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Experimental and numerical investigation of CFRP strengthened steel beams under impact load

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Abstract

Use of carbon fibre reinforced polymer (CFRP) strengthening of structural elements has been gaining increased traction over the past few years. Although some research has been carried out on the behaviour of CFRP strengthened steelwork under static and fatigue loads, no single study exists which experimentally captures the response of CFRP strengthened steel beams under impact load. In the present study, a series of tests was conducted to gain insight into the effect of impact load on such beams. The parameters examined in the experiments were namely the thickness and length of the CFRP layers. The impact test was performed by dropping a 91 kg impactor with a velocity of 4.43 m/sec. A finite element analysis (FEA) model was developed in which the bond between CFRP and steel, strain rate effects for steel, and failure of both CFRP and adhesive material were included. Comparing the test data with corresponding FE results confirmed a high level of accuracy of the predicted results. A series of detailed analyses on the impact behaviour of CFRP strengthened steel beams was performed using the validated FE model to provide further insight.

Keywords: carbon fibre reinforced polymer, impact, steel beams, finite element analysis

Introduction

The FRP strengthening technique has been increasingly adopted in the structural enhancement of steelwork as a result of FRP's highly favourable characteristics. Since 1997 when the first early steel highway bridge (Slattocks Canal Bridge, UK) was strengthened with CFRP plates (Hollaway and Teng, 2008), the use of this technique has increased in civil engineering infrastructure with notable examples including Ashton Bridge, USA and Bridge MR46A at North Harrow, UK. A large body of research on CFRP strengthened steel members under various load conditions has been undertaken in the last few years (Colombi and Poggi, 2006, Deng and Lee, 2007). Additionally, in some of this research, design guidelines for CFRP strengthened steel members under static loads have been proposed (Haedir and Zhao, 2011, Moy, 2001, Schnerch, et al., 2007). One important load condition that should also be considered in design situations is impact load which can be caused by several kinds of events such vehicular or ship collisions, debris etc.

Several studies have been aimed at investigating the effect of impact load on FRP strengthened steel members. Among these studies, Al-Zubaidy, et al. (2012) tested a series of CFRP sheet /steel double strap joints at various dynamic (3.35, 4.43 and 5 m/sec) and quasi-static (3.34×10^5 m/sec) tensile loading speeds. These types of joints are often utilised to investigate the bond between steel plates and CFRP sheets (Zhao and Zhang, 2007). Double strap joints are made of two steel plates and one (or more) CFRP ply on each side of the joint. It was found that the bond strength of double strap joints achieved greater increases under impact loading compared to the quasi-static loading rate. Similarly, the bond strength of CFRP plate/steel double strap joints has also been investigated for the same quasi-static and dynamic tensile loading rates mentioned above (Al-Mosawe, et al., 2016). The tests results showed a significant increase in the load-carrying capacity for the joints tested under high loading rates compared to those tested under quasi-static loading. The above two groups of studies showed that the bond strength between CFRP and steel which is the weak point in the case of CFRP strengthened members was improved under higher loading rates. This conclusion was the motivation to study the use of the CFRP strengthening technique in the enhancement of steel structural members vulnerable to impact load.

To date a few numerical studies have been successfully carried out on the dynamic behaviour of CFRP strengthened steel beams. Kadhim, et al. (2017) numerically analysed the performance of CFRP strengthened I-section steel beams under impact loads using ANSYS.

It was found that the use of CFRP can reduce the beam deflection by more than 11% compared to the un-strengthened case. In addition, the effect of impact load has also been studied for CFRP strengthened steel columns with various pre-compression load values, CFRP configurations etc.(Alam and Fawzia, 2015, Kadhim, et al., 2017). However, in all of the above studies no physical test has been undertaken. Thus, it is important to experimentally investigate the behaviour of CFRP strengthened steel beams subjected to impact load.

In the present study, a total of five specimens were tested under impact load using a purpose-built test rig. Various CFRP thicknesses and lengths were investigated. The results from the experimental tests were then used to validate a numerical model which in turn was used to investigate the behaviour of the specimens in more detail. Using the validated numerical model a range of CFRP thicknesses was investigated including 1.2, 2.4, 3.6 and 4.8 mm. In addition, the effect of CFRP length (while maintaining constant overall CFRP volume) was further investigated to find the optimum CFRP distribution. Finally, the effect of varying the impact energy generated by two velocities (4.43 and 6.26 m/sec) and masses (91 and 182 kg) was examined numerically.

