

FE modelling of CFRP strengthened steel members under impact loads

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ABSTRACT

Recently, the strengthening of steel structures using carbon fibre reinforced polymer has become more attractive for designers due to the advantages of high strength-to-weight ratio and superior environmental durability. Significant research has been performed on the behaviour of CFRP strengthened steel members under static loads. Dynamic behaviour, and in particular impact loading, of CFRP strengthened steelwork has been scarcely studied. In practice, steelwork could be subjected to impact from different events such as road vehicle or ship collisions, and impact by flying debris after an explosion etc.

This study discusses the numerical investigation of the effectiveness of CFRP sheets in strengthening square hollow section (SHS) steel columns under transverse impact loads. The study was conducted using the finite element (FE) programme ABAQUS 6.13. The proposed three-dimensional FE model was validated using existing experimental results. The strain hardening and strain rate effects were accounted for in this model using classical metal plasticity and the Cowper Symonds model respectively, while the CFRP and adhesive material were modelled using the elastic lamina and traction separation model respectively. The effect of different parameters has been investigated in this study such as the compression load level, boundary conditions and CFRP configurations. It has been found that the CFRP can significantly improve column performance for different values depending on the above parameters.

Keywords: *impact; steelwork; carbon fibre reinforced polymer*

1. Introduction

In recent years, there has been an increasing amount of studies on strengthening and repair of steel structures using the technique of adhesively bonded carbon fibre reinforced polymer (CFRP). Most of these studies examined the effectiveness of CFRP strengthening on I' beams such as [1, 2] while hollow structural sections have received less attention from researchers. Photiou [3] found that the ultimate strength of RHS beams with artificial degradation could be restored by using CFRP. In another study, the strengthening of circular hollow section (CHS) beams using CFRP fabric was investigated with emphasis on curing the resin materials under seawater [4]. Different slenderness ratios were examined by Shaat [5] to find out the effect of column slenderness ratio on the strengthened members. During its life span, a steel structure may be subjected to different types of dynamic loading such as impact. To date only a limited amount of research has been conducted on the behaviour of CFRP strengthened steel members under impact loads. Recently Alam et al [6] examined numerically the effectiveness of fully bonded CFRP plate on SHS columns using ABAQUS. SHS sections with 89×89×3.2 cross section and length 2380 mm strengthened with longitudinal CFRP plates were adopted in the numerical model. According to the aforementioned literature review, the effect of impact load on the CFRP strengthened members needs more study to find out the influence of parameters such as boundary conditions, CFRP configuration and partial bond between the CFRP and steel members. This paper focuses on the behaviour of CFRP strengthened SHS columns under impact load taking into account the boundary conditions, compression load level and different CFRP configurations.

2. Finite element model validation

The simulation model is built using the general finite element software ABAQUS 6.13-1. The steel member was modelled using a four-node shell element S4R, while an eight-node brick element

C3D8R is adopted to model the impactor. In the later simulations, the CFRP and adhesive material were modelled using S4R and the cohesive element COH3D8 respectively. The strain hardening and strain rate effects were accounted for steel using isotropic strain hardening and Cowper Symonds model respectively. The failure behaviour of the materials was defined using the progressive damage and failure models provided by ABAQUS including the shear damage criterion for steel, Hashin's failure criteria for CFRP and the quadratic traction damage criterion for adhesive material.

The proposed finite element model is validated using the experimental test results conducted by Zeinoddini, et al. [7]. Un-strengthened, 1-meter long CHS specimens were tested with one fixed and one sliding end subjected to a 25.54 kg mass with a falling velocity 7 m/s (more detail on the experimental test is given in [7]). The specimens were tested under different compression load levels (P/Py) from 0 to 70% as listed in table 1.

Table 1: comparison between experimental and numerical results

P/Py(%)	Experimental (mm)		Numerical (mm)	
	Permanent deflection	Shortening	Permanent deflection	Shortening
0	15.5	0.3	17.3	0.4
25	21.5	0.8	19.4	1.4
50	25.3	2.3	26.6	3.5
60	28.4	3.1	33.6	5.7
70	-	113	195.1	112

Table 1 summarises the comparison between experimental and numerical permanent deflection and axial shortening. Good agreement was achieved using the numerical model in terms of maximum deformation; shortening and deformation at failure (see Figure 1 (a)). On the other hand, the impact load, which is the interface force developed under the indenter, recorded during the tests for different levels of axial load was compared with corresponding numerical values as shown in Figure 1(b). It can be noticed from this figure that maximum impact load happens with a lower level of axial load while the specimen with 70% P/Py has the minimum value of impact load. This indicates the higher the pre-compression, the less stiff the response.

