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On crashing behaviors of aluminium/CFRP tubes subjected to axial and oblique loading: An experimental study

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ABSTRACT

Thin-walled energy-absorbing structures rarely experience in pure axial loading in real crash events, but rather a combination of axial and off-axial loads. In this perspective, it is critical to understand the oblique crushing process of thin-walled structures. To address this issue, circular aluminum and carbon fiber reinforced plastics (CFRP) tubes were experimentally investigated for characterizing their crashworthiness subject to quasi-static axial and oblique compression in this study. The tests were conducted at five different loading angles (θ) of 0°, 5°, 10°, 20° and 30° to the tubal axis. Five sets of specific fixtures were fabricated to apply the desired axial and off-axial loads onto the aluminum and CFRP specimens, respectively. The failure modes, load-displacement curves, crushing force and energy absorption of all the specimens were analyzed; and the effects of loading angle were explored. It is found from the experiments that with the increase in loading angle, aluminum tubes were more prone to collapse in an irregular diamond mode ($\boldsymbol{I_d}$) instead of axisymmetric concertina mode ($\boldsymbol{A_c}$), while the CFRP tubes collapsed in much more complex failure modes which included splaying mode ($\boldsymbol{S_p}$), tearing mode ($\boldsymbol{T_e}$), socking mode ($\boldsymbol{S_o}$), micro-fragmentation mode ($\boldsymbol{M_f}$) and catastrophic failure ($\boldsymbol{C_f}$). As for the energy absorption characteristics, the loading angle (θ) ranged from 0° to 10° had little impact on the energy absorption for the both aluminum and CFRP tubes, nevertheless, the energy absorption of the CFRP tubes decreased more significant from θ = 10° to 30°, while that of aluminum tubes declined fairly steadily.

1. Introduction

Over years, conventional metals, e.g. aluminum/steel, are the dominant materials for thin-walled structures in automotive, aerospace and other industries for their excellent weight to energy absorption capacity under complex impact and/or crash conditions [1–4]. Recently, composite materials, especially carbon fiber reinforced plastics (CFRP), have gained growing popularity to replace conventional metals for their extraordinary capacity of lightweight to mechanical characteristics such as specific stiffness, strength, crushing force and energy absorption, which are considered superior to those of metals [5–10].

Traditionally, extensive studies on thin-walled metal and composite structures have been largely focused on the crash behavior, failure modes and energy absorption capacity under axial loading condition. For example, Andrews et al. [11] experimentally investigated the crushing behavior of thin-walled aluminum tubes under a quasi-static axial compression by classifying four different collapse modes with concertina, diamond, mixed and buckling failure. Langseth and Hopperstad [12] conducted experimental studies on the deformation modes and energy absorption of empty aluminum tubes under static and dynamic axial crushing. Many other researchers, e.g. Refs. [13–17], employed numerical simulation for predicting the plastic deformation and load carrying capacities of thin-walled energy-absorbing metal structures. As for composites, Mamalis [18] investigated the crashworthy characteristics of composite structures by observing the brittle failure modes, such as progressive end-crushing, local tube-wall buckling and mid-length collapse, through a series of static and dynamic axial compressive tests. More recently, Liu et al. [19,20] studied the failure mechanism and crushing characteristics of the CFRP square tubes filled with aluminum honeycomb under quasi-static axial and lateral crushing. Sun et al. [21] carried out substantial quasi-static axial crushing experiments to comparatively explore the crashworthiness performance of circular CFRP/aluminum/steel tubes with or without cellular fillers; and they concluded that the aluminum foam/honeycomb-filled specimens could produce a more stable progressive folding than the empty counterparts. These studies indicated that the loading-carry capacity, energy absorption and failure modes of thin-walled structures can be affected by such factors as sectional shape, geometric

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parameters and loading conditions [22–27], etc, significantly.

During an actual crash event, the thin-walled structures to be used as energy-absorbing components could seldom be subjected to a net axial crushing or net transverse bending, but more likely subjected to combination of these two loading cases at different extents. According to the requirements in automotive industry, for instance, a bumper system must bear an oblique load with up to 30° angle to the longitudinal axis [28]. As such, it is important to understand the crushing responses of energy absorber under oblique loading. Unfortunately, there have been relatively fewer studies on thin-walled structures that collapse at different oblique loadings to date. In this regard, for example, Reyes et al. [29] investigated the behavior and energy absorption capacity of obliquely loaded aluminum square tubes through substantial off-axial compressive tests; and further the experimental results were employed to verify the accuracy of numerical results. Song and Du [30] experimentally studied the energy absorption of five different circular GFRP tubes with different off-axial crushing angles, varying from 5° to 25° with an increment of 5°. Greve et al. [31] conducted the impact tests and simulated the fragmentation process of braided carbon/epoxy composite tubes under axial and oblique loading conditions. Furthermore, Qi and Yang [32,33] performed multi-objective design optimization of empty and foam-filled square columns, and a class of multi-cell tapered square tubes for improved crashworthiness under oblique crushing.

