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Fibre composite strengthening of thin steel passenger vehicle roof structures

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ABSTRACT

There is an increasing pressure on vehicle manufacturers internationally to increase the strength of vehicle roofs, in response to the ongoing morbidity and mortality related to vehicle rollover crashes. Several countries are mandating increased roof strengths for future vehicle fleets, and this is occurring at the same time as increased regulations to reduce vehicle emissions. Thus light weight strengthening solutions are required to increase roof strengths while minimising structural mass. This paper presents the novel approach of strengthening vehicle roof structure components by bonding carbon fibres to the steel surface. Such fibre strengthening systems have been shown to provide substantial increases in force and energy resistance for steel tubes under both axial crushing and pure bending. The strengthening potential is assessed with a numerical study of two different passenger vehicles subjected to various roof crush test protocols. Numerical models of fibre composite strengthening systems are validated against experiments, then applied to numerical models of the vehicles. Substantial improvements in the roof strength, and correspondingly the vehicles' roof strength to weight ratio, are demonstrated with the fibre strengthening technique. Comparisons are made with models of strengthening the roof structure components by adding steel rather than fibre composite, and the implications with regards to vehicle light-weighting are discussed. It is shown that fibre composite strengthening of vehicle roof structures has the potential to contribute to higher roof strengths and/or light-weighting in future vehicle fleets.

1. Introduction

Vehicle rollover crashes are the cause of many fatalities and severe head, neck and spine trauma around the world. Since 2000 in the United States alone, more than 10,000 people every year have been killed in vehicle rollovers [1]. Recognising that roof intrusion (intrusion of the roof structure into the internal survival space) plays a role in rollover crash trauma, there is increasing pressure on vehicle manufacturers to increase the strength of vehicle roofs for rollover crash resistance. The long standing FMVSS 216 roof crush test, a mandatory regulatory requirement in the United States, Brazil and Canada for passenger vehicles with a maximum gross vehicle weight of 6000 lbs, is scheduled to be updated during a phase-in period beginning with 2013 model vehicles [2]. The update will double the previous force resistance requirement of 1.5 times the unloaded vehicle weight to three times, and will require the test to be applied to both sides of the vehicle. In Australia, the Australasian New Car Assessment Program (ANCAP) will begin roof crush testing in a manner similar to the single-sided FMVSS 216 roof crush test in 2014 [3]. Initially, in order for a vehicle to achieve a five star rating the force requirement will be 2.5 times the unloaded vehicle weight, increasing to 3.25 times in 2016.

The roof structure components in passenger vehicles consist of pillars, roof rails and header rails, and are typically constructed from thin-walled steel sections spot-welded to form tubular members. Typically vehicle structural components are strengthened by adding steel and/or increasing the steel yield stress. However, increasing the amount of steel by increasing the thickness of the roof components and/or adding strengthening components increases the mass of the roof structure, which is an undesirable outcome. Increasing demands are being placed on vehicle manufacturers to reduce vehicle masses in order to reduce engine emissions, for example the United States Corporate Average Fuel Economy (CAFE) regulations which now mandate improvements in fuel efficiency for passenger vehicles of around 5% every year until 2025 [4]. Additionally, adding mass to the roof increases the height of the centre of gravity of the vehicle, which can increase the propensity of the vehicle to undergo a rollover.

There is therefore a need for passenger vehicle manufacturers to increase the strength of vehicle roofs while minimising structural mass. In a previous study by the author, the application of fibre composite strengthening systems bonded to the steel components of vehicles was assessed for the frontal crush tubes (front rails), for increased strength and energy absorption during frontal crashes [5]. The study demonstrated the substantial strengthening

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ability of such systems, and the light-weighting potential of fibre strengthened steel tubes used in place of steel-only tubes as structural components in vehicles. The application addressed steel tubes under uni-axial crushing, such as occurs to the energy absorbing crush tubes during a frontal crash [5].

In the present study the steel roof structure tubular components undergo large curvature bending during a roof crush test, which idealises the deformation of the roof structure during a rollover event [2]. The large curvature bending of thin-walled steel tubes has received considerable attention over recent decades, and the behaviour of rectangular and circular members is well known [6–10]. More recently, several studies have investigated the large curvature bending of thin-walled steel tubes strengthened with carbon fibre reinforced polymer (CFRP), manufactured by bonding carbon fibres to the steel surface of the tube [11,12]. Similar to other studies on the performance of steel tubes with externally bonded carbon fibres [13–19], substantial improvements in the strength of the steel tubes were achieved, where the moment resistance was increased by up to nearly two times with the application of bonded fibres [11]. In pure bending, the fibres in the compression zone delayed the onset of local buckling, while those in the tension zone provided enhanced bending resistance, thus allowing the moment to increase and maintain its value throughout large curvature bending, which also provided enhanced energy absorption.