Description of the experimental work

In this research, a total of four specimens strengthened with CFRP and one unstrengthened specimen were prepared and tested under a constant kinetic energy. The kinetic energy was derived from a 91 kg mass dropped from a 1.0 m height. There are two reasons for designing the purpose-built test rig (see Figure 1): to hold the specimens with certain boundary conditions, and to apply a pre-compression axial force. Note that in the current study, no axial pre-compression force was applied across the test series. The boundary conditions of the tested beams can be described as both ends having rotational and translational restraint except at one end which has freedom in axial translation only (see Figure 1). The impact was applied using an indenter made from high strength steel (EN24). The head of the indenter was carefully rounded with a 2 mm radius to avoid local failure in the specimens.

Figure 1: Schematic view of the test rig.

Steel section

The steel beams used in the tests were Grade S355 SHS 40×40×3 (square hollow sections) which have an overall width of 40 mm and wall thickness of 3 mm. The yield stress and ultimate strength were obtained through tensile coupon tests. An average yield stress of 538 MPa and an ultimate strength of 611 MPa were obtained from the tensile tests with an average Young's modulus of 185 GPa.

CFRP laminates

Coupon specimens from the unidirectional CFRP sheets were prepared and tested according to ASTM3039 (ASTM, 2000) to find their tensile mechanical properties. The ultimate tensile strength, strain to failure and elastic modulus along the fibre direction were 1397.8 MPa, 0.01404 and 105.3 GPa respectively.

Araldite 420 adhesive

Araldite 420 epoxy is a two-part epoxy with 7 days curing time under 25°C. The manufacturer reported that the tensile strength, strain at fracture and modulus of elasticity are 29 MPa, 4.6% and 1495 MPa respectively (Huntsman, 2009). In addition, the manufacturer declared the shear strength of the adhesive material as 27.5 MPa and shear modulus as 730 MPa.

Specimens dimensions and preparation procedure

Each specimen was 850 mm in length and cut from a 4.2m long section. Two end plates (140×140×12mm) were carefully welded to the ends of the specimens. Four holes had been drilled on these plates prior to welding to allow the specimens to be bolted to the test rig. The control steel beam was cleaned carefully and 6 strain gauges were affixed to its surface as shown in Figure 2. The CFRP strengthened beams were prepared according to the recommendations of the adhesive material manufacturer (Huntsman, 2009). The first step in this procedure is to wipe the steel surface with acetone to remove contaminants on the surface such as grease and oil. Mechanical abrasion is then usually employed to remove the weak oxide layer and to roughen the surface for good adhesion. Next, the abraded surface is cleaned with acetone to remove any grease or oil before applying the CFRP layer. At this stage, several post-yield strain gauges were affixed at certain locations as shown in Figure 2. In this research, a wet lay-up technique (Al-Zubaidy, et al., 2012) was used to fabricate the CFRP strengthened steel specimens by bonding unidirectional carbon fibre sheet oriented in the beam's longitudinal direction. Two layers of CFRP were cut to the designed lengths and a constant thickness of 32 mm. The CFRP layers were bonded to the lower face of the beams. These layers are then wiped with acetone to remove dust. A layer of Araldite 420 was applied to the steel surface using a brush. Efforts were made to ensure a uniform thickness of adhesive layer on all specimens. However, a 100% uniform adhesive layer thickness is impossible to achieve in practice by using the wet lay-up technique. It was found that the average thickness of the adhesive layer was 0.88 mm with a deviation of ± 0.2 mm along the specimen length. This was followed by saturating a ply of carbon fibre sheet with the adhesive material using a brush before applying the saturated layer onto the adhesive-steel surface (Al-Zubaidy, et al., 2012). The same procedure was then used to add the rest of the layers. The specimens were cured at room temperature for at least 1 week as per the resin manufacturer's instructions. The 5 mm strain gauges were finally mounted on the CFRP

surface as shown in Figure 2. Note that six strain gauges were also affixed to the strengthened beams having 800 mm length (B1 and B4) these being G1-G3 and CG2, CG4 and CG6 as shown in Figure 2, while for beams (B2 and B3) the strain gauges G1-G3 and CG2 and CG4 only were attached to these specimens. The beam identification details are summarised in Table 1.

Figure 2: Strain gauge positions.

In addition to the six strain gauges affixed to each beam, a 650kN capacity Kistler load cell was positioned in the test rig between two steel plates under pre-compression (around 40kN) to reduce the effect of vibration on the load cell. This load cell was used to measure the transverse impact force during the tests. Displacement versus time was measured using a digital video camera operating at 240 frames/sec. Finally, the data for the impact tests was recorded depending on the triggering of the laser sensor that was positioned above the specimen with a specific distance. Once the impactor passes through this sensor, all other sensors (the strain gauges and the load cell) start recording the data. It should be mentioned that the overall recorded time was 0.05257 sec with one reading taken every 0.000001 sec. This means that the total amount of recorded data for every sensor comprised more than 52570 readings. This short recording interval (0.000001 sec) was used to enable obtaining data with a high level of accuracy.

Table 1: Specimen Identification and key results

Specimen	CFRP thickness (mm)	CFRP length (mm)	Plateau value (kN)		Impact duration (sec)	
			Experimental	Numerical	Experimental	Numerical
C0	-	-	24.6	25.1	0.0285	0.0256
B1	1.2	800	25.9	26.2	0.0276	0.0243
B2	1.2	600	24.9	25.7	0.0279	0.0251

B3	1.2	400	25.6	25.7	0.0256	0.0250
B4	2.4	800	26.5	26.7	0.0275	0.0240

Finite element modelling

ABAQUS 6.13 software was used to numerically investigate the impact behaviour of the CFRP strengthened steel beams. The steel beam was modelled using linear three-dimensional four-node shell elements with reduced integration and membrane strain (S4R). Similarly the same type of element was used to model the CFRP layer. This kind of element is commonly used to model CFRP layers (Alam and Fawzia, 2015, Fernando, et al., 2009). While this type of element has some limitations, namely an inability to capture through-the-thickness shear stress or CFRP delamination, it should be noted that CFRP delamination did not occur in the current experiments. The adhesive layer is meshed with 8-node three-dimensional cohesive elements (COH3D8), while the other part such as the impactor and the striking system (including load cell) were modelled by 8-node three-dimensional elements with reduced integration and hourglass control (C3D8R). The typical geometrical modelling is plotted in Figure 3. It can be seen from this figure the exact positions over which the boundary conditions were applied. In addition, the density of the impactor was adjusted to achieve a specific mass. The impact velocity was imposed using the PREDEFINED FIELD option available in ABAQUS.

Classical metal plasticity available in ABAQUS/Explicit was used for the steel section to define the strain hardening using input data from the tensile coupon tests. The strain-rate has significant effects on the behaviour of steel material under impact load (Jones, 1997), while for the CFRP material many studies have shown that the CFRP material may be insensitive to strain rates ranged between 10^{-4} and 100 sec^{-1} (Hallett and Ruiz, 1997, Taniguchi, et al., 2007). Thus, the strain rate effect was only applied to the steel using the well-known Cowper-Symonds model (Jones, 1997) as listed in equation (1).

$$\sigma_o' = \sigma_o \left(1 + \left(\frac{\dot{\epsilon}}{D} \right)^{\frac{1}{q}} \right) \quad (1)$$

Figure 3: Typical numerical model schematic.

Where σ_0' is the dynamic flow stress at a uniaxial plastic strain rate $\dot{\epsilon}$, σ_0 is the associated static flow stress and D and q are constants for a given material. The values of these constants are 40.4 sec^{-1} and 5 respectively for mild steel (Jones, 1997). It should be mentioned that since no material failure occurred in the steel section during all experiments, no material failure model for steel was adopted.

The general behaviour of the unidirectional CFRP sheet can be characterised as elastic and brittle. Among the available material models ABAQUS/Explicit offers a damage model which is able to predict the initiation of damage and model damage evolution for elastic-brittle materials with anisotropic behaviour, therefore this model is mainly intended to be employed with CFRP. The modelling of CFRP will proceed in two stages. In the first stage, the linear elastic response of unidirectional CFRP is defined by using a lamina model in which the material properties should be specified in a local coordinate system. Afterwards, the damage initiation criterion and damage evolution are defined using Hashin's failure criteria which can be used to model the failure of fibre-reinforced composites (Hashin, 1980). The main inputs for the elastic response and Hashin's failure criteria were listed in Table 2.

Table 2: Material properties of the CFRP sheet

Property	Value
Density*	1600 kg/m^3
E1 Elastic modulus in the longitudinal direction	105.3 GPa
E2 Elastic modulus in the transverse direction*	17 GPa
G12 In-plane shear modulus*	6 GPa
X^T Longitudinal tensile strength	1397.8 MPa

X^C Longitudinal compressive strength*	1200 MPa
Y^T Transverse tensile strength*	50 MPa
Y^C Transverse compressive strength*	250 MPa
S^L Longitudinal shear strength*	70 MPa

*material properties were obtained from Dolce (2009)

The traction-separation model is most commonly used for the modelling of the adhesive material in the case of CFRP strengthened concrete members and steel members under static and impact loads (Al-Mosawe, et al., 2016, Al-Mosawe, et al., 2016, Al-Zubaidy, et al., 2013, Fernando, 2010). In General, the adhesive material modelling comprises two stages including linear elastic response and progressive damage modelling. The first part represents the linear stage in which the stress increases as separation increases until the damage initiation criterion is reached when the second stage starts. The quadratic nominal stress criterion is commonly used as a damage initiation criterion by researchers who studied the behaviour of CFRP/steel joints such as (Al-Mosawe, et al., 2016) because the failure of the adhesive material seems to be subjected to a complex state of stress (peeling and shear stresses) and these stresses contribute to the adhesive failure (Al-Zubaidy, et al., 2013). The following quadratic strength criterion is adopted in the current study (SIMULIA, 2013):

$$\left(\frac{\langle t_n \rangle}{t_n^o} \right)^2 + \left(\frac{\langle t_s \rangle}{t_s^o} \right)^2 + \left(\frac{\langle t_t \rangle}{t_t^o} \right)^2 = 1 \quad (2)$$

Where t_n, t_s and t_t refer to the stresses in the three directions of the adhesive layer (normal, first and second shear directions), t_n^o, t_s^o and t_t^o denote the peak value of the nominal stresses in the three directions of the adhesive material (normal, first and second shear directions). The negative quantity within the Macaulay bracket $\langle \rangle$ is equal to zero, signifying that a pure compressive stress state does not contribute to damage. After the damage initiation criterion is met, the damage degradation then starts to affect the traction-separation model. The inputs of the adhesive material were mainly dependent on the data that was presented in the previous section including the thickness of adhesive material which was 0.88 mm.

Using the TIE constraint option in ABAQUS, the adhesive layer was tied to CFRP on one side and to steel on the other side. This tie constraint was used to prevent parts from sliding out and ensures that the tension load transfers from one layer to another (Al-Mosawe, et al., 2016).

The authors carried out a mesh sensitivity study to ensure that accurate results from ABAQUS/Explicit was obtained. In this study, it was found for the steel section that the mesh size along the beam length of 5 mm and impact zone of 1.5mm provided reasonable results in comparison to finer mesh sizes with a divergence of less than 1%. For CFRP and adhesive material, using a 5mm mesh size was found to have a sufficient accuracy compared to finer mesh sizes. It should be mentioned that damping was neglected in the current simulation due to its minor effect in the case of impact simulations (Al-Thairy and Wang, 2011, Zeinoddini, et al., 2008)

Experimental and finite element results

The results obtained from the FEA were compared to those from the experimental tests. The results will be presented in terms of impact force-time history, displacement time history, residual displacement and strain development.

Impact force-time history

One of the most important datasets recorded during the impact test is the impact force. A typical impact force-time history (as shown in Figure 5) can be divided into three stages, i.e. initial peak stage: in which the force reaches a peak value in a short time when the mid-span of the specimen has reached the velocity of the impactor then the curve descends to zero when the specimen and the impactor are separated. Then, the impactor hits the specimen a second time but with a smaller value. This process of striking and rebounding is repeated several times until the impact force becomes nearly constant when the second stage commences which is referred to henceforth as the plateau stage. In this stage, most of the impact energy is dissipated. In the end of the second stage (plateau stage), the displacement reaches the maximum value. Finally, the curve goes into the unloading stage and reaches zero gradually as the impact energy is dissipated.

The duration from the first contact between the impactor and the specimen until the impact energy is dissipated (the specimen and impactor are separated) is called the impact duration. Generally in these tests, the impact duration is several times longer than the first natural period of the specimen. The natural period of the specimen depends on its equivalent mass and stiffness, while in the case of impact duration, the overall impact period depends on the total mass, which consists of the equivalent mass of the specimen and the impactor together (Zeinoddini, et al., 2002). Since the total mass increases, the overall impact duration becomes

longer than the fundamental natural period of the specimen. For example, the main natural period of the control C0 beam is about 0.0086sec in it's elastic response which dominates the structural deformation until plastic yielding happens, whereas the impact duration was 0.0285 sec (see Table 1). The impact duration for the strengthened beams was normally less than the control beam (C0) as listed in Table 1. As mentioned in this paragraph, the total impact duration depends on the stiffness and total mass (of the specimen and impactor). The reduction in the impact duration is expected to be caused by the increase in the stiffness of the beam as a result of applying CFRP. However, the reduction in the impact duration was not substantial because the amount of CFRP used to strengthen the beams was relatively small.

The plateau value for each specimen was calculated by taking the average impact force during the time after the peak stage until the unloading stage, this is shown schematically in Figure 4.

Figure 4: Schematic representation of loading stages

It can be seen from Table 1 that the plateau value increased by different amounts depending on the CFRP configuration. In particular, the increase in the CFRP thickness layer led to increases in the plateau value, which indicates higher strengthening effectiveness for a thicker CFRP layer. For the different CFRP lengths, the plateau value was reduced by a small amount when using a shorter CFRP length as listed in Table 1. This was thought to be partially caused by the enhancement that was provided by the longer CFRP layer (0.8 m) for the negative moment developed at the ends of the beam. In this case, a degree of membrane

action in the CFRP may be more pronounced in the longer CFRP providing further enhancements to moment capacity.

Figure 5: Comparison of experimental and numerical impact force-time history.

The key results obtained from the experimental and numerical impact force-time history are listed in Table 1 which summarises the plateau force value and the impact duration for both experimental and numerical simulations. In regards to the repeatability of the experimental results, it is important to note the location of measuring points and measurement techniques must be consistent with those in the series presented here, small divergence from this can lead to different resulting impact time series. Note that the location of the impact force

measurement in the numerical modelling was exactly the same as in the experiments as shown in Figure 1 and Figure 3. A graphical comparison of the impact force histories is shown in Figure 5. This comparison showed that very good agreement is obtained between the impact force obtained from the experimental and numerical results. However, the impact duration gained from the numerical simulation was slightly less than that obtained from the tests. The impact duration of the simulated specimens was found to be a maximum of $\sim 13\%$ less than the corresponding value obtained from the experimental results. The variation might be related to the differences of the fixity in the tests and simulation. The damping force introduced by the experimental test rig might also be another reason for this variation. However, the variation was not found to be significant in the current simulation. This difference between the impact duration values obtained from experimental and numerical results was also observed in other studies when a similar test procedure was used. For instance, the maximum variation between the numerical and experimental impact duration was found by (Zeinoddini, et al., 2008) to be about 26%.

Transverse displacement-time history

The transverse displacement-time histories for the beams were plotted in Figure 6. It can be seen from this figure that the strengthened specimens usually have a transverse displacement less than the unstrengthened beams with different values depending on the thickness of the CFRP layer. The reduction in the maximum value of the transverse displacement was about 10% and 13.7% for the beams strengthened with 1.2 mm and 2.4 mm respectively. It should be mentioned here that the transverse displacement was measured at the impact zone on the top surface.

The comparison of the transverse displacement-time histories for the beams is shown in Figure 6 from which it can be concluded that the numerical model was able to capture the transverse displacement with a maximum divergence less than 2% when the maximum transverse displacements were compared. However, the divergence in prediction of the initial slope of transverse displacement by the numerical model was higher as discussed in the next paragraph. It is presumed that the differences in the transverse-displacement-time history are related to the fact that the impact duration obtained from numerical results was usually less than the corresponding experimental test as discussed in the previous section.

The average difference between the transverse displacement obtained from the experimental and numerical results was 22% for specimen C0, while this value was 16% for specimen B2.

This value was calculated for the initial slope of the transverse displacement-time history (from 0 to 0.01 sec). The variation between the accuracy of the numerical model in capturing the transverse displacement-time history for these specimens was caused by the sharp slope in the curve in the first 0.004 sec of the impact test for the unstrengthened specimen (C0). This initial aggressive transverse displacement in specimen C0 may be caused by a small bedding-in movement in the test-rig itself since this was the first specimen to be tested in the experimental series. While in the numerical model, perfect fixity at the boundary conditions is invoked. Note that there is no displacement data available for specimens B1 and B3 due to unavoidable malfunction of the camera.

Figure 6: Comparison of experimental and numerical transverse displacement-time history.

Residual deformation

The residual deformation was measured for all tested specimens using a linear variable displacement transducer (LVDT) with ± 0.001 mm accuracy. It should be noted that all residual deformations are referred to here as the final permanent deflection after impact. The deformed shape was measured along the top and bottom faces of the beams with one reading every 10 mm at mid-span (for 100 mm in the middle) and 100 mm in the rest of the beam. The residual transverse displacement along the top and bottom of the strengthened beams was usually less than the corresponding values of the unstrengthened specimen (C0) (see Figure 7). In fact, the beam strengthened with the thickest CFRP layer (B4) had the lowest residual transverse displacement (in the top and bottom surfaces) compared to others. For example, the reduction in the maximum residual transverse displacement for beam B1 compared to the unstrengthened beam was 18%, while the value was 21% when beam B4 was compared with the unstrengthened beam. In addition, the reduction in the residual maximum transverse

displacement for the beams having 0.6 and 0.4 m CFRP length compared to beam C0 was about 13% in average which was less than the reduction for beams B1 and B4 due to the enhancement mechanism discussed earlier.

(A)

(B)

Figure 7: Transverse residual displacement along the (A) top, (B) bottom surface of the beams.

Failure modes

The failure mode was dominated by CFRP rupture for specimens B2 and B3, while no failure was observed for specimens B1 and B4. The CFRP rupture for both specimens occurred at beam mid-span as shown in Figure 8-A. Although the same CFRP thickness was used for the strengthened specimens B1, B2 and B3 (1.2 mm) while the difference was the length of the CFRP sheet 0.8, 0.6 and 0.4m respectively, CFRP rupture only occurred in specimens B2 and B3 while specimen B1 did not exhibit any sign of failure. The reason for this is that the longer CFRP layer provided an enhancement to the negative moment at the beam ends and a degree of membrane action causing a reduction in the transverse displacement at the beam's

mid-span (as earlier presented), this then led to a reduction in tensile strain in the CFRP layer which will be discussed in the next section. It should be noted that the exact time of CFRP rupture can be captured using the strain gauge affixed on the CFRP (at the beams' mid-span, strain gauge CG2 see Figure 2).

Using Hashin's failure criteria, the numerical model was able to predict the failure in the CFRP patch correctly as shown in Figure 8A. Based on the strain gauge readings, the rupture in the CFRP sheet occurred after 0.0137 sec. Figure 8B reveals that the value for tensile fibre damage initiation criterion reached the maximum allowable value (1.0) after 0.012 sec from the impact. Generally, the comparison between the numerical modelling and test results shows a good level of correlation. In addition, it seems that the numerical model was able to capture the failure in the CFRP correctly although there was a slight difference in the time that the CFRP rupture occurred which may be related to the time lag in the numerical results as discussed in the previous sections.

Figure 8: (A) Failure modes of the beams at mid-span. (B) Tensile fibre damage initiation criterion-time relationship for beam B3 at mid-span.

Strain development

As shown in Figure 2 several strain gauges were mounted to the surface of the beam including both the steel and CFRP surfaces. Figure 9A illustrates that the beam strengthened with a thicker CFRP has the highest strain value in the side face (web) of all the beams (strain gauge G1 is mounted on the beam web as per Figure 2). This reflects the fact that the local

deformation of the side faces (web) of the beam strengthened with a thicker CFRP layer was higher compared to the other strengthened beams. The reason for this is that the CFRP layer was bonded only on the lower face of the beam while the rest of the beam surfaces had no strengthening.

The readings of the strain gauge CG2 mounted on the CFRP at the beams' mid-span showed that the strain value for specimen B4 was less than the other specimens due to the presence of a thicker CFRP layer. The readings of the strain gauges also reflected the time that the CFRP rupture occurred as presented earlier (see Figure 9-B). It is evident from this figure that the CFRP rupture occurred after 0.0133 sec from the time of impact initiation for specimens B2. In addition, this figure shows that the strain in specimen B1 was less than the other specimens strengthened with the same CFRP thickness (B2) because of the ability of the longer CFRP to enhance the beam's ends.

Figure 9: (A) Strain gauge G1 for the CFRP strengthened beams. (B) Comparison of the strain gauge CG2 readings for the strengthened beams (B1, B2, B3 and B4) with the corresponding simulation results.

It can also be seen from this figure that the maximum strain values were predicted by the numerical model with a maximum difference less than 5% compared to the corresponding experimental value apart from beam B4 where the maximum strain value had an 11% divergence in the maximum compared to the corresponding experimental value. Generally,

the comparison of the numerical results shows a good agreement with the corresponding experimental results confirming the reliability of the simulation results.

Parametric study on performance of the CFRP strengthened beams

The experimental programme included only a limited number of CFRP strengthened steel beams tested under impact load, therefore in order to provide a comprehensive conclusion with regard to the behaviour of CFRP strengthened steel beams subjected to impact load, more parameters should be investigated. Consequently, a set of parameters will be considered for the strengthened steel beams. Since only two thicknesses were examined in the experimental tests, additional thicknesses will be investigated numerically. Similarly further variation in impact energy will be examined in the numerical model.

Effect of CFRP thickness

As discussed earlier, in order to have a clear concept of the influence of the CFRP thickness on the impact performance of the strengthened steel beams, several CFRP thicknesses were examined in this section including 3.6 mm and 4.8 mm in addition to the already simulated thicknesses (1.2 mm and 2.4 mm). All beams were simulated under the same boundary conditions and impacted with the same kinetic energy. In addition, the length of CFRP was maintained constant during this investigation.

It can be seen from Figure 10 that the transverse displacement was less for the beams strengthened with a thick CFRP layer. However, the same figure reveals that the thickness of the CFRP layer reduced the maximum transverse displacement in the bottom surface more effectively than the top surface. The reason for this is that the impact load was applied using an indenter with a small head radius which led to the relatively deep indentation in the top surface of the steel section. Nevertheless, bonding CFRP to the bottom surface of the steel section seems to increase the indentation at the top surface as shown in Figure 11. This may be due to the fact that while the overall section stiffness is increased with CFRP strengthening. The top surface remains locally unstrengthened. It should be noted that Figure 11 shows the transverse displacement in the impact region (with point of impact in the centre) over a length of 30mm, the values are shown relative to the ends of the zone.

Figure 10: The reduction in the maximum transverse displacement against CFRP thickness for the top and bottom surfaces compared with unstrengthened specimen.

Figure 11: Transverse displacement along beam length (top surface, centreline) measured from the fixed end, time=0.027 sec.

Due to the increase in the thickness of the CFRP layer, the value for the quadratic damage initiation criterion developed in the adhesive layer slightly increased as shown in Figure 12. This occurred because the increase in the CFRP thickness raised the interfacial shear stress in the adhesive material due to the stiffness imbalance between the adherents i.e. CFRP and steel (Wu, et al., 2012) that consequently caused an increase in the damage initiation criterion value in the adhesive material. This observation seems to be consistent with other existing

research, which revealed that the interfacial shear stress in the adhesive material is partially dependent on the thickness and elastic modulus of adhesive material (Wu, et al., 2012, Yuan, et al., 2004)

Figure 12: Damage initiation criterion along adhesive material (measured from the fixed end) after 0.027 sec of impact.

Effect of CFRP distribution

The quantity i.e. total volume of the CFRP is kept constant in this section, while the change is made to the thickness and length of the CFRP layer to find the optimum distribution of the CFRP. Since the beam has rotational fixity at both ends, a significant role is expected for the CFRP to resist the negative moments. However, this section is aimed at finding the most appropriate distribution of the CFRP to provide the maximum transverse displacement reduction which can be achieved either by reducing the CFRP length and increasing its thickness or vice versa.

The beam strengthened with CFRP having 1.2mm thickness and 0.8 m length has been chosen in this section to investigate any additional enhancement that can be achieved by redistributing the CFRP quantity. Three more CFRP lengths were examined including 0.6, 0.4 and 0.2m corresponding to a CFRP thickness of 1.6, 2.4 and 4.8 mm respectively to maintain constant volume as shown in Figure 13. In order to verify the best CFRP distribution, two impact energy values have been chosen which are 892.7 and 1785.4J, corresponding to the scenarios of using a 91 kg mass dropping from 1 and 2m respectively.

Figure 13: CFRP distribution

It can be seen from Figure 14A that the transverse displacement of the beams strengthened with CFRP having the same quantity but different lengths and thicknesses was slightly different for the beams struck with 892.7J impact energy. This figure illustrates that the beam strengthened with the 4.8 mm CFRP (length =0.2m) had the minimum reduction in the transverse displacement compared to the unstrengthened beam because of the debonding that occurred at one end of the CFRP layer and for both impact energies as shown in Figure 15. However, it was expected that debonding would occur in the case of the 0.2m CFRP length because the bond length was likely to be insufficient to fully mobilise the CFRP, i.e. the effective bond length was not achieved. Some studies conducted on quasi-static loading rates have revealed that generally the average effective bond length for normal modulus CFRP bonded using the same adhesive material (Araldite 420) is around 110mm (Al-Mosawe, et al., 2016, Xia and Teng, 2005).

Concerning the second impact energy, Figure 14-B reveals that the beam strengthened with the 2.4mm CFRP had the maximum reduction in the transverse displacement compared to

other strengthening schemes. However, all other strengthened beams exhibited either a CFRP rupture (1.2 and 1.6mm thickness) or a debonding (4.8mm thickness).

Figure 14: Transverse displacement histories for the beams strengthened with CFRP having various lengths and thicknesses under two different impact energies.

Figure 15: Beam strengthened with the 4.8mm CFRP (Impact energy= 892.7J).

Comparing the internal energy dissipated by the CFRP layer demonstrates that the average energy dissipated by the CFRP represented about 5% of the energy dissipated by the steel section. However, it can be seen from Figure 16 that the distribution of the CFRP had a significant influence on the CFRP and adhesive material dissipated energy which reflects the strengthening effectiveness of the CFRP. This figure also indicates the exact time of CFRP debonding or rupture. For instance, the beams strengthened with the 4.8mm CFRP exhibited CFRP debonding but at different times i.e. 0.0065 and 0.0037 sec after the impact for an impact energy of 892.7 and 1785.4 J respectively. The reason for this variation is related to

the fact that the higher impact energy caused an earlier debonding due to the limitation of the adhesive material's strength.

Figure 16: Energy absorbed by the CFRP and adhesive material for the beams strengthened with CFRP having various lengths and thicknesses and for two different impact energy values.

Effect of Impact energy

The experimental programme established for the CFRP strengthened steel beams included using only one impact energy for all the beams. Thus, here an additional impact energy is investigated, this being 1785J generated by either a 91kg mass and 6.26 m/sec velocity or an 182kg mass and 4.43 m/sec velocity. The change in impact energy components is chosen to investigate whether the use of impact energy without the need for specifying its components is appropriate to define the impact events or if for the same impact energy the components play significant roles. Two different CFRP thicknesses were used in this section including 2.4 and 4.8mm, while the length of the CFRP was kept at 0.8m for all the simulations in this section.

Table 3: Maximum transverse displacement and the reduction in the transverse displacement for the CFRP strengthened steel beams under various impact energy values.

Impact energy	Maximum transverse displacement (mm)/ reduction in the maximum transverse displacement compared to unstrengthened beams (%)					
	Unstrengthened		CFRP thickness= 2.4 mm		CFRP thickness= 4.8 mm	
	Top	Bottom	Top	Bottom	Top	Bottom
Mass=91 kg, velocity =4.43 m/sec	28.18	24.60	25.23/ 10.5	21.90/ 11.0	24.49/ 13.1	21.00/ 14.6
Mass=91 kg, velocity =6.26 m/sec	48.40	43.14	43.98/ 9.1	37.89/ 12.2	42.89/ 11.4	36.64/ 15.1
Mass=182 kg, velocity =4.43 m/sec	53.04	47.24	48.72/ 8.2	42.22/ 10.6	46.77/ 11.8	39.83/ 15.7

Table 3 summarises the maximum transverse displacement for the strengthened and unstrengthened beams under various impact energies in addition to the reduction in maximum transverse displacement of the strengthened beams compared to unstrengthened beams. This table demonstrates that the reduction in the maximum transverse displacement measured in the bottom surface increased when applying higher impact energy. However, the beam strengthened with the 2.4 mm CFRP exhibited a different behaviour under the impact energy generated by a 182 kg mass and 4.43 m/sec velocity (the third energy in Table 3) because of the rupture of the CFRP layer. The same beam under the same impact energy with different components (the second energy in Table 3) did not show failure in the CFRP sheet due to the effect of the strain rate for the steel material. For example, the average strain rate (measured at the beams' mid-span) for the beam struck with an impactor having a 91 kg mass with velocity of 6.26 m/sec was around 45% more than the corresponding value of the beam struck with the same impact energy with different components (mass= 182 kg and velocity= 4.43 m/sec). It is well known that the flow stress for the steel is normally increased when the strain rate is increased. Therefore, the transverse displacement value is expected to be smaller for a member having a high strain rate compared to the same member when the strain rate is lower.

Although there is an increase in the effectiveness of the CFRP under higher impact energy when comparing the maximum transverse displacement for the bottom surface, nearly the opposite trend is observed when comparing the maximum transverse displacement for the top surface. The reason for this is the increase in the indentation as a result of strengthening the bottom surface only as discussed earlier. In general, it is found that the strengthening

effectiveness is increased with higher applied energy. This is thought to be caused mainly by increasing the plastic deformation in the impacted beam. It is well known that the elastic modulus of both materials (steel and CFRP) are relatively comparable in magnitude. However, when steel sections undergo severe plastic deformation the tangent modulus of steel becomes small compared to the elastic modulus of CFRP, therefore, the role of CFRP becomes more significant. For example, on average the tangent modulus for the steel grade used in the study is about 1GPa while the elastic modulus of CFRP is 105.3GPa.

Conclusions

This paper is aimed at investigating the behaviour of CFRP strengthened steel beams subjected to impact load. Initially a series of experimental tests was conducted for CFRP strengthened steel beams, a numerical model was then validated against the experimental results and used to carry out a parametric study to gain further insight. The following conclusions can be drawn from this investigation:

1. For the beam series examined, the CFRP strengthening technique showed a good performance in enhancing the steel beam against impact loads. It was found that using a 1.2 and 2.4 mm CFRP layer could reduce the maximum transverse displacement by around 10% and 14% respectively.
2. It has been found that the impact force plateau value was increased when using a thicker CFRP layer while using a shorter CFRP layer caused a reduction in the plateau value for same CFRP thickness. A similar observation can be found in terms of the transverse displacement-time history and the residual transverse displacement.
3. The numerical model showed an excellent agreement with the experimental results including impact force history, transverse displacement, failure modes and strain development. This underlines the validity of the model and the subsequent parametric studies.
4. Using a thicker CFRP layer can increase the effectiveness of the CFRP in strengthening the steel beams. In particular, using a 4.8 mm CFRP thickness layer instead of 1.2 mm nearly doubled the reduction in the maximum transverse displacement.
5. The distribution of the CFRP quantity (thickness and length) plays a significant role for an effective strengthening design.
6. In changing the impact energy, the internal energy absorbed by the composite patch was increased accordingly.

Further research may be required to expand the current study by adopting different cross-section dimensions and/or shape of the cross-section. In addition, the effectiveness of CFRP in preventing the failure of steel beams may be further investigated.

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