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Modelling Impact Resistance of Polymer Laminated Steelwork

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ABSTRACT

This paper reports the numerical simulation of a series of carbon fibre reinforced polymer (CFRP) strengthened steel beams under impact loads. Non-linear finite element (FE) analysis is conducted using a proposed FE model validated via comparison with available experimental tests. The numerical model includes the effect of the strain rate for steel using the Johnson-Cook model, while for CFRP and adhesive materials the Cowper-Symonds model is employed. Several possible failure modes for the strengthened member can be captured using the FE model such as global steel failure, CFRP rupture and debonding between steel members and CFRP laminates. The numerical results show that the use of externally bonded CFRP laminates decreases mid-span deflection of strengthened beams in the series by 11%. While having the same level of impact kinetic energy, it is found that a beam struck at a lesser velocity and with a larger mass of impactor tends to have higher deflection both for the strengthened and un-strengthened cases. Additional key parameters such as CFRP laminate thickness are also investigated in this study.

Keywords:

Composite Structures, Dynamics, Steel Structures

1. Introduction

In today's built environment, strengthening of existing steel structures is often necessary to extend service life. The need for strengthening may be the result of one or a combination of several issues including deterioration due to aging, changes in use and associated load regimes, increased environmental loads due to climate change, blast resilience etc. External bonding with carbon fibre reinforced polymers (CFRP) can be a convenient means of strengthening existing members and has advantages over traditional strengthening using steel plate, most notably superior durability and lesser density. In view of this, several studies have been conducted on the behaviour of CFRP strengthened steel members under static load such as (Colombi and Poggi, 2006, Linghoff et al., 2010, Linghoff and Al-Emrani, 2010, Hmidan et al., 2011) and under cyclic loads (Tavakkolizadeh and Saadatmanesh, 2003, Kim and

Harries, 2011, Jiao et al., 2012). Similarly, the behaviour of CFRP strengthened aluminium beams subjected to transverse blast load was examined in a number of recent studies (Bambach et al., 2010, Bambach, 2014). All these studies found CFRP composite to be a promising material for strengthening and repairing metallic members in civil engineering applications.

In many cases, the need for strengthening may be in response to damage from impact loads. Impact loads such as those arising from flood debris, rock-falls, vehicle strikes etc. have been reported as being among the major causes of bridge collapse around the world (Imam and Chryssanthopoulos, 2010). In response to this, the influence of impact on CFRP strengthened steel members has been the subject of attention by researchers since at least 2012 when Al-Zubaidy et al. (2012b, 2012a, 2013a, 2013b) studied the effect of impact on the behaviour of the bond between CFRP and steel plates by testing a total of 160 CFRP/steel double strap joints. Several parameters were investigated such as the number of CFRP layers, length of CFRP layer and loading rates. It was found that adhesive material failure and steel/adhesive material debonding are one of the major reasons for joint failure. However, in the aforementioned studies by Al-Zubaidy et al, impact load on whole structural members such as beams and columns was not investigated. Subsequently, Alam and Fawzia (2015) presented a numerical study on the behaviour of CFRP strengthened square hollow section (SHS) steel columns under transverse impact using the finite element programme ABAQUS. The effect of boundary conditions, level of axial loading and CFRP thickness were also studied. In this work, the authors adopted full bond between steel members and CFRP materials. A significant improvement of behaviour of strengthened columns was observed, minimising the lateral displacement at the impact region by about 58% compared to the unstrengthened columns by applying a CFRP layer to every face of the column.

Prior to the above, many researchers have carried out investigations on the behaviour of unstrengthened steel members subjected to impact loads. For instance, Bambach et al. (2008), Huo et al. (2011) tested fully clamped hollow square sections and simply supported I-sections under a dropped mass respectively. Al-Thairy (2012) and Pei and Wang (2012) studied the effect of impact loads on structural members using the finite element method (FEM) and found the models capable of simulating the behaviour of steel members under impact loads.

According to the aforementioned literature review, there is only one readily available study that has been carried out the numerical modelling of CFRP strengthened steel structural

members under impact, this was conducted by Alam and Fawzia (2015). However, in their study, the scope was limited to the behaviour of CFRP strengthened SHS steel columns under a pre-compression static load. In addition, steel/CFRP debonding was not accounted for in the numerical model. In the present study, the effect of impact loads on CFRP strengthened steel I-section beams have been studied to assess the ability of the strengthened system to enhance impact load performance. Potential debonding between the steel members and CFRP laminates and strain rate effects have been included. A proposed numerical model built using the finite element programme ANSYS (ANSYS, 2013) has been validated using available experimental results from the literature; Colombi and Poggi (2006) and Huo et al. (2011). Then, simulation of CFRP-strengthened steel members is carried out using the proposed numerical model. A number of parametric studies are investigated such as the effect of impact location, CFRP layer length and level of impact energy.

2. Finite element model validation

2.1. Model description

2.1.1. Element types

The FE software package ANSYS 14.5 has various types of elements. Three element types are adopted to represent steel, CFRP and adhesive materials. Three dimensional brick elements, which according the ANSYS terminology have eight nodes having nine degrees of freedom (velocities, accelerations, and translations in x, y and z) are used to model the steel, CFRP and adhesive materials (ANSYS, 2013). (It should be noted that in static simulation, each node in an eight-node brick element has only three degrees-of- freedom, namely, translations in x, y and z directions). A reduced integration technique with hourglass control was used in this model. The idea behind this method is to add stiffness, which resists hourglass modes but not rigid body motions and linear deformation fields. The contact regions between steel/CFRP and CFRP/adhesive material are simulated using two element types (TARGE170 and CONTA174) to define the target and contact surfaces, respectively, as shown in Fig. 1. The contact elements (CONTA174) overlay the solid elements characterising the boundary of a deformable body and are in contact with the target surface, defined by TARGE170.

The target surface can be a rigid or deformable body. In the case of rigid-flexible contact, the rigid surface must be represented by a target surface. For flexible-flexible contact, the softer

surface should be the contact surface and the stiffer surface should be the target surface. In this study, the damping effect is neglected because it has no clear influence on structural behaviour for the studied cases. This can be attributed to the short duration of the impact compared to the natural period of the structural system (Jones, 1997, Al-Thairy, 2012).

Fig. 1. The locations of the contact elements in the proposed model.

2.1.2. Material models

a) Steel

The modelling of the steel includes the effect of both strain hardening and strain rate. The Johnson-Cook model is chosen in this study because the effects of strain hardening, strain-rate and thermal softening can be included (Johnson and Cook, 1985). Many studies have shown that the Johnson-Cook model provides accurate predictions for steel structure behaviour under impact and blast loading (Dey et al., 2007, Chung and Nurick, 2005). The general equation for the Johnson-Cook model is presented as

$$\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T^{*m}) \quad (1)$$

The first set of brackets provides the strain-hardening effect, while the second and third sets of brackets represent the effect of strain rate and temperature. Where ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1.0 \text{ s}^{-1}$, (A , B , n , C , and m) are material constants (as listed in Table 3) and T^* is the homologous temperature and is defined as

$$T^* = \frac{T - T_r}{T_m - T_r} \quad (2)$$

where T_m is the melting point, T_r is a reference temperature at which σ_r , a reference equivalent stress, is measured (usually T_r is room temperature) and T is the temperature at

which σ is calculated. The maximum equivalent plastic strain failure is used to capture the failure in the steel material.

b) CFRP material

The general behaviour of the unidirectional CFRP can be characterised as an elastic-brittle material (Al-Zubaidy et al., 2013b). The failure criterion that has been employed to capture rupture in the CFRP material is a maximum tensile strain. Since low strain rate (less than 2 s^{-1}) is investigated in this study and based on the findings of a number of studies such as Kimura et al. (2001) which assume that the CFRP unidirectional composite is strain rate insensitive for strain rates between 10^{-5} s^{-1} to 10^2 s^{-1} , the effect of strain rate for CFRP and the adhesive material is neglected at the very beginning of this simulation. However, the implication of this assumption will be investigated in section 4.1 as a parametric study.

c) Contact regions

In explicit dynamic analysis, the failure criterion depends on the stress limit in a contact region. Equation (3) shows the stress limiting criteria for contact elements in explicit dynamic applications (ANSYS, 2013).

$$\left(\frac{\sigma_n}{\sigma_n^{limit}}\right)^\alpha + \left(\frac{|\sigma_s|}{\sigma_s^{limit}}\right)^\beta \leq 1 \quad (3)$$

Where σ_n and σ_s are the normal and shear stresses at the bond location respectively (σ_n =zero if compressive), σ_n^{limit} and σ_s^{limit} are the normal and shear stress limits respectively, and α and β are the exponents of normal and shear stress respectively. The node will be released from bonded contact if the above criterion is exceeded. In this study, the values of α and β are assumed equal to 2 which is similar to the Tresca model under unidirectional stress (Al-Zubaidy et al., 2013b). On the other hand, in the implicit solver, three debonding modes can be used to model the contact region in ANSYS, these being: normal separation, tangential slip and mixed mode where the interface separation depends on both normal and tangential components. In the present study, the mixed mode is appropriate to model debonding between steel and CFRP. Therefore, the difference between the implicit and explicit solvers regarding contact modelling is debonding initiation, whereby the explicit solver depends on equation (3) while for the implicit solver the debonding initiates when one of the normal or tangential stresses reaches the allowable values.

2.1.3. Failure modes

Since this study is aimed at modelling the behaviour of CFRP strengthened steel members, the failure mechanism provides important information about the efficiency of the strengthening technique and how it can change failure modes. Several studies (Al-Thairy, 2012, Jones, 1997) have suggested different failure modes for steel members under impact loads including global plastic failure, tensile tearing failure and shear failure. For externally bonded CFRP strengthened steel elements under static load, six possible failure modes have been suggested by (Zhao and Zhang, 2007). The first failure mode that can happen in a strengthened system is steel failure, while the other five failure modes include steel and adhesive interface failure, cohesive failure (adhesive layer failure), CFRP and adhesive interface failure, CFRP delamination and CFRP rupture. However, for CFRP strengthened steel elements under impact load, Al-Zubaidy et al. (2012a) showed experimentally that the cohesive failure mode is not likely to happen under impact load. According to the description in section 2.1.2., the proposed FE model is able to capture all possible failure modes that could occur in a strengthened structure. In such cases, ANSYS removes the failed element from the model mesh when material failure is reached.

2.2. Validation of proposed FE model

In order to illustrate the accuracy and capability of the proposed model two series of experimental tests are selected and simulated. These series were conducted by Colombi and Poggi (2006) and Huo et al. (2011) and comprise testing CFRP strengthened steel beams under static load and steel beams under impact load respectively.

2.2.1. Validation 1: CFRP reinforced steel beams under static load

Two 2.5m long simply supported beams are simulated using the proposed FE model. Both beams were strengthened using a 1.4mm thick CFRP strip with different adhesive materials (a 1.1 mm thick Sikadur30 and 0.8 mm thick Sikadur330 for beams TR1 and TR2 respectively). The arrangement of strain gauges, beam dimensions and material mechanical properties are illustrated in

Fig. 2 and **Table 1**. A linear voltage displacement transducer (LVDT) was mounted on the mid-span section of the beam to measure the deflection. However, the LVDT was removed during the test for beam TR2 because the deflection reached 1/80 of the clear span (Colombi and Poggi, 2006). In addition, beam TR1 was left without lateral support, while specimen TR2 was equipped with lateral support to prevent lateral torsional buckling.

Fig. 2: Beam setup (all dimensions in mm)(Colombi and Poggi, 2006).

Table 1: Material properties (Colombi and Poggi, 2006)

Material	Young modulus (GPa)	Yield stress (MPa)	Ultimate stress (MPa)
Steel	210	331	469
CFRP	197	2800	-
Adhesive Sikadur30	4.5	24.8	-
Adhesive Sikadur330	3.8	30	-

The steel beam is modelled using a bilinear elastic-plastic constitutive model, whereas, a linear elastic stress-strain relationship is adopted for both unidirectional CFRP sheet and adhesive materials. The finite element mesh for both beams includes a total of 5579 elements and 7464 nodes. It can be noticed from Fig. 3 that the numerical load-deflection curves show reasonable agreement with the corresponding experimental curves, with a maximum divergence less than 11% and 10% in failure load and the deflection at failure respectively. One reason for this difference may relate to the fact that the average value of yield and ultimate stress found from coupon tests (for both web and flanges) were used in the simulation. Idealisations of the boundary conditions will add further inaccuracies to the model. In addition to **Fig. 3**, the applied load versus strain was also compared to examine the accuracy of the proposed model as shown in **Fig. 4** for both beams. Beam TR1 showed lateral torsional buckling in both experimental and numerical analyses because it was not laterally restrained, whereas, partial CFRP debonding developed in beam TR2 (as shown in **Fig. 5**) followed by yielding in the steel beam in both the numerical and experimental results, thus underscoring the capability of the model in capturing the key physical phenomena.

Fig. 3: Load-deflection curve for the beam TR1 and TR2.

Fig. 4: Load versus strain of beam (a) TR1 (b) TR2.

Fig. 5: Partial debonding for beam TR2 at mid-span.

2.2.2. Validation 2: *Steel beams under impact load*

Four 2.5m long beams $H250 \times 125 \times 6 \times 9$ (JIS-G-3192, 2005) were tested under a dropped mass by Huo et al. (2011). There were two different masses (450kg and 575kg) dropped from three various heights. The 450kg mass was dropped from 3.2m, 6m, and 8m, while the 575kg mass was dropped from 6m as summarised in Table 2.

Table 2: Details of the beam test series (Huo et al., 2011)

Beams	Dimensions	Hammer mass (<i>kg</i>)	Drop height (<i>m</i>)	Velocity (<i>m/s</i>)
HR4-3	H250 × 125 × 6 × 9	450	3.2	7.9
HR4-6	H250 × 125 × 6 × 9	450	6	10.8
HR4-8	H250 × 125 × 6 × 9	450	8	12.5
HR5-6	H250 × 125 × 6 × 9	575	6	10.8

The brick element employed in the static analysis has three degrees-of-freedom (translation in x , y and z) in each node rather than nine degrees-of-freedom (for elements used in ANSYS explicit analysis). Fig. 6 shows the boundary conditions, impact location and the strain gauge positions (S1 and S2) for both tested and modelled beams. Differences in the tested beams were introduced via the mass of hammer and/or the dropped height of the hammer. The mechanical properties of steel used in the test (Q235) are summarised in Table 3. However,

some data omitted by the original authors for the mechanical properties of steel Q235 (with respect to J-C model) are gained from Li et al. (2013).

Table 3: Johnson Cook parameters for Q235 and S355 steel.

Parameter	Definition	Steel Q235 (Li et al., 2013)	Steel S355 (NPR, 2011)
A	Initial yield stress (MPa)	249.2	365
B	Hardening constant (MPa)	45.6	1037.32
n	Hardening exponent	0.875	0.71
C	Strain rate constant	0.32	0.012
m	Thermal softening constant	0.76	1
T_m	Melting temperature (K)	1793	1673

Fig. 6. The beam dimensions (*mm*) and locations of strain gauges. (Huo et al, 2011)

In order to model the drop height, different velocities are used as listed in Table 2. The contact between the steel beam and the steel shaft (shown in Fig. 6) is modelled by employing a frictional contact region using a frictional coefficient of 0.4 as suggested by Pei and Wang (2012). According to the test results, no material failure was encountered in the experiments. However, in the numerical model, an equivalent plastic strain of 1.0 for Q235 according to Li et al. (2013) is input to check if failure could occur in the analysed beams.

Table 4 contains the values of maximum deflection at beam mid-span and the energy absorbed in the beams obtained from the experimental test with corresponding numerical results. The maximum difference between experimental and numerical results is about 6%.

Table 4: Comparison between experimental results and numerical simulations

Beam	Maximum deflection (<i>mm</i>)		Internal energy (<i>kJ</i>)	
	Experimental	Numerical	Experimental	Numerical
HR4-3	58.0	55.0	12.6	12.5
HR4-6	93.2	91.4	23.3	23.2
HR4-8	123.0	116.5	29.8	31.1
HR5-6	120.5	113.9	30.6	29.7

The deflection-time history is plotted for all beams in Fig. 7 with respect to experimental and numerical results. It can be seen from the figure that the deflection-time history from numerical analysis has small differences with the experimental curve. On the other hand, the numerical force-time history for all beams gives acceptable agreement with the experimental result. No smoothing has been applied to the numerical force time history. For instance, Fig. 8 shows the impact force-time history for beams HR5-6 and HR4-6. It can be noticed from these figure that the force-time history can be divided into three parts (a) initial impact force when the impact occurs; (b) mean impact force (plateau): the beam begins to deform gradually and the value of the impact force is almost constant. At this stage most impact energy is dissipated and (c) the descending part; the curve goes into the unloading stage when all impact energy is dissipated. Moreover, the value of the initial impact force for beam H4-6 gained from the experimental test was more than the corresponding value for beam H5-6, while the trend seems to be opposite in the numerical results. Researchers who have studied experimentally the behaviour of concrete filled steel members under transverse impact load reported similar findings (Han et al., 2014, Wang et al., 2013) to the numerical model. They found that when the mass and/or velocity increase the initial impact force increases.

Fig. 7. Deflection time history of the test series.

Fig. 8. Force time history a) Beam HR5-6; b) Beam HR4-6.

The strain gauge records are plotted against the numerical strain values in Fig. 9. The comparison between strain values in both locations gives excellent agreement.

Fig. 9. Strain-time for beam HR 4-3 for gauges S1&S2.

The performance of the model outlined here demonstrates its capability in capturing some of the key phenomena of the impact process. The model will now be used to conduct a parametric investigation in the forthcoming sections.

3. Simulation of CFRP strengthened steel beams under impact loads

3.1. Beam descriptions

To illustrate the effect of impact loads on the strengthened steel beam, the proposed FE model is adopted to analyse a simply supported beam (UKB 254 x 146 x 43) with clear span $7.5m$ as shown in Fig. 10. The beam has been previously designed for static loads based on the British Standard BS EN 1993-1-1 (BSI, 2005). The ultimate goal of the authors' research is to find appropriate strengthening methods for buildings and infrastructure, hence these dimensions are chosen to represent a full-scale beam and loads typical of that seen in practice rather than laboratory scaled specimens previously discussed. The steel is assigned to be grade S355 with an elastic modulus of $200GPa$ and a strain at failure of 0.65 based on Al-Thairy (2012). The strain hardening and strain rate effect for steel are taken into account by using the Johnson Cook model as listed in Table 3. Since the current study is aimed at examining the effect of impact loads on strengthened steel beams, the emphasis will be on the beam properties rather than impactor properties. It is assumed that the impactor dimensions are $(0.2 \times 0.2 \times 1.0) m$ as shown in Fig. 10. The contact between the impactor and the steel beam is assumed as a FRICTIONAL contact surface with a coefficient of friction of 0.4 , this will be further investigated in section 4.5. The density of the impactor is adjusted depending

on the value of mass required. The top flange of the beam is constrained in the lateral direction to stop lateral buckling.

Fig. 10. Typical FE beam and impactor.

The properties of carbon fibre and adhesive materials used to strengthen the steel beams are shown in **Table 5** and are based on values presented in Al-Zubaidy et al. (2013b) as presently there is no readily available experimental data on CFRP strengthened steel beams under impact loading. All failure modes mentioned in section 2.1.3 are included in the current simulation except tensile tearing failure for the steel because in these cases it is unlikely happen with the member having no axial restraint (i.e. simply supported).

Table 5: Mechanical Properties of CFRP and adhesive material(Al-Zubaidy et al., 2013b).

	CFRP	Adhesive material
Tensile modulus (<i>GPa</i>)	206.6	1.455
Tensile strength (<i>MPa</i>)	1935	29
Shear strength (<i>MPa</i>)	-	25
Tensile failure strain (%)	0.91	9.32

3.2. Mesh size sensitivity

The process of the mesh size sensitivity will be divided into two stages. In the first stage, the mesh through the length of the beam is examined while in the second stage the mesh in the web and flanges is studied. Firstly, the numerical simulation results for different mesh sizes are examined by determining the natural frequency for various element sizes (Al-Thairy, 2012) using ANSYS. The numerical natural frequency values are compared with the theoretical value (Blevins, 1979) as listed in Table 6.

Table 6: Natural frequency against element size

Elements size (<i>mm</i>)	Natural frequency numerical (<i>Hz</i>)	Numerical/ Theoretical(15.402 <i>Hz</i>)
250	14.570	0.946
100	15.109	0.981
50	15.232	0.989
30	15.279	0.992
20	15.279	0.992

It can be noticed from Table 6 that all element sizes are appropriate for dynamic analysis but there is no effect on the natural frequency value when the element size is reduced to less than 30mm. Secondly, the same mesh sizes proposed in the first simulation can be used to find the effect of mesh sizes on the maximum stress developed in the beam subjected to impact load (the velocity and mass of impactor are 5m/s and 3000kg respectively).

Fig. 11. Von Mises stress-time history against various mesh sizes through the beam length.

It can be seen from Fig. 11 that the difference between stress values during the time of simulation is very small but this difference is negligible when the mesh size is smaller than 30mm, therefore, the 30mm mesh size is chosen for the rest of the simulations. In the second step, the web height and flange width of the beam are divided into 10, 15 and 20 divisions, while the mesh size through the beam length is kept at 30 mm. It can be observed from Fig. 12 that the number of divisions for the web and flanges of the beam does not have a significant effect on the maximum stress during the time of simulation therefore 10 divisions is the minimum number that will be used for all forthcoming simulations (for both web and flanges). However, the element size for CFRP and adhesive material is chosen to be similar to the element size of the bottom flange because of the limitation of the programme to get a good convergence (ANSYS, 2013) and also in order to obtain an accurate solution in a minimum run time.

