max} \\ \tau_{\max} e^{-hD}, & s > s_{\max} \end{cases} \quad (1)$$

Where τ is the bond shear stress of the GFRP bars.

Modelling of materials

Concrete

The Winfrith¹⁹ concrete model, chosen for this study, has been developed over many years by Broadhouse and Neilson³² and Broadhouse³³. This model was developed to model structures subjected to blast and impact loads. This concrete model was validated extensively in the literature and its ability to capture the complex behaviour of RC structures under impact loads is well established^{25, 34-39}. An advantage of this concrete model is that a small number of input parameters required, including the density, initial tangent modulus ($E_c = 4,700\sqrt{f'_c}$ [when f'_c is in MPa] and $E_c = 57,000\sqrt{f'_c}$ [when f'_c is in psi], as specified by ACI⁴⁰), Poisson's ratio, uniaxial compressive and tensile strengths, and aggregate size of concrete. These parameters were determined in Goldston et al.¹¹. The stress-strain diagram of the concrete is generated automatically by the Winfrith Concrete Model. Moreover, the Winfrith model has the ability to include strain rate effects and to generate crack growth algorithms. The additional binary output file includes information about the number, location, and width of the cracks. However, since the Winfrith model does not implicitly include an erosion criteria, an additional function was added such that, upon satisfying an appropriate failure criteria of concrete in compression, concrete elements were removed from the model.

Reinforcement

The Piecewise Linear Plasticity model¹⁹ was chosen to model the GFRP bar in this study. The input parameters for this model include the modulus of elasticity, Poisson's ratio, yield stress, tangent modulus, and plastic failure strain. This material model can be used for GFRP bars

with an adequate choice of the input parameters. **Fig.3** shows the stress-strain curve of a typical GFRP bar using the Piecewise Linear Plasticity model. In order to replicate the behaviour of GFRP bar, a tangent modulus value of zero ($E_{TAN}=0$) is assigned, allowing an elastic-perfectly-plastic behaviour. The value of the ultimate strain is then chosen for the pseudo-plastic strain in order for the GFRP bars to fail upon entering the plastic phase. Specifying those values ensures that the behaviour of GFRP bars is perfectly linear until the failure specified by the pseudo yield stress. Once the failure criteria is reached, the beam element is deleted from the calculation.

Supports and drop hammer

The steel supports and steel drop hammer were modelled using ‘Rigid’ model. An input of density, modulus of elasticity, and Poisson’s ratio are required by this material model. Since the drop hammer and supports consisted of steel, the density and modulus of elasticity of steel were used in this material model.

EXPERIMENTAL INVESTIGATION

This section includes a description of the experiments carried out by the authors to investigate the impact response of six GFRP-RC beams. The full details of the impact experiment can be found in Goldston et al.¹¹. For the purpose of completeness of the numerical analysis, a brief description of the experimental investigations is presented below.

A total of six GFRP-RC beams were tested under impact loads. The beams were designed in accordance with ACI⁴⁰. One beam was designed as under-reinforced beam, one beam was designed as balanced beam, and four beams were designed as over-reinforced beams. These beams were chosen to investigate all three different types of failure modes. The beams were 100 mm (3.94 inch) in width, 150 mm (5.91 inch) in height, and 2400 mm (7.87 ft) in length

