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Experimental and numerical investigation into axial compressive behaviour of thