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Crashworthiness analysis of glass fibre/epoxy laminated thin walled composite conical frusta under axial compression

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ABSTRACT

The quasi-static axial compression of thin-walled E-glass fibre/epoxy resin reinforced (GFRP) composite conical frusta was carried out to study the crashworthiness of conical shells. The hollow frustrated E-glass fibre reinforced polymer (GFRP) conical specimens having semi-apical angle ranging from 15° to 27° were fabricated using random ply chopped, plain woven roving cross ply [0/90], and uni-directional angle ply [±60°] oriented mats to the required dimensions by hand layup process. Quasi-static axial compression load was applied over the small end of the conical specimen with a crosshead speed of 2 mm/min using Universal Testing Machine (UTM). From the experiment results, the load deformation characteristics of thin GFRP composite conical shells were analyzed and the results were validated through finite element analysis package ABAQUS®. Further, the influence of ply orientation and the laminate wall thickness towards the energy absorbing capability of each GFRP conical specimen was studied. The buckling mode of collapse and the crushed zones of GFRP composite conical shells were also investigated to identify the collapse mechanisms involved in thin fibre/resin composite laminated conical specimens under quasi-static axial compression.

1. Introduction

The fibre laminated composite materials find applications in many fields including the hollow structures of transportation vehicles because of their high specific strength, modulus and high damping capability. Mostly, the laminated shell structures are introduced in the design of lightweight structures to reduce the total weight of the vehicle without sacrificing its high level of crashworthiness capability. It is necessary to analyze the crashworthiness of such structural members before implementing it in the actual field. In this regard, the researchers studied the influence of geometry of the structural members, different composite materials and their fibre ply orientation towards the level of crashworthiness. Price et al. [1] conducted experimental study on axial crushing of glass fibre–polyester composite cones and found that the cones with a wall thickness greater than 2 mm, fail by progressive crushing which starts at the small end. Unlike tubular specimens, no trigger is necessary. It is also found that the crashworthiness parameters such as specific energy absorption and absorbed energy of specimen increase with the increase in wall thickness and section diameter but decrease with the increase of the cone semi apical angle in a complex way. Ferreira and Chattopadhyay [2] found that increasing the slenderness ratio, indicates that shells of smaller radii are more efficient for energy absorption.

Mamalis et al. [3] studied the analytical modeling of the static and dynamic axial collapse of thin-walled fibreglass composite conical shells having semi apical angle 5–20°. The results of the study proved that the circular frusta of 5° semi-apical angle show the best crashworthy capability. It is also found that the absorbed energy due to friction between wedge-fronds and fronds-platen constitutes the most significant energy-absorbing source and it was estimated to be 48–50% of the total energy dissipated during the crushing process. A great amount of the energy absorbed, 40–45%, is also dissipated due to fronds bending. Tong et al. [4] studied the buckling analysis of laminated composite conical shells. Eight first-order homogeneous differential equations were derived for buckling analysis of laminated conical shells with the stretching-bending coupling under axial loads. The larger the stretching-bending coupling, the less critical buckling loads tend to be. Shadmehri et al. [5] proposed a semi-analytical approach to obtain the linear buckling response of conical composite shells under axial compression loading using the principle of minimum

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Nomenclature

C	chopped strand	M_{cs}	crushed composite conical shell mass (g)
D_b	bottom diameter of the conical shell (mm)	P_{avg}	average crushing load (kN)
D_i	internal diameter (mm)	P_{fst}	first peak load (kN)
D_m	mean diameter of the cone (mm)	P_{max}	maximum compressive load (kN)
D_t	top diameter of the conical shell (mm)	t	thickness of composite conical shell (mm)
E_{abs}	absorbed crash energy (J)	UD	uni-directional
E_s	specific crash energy absorption(J/g)	V_f	fibre volume content
H_c	height of conical shell (mm)	W	woven roving
H_d	axial deformation or compression height (mm)	α	semi-apical angle (°)
LUI	load uniformity index		
M_c	composite conical shell mass (g)		

total potential energy, and the corresponding governing equilibrium equations were solved by Ritz method. The results show that the critical buckling load decreases as the semi-cone angle (α) increases for all lay-ups. In between the range 0° and 20°, the reduction in critical buckling load is not to a considerable amount. Once α exceeds 20°, the reduction in critical buckling load is to a considerable amount, and it increases up-to 33% from initial value at $\alpha = 0°$. This reduction in buckling strength can be attributed to the change in the geometry of the conical shells. As α increases, the radius of the small side of the conical shell gets smaller, and consequently the critical buckling load decreases.

