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A numerical study on the energy-absorption of fibre metal laminate conical frusta under quasi-static compression loading

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ABSTRACT

The energy-absorption (EA) of fibre metal laminate (FML) conical frusta under quasi-static compression loading is studied by performing virtual test. A progressive deterioration model combined with the conventional shell model is initially employed to simulate collapse behaviors of composite wrapped aluminium conical (CWAC) frusta. To sufficiently understand collapse behaviors, the stacked shell model is used to reproduce intralaminar damage and delamination. The numerical models are validated with available experimental results and the collapse behaviors of aluminium wrapped composite conical (AWCC) frusta are detailedly discussed. The effects of conical frusta with single and hybrid materials towards EA are investigated. The triggering mechanisms including inward and outward chamfer triggers, and convex and concave plug-type triggers are studied to better induce collapse modes of FML conical frusta. Results show that the stacked shell model has better predictive ability of collapse behaviors. The only difference between experiment and simulation is that the initial load is not perfectly captured due to specific conical profile, complex failure modes and hybrid fibre metal materials. The FML conical frusta with appropriate hybrid materials, such as AWCC frusta, present a higher EA capacity with an increase of 28.7% in SEA. The outward chamfer trigger and convex plug-type trigger can effectively improve EA of FML conical frusta.

1. Introduction

The occupant protection during unexpected crash event often necessitates the need for thin-walled buffer structures designed to absorb large amounts of impact kinetic energy in a controlled manner [1–6]. Hence, thin-walled buffer structures play a major role in automobile and aerospace application [7–9]. Early, for the lightweight application, thin-walled metal buffer structures were extensively investigated to gain a deep understanding of their axial crushing behaviors [10–16]. With the development of engineering material and fabrication technique, metallic materials applied for buffer structures have been gradually replaced by composite materials due to their higher specific strength, modulus and further reduction in weight [17–21]. Therefore, in the recent decades, various thin-walled composite buffer structures with different shapes, such as circular tube, rectangular tube, corrugated plate, conical structure, etc., have been put forward and their axial collapse behaviors have been studied [22–26]. Among various shapes, the conical composite buffer structures have recently attracted a great deal of attention among relevant researchers due to specific profile, high EA capacity and progressive collapse modes during impact loading [26,27].

Up to date, many researchers worldwide have reported the experimental and numerical investigations into the quasi-static or dynamic axial collapse responses of composite conical-shaped structures [26–31]. Also, more parameter studies, such as wall thickness, semi-apical angle and type of fibre, etc., were included in their works. Boria et al. [28] performed an experimental study on energy-absorption behavior of carbon fibre reinforced polymer truncated cones with different semi-apical angle under axial quasi-static and dynamic loading. It was found that the energy-absorption of truncated cones increased with the increase of wall thickness but the decrease of semi-apical angle. Morthorst et al. [29] conducted an experimental and numerical investigation into the axial crushing response of conical composite shells. This investigation analyzed the influences of fibre type and cone angle, ranging from 5° to 25°, on crushing response of the conical shell. Through a quasi-static crushing experiment of composite solid cones,

Abbreviations: SEA, Specific energy absorption; FEM, Finite element model; EA, Energy-absorption; FML, Fibre metal laminate; CWAC, Composite wrapped aluminium conical; CDM, Continuum damage mechanics; AWCC, Aluminium wrapped composite conical

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Mahdi et al. [30] mainly proved that an increase in cone vertex angles yielded non-flatter load-deformation curves. It was also proved that the sudden large drop in the crush load was related to the cone vertex angle, where the crush load value relied on the type of fibre. Kathiresan et al. studied the low-velocity axial impact collapse behavior and quasi-static axial compression behavior of E-glass fibre/epoxy composite conical frusta in Ref. [26,27]. For foam-filled conical structures, an investigation into the crushing force and energy absorption of foam-filled conical tubes under axial loading was also carried out by Lin et al. [31] by an analytical method. The influences of fibre reinforced orientation, fibre layer thickness, base angle and foam density on the energy-absorption capability were given. Despite the superiority of composite, bare composite conical frusta may collapse catastrophically under complex impact load conditions, which can lead to low EA.