Fig. 12. Von Mises stress-time history against number of divisions for the beam web and flanges.

3.3. Simulation results

The thicknesses of CFRP plate and adhesive material are set as 3mm and 1mm respectively, while the influence of CFRP thickness will be investigated later in section 4.2. The most simplified analysis approaches for members subjected to impact loading are based on the energy balance principle, therefore it is essential in this study to investigate the effect of impactor kinetic energy and its components (velocity and mass). In the numerical simulation a constant value of the kinetic energy (37.5kJ) is set, this is varied later as part of the parametric study, with different values of components (velocity and mass of impactor) as listed in Table 7.

Table 7: Velocity and mass values used in simulation

Beam no.	Velocity of impactor (m/s)	Mass of impactor (kg)
BM1V8.6	8.66	1000
BM3V5.0	5	3000
BM5V3.8	3.87	5000

It can be noticed from Fig. 13 that the bonded CFRP plates reduce the defection for all beams by more than 11%. This result seems to be reasonable when compared to the corresponding result under static loads. For instance, Colombi and Poggi (2006) investigated the behaviour of CFRP strengthened steel beams under static load. It was found that the load-carrying capacity of one-layer CFRP strengthened steel beams increased by about 10% compared to unstrengthened beams. Nevertheless, the impactor kinetic energy, which is $MV^2/2$, where M is the mass of the impactor and V is the velocity of the impactor, is absorbed

by the strengthened beams over a duration of about 15% less than the time needed by the unstrengthened beams. It is also evident from Fig. 13 that a larger mass with a smaller velocity value gives more deflection under the same level of kinetic energy for both strengthened and unstrengthened beams. This is because as explained in the introduction (Equation 1), the flow stress increases with increasing strain rate, while a beam subjected to a larger velocity value tends to be under a higher strain rate than a beam under smaller velocity value.

It can be noticed from **Table 8** that the initial peak and mean impact forces tend to increase with smaller mass and larger velocity when the increase of the initial peak force for strengthened beams is from 3% to 10% of the unstrengthened beams, while the mean impact force increases about 12% for all strengthened beams. It can be concluded that the initial peak force does not affect the displacement response of the strengthened beams, whereas the beams subjected to high mean impact forces produced higher reductions in deflection. Fig. 14 shows the typical force-time history for strengthened beams and unstrengthened beams. It can be noticed from this figure that the peak impact force is first reached at 0.002s, while the impact force continues to 0.08s to 0.14s depending on the velocity value and mass of impactor. It is also concluded from the simulation that no failure occurred in any of the beams (listed in **Table 7**), strengthened or unstrengthened. No debonding or CFRP rupture occurred in any strengthened beam. In terms of energy balance, **Fig. 15** shows the energy balance for strengthened beam (BM3V5.0). It can be seen from this figure that the CFRP absorbed about 6% from the total energy absorbed by the beam, while the rest of the energy was dissipated by the steel beam.

Fig. 13. Deflection-time history for strengthened and unstrengthened beams under equivalent impact energy (37.5kJ).

Fig. 14. Typical force-time history for strengthened and unstrengthened beams (BM3V5.0).

Fig. 15. Energy histories for strengthened beam BM3V5.0.

Table 8 Initial and mean impact force for strengthened and unstrengthened beams via different velocities and masses

Velocity (m/s)	Mass (kg)	Initial impact force (kN)		Mean impact force (kN)	
		Unstrengthened beams	Strengthened beams	Unstrengthened beams	Strengthened beams
8.60	1000	759	779	153	173
5.00	3000	730	756	145	163
3.86	5000	618	679	140	156

4. Parametric study

A number of parameters are now investigated to evaluate their influence on the impact performance of the CFRP strengthened steel beam.

4.1. Effect of strain rate on CFRP and adhesive material

In the previous section, it is assumed that the CFRP and adhesive material were insensitive to strain rate (Kimura et al., 2001, Alam and Fawzia, 2015). However, some previous studies have included strain rate effects for CFRP and adhesive material such as (Al-Zubaidy et al., 2013c, Hou and Ruiz, 2000, Wang et al., 2005). In this section, the empirical parameters that were suggested by Al-Zubaidy et al. (2013c) will be used to include the effect of strain rate for CFRP and epoxy in the Cowper-Symonds model (Jones, 1997).

$$\sigma_{dynamic} = \sigma_{static} \times \left(1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/q} \right) \quad (4)$$

Where $\sigma_{dynamic}$ is the dynamic flow stress at a uniaxial plastic strain rate $\dot{\epsilon}$, σ_{static} is the associated static flow stress and D and q are constants for a particular material.

For the tensile stress in CFRP, it is suggested that (Al-Zubaidy et al., 2013c):

$$D = 154.57 \text{ s}^{-1} \text{ and } q = 0.654 \quad \text{for } 2.42 \times 10^{-4} \leq \dot{\epsilon} \leq 87.4 \text{ s}^{-1}$$

and for the adhesive material:

$$D = 59.76 \text{ s}^{-1} \text{ and } q = 0.9 \quad \text{or } 2.42 \times 10^{-4} \leq \dot{\epsilon} \leq 54.2 \text{ s}^{-1}$$

The beam (BM3V5.0) is chosen to investigate the effect of strain rate on the behaviour of the strengthened beams. The strain rate chosen in this study is no more than 2 s^{-1} . FE results confirm that with and without the strain rate effect there is no significant difference in the impact force and the deflection of the beam. This may be a function of the relatively modest strain rate chosen in this study.

4.2. Effect of CFRP thickness

In the previous simulation results, it is assumed that the thickness of CFRP is constant (3mm). To give a maximum reduction in deflection and increase in the beams ability to carry impact loads, it is very important to investigate the optimum thickness. For this purpose, five CFRP thicknesses are chosen to measure this effect on the strengthened beams. Beam (BM3V5.0) is selected to examine the influence of CFRP thickness. It can be noticed from Fig. 16 that increasing CFRP thickness reduces the deflection but this reduction increment tends to diminish beyond a CFRP thickness of 2mm.

Fig. 16. Deflection-time history for beam BM3V5.0 with different CFRP thicknesses.

It can be seen from Fig. 17 that after 0.065s, the 1mm CFRP plate ruptures because it reaches the tensile failure strain (0.0091), while the CFRP strain values in all other beams do not reach the failure strain.

Fig. 17. CFRP at bottom mid-span of beam BM3V5.0+CFRP 1mm at time =0.065s showing a cut-out region of the CFRP.

4.3. Effect of impact location

In real situations, beams may be shocked at any position in the span. However, all of above simulations assumed that the impactor is dropped at the mid-span. In order to investigate the effect of impact location, three locations are proposed which are 0, 1 and 2m from the beam mid-span. It can be noticed from Fig. 18 that the reduction in the maximum deflection of the strengthened beams is still about 11% of the unstrengthened beams. Similarly, the mean impact force showed an identical trend for the beams struck at their mid-span with a slight difference for the beams impacted at 2 m from mid-span when the increase in the mean

impact force (compared to unstrengthened beams) was about 9% compared to 12% for the rest of beams as shown in **Fig. 20**.

Fig. 18. Deflection-time history against impact location.

Fig. 19. Deflection along the strengthened and unstrengthened beams with different impact locations.

Fig. 20. Mean impact force for strengthened and unstrengthened beams with different impact locations.

As would be expected, Fig. 19 illustrates that if the impact location is positioned away from the mid span of the beam, the maximum deflection is less than the deflection when at the mid-span. It also can be noticed that the location of the maximum deflection of the beams tends to change depending on the location of the impactor. However, the maximum deflection locations of strengthened beams do not show significant changes when compared to the unstrengthened beams subjected to non-central impacts.

4.4. Effect of impact energy

In all the above simulations, an impact energy of 37.5kJ is adopted with different components. However, it is important to investigate the effect of different impact energy levels on the strengthened beams. For this purpose, two additional energy values are investigated: 9.375 and 75 kJ .

No failure or debonding occurs in the strengthened and unstrengthened beams subjected to impact energy 9.375 and 37.5 kJ , while when the impact energy is 75 kJ , the unstrengthened beams show high plastic strain at beam mid-span.

Fig. 21. Effect of impact energy on the CFRP strengthened beams.

Fig. 21 illustrates that the contribution of CFRP in the strengthened beams increases with a larger impact energy value. Here the CFRP laminates minimise the permanent deflection by about 9% compared to unstrengthened steel beams for an impact energy of 9.375 kJ and 13% for an impact energy of 75 kJ .