with a clear concrete cover of 15 mm (0.591 inch). The clear span of the beam was 2000 mm (6.56 ft). The beams were divided into two main groups according to their concrete compressive strength. The compressive strengths of concrete at the day of testing for Groups A and B were 57.4 MPa (8.33 ksi) and 72.3 MPa (10.5 ksi) respectively. Moreover, each group included three GFRP-RC beams with different reinforcement arrangements. The number following the group name (A and B) indicates the type of reinforcement used in the GFRP-RC beams. The GFRP bars of diameters 6.35 mm (0.25 inch), 9.53 mm (0.375 inch), and 12.7 mm (0.5 inch) were used in the experiment. In the beam name, number 1 indicates that two GFRP bars of 6.35 mm (0.25 inch) diameter were used as longitudinal reinforcement, numbers 2 and 3 indicate that two GFRP bars of diameters 9.53 and 12.7 mm (0.375 and 0.5 inch) each, respectively were used as longitudinal reinforcement. Beams with the numbers 1, 2, and 3 in the names had reinforcement ratios of $\rho_f = 0.5\%$, 1%, and 2%, respectively. The compression reinforcement was similar to the tension reinforcement in all the GFRP-RC beams and consisted of two GFRP bars of the same diameter as those in tension. Steel bars of 4 mm (0.157 inch) diameter spaced at 100 mm (3.94 inch) centre-to-centre were used as transverse reinforcement. The properties of the GFRP and steel bars were tested by the authors in Goldston et al.¹¹, were presented in **Table 1**. The mass of the drop hammer used in the experimental investigations was 110 kg (243 lbs). The drop height was 1200 mm (3.94 ft) and could be assumed to be a free falling system without friction. The drop velocity was 4.85 m/s (15.9 ft/s) at impact. All the GFRP-RC beams were designed to fail in flexure (flexure-critical) with a shear-to-bending resistance ratio larger than one. The predicted failure modes according to ACI⁴⁰ were balanced failure for Beam A1, under-reinforced failure for Beam B1, and over-reinforced failure for the remaining beams (Beams A2, A3, B2, and B3). The midspan deflections were measured by a Laser-type Variable Displacement Transducer (LVDT) with a measuring range of 90 mm (3.54 inch). The strain in the GFRP bars was measured using strain

gauges attached to the GFRP bars. In order to allow the strain gauges to be in direct contact with the GFRP bars, the sand coating on the GFRP bars was removed and the strain gauges were placed at the midspan of the GFRP bars. The impact and reaction forces were measured using load cells attached to the drop hammer and the supports. The variables of the experiment were the longitudinal reinforcement ratio and the compressive strength of concrete. The investigation aimed at understanding the behaviour of GFRP-RC beams under impact loads in terms of failure modes, midspan deflection, strain in GFRP bar, and impact and reaction forces.

To determine the values of the bond shear stress, maximum slip and damage coefficient, four specimens were tested under static loads according to RILEM⁴¹. All specimens were formed of two parts, as shown in **Fig.4**. Each specimen was formed of two parts separated by a distance of 50 mm (1.97 inch). Each part of the specimens was 100 mm (3.94 inch) in width, 180 mm (7.1 inch) in depth, and 375 mm (1.23 ft) in length. The embedment length used was six times the bar diameter according to Yan et. al⁴², as it provides a desirable failure. The diameters of the GFRP bars tested were 9.53 mm (0.375 inch) and 12.7 mm (0.5 inch). The specimens were tested using a 5000 kN (1124 kips) Instron machine (**Fig.4**). The applied displacement was 1 mm/min (0.0394 inch/min). The displacement was applied until the failure of the bond between the GFRP bar and the concrete. The slip between the GFRP bars and the concrete was measured using LVDT's. The strains in the GFRP bars were measured using strain gauges attached to the GFRP bars.

EXPERIMENTAL RESULTS AND DISCUSSION

Failure modes

As per the design codes ACI⁴⁰ and CSA⁴³, since GFRP bars do not yield, the preferred failure mode is concrete crushing in over-reinforced beams, which provides a warning prior to the collapse of the structure. The under-reinforced failure mode occurs due to GFRP bar rupture,

whereas the balanced failure mode occurs due to simultaneous rupture of FRP bars and failure of concrete in compression. A brief description of the failure modes of the GFRP-RC beams is presented below.

Under-reinforced and balanced failure

The balanced Beam A1 and the under-reinforced Beam B1 failed due to the rupture of GFRP bars. The impact energy (1295 J) transferred to the beams from the drop hammer was sufficient to cause failure of the beam. The term energy absorption capacity has been used by Adhikary et al.^{17, 44} as the energy absorbed by the beam. The energy absorption capacity of the beam was calculated as the area under the load-midspan deflection curve from zero deflection until the midspan deflection corresponding to the maximum load. The energy absorption capacities of Beams A1 and B1 were 518 J and 435 J, respectively. The beams started deflecting upon contact with the drop hammer and kept increasing until the GFRP bars ruptured. The cracks were predominantly flexural cracks which started developing and propagating vertically upwards until the failure of the beam. The beams were then split into two parts at the impact zone. Moreover, a local failure was observed, which was due to the spalling of concrete in the impact zone.

