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Impact behaviour of carbon fibre reinforced polymer (CFRP) strengthened square hollow steel tubes: A numerical simulation

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A B S T R A C T

Carbon fibre reinforced polymer (CFRP) has become popular and used in various engineering applications. Strengthening of hollow steel sections using CFRP has proven improved structural characteristics under static loading conditions. However, there are very few studies available related to the axial dynamic impact behaviour of CFRP strengthened steel hollow sections. This paper evaluates the behaviour of CFRP wrapped hollow square steel tube sections under axial impact loading through validated numerical models. A comprehensive parametric study has been conducted to evaluate the effects of impact mass, impact velocity, adhesive strength and fibre modulus on the impact performance of these tubes. Crash behaviour is studied by comparing the peak impact force, axial deflection, absorbed internal energy and failure modes between CFRP wrapped and bare steel models. The results show that the variations in impact velocity and fibre modulus can have significant effect on the impact response of CFRP wrapped tubes.

1. Introduction

Structural hollow steel sections are widely used in construction industry as well as in automobile industry. CFRP technology has been used as an external reinforcement system for steel structural systems to serve the same purpose as steel jacketing but with some added advantages [1]. The improved strength and behaviour of steel tubular sections wrapped with CFRP under static loading have proven that this CFRP wrapping technique is an efficient strengthening method [2–9]. The use of CFRP appears to be an excellent solution for retrofitting and strengthening of steel structures because of its superior physical and mechanical properties. CFRP wrapped steel tubes are considered as an innovative retrofitting solution because of its advantages, such as high strength compare to the traditional method, lighter construction, aesthetically pleasant, minor interruption of the structures during strengthening or rehabilitation, no heavy scaffolding or cranes and limited workforce requirement during the instalment. Most of the earlier research focused on the flexural and tensile behaviour of CFRP wrapped steel. However, there is limited research on the CFRP wrapped steel tubes to resist axial loading. There are even fewer studies to investigate the behaviour of CFRP wrapped steel tubes when subjected to axial impact loading.

Teng and Hu [8] studied the behaviour of CFRP wrapped circular steel tubes and cylindrical shells under axial compression and concluded that CFRP wrapping is a very promising strengthening technique for retrofitting circular hollow steel sections in terms of improving the ductility of steel. In contrast, load carrying capacity was not greatly increased. Bambach [10] investigated the axial capacity and crushing behaviour of metal-fibre stainless steel and aluminium square tubes with CFRP under axial impact loading. Tubes with different metal square hollow section (SHS) geometries and two different matrix layouts of CFRP were studied, and a general theory was developed to predict the axial capacity, axial collapse and mean crush loads of these tubes and validated using experimental data. This study concluded that CFRP could be used as an externally bonded reinforcement to steel square hollow section (SHS) successfully. Such applications may improve the performance of existing structures and play a major role in the design of new structures with enhanced strength-weight and energy absorption-weight ratios. Furthermore, different strengthening schemes of CFRP wrapped steel tubes have been studied by various researchers [11–15] including double-strap joints [16,17], lap joints, CFRP wrapped concrete filled tubes and open steel sections.

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Nomenclature

COV	Coefficient of variance
D_{max}	Maximum axial deflection
E_{max}	Maximum absorbed energy
NFLS	Tensile failure strength of adhesive
P_{ave}	Average crushing force
SEA	Specific energy absorption
SFLS	Shear failure strength of adhesive
t_{ad}	Thickness of the adhesive
t_{CFRP}	Thickness of CFRP
X_C	Compressive strength in *a* direction
X_T	Tensile strength in *a* direction
Y_C	Compressive strength in *b* direction
Y_T	Tensile strength in *b* direction
β	Weighting factor for the ratio of shear stress to shear strength
$\dot{\varepsilon}$	Strain rate of steel
σ_{aa}	Stress in direction *a*
σ_{ad}	Tensile strength of adhesive
σ_{bb}	Stress in direction *b*
σ_{CFRP}	Tensile strength of CFRP
$\sigma_{(eq)CFRP}$	Tensile strength of the composite
τ_{ab}	Shear stress

The material properties are significantly affected by the strain rate. Research studies related to steel showed that steel properties such as yield strength and failure strain were dependent on the strain rate [18–21]. However, the behaviour of CFRP under high strain rates is not clearly understood, and it is a complicated procedure because of the involvement of a large number of material properties due to its non-isotropic behaviour. A recent research work carried out by Orton et al [22]. showed that there is no increase in the tensile strength of the CFRP material in the range of 0.0015–7.81 s^{-1} strain rates. In contrast, another study conducted [23] on CFRP materials showed that CFRP and adhesive properties were strain rate dependent within the tested loading rates.

Studying the behaviour of CFRP wrapped steel sections under axial impact load is vital to evaluate their potential as crash energy absorbers. The majority of the research works related to CFRP-steel composites have been conducted under static loading conditions. This paper aims to evaluate the crashworthiness properties of the CFRP wrapped steel tubes under axial impact conditions. Finite element (FE) models were developed and validated using existing experimental data [24]. The experimental study consisted of CFRP wrapped hollow steel tubes with two different fibre layouts. The SHS members were tested under axial impact load in a drop-mass rig using a mass of 574 kg from a height of 1.835 m, resulting in a nominal impact velocity of 6 ms^{-1} and impact energy of 10.3 kJ. FE modelling and analysis were performed using LS-DYNA finite element code. The validated FE models were used to conduct a detailed parametric study to evaluate the influence of several structural parameters including peak impact force, axial displacement and internal energy of CFRP wrapped tubes. The structural response was evaluated by varying the impact mass, impact velocity, adhesive strength and fibre modulus.

2. Finite element modelling

2.1. Model description

The steel tubes were modelled with four node shell elements [25] containing five integration points through element thickness with Belystchko-Tsay element formulation. CFRP layers were also modelled with the same type of Belystchko-Tsay shell elements. It should be noted here that the first (close to steel) CFRP layer is transverse layer and the second CFRP layer is longitudinal layer (top layer). A control type hourglass mode was used with hourglass coefficient equals to 0.3 for crash analysis to avoid zero energy modes during the simulation. The impactor was modelled as a moving-rigid-wall having an initial velocity of 6 ms^{-1} and a mass of 574 kg. The bottom of the steel tube was modelled as a fixed support by restraining all degrees of freedoms of the bottom nodes of steel tube. The stationary baseplate was modelled using another stationary type rigid wall at the lower part of the composite tube. In addition to geometry, meshing and material properties, the other important consideration for the computational model in this study is the definition of contact interface types between the independent interacting components of the model. In this simulation, penalty based contact types were used. single surface contact was used to avoid the interpenetration of nodes during the folding of the tube. Tie-break contact was used to define the contacts between Steel tube and CFRP and between two CFRP layers. Tiebreak allows the separation of the surfaces, and ultimately the failure of the tied surfaces will occur under the failure criterion expressed in Eq. (1).

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geq 1 \tag{1}$$

where *NFLS* is tensile failure strength, and *SFLS* is shear failure strength of the adhesive. σ_n and σ_s are respectively the tensile stress and the shear stress. Strength of the epoxy (36 MPa) was nominated as the NFLS and SFLS values in the tie-break model since this is the maximum possible value to be reached during the tie-break process.

All models were meshed with quadrilateral elements with a dimension at 2.5 mm × 2.5 mm. The mesh size was selected based on mesh convergence study and also with consideration of the relative dimensions of the steel tube and CFRP layers. Full geometry was modelled. The geometry and the FE mesh of the model are presented in Fig. 1.

2.2. Material properties

Table 1 summarises the Material properties used for FE models created based on the experimental results available in the literature [24]. The summary of the details of the FE models created is shown in Table 2 with current FE model identification. The steel used in the experiment had 350 MPa nominal strength, and commercially available CFRP type CF-130 was used with Araldite 420 epoxy. Impact force was applied by dropping a mass of 574 kg from a height of 1.835 m resulting in an impact velocity of 6 ms^{-1} and with impact energy of 10.3 kJ.

2.3. Material models and failure criteria

The material properties of steel under static loading cannot be used for dynamic simulations, and strain rate effects need to be considered. Therefore, steel was modelled using strain rate sensitive model [26] as it is capable of simulating the strain rate effects based on Cowper-Symonds model. The Cowper-Symonds model scales the yield stress of steel by a factor of $1+\left(\frac{\dot{\varepsilon}}{c}\right)^{1/p}$ where, $\dot{\varepsilon}$ is the strain rate and *C*, *P* are strain rate parameters. $C = 40$ and $P = 5$ are used in this simulation as suggested in the research literature [27–29].

CFRP was modelled using an enhanced composite material model. This material model considers the effects of directionality in the material stress–strain response by allowing different fibre orientations specified at each through-thickness integration point. Unidirectional laminated fibre composite shell thickness, each fibre orientation, and constitutive constants are required to input. This material model is built on a set of stress-based failure criteria for the fibre and matrix failure under tensile, compressive and/or in-plane shear loading. These failure