The fibre metal laminate conical frusta with excellent performances have been widely used as collapsible thin-walled buffer structures of automotive and aircraft to protect occupants. The FML conical frusta simultaneously take the advantages of metal and fibre-reinforced composite. The metal laminate in FML conical frusta can provide ductile, stable plastic collapse mechanisms as they progressively deform in controlled and stable manner, which increases the energy-absorption during impact process. Recently, several studies were made about FML conical shells for better energy-absorbing applications [32,33]. Kathiresan et al. [32] studied the low-velocity axial crush behaviors and energy-absorption of aluminium conical and E-glass/epoxy composite hybrid aluminium conical shells through experimental and numerical procedures. The quasi-static axial compression behavior of bare metal and FML hybrid conical shell was experimentally and numerically studied in Ref. [33] by Kathiresan's team as well. Both of results proved that the FML conical shells yielded more specific energy and higher energy-absorption capacity when compared with bare aluminium metallic frusta. Meanwhile, both experiment and simulation showed broadly similar trend in load-deformation curves and collapse modes of FML conical shell. However, the delamination failure could not be simulated by the conventional shell model, resulting in that simulated local load-deformation curves were not accurate enough. In the impact failure of FML conical frusta, multiple failure modes of composites including fibre failure and matrix failure, delamination, etc. are fairly complicated. Thus, both the intralaminar failure and delamination are necessarily simulated to analyze complex failure mechanisms of FML conical frusta.

In this work, the axial quasi-static compression virtual test of CWAC frusta was conducted to study collapse behaviors and EA. The material deterioration model combined with single shell or stacked shell model was validated with available experimental data to expose the intralaminar damage and delamination. Based on stacked shell and deterioration model, collapse behaviors of CWAC frusta were studied and comparisons of EA between conical frusta with different materials were analyzed. Moreover, several typical triggers, such as inward and outward chamfer triggers, convex and concave plug-type triggers, were proposed to study links between triggering and EA mechanisms. Finally, the obtained results confirmed the quality of material deterioration model combined with different shell models. The present forecast analysis of crashworthy characteristics was summarized to give some advice for the crashworthiness design of hybrid conical frusta.

2. Experiment and specimen

Both of the detailed specimen preparation and axial compression test were directly obtained from Ref. [33]. The glass fibre/epoxy resin composite wrapped aluminium conical shell was fabricated by hand layup process. Firstly, the aluminium conical shell obtained from metal spinning process was placed over the conical-shaped wooden mandrel which was used as a mould for the fabrication of specimens. Then, the glass fibre lamina with the layup of $[0/45/90]_3$ was overwrapped on the outer surface of the hollow frustrated thin-walled aluminium conical specimen using hand layup method, constituting a hybrid shell. The hybrid conical frusta were shown in Fig. 1 and their dimensions were detailed in Fig. 2.

Fig. 1. The hybrid conical frusta [33].

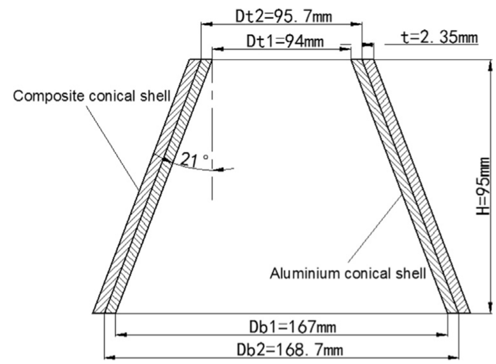

Fig. 2. Dimensions of hybrid conical frusta.

The axial compression test was performed on specimens with a crosshead speed of 2 mm/min. The compressed specimen was just placed in between the top and bottom rigid platen, and the specimens were progressively crushed by the top platen as a loading platen. The crushing response datum of bare aluminium conical and CWAC frusta were recorded up to 30 mm axial compression of specimen.

3. Deterioration model for glass fibre/epoxy composite

The deterioration of composite structures due to the axial crush loading commonly are composed of several coupled failure modes such as fibre tensile and compressive breakage, matrix tensile cracking, matrix compressive buckling and fibre/matrix debonding, etc. [34]. Among these complicated failure modes, the interlaminar delamination is assumed to be one of the most important failure modes, affecting the load capacity of thin-walled structures [35,36]. Therefore, both the intralaminar damage and interlaminar damage are simultaneously considered in the continuum damage mechanics (CDM) based deterioration model to simulate all kinds of failure modes.

3.1. Intralaminar damage theory

The intralaminar damage model used in this work refers to the plane stress formulation in Matzenmiller's work [37]. For each intralaminar damage mode, the ply constitutive model used in this model follows the general form schematically represented in Fig. 3.

Firstly, it can be seen from Fig. 3 that the intralaminar materials undergo an elastic deformation phase, which correspond to the path of OA. Meanwhile, the relation between the stress and strain during this stage is linear, and the material constitutive equation is given in Eq. (1).

$$\sigma_{ij} = C_d \cdot \varepsilon_{ij} \tag{1}$$

where σ_{ij} and ε_{ij} ($ij = 11, 22$ *or* 12) are the stress and the elastic strain respectively. Index 11, 22, 12 refers to the in-plane axial direction, transverse direction and shear direction, respectively. C_d is the damage