Over-reinforced failure

The over-reinforced Beams A2, A3, B2, and B3 failed due to concrete crushing. The impact energy (1295 J) of the first drop was not sufficient to cause failure of the beams. The beams returned to their initial position showing an elastic behaviour indicating reserve capacity. Shear cracking was evident at the impact area with the crushing of the concrete cover. The cracks observed in these beams were flexural cracks in addition to shear cracks. The flexural cracks propagated vertically upwards and were observed in the areas closer to the supports. In the impact area, on the other hand, the cracks were predominantly shear cracks with the shear plug

developing at the impact zone. Shear plug failure was observed in these beams with cracks originating from the impact zone and propagating at 45 degrees angle. Moreover, all beams showed shear cracks regardless of the reinforcement ratio and compressive strength of concrete. It was also observed, however, that as the reinforcement ratio and compressive strength of concrete increased, the number of shear cracks in the beams decreased.

Midspan deflection

The midspan deflection was measured for all the beams under impact loads. For the Beams A1 and B1, the midspan deflection was not recorded since the beams completely failed and were split into two parts. For the remaining over-reinforced beams, all beams started deflecting from zero to reach a maximum midspan deflection after about 25 milliseconds. The beams then rebounded and returned to their initial state within 60 milliseconds with a parabolic trace of the midspan deflection-time curve. Moreover, beams with higher reinforcement ratios and concrete compressive strengths experienced lower maximum midspan deflections.

Dynamic strain in GFRP bar

The dynamic strains in the GFRP bars were measured using strain gauges attached to the bars at the midspan. The dynamic strains in the GFRP bars started from zero and increased with a high strain rate at the beginning where the response of the beam was still elastic. After cracks started to develop (approximately at 3 milliseconds), the rate of the development of the dynamic strain was decreased. The dynamic strain kept increasing with some fluctuations until reaching the maximum dynamic strain when the maximum midspan deflection was reached. The dynamic strain then dropped after the beam rebounded to its initial position. Moreover, the dynamic strains were not measured in Beams A1 and B1 due to the rupture of the GFRP bars.

Impact and reaction forces

The forces during an impact are the impact force, reaction forces, and inertia forces. The impact force equals the sum of the inertia forces and reaction forces. All beams showed a similar shape for these forces. The impact force was generated upon the contact between the drop hammer and the GFRP-RC beam. This impact force was demonstrated by a high magnitude impulse (approximately 200 kN [45 kips]) over a short duration of time (10 milliseconds) representing the contact between the drop hammer and the beam. The recorded inertia force was similar to the impact force for this duration. The reaction forces recorded were zero due to the delay in the travel of the stress wave from the impact point to the supports. The total reaction forces of both supports (reaction force hereafter) then started resisting the impact force until the end of the impact (approximately 60 milliseconds). Also, after almost 15 milliseconds from the start of the impact, the reaction force matched the impact force (at around 30 kN [6.75 kips]) while the inertia force was negligible.

Bond-slip

Table 2 presents the results of the bond-slip tests carried out in this study. The averages of the maximum shear bond stresses for the GFRP bars with diameters 9.53 mm (0.375 inch) and 12.7 mm (0.5 inch) were 38.45 MPa (5.6 ksi) and 31.3 MPa (4.5 ksi), respectively. Moreover, the averages of the slip at maximum stresses for the GFRP bars with diameters 9.53 mm (0.375 inch) and 12.7 mm (0.5 inch) were 0.14 mm (0.0055 inch) and 0.11 mm (0.0043 inch), respectively. Furthermore, the averages of the exponential decays for the GFRP bars with diameters 9.53 mm (0.375 inch) and 12.7 mm (0.5 inch) were 0.11 and 0.15, respectively. These values were used in the numerical bond-slip model of the GFRP bars with concrete in this study. However, due to the unavailability of the GFRP bars with diameter 6.35 mm (0.25 inch) during the testing of the bond-slip, the values were taken to be the same as those of the GFRP bar with a diameter of 9.53 mm (0.375 inch). It was reported in the literature^{45, 46} that

the bond strength increases with the decrease of the bar diameter. Hence, using the bond properties of the GFRP bar with a diameter of 9.53 mm (0.375 inch) to model the GFRP bar with a diameter of 6.35 mm (0.25 inch) was considered conservative.