Marion Morthorst et al. [6] performed an experimental and numerical analysis on angled and axial crushing of conical composite shells. The analysis includes the study of influence of fibre type on the crushing response geometries with a half cone angle ranging from 5° to 25°. Stanislaw Ochelski et al. [7] executed an experimental assessment of energy absorption capability of carbon-epoxy and glass–epoxy composites. Mamalis et al. [8] proved that the composite having 0° layers does not possess a large ability of energy absorption because of lack of layers with the structure close to 90°, favoring fast growth of longitudinal cracks, which cause low level of energy absorption. Alkateb et al. [9] studied the energy absorption capability of axially crushed composite elliptical cones. A series of experiments were performed on the composite elliptical cones with the same ellipticity ratio with different vertex angles ranging from 0° to 24°. The elastic energy absorbed is reduced considerably by implementing the elliptical conical cross-sectional geometry, and the crushing behaviour of the elliptical cones is very sensitive to the change in the vertex angle. Mahdi et al. [10] investigated the effect of cone vertex angle on the crushing behaviour, energy absorption, failure mechanism and failure mode of filament-wound laminated (FWL) cone-cone intersection composite shells. The results indicated that the structure with vertex angles 20° and 25° exhibited good energy absorption capability. Mahdi et al. also [11] conducted an experimental work on quasi-static crushing behaviour of hybrid and non-hybrid natural fibre composite solid cones. An increase in cone vertex angles results in non-flatter load–deformation curves, and sudden large drops in load was related to the cone vertex angle, where the magnitude of the load drops depends on the type of fibre. Hybridisation of the coir fibre/polyester with oil palm fibre/polyester alters the mode of failure to non-catastrophic.

In addition to the fibre composite, thin-walled metallic shells were used along with fibre/resin laminate to increase the crashworthiness of the shell structures. These Fibre metal laminated (FMLs) structural members have been widely used as collapsible energy absorbers in structural crashworthiness applications such as the automotive and aeronautical industries to protect occupants and cargos. Different kinds of studies were made to understand the performance of fibre metal laminate technology for better crashworthiness application [12–16]. One of the studies [12] proved that the FML structures are having more specific energy and higher energy absorption capacity when compared with the same height of an axial compression of bare aluminium metallic specimens. However, the same study does not explain any data about the characteristics of pure GFRP conical shells towards the crashworthiness characteristics. Hence, it is necessary to study the standalone performance of GFRP composite shell structures.

In this aspect, the GFRP conical frustums having 15–27° semi-apical angles were tested and the results are exploited in this paper. Further, the performance of GFRP specimens is compared with the previous work [12] to evaluate the level of crashworthiness capabilities of individual structural members. The corresponding results would be more useful before the implementations of such structural members into the actual field of applications.

2. Specimen preparation

The thin walled truncated GFRP conical test specimens were fabricated by using commercial available 450 g/m^2 mesh density of random, woven roving [0/90], uni-directional [±60°] ply oriented E-glass fibre mats, and epoxy resin by hand layup method. Initially, five numbers of the conical shaped wooden mandrels were fabricated as per the specimen category dimensions and they were used as a mould. The outer surface profile of each wooden mandrel was traced using a plain cardboard paper to get the required truncated cone profiles or templates. Then each template was divided into six equal numbers of individual trapezoidal sections, and the corresponding individual sections were transferred to woven roving and uni-directional E-glass fibre mats to get the required ply orientated trapezoidal sectional laminas. The individual trapezoidal sectional laminas were assembled into a single ply or lamina and the same was wrapped on the wax coated wooden mandrel as shown in Fig. 1(a–c). The first ply was placed so that no significant gaps or overlaps resulted. Similar procedures were adopted to prepare successive plies. During lamination process, extreme care was taken so that the subsequent plies were laid up in-centred with respect to the preceding trapezoidal sectional laminas [17]. At the same time, the outer most of ply was prepared as a single lamina from respective E-glass fibre mat. Then it was over wrapped to encapsulate previous layers or plies. This prevents the building-up of discontinuities through the thickness of the specimen. Similar fabrication process steps were repeated to get the required ply orientated ([0/90], [±60°]) woven and uni-directional GFRP test specimens. However, the random ply orientated GFRP test specimens were fabricated using chopped strand mat of laminas without considering such trapezoidal sections.

There are six and twelve numbers of laminas prepared from each category of E-glass fibre mats, and then they were stocked