Recently, the studies on the crushing structures for axial and oblique loads have gained increasing attention [34–37]. For example, Zhou et al. [38,39] investigated the origami crash boxes and conventional square tubes subjected to axial and oblique loading; and they suggested that the origami crash box could be more desirable than the conventional square tube in range of loading angles. Li et al. [40] carried out the experimental studies on the deformation and energy absorption of empty and foam-filled aluminum tubes which were crushed under four different loading angles of 0°, 5°, 10°and 15°. Three deformation modes, namely axisymmetry, diamond and irregular diamond modes, were identified in the empty specimens. Sun and his coauthors [41–43] investigated the crash characteristics of the thin-walled functionally-graded structures under multiple loading angles by using finite element (FE) analyses. It should be pointed out that some researchers explored the crushing responses of composite tubes subjected to axial and oblique impact loads. Among them, Zarei [44] studied the simple and hybrid composite tubes with different number of E-glass fiber-reinforced epoxy overwrap. Othman et al. [45] investigated the performance of polyurethane-filled composite tubes made of E-glass/polyester. Zhu et al. [46] developed numerical models of aluminum, CFRP and aluminum/CFRP hybrid tubes to explore the effects of loading angles, wall thickness, CFRP stacking sequence and thickness of composite layers on the crashworthiness comparatively.

In spite of these abovementioned reports, systematic studies on tubal structures under oblique crushing conditions are still fairly limited, especially on the CFRP components in comparison with metal counterparts. The effects of loading angles on the collapse behavior and energy absorption remain to be an open question which does necessitate indepth studies through experiments.

In this study, five different loading angles (θ) of 0°, 5°, 10°, 20° and 30° were considered in the quasi-static axial and off-axial crushing tests. This paper reports the crushing behavior and crashworthy characteristics of thin-walled circular aluminum and CFRP tubes under axial and oblique loading. The load-displacement curves and failure modes from the experimental tests were analyzed. The effects of the loading angles on the collapse process and energy absorption capacity of these two different materials of specimens were investigated in detail.

Fig. 1. Specimens before quasi-static axial and oblique compression test.

2. Experimental procedures

2.1. Specimens preparation

Thin-walled circular aluminum and CFRP tubes were investigated for the crashworthiness under quasi-static axial and oblique loading conditions here, as shown in Fig. 1. The aluminum specimens were made of aluminum alloy 6063-T6, whose mechanical properties were summarized in Table 1 [51]. The CFRP specimens were made of 0°/90° woven carbon fiber T300/epoxy prepreg. The volume fraction of fibers was 56% and the properties of T300 yarns and resin are given in Table 2.

Table 3 summarizes the geometries of thin-walled aluminum and CFRP tubes, which have the same length and external diameter of 135 mm × 60 mm and a similar wall thickness. All the CFRP specimens comprise 5-ply laminates; whose thickness is 1.28 mm while the thickness of aluminum specimens is 1.35 mm. In this study, the final displacement was set to be 90 mm, which is 2/3 of the initial length (135 mm) for each specimen.

2.2. Fixture design

Five sets of dedicated fixtures were prepared, which were capable of experiencing in axial and oblique crushing with five different loading angles of 0°, 5°, 10°, 20° and 30° (Fig. 2). To ensure that no transverse load was generated to the testing system for protecting the machine from potential damage, two identical specimens were placed and tested simultaneously at the symmetric positions. It should be noted that all of the experimental data presented in the tables and figures of this paper were obtained from such a dual-tubal crushing test system.

As illustrated in Figs. 2 and 3, each set of fixture consisted of two essential blocks - a load block (VI) and a support block (VII). Except for the first pair of fixture (Fig. 2 (a) with a loading angle θ = 0°), the other four sets of fixtures consisted of five different parts. The top connecting plate (I) and the upper platen (III) were assembled to be a loading block (VI). A support block (VII) consisted of one bottom connecting plate (II), two lower platens (IV) and two stop blocks (V), which were fixed together with the two lower platens, respectively. The stop blocks were designed to limit the slip of tubular specimens; and the upper platens were kept parallel to the lower platen during the crushing test.

Table 1
Properties of aluminum alloy 6063-T6 [51].

Density/ kg/m^3	Young's modulus/ GPa	Poisson's ratio	Yield stress/ MPa	Ultimate tensile stress/ MPa
2700	70	0.30	162	192