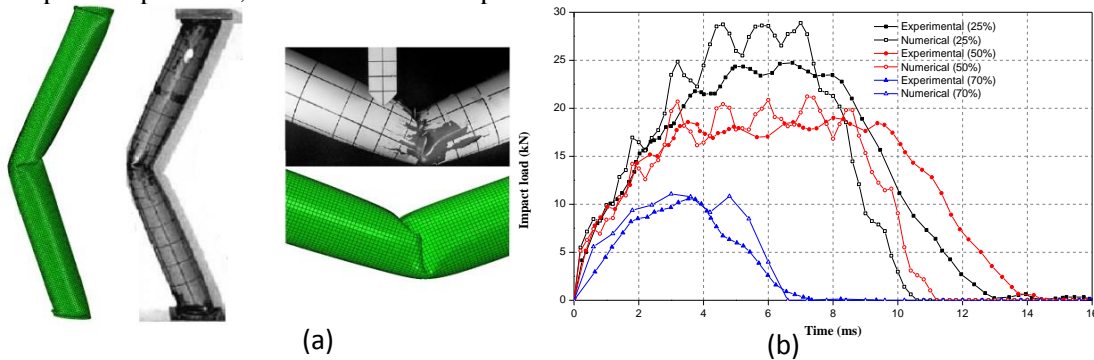


Figure 1: comparison between experimental [7], and numerical results (a) deformation shape; (b) impact load

3. CFRP strengthened steel columns

In order to investigate the effectiveness of CFRP in strengthening steel members under impact loads, a full-scale column section 3.5 m long was designed according to Eurocode 3 to carry a load consistent with a six storey commercial building. Two different boundary conditions were chosen: simply supported and fixed-fixed to find out the effect of the boundary conditions on the strengthened members. The modulus of elasticity and yield stress of steel were assumed as 200000 and 355 MPa respectively. Different kinetic energies were applied on the designed column (SHS 200×200×8.8) with different components (velocity and mass), while four compression static load levels were suggested as listed in Table 2. It is clear from previous studies[5] that the CFRP orientation has a considerable effect on the strengthening efficiency, therefore three CFRP configurations 6 mm CFRP in the longitudinal direction (L), 6 mm CFRP in the transverse direction (T), 3mm CFRP in the longitudinal direction and 3 mm CFRP in transverse direction (LT), wrapped around the whole

section in all cases) were investigated in this study to ascertain the most efficient. The length of the CFRP was kept constant and is equal to the column length. The material properties of the carbon fibre and the adhesive material gained from Al-Zubaidy, et al. [8].

Table 2: Failure modes for simply supported and fixed-fixed columns

P/Py	BC	Mass=0.5 tonnes												Mass=2 tonnes											
		Impact Velocity (m/s)																							
		5				10				15				5				10							
		U	L	T	LT	U	L	T	LT	U	L	T	LT	U	L	T	LT	U	L	T	LT				
0	SS	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
	FF	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
0.25	SS	S	S	S	S	S	S	S	S	G	S	S	S	G	S	S	S	G	G	G	G	S	S	S	S
	FF	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	G	S	S	S	S	S	S	S
0.50	SS	S	S	S	S	G	S	S	S	G	G	G	G	G	S	S	S	G	G	G	G	G	G	G	G
	FF	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	G	G	G	G	G	G	G	G
0.75	SS	G	S	S	S	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	FF	S	S	S	S	G	S	S	S	G	G	G	G	G	S	S	S	G	G	G	G	G	G	G	G

S: Stable; G: Global buckling failure; U: unstrengthened; L, T, and LT: strengthened columns with CFRP oriented in the longitudinal, transverse and both longitudinal and transverse direction; SS: simply supported; FF: fixed-fixed

As described in section 2 all possible failure modes were included in the validated model. However, in this simulation two main failure modes were investigated namely global buckling failure and transverse shear failure which likely happens when the impact point is close to a support. Therefore, global buckling failure is the unique failure in table 2, while other material failures such as debonding and CFRP rupture were not listed in this table because they are not likely to cause a column failure during this study. It is apparent from Table 2 that the CFRP can enhance the column capacity for the applied compression force in addition to impact load in many cases for the investigated boundary conditions, while for the unstrengthened stable columns the corresponding strengthened column showed less lateral displacement value under the same loading conditions.

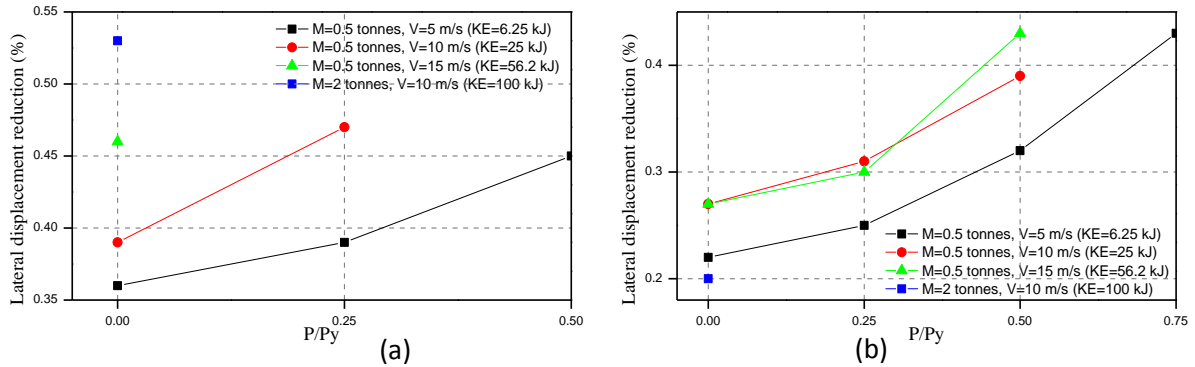


Figure 2: Lateral displacement reduction against pre-loading level for CFRP strengthened columns in longitudinal direction (a) simply supported column; (b) fixed-fixed column.

However, the percentage of lateral displacement reduction is different depending on the CFRP configuration, loading level (P/Py), applied kinetic energy and the boundary conditions. In Figure 2 there is a clear trend of increasing lateral displacement reduction with high levels of P/Py and kinetic energy for simply supported columns strengthened in the longitudinal direction, while for fixed-fixed columns it seems that this trend is slightly different in the last value of kinetic energy (KE). The reason for this difference is related to the severe deformation happening under the impactor for the fixed-fixed columns compared to corresponding simply supported columns, which is caused by the relatively high stiffness of the fixed-fixed member. The above reason may also account for why the CFRP in the transverse direction plays more significant role in fixed-fixed columns, while the enhancement role of the other CFRP configurations reduce with fixed-fixed boundary condition

columns as shown in Figure 3 (a). The above finding is consistent with the study by Shaat [5], which revealed that the CFRP in transverse directions can reduce the local buckling while having fibres oriented in the longitudinal direction can improve the stability of the columns against lateral displacement under static load. It can also be seen from Figure 3(a) that the columns strengthened with CFRP oriented in the longitudinal direction have the highest lateral displacement reduction, whereas the columns strengthened with CFRP in the transverse direction tend to give more severe column response (large displacement) compared to other strengthening configurations. However, these results are significantly different from a similar study by [6] which revealed that CFRP in longitudinal direction can minimise the lateral displacement by about 58% while in this study the average reduction in lateral displacement is about 44%. One reason why that happened may be the result of using partial bond between CFRP and steel in the current study, this being more representative of actual behaviour. Figure 3 (b) proves that CFRP can enhance local buckling resistance of the columns strengthened with CFRP oriented in the transverse direction more than the columns in other directions.

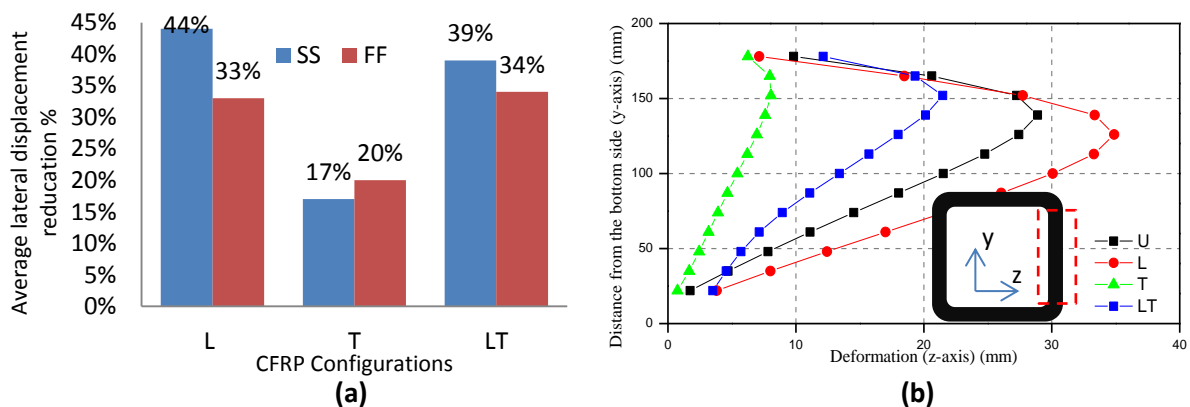


Figure 3: (a) Average lateral displacement reduction against CFRP configuration; (b) Deformation along right side at the point of maximum lateral displacement (Mass=2, V10m/s, fixed-fixed column).

4. Conclusions

Externally bonded CFRP can improve steel column behaviour under impact loads. The numerical results showed that the CFRP could minimise the lateral displacement of the impacted columns with different amounts (44% to 17%) depending on factors such as CFRP configuration, preloading level, boundary conditions and applied kinetic energy.

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