COMPARISONS OF THE FINITE ELEMENT MODEL AND EXPERIMENTAL RESULTS

The FE model was validated against the experimental results. The validation was carried out in terms of the failure modes, midspan deflection, strain in GFRP bar, and impact forces. The numerical results seem to be in good agreement with the experimental results. A brief description of the results is presented below.

Failure modes

The FE models created with LS-DYNA show the ability to capture the experimental behaviour of the GFRP-RC beams under impact loads. In terms of the general failure mode, beams that were under-reinforced and balanced (Beams B1 and A1) failed due to GFRP bar rupture, as predicted. **Fig.5** presents the failure of Beam A1 (only Beam A1 was chosen for presentation purposes since Beam B1 had a similar failure mode). It is evident from **Fig.5** that Beam A1 failed due to the rupture of the GFRP bars. The concrete spalling at the midspan was captured by the high-speed video camera and by the FE model as well. The cracks were predominantly flexural cracks originating from the tension side of the beam and propagating vertically upwards. The FE model was able to capture those cracks in addition to the GFRP bar rupture, which caused the failure of the beam.

Moreover, the four over-reinforced beams failed due to concrete crushing. Concrete crushing was observed along with shear cracks originating from the impact zone and propagating at 45°. **Fig.6** shows the damage profile of Beam A2 (only Beam A2 was chosen for presentation purposes since the damage profile of Beam A2 is similar to Beams A3, B2, and B3). The cracks

in the beam were flexural cracks that developed away from the impact area and shear cracks concentrated in the vicinity of the impact area. However, the shear cracks were larger and more dominant. The local damage at the impact area was also captured by the FE model.

Midspan deflection

The midspan deflection in the experiment was analysed and the midspan deflection-time curves were plotted. These curves were compared against the results of the FE model. For the under-reinforced and balanced beams, the midspan deflection was not captured due to the rupture of the GFRP bars, which split the beam into two parts. Therefore, only the results of the over-reinforced beams were compared in this section. All four over-reinforced beams followed a parabolic midspan deflection-time curve. The deflections of the GFRP-RC beams started when the drop hammer impacted the beams. The beams accelerated at the midspan vertically downwards until reaching the maximum midspan deflection. The velocity measured at the maximum midspan deflection was zero. The beams then rebounded and came back to the initial position within a timeframe of 60 milliseconds. The midspan deflection-time curves of Beams A2, A3, B2, and B3 were presented in **Fig.7**. The experimental and numerical results seem to be in good agreement with each other. The parabolic shape at the midspan deflection was captured by the FE model. The response time (time from beginning of impact until the beams rebounded) of the GFRP-RC beams was also captured by the FE model. Moreover, the values of the maximum midspan deflections were in very good agreement. A comparison of the maximum midspan deflection values is presented in **Table 3**. It was observed from **Table 3** that the midspan deflection results of the numerical analysis match very well with the experimental results. It was observed as well that all the numerical results of the midspan deflection were higher than the experimental midspan deflection results. The ratio of the numerical-to-experimental midspan deflections was presented in **Table 3**. The numerical analysis over-predicts the midspan deflection of the GFRP-RC beams by an average of 3%.

Dynamic strain in GFRP bar

The experimental dynamic strain in the GFRP bar was measured by strain gauges placed on the midspan of the GFRP bar. The experimental and numerical results of the dynamic strain were presented in **Fig.8** (only Beam A3 was chosen for presentation purposes, since all four over-reinforced beams had a similar shape of the dynamic strain-time curves). The experimental dynamic strain of the under-reinforced and balanced beams was not available due to the failure of the GFRP bars. The dynamic strains in the GFRP bar started at zero and increased with a high strain rate. The strain rate decreased once the cracking of concrete started. The dynamic strain kept increasing with some fluctuations until reaching the maximum dynamic strain when the maximum midspan deflection was reached. The dynamic strain then dropped again after the beam returned to its initial position. The overall shapes and values of the numerical dynamic strains match that of the experiment very well. The initial increase at a high rate, the decrease after cracking of concrete, the fluctuation, and reaching a maximum value when the maximum midspan deflection is reached were all captured by the FE model. **Table 3** also presents the numerical and experimental values of the maximum dynamic strain. The values of the dynamic strain using the numerical analysis were 2% higher than the experimental values.