Fibre–resin composites have been identified as a potential material for light-weighting structures, and already have extensive uptake in the automotive racing and aeronautical industries. However, the uptake of fibre–resin composites in the passenger vehicle market has been slow, and typically involves only non-structural components such as interior elements, bumpers, panels, cargo carriers, etc. This paper presents the novel approach of fibre strengthening thin-walled steel structural components used in vehicle roof structures (i.e. bonding fibres to the steel surface), in order to provide strengthening and increases in energy absorbing potential and/or for light-weighting of the vehicle structure.

2. Methods

2.1. General

This paper presents a numerical investigation of fibre strengthening steel roof components of passenger vehicle roofs. Numerical models of fibre strengthened steel tubes under large curvature bending were first developed and validated against experimental results [11]. Numerical models of two production passenger vehicles with the roof components subjected to large curvature bending were then developed, where the bending was generated by subjecting the vehicles to different roof crush test protocols, and these models were also validated against experiments [20–23]. The modelling approach developed and validated for fibre strengthened steel tubes was then applied to the roof structure components of the passenger vehicles. Separate models were also developed where the thicknesses of the original steel roof components were increased by several times, in order to compare the fibre composite strengthening approach with that of the increased steel approach. The commercial dynamic FEM package LSDYNA [24] was used for all of the numerical modelling. While both the experiments on steel tubes and passenger vehicles were performed quasi-statically, the explicit solver in LSDYNA was used in all models, since difficulties were encountered in achieving convergence with the implicit solver with the very large vehicle models. The strain-rate properties of all steel tube members, vehicle roof components and fibre-epoxy components were set to zero, so that the material strengths were not enhanced with the application of the load dynamically.

2.2. Experiments of fibre composite strengthened steel CHS under large curvature bending

The experiments on steel circular hollow sections (CHS) strengthened with externally bonded CFRP were reported in [11] and are summarised herein. The steel CHS had diameters (d) varying between 34 mm and 87 mm, thicknesses (t) between 0.9 mm and 2.7 mm, slenderness values (λ, Eq. (1)) between 24 and 180, and section classes between slender and compact [25]. All members were 1500 mm in length, however the ends were filled with plaster to avoid local crushing in the testing apparatus, which resulted in a tested length of 400 mm. The average measured 0.2% proof stress (f_y) and ultimate stress (f_u) values from quasi-static tensile coupon tests were 468 MPa and 504 MPa, respectively.

$$\lambda = \frac{d}{t}\sqrt{\frac{f_y}{250}} \tag{1}$$

High strength unidirectional carbon fibre was bonded to the exterior of the steel CHS with epoxy. The commercially produced high strength carbon fibre (MBrace CF 130) was nominally 3790 MPa ultimate tensile strength, 211 GPa elastic modulus and 0.176 mm thick. Several different fibre layouts were investigated, including combinations of transverse layers (fibres orientated around the circumference of the tube) and longitudinal layers (fibres orientated along the length of the member), hereafter termed layer directions '*T*' and '*L*'. Araldite 420A/B epoxy was used between the steel and the first carbon fibre layer, and each fibre layer thereafter. The most common fibre layout tested was two layers transversely with two layers longitudinally, thus this layout was considered in the present study. The members were subjected to large curvature bending using a pure bending testing apparatus [9–11].

2.3. Numerical models of fibre composite strengthened steel CHS

The numerical modelling approach developed previously [5] was based on the experimental observations that debonding of the carbon fibres from the steel and tensile fibre fracture was infrequently observed, such that the bond, bond failure and fibre fracture were not especially important in the model. These considerations were equally valid for the experiments considered in the present study [11], thus the previous approach of using laminated shells was adopted and is described herein.

The laminated shell approach consists of defining a single shell layer for the full thickness of the fibre–steel composite tube walls. Integration points through a laminated shell thickness may be defined arbitrarily; five integration points were defined for the steel thickness, and one integration point was defined for each of the layers of epoxy and carbon fibres (Fig. 1). All integration points defined an isotropic layer, which is appropriate for the isotropic materials of steel and epoxy. The carbon fibres were unidirectional, however were considered as orthogonal pairs (one transverse and one longitudinal) such that each fibre pair provides pseudo-isotropy. Thus each orthogonal pair of carbon fibres was considered as a single integration point, with a thickness of one fibre layer (0.176 mm). This assumes that the strength of the unidirectional fibres is zero in the transverse direction, which is a conservative assumption (the fibre properties in the transverse direction are typically taken to be around 10% of those in the longitudinal direction [26]). It was noted in the experiments that the results for CHS with two layers each of transverse (T) and longitudinal (L) fibre pairs were nearly identical regardless of the order in which the fibres were laid (sections CF-SL3B and CF-SL3D in Table 1), thus all specimens were modelled as 2T2L (Fig. 1), which simplified the modelling approach. The epoxy layers were simplified to one layer adjacent to the steel and an additional layer