4.5. Effect of frictional coefficient

Several researchers assumed different values for the frictional coefficient between impactors and the impacted member such as 0.4 (Pei and Wang, 2012) and 0.6 (Al-Thairy, 2012). In this study, different values are used to investigate the effect of the frictional coefficient.

Table 9: Effect of the frictional coefficient.

Frictional coefficient	Maximum deflection (<i>mm</i>)	Maximum stress (<i>MPa</i>)	Initial peak force (<i>kN</i>)	Mean impact force (<i>kN</i>)
0	316.45	444.2	730.0	145.14
0.4	316.23	443.49	729.4	145.06
0.5	316.2	443.34	729.2	145.05
0.6	316.16	443.16	729.1	145.04

It can be noticed from Table 9 that the frictional coefficient does not have a clear effect on the overall behaviour of impacted beams. This may be related to the short period of the overall loading time, which is normally less than 0.12s, consequently there may insufficient time to develop a noticeable frictional force value which could be comparable with the overall impact force.

5. Conclusion

In this paper, a three-dimensional FE model using ANSYS 14.5 is employed to study the behaviour of CFRP strengthened steel beams under impact loads. The core findings from this work are:

- The proposed numerical model achieved good comparison with related experimental work, capturing all the key phenomena.
- It is found that for the strengthened beams studied, the CFRP can minimise mid-span deflection (with different velocities and masses of impactor) by more than 11% compared to the unstrengthened beams. This trend is to be expected when considering the corresponding static results which show that the load carrying capacity of strengthened beams can increase by 10% under static load (Colombi and Poggi, 2006).
- The mean impact force increases for strengthened beams by about 12% for all beams in the series, while no obvious change occurs in the value of initial impact force of the strengthened steel beams.
- In relative terms, the initial impact force does not have an effect on the deflection of impacted members, whereas the mean impact force has a significant effect on the beam deflection which is in agreement with Alam and Fawzia (2015).

- By assuming the same level of impact kinetic energy but different velocity and mass combination values, a beam shocked by a smaller velocity and a larger mass of impactor tends to have higher deflection for strengthened and unstrengthened steel beams.
- To investigate the effect of strain rate on the CFRP and adhesive material, a parametric study was undertaken. The numerical results suggest that the strain rate effects for both CFRP and adhesive do not play a vital role for the given strain rate in this test series.
- The increase of the CFRP thickness reduces the mid-span deflection of the strengthened beams but this reduction diminishes when the thickness of CFRP layer is more than *2mm* for the beams studied.
- The maximum deflection of strengthened beams reduces by about 11% compared to unstrengthened beams when the impact load is positioned at various locations along their length.
- A strengthened beam subjected to a larger impact energy value enacts a greater reduction in percentage of maximum deflection when compared to a corresponding beam subjected to smaller impact energy. In other words, CFRP is more efficient at preventing potential damage in a higher energy impact as clearly shown in **Fig. 21**.

6. On-going work

The research presented here forms part of a wider study examining the behaviour of CFRP strengthened steel members subjected to impact loads. Future work will include an extensive programme of physical testing in parallel with numerical models.

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List of Notation:

σ	is the equivalent stress in the Johnson-Cook model
A	is a material constant used in the Johnson-Cook model
B	is a material constant used in the Johnson-Cook model
ϵ	is the equivalent plastic strain in the Johnson-Cook model
n	is a material constant used in the Johnson-Cook model

C	is a material constant used in the Johnson-Cook model
$\dot{\epsilon}^*$	is the dimensionless plastic strain used in the Johnson-Cook model
T^*	is the homologous temperature calculated in the Johnson-Cook model
m	is a material constant used in the Johnson-Cook model
$\dot{\epsilon}$	is strain rate
$\dot{\epsilon}_0$	is a reference strain rate used in the Johnson-Cook model
T	is the temperature at which the stress is calculated in the Johnson-Cook model
T_r	is a reference temperature in the Johnson-Cook model
T_m	is the melting point in the Johnson-Cook model
σ_n	is the normal stress at the bond location
σ_n^{limit}	is the normal stress limit
α	is the exponent of the normal stress
σ_s	is the shear stress at the bond location
σ_s^{limit}	is the shear stress limit
β	is the exponent of the shear stress
σ_{dynamic}	is the dynamic stress used in the Cowper-Symonds equation
σ_{static}	is the static stress used in the Cowper-Symonds equation
D	is a material parameter used in the Cowper-Symonds equation
q	is a material parameter used in the Cowper-Symonds equation

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