Impact and reaction forces

The numerical and experimental forces compared in this section are the impact force and the reaction force. All beams showed a similar shape for both forces. The impact force is attributed initially with a high magnitude impulse over a short duration of time. This impact force then drops back to zero before having a second peak and then fluctuates until going back to zero at the end of the response. The reaction force lags behind the impact force. **Fig.9** shows the experimental and numerical response of Beam A2 in terms of the impact force and reaction of supports (only Beam A2 was chosen for presentation purposes since all the over-reinforced

beams have similar impact force and reaction force shapes). The results seem to be in very good agreement in terms of the overall shape, duration, and mean values of the impact and reaction forces. Moreover, **Table 3** presents the numerical and experimental values of the areas under the impact force curve and the reaction force curve. The impulse of these forces was calculated by integrating the area under the force-time curves. It was shown that the FE model over-predicts the values of the impact force and reaction force by 6% and 7%, respectively.

PARAMETRIC STUDY

A parametric study was carried out to investigate the effect of the reinforcement ratio, compressive strength of concrete, drop height, drop mass, and impact energy. The beams were 200 mm (7.87 inch) in width, 300 mm (11.81 inch) in height, and 2400 mm (7.87 ft) in length with 2000 mm (6.56 ft) clear span. Moreover, the modulus of elasticity of the GFRP bars was 50 GPa (7251 ksi) and the ultimate strength was 1200 MPa (174 ksi). The bond-slip model was taken into account with a maximum slip of 0.15 mm (0.006 inch), bond shear modulus of 111 MPa/mm (41 ksi/inch), and exponential decay of 0.12. The findings of this study are important for developing guidelines for the design of GFRP-RC beams under impact loads. The development of design guidelines and the development of an analytical model is considered beyond the scope of this paper.

Influence of the longitudinal reinforcement ratio

To investigate the effect of the longitudinal reinforcement ratio, six GFRP-RC beams were modelled under low-velocity impact loads. The reinforcement ratios of the six beams were 0.5%, 1%, 1.5%, 2%, 2.5%, and 3%. All six beams in this study had shear reinforcement comprised of 8 mm (0.31 inch) diameter bars spaced at 100 mm (3.94 inch) centre-to-centre ensuring flexure-critical design failure. The compressive strength of concrete for the beams was 40 MPa (5.8 ksi). The beams were subjected to a drop load of 400 kg (882 lbs) impacting

the beam at 5 m/s (16.4 ft/s [drop height of 1.3 m (11.8 inch)]). The impact energy was calculated as 5000 J.

The results show that, as the reinforcement ratio of the GFRP-RC beams increased, the maximum midspan deflection and the maximum dynamic strain in the GFRP bars at the midspan decreased, whereas the reaction force increased. **Fig.10** presents the maximum midspan deflection, maximum dynamic strain in GFRP bars at midspan, and maximum reaction force as a function of the reinforcement ratio. The maximum midspan deflection decreased from 40.52 mm (1.6 inch) to 20.17 mm (0.79 inch) upon increasing the reinforcement ratio from 0.5% to 3% (**Fig.10 (a)**). This 50% decrease in the maximum midspan deflection was also associated with a 50% decrease in the time to reach the maximum midspan deflection (from 19 ms to 9.8 ms). Moreover, the maximum dynamic strain in the GFRP bars at the midspan significantly reduced from 0.016 to 0.0053 upon increasing the reinforcement ratio from 0.5% to 3% (**Fig.10 (b)**). As observed from **Fig.10 (c)**, the impact force was not affected by the increase in the reinforcement ratio, whereas the reaction force increased. This is due to the impact force being influenced by the drop mass, drop height, and contact surfaces, whereas the reaction force depended on the energy absorbed by the beam and the inertia forces. The resistance of the beam increased with an increase in the longitudinal reinforcement ratio.

Influence of the compressive strength of concrete

To investigate the effect of the compressive strength of concrete, five GFRP-RC beams were modelled under low-velocity impact load. The compressive strengths of concrete were 30 MPa (4.35 ksi), 40 MPa (5.8 ksi), 50 MPa (7.25 ksi), 60 MPa (8.7 ksi), and 70 MPa (10.5 ksi). The impact mass was 400 kg (882 lbs) and the drop velocity was 5 m/s (16.4 ft/s [5000 J impact energy]). The beams in this study and all the studies that follow had a longitudinal reinforcement ratio of 1% and 8 mm (0.31 inch) shear reinforcement spaced at 100 mm (3.94 inch) centre-to-centre.

The results showed that, as the compressive strength of concrete increased, the maximum midspan deflection decreased. The maximum midspan deflection decreased by 10 % upon increasing the compressive strength of concrete from 30 MPa to 70 MPa (4.35 ksi to 10.5 ksi). The compressive strength of concrete had a minor influence on the maximum dynamic strain at the midspan of the GFRP bars. Moreover, the impact and reaction forces increased with an increase in the compressive strength of concrete. A 57 % increase in the reaction force was observed when the compressive strength of concrete increased from 30 MPa to 70 MPa (4.35 ksi to 10.5 ksi). This means that the resistance of the beam increases with an increase in the compressive strength of concrete.

Influence of the drop mass

To investigate the effect of the drop mass on the response of GFRP-RC beams under low-velocity impact loads, five different drop masses were investigated. The masses were 200 kg (441 lbs), 300 kg (661 lbs), 400 kg (882 lbs), 500 kg (1102 lbs), and 600 kg (1323 lbs). All the impact velocities were fixed to 5m/s (16.4 ft/s). The compressive strength of concrete in this study and the studies that follow was 40 MPa (5.8 ksi).

It was observed that the drop mass significantly influenced the crack profile of the GFRP-RC beams. When the drop mass was 200 kg (441 lbs), only flexural cracks were observed propagating vertically upwards from the bottom of the beam. As the mass increased, more shear cracks were observed propagating at an angle of 45°. At a mass higher than 600 kg (1323 lbs), shear cracks appear to dominate the failure of the beams. Moreover, maximum midspan deflection and the maximum dynamic strain in the GFRP bars increased by 127 % and 89 %, respectively when the drop mass increased from 200 kg (441 lbs) to 600 kg (1323 lbs). The drop mass had a relatively lower influence on the impact and reaction forces. The impact and reaction forces increased by 15% when the drop mass increased from 200 kg (441 lbs) to 600 kg (1323 lbs).

Influence of the drop velocity

To investigate the effect of the drop mass on the response of GFRP-RC beams under low-velocity impact loads, five different drop velocities were investigated. The impact velocities were 3 m/s (9.8 ft/s), 4 m/s (13.1 ft/s), 5 m/s (16.4 ft/s), 6 m/s (19.7 ft/s), and 7 m/s (23 ft/s). The impact mass was 400 kg (882 lbs).

Similar observations to those reported in the above section were observed upon increasing the impact velocity. The maximum midspan deflection and maximum dynamic strain in the GFRP bars increased by 162% and 113%, respectively when the drop velocity increased from 3 m/s to 7 m/s (9.8 ft/s to 23 ft/s). The impact force was significantly influenced by the drop velocity where an increase from 3 m/s to 7 m/s (9.8 ft/s to 23 ft/s) led to a 160% increase in the impact force and a 45 % increase in the reaction force. Also, the crack profile was influenced by the drop velocity. When the drop velocity was 3 m/s (9.8 ft/s), flexural cracks developed propagating vertically in the beam. Upon increasing the drop velocity to 7 m/s (23 ft/s), shear cracks propagating at 45° dominated the beam.

Influence of the impact energy

To investigate the effect of the drop mass and drop velocity on the response of GFRP-RC beams under low-velocity impact loads, the impact energy of this study was fixed to 5000 J. The drop masses chosen for this study were 200 kg (441 lbs), 300 kg (661 lbs), 400 kg (882 lbs), 500 kg (1102 lbs), and 600 kg (1323 lbs). The drop velocities of these masses were 7.07 m/s (23.2 ft/s), 5.77 m/s (18.9 ft/s), 5 m/s (16.4 ft/s), 4.47 m/s (14.7 ft/s), and 4.08 m/s (13.4 ft/s), respectively. This ensured that all the drop tests had an impact energy of 5000 J. The aim of this study is to investigate the effect of increasing the mass while decreasing the velocity of the drop hammer on the response of the GFRP-RC beams.

It was observed that varying the drop mass and drop velocity while keeping the impact energy fixed has a significant influence on the failure mode of the GFRP-RC beams. **Fig.11** presents the damage profiles of two beams impacted with the same impact energy using different drop masses and velocities. The damage profiles are presented at 5 ms and 20 ms. In **Fig.11 (a)**, when the drop velocity was low and the drop mass was high (4.08 m/s [13.4 ft/s] and 600 kg [1323 lbs]), flexural cracks dominated in the first 5 milliseconds. Shear cracks developed after the flexural cracks. However, in **Fig.11 (b)**, when the beam was impacted with high drop velocity and low drop mass (7.07 m/s [23.2 ft/s] and 200 kg [441 lbs]), shear cracks dominated throughout the whole response. Also, it was observed that the drop mass influenced the maximum midspan deflection and the dynamic strain in the GFRP bars, whereas the drop velocity influenced the impact and reaction forces. The maximum midspan deflection and the dynamic strain in the GFRP bars increased by 22 % and 18 %, respectively when the drop mass increased from 200 kg (441 lbs) to 600 kg (1323 lbs) while keeping the impact energy fixed at 5000 J. Moreover, the impact and reaction forces increased by 42 % and 20 %, respectively when the drop velocity increased from 4.08 to 7.07 m/s [13.4 to 23.2 ft/s] while keeping the impact energy fixed at 5000 J.

CONCLUSIONS

The test results of six GFRP-RC beams were used to calibrate a finite element model to investigate the behaviour of GFRP-RC beams under low-velocity impact loads. The finite element model captured the midspan deflections, dynamic strains in the GFRP bars, impact force, reaction force, crack patterns, and failure modes. After calibrating the finite element model, a comprehensive parametric study was carried out to investigate the influence of the longitudinal reinforcement ratio, compressive strength of concrete, drop mass, drop velocity,

and impact energy on the behaviour of GFRP-RC beams under low-velocity impact loads. The following conclusions were drawn:

1. The maximum midspan deflection and maximum dynamic strain in GFRP bars decreased significantly with an increase in the longitudinal reinforcement ratio. Moreover, the impact force and crack profile were not influenced by variation of the longitudinal reinforcement ratio, whereas the reaction force increased with an increase in the longitudinal reinforcement ratio.

2. The maximum midspan deflection decreased with an increase in the compressive strength of concrete. Moreover, the maximum dynamic strain in the GFRP bars was not influenced by the compressive strength of concrete, whereas the impact and reaction forces increased leading to a higher resistance of the beam with an increase in the compressive strength of concrete.

3. The drop mass significantly influenced the crack and damage profiles of the beams. More shear cracks developed when the drop mass increased. At high masses (600 kg [1323 lbs]), shear cracks appeared to dominate the failure of the beam. Moreover, the maximum midspan deflection and maximum dynamic strain in the GFRP bars significantly increased when the drop mass increased.

4. The drop velocity significantly influenced the crack and damage profiles of the beams. Flexural cracks were observed at low impact velocities (3-4 m/s [9.84-13.1 ft/s]), whereas shear cracks dominated in higher velocities (6-7 m/s [19.7-23 ft/s]). The maximum midspan deflection, maximum dynamic strain in the GFRP bars, impact force, and reaction force significantly increased with an increase in the drop velocity.

5. A combination of low drop velocity and high drop mass (4.08 m/s [13.4 ft/s] and 600 kg [1323 lbs]) led to flexural cracks at the beginning of the impact followed by shear cracks. However, a combination of high drop velocity and low drop mass (7.07 m/s [23.2

ft/s] and 200 kg [441 lbs]) led to shear cracks dominating throughout the whole impact duration. Also, it was observed that the drop mass significantly influenced the maximum midspan deflection and the maximum dynamic strain in the GFRP bars, whereas the drop velocity significantly influenced the impact and reaction forces.

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TABLES AND FIGURES

List of Tables:

Table 1– Properties of the GFRP and steel reinforcement used in the experiment (Goldston et al¹¹)

Table 2– Bond-slip results of the tested GFRP bars

Table 3– Numerical versus experimental results of GFRP-RC beams

List of Figures:

Fig.1– 3D model of the GFRP-RC beam

Fig.2– Stability of the solution – Hourglass Energy

Fig.3– Numerical stress-strain curve for GFRP reinforcement bar

Fig.4– Bond-slip test of the GFRP-RC specimens (Dimensions in mm. 1 mm = 0.0394 inch)

Fig.5– Failure mode of balanced GFRP-RC beam (Beam A1)

Fig.6– Damage profile of over-reinforced GFRP-RC beam (Beam A2)

Fig.7– Midspan deflection-time curves: (a) Beam A2 (b) Beam A3 (c) Beam B2 (d) Beam B3

Fig.8– Dynamic strain-time curve at the midspan of GFRP bar (Beam A3)

Fig.9– Numerical and experimental forces (Beam B2): (a) Impact (b) Reaction

Fig.10– Influence of reinforcement ratio on: (a) maximum midspan deflection (b) maximum dynamic strain (c) maximum reaction force

Fig.11– Crack profile of beams with constant impact energy at different stages of impact

Table 1– Properties of the GFRP and steel reinforcement used in the experiment (Goldston et al¹¹)

Type of reinforcement bar	Diameter of the reinforcement bar (mm)	Modulus of elasticity E_f (GPa)	Tensile strength f_u (MPa)	Rupture strain (%)
GFRP	6.35	37.5	732	1.96
GFRP	9.53	55.6	1764	3.18
GFRP	12.7	48.6	1605	3.30
Steel	4	200	500	N/A

Note: 1 mm = 0.0394 inch, 1 MPa = 145 psi, 1 GPa = 145 ksi, The fiber volume fraction of GFRP bars was 70%

Table 2– Bond-slip results of the tested GFRP bars

Sample tested	1	2	3	4
Bar diameter (mm)	9.53		12.7	
Maximum bond stress (MPa)	39.87	37.02	29.02	33.57
Slip at maximum stress (mm)	0.18	0.10	0.11	0.11
Exponential decay	0.12	0.10	0.14	0.16
Average bond stress (MPa)	38.45		31.3	
Average slip (mm)	0.14		0.11	
Average exponential decay	0.11		0.15	

Note: 1 mm = 0.0394 inch, 1 MPa = 145 psi

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Table 3– Numerical versus experimental results of GFRP-RC beams

Beam name	Numerical				Experimental				Numerical/Experimental			
	Δ_m (mm)	ε_{frp}	J_I (N.sec)	J_R (N.sec)	Δ_m	ε_{frp}	J_I (N.sec)	J_R (N.sec)	Δ_m	ε_{frp}	J_I	J_R
A2	59.1	0.99	964	911	57.5	0.96	901	799	1.03	1.03	1.07	1.14
A3	53.3	0.74	952	898	52.3	0.73	914	872	1.02	1.01	1.04	1.03
B2	52.8	0.96	901	865	51.6	0.96	847	833	1.02	1	1.06	1.04
B3	46.8	0.71	976	927	43.8	0.68	931	874	1.07	1.04	1.05	1.06

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* Δ_m : maximum midspan deflection, ε_{frp} : dynamic strain in the GFRP bars, J_I : area under the impact force, J_R : area under the reaction force. Note: 1 mm = 0.0394 inch, 1 N = 0.225 lb

Fig.1– 3D model of the GFRP-RC beam

Fig.2– Stability of the solution – Hourglass energy

673

Fig.3– Numerical stress-strain curve for GFRP reinforcement bar

674

Fig.4– Bond-slip test of the GFRP-RC specimens (Dimensions in mm. 1 mm = 0.0394 inch)

676

Fig.5– Failure mode of balanced GFRP-RC beam (Beam A1)

678

Fig.6– Damage profile of over-reinforced GFRP-RC beam (Beam A2)

Fig.7– Midspan deflection-time curves:(a) Beam A2 (b) Beam A3 (c) Beam B2 (d) Beam B3

Fig.8– Dynamic strain-time curve at the midspan of GFRP bar (Beam A3)

(a)

(b)

Fig.9– Numerical and experimental forces (Beam B2): (a) Impact (b) Reaction

(a)

(b)

(c)

Fig.10– Influence of reinforcement ratio on: (a) maximum midspan deflection (b) maximum dynamic strain (c) maximum reaction force (impact velocity = 5 m/s)

Fig.11– Crack profile of beams impacted with a constant impact energy at 5 ms and 20 ms (a) 4.08 m/s (13.4 ft/s) and 600 kg (1323 lbs) (b) 7.07 m/s (23.2 ft/s) and 200 kg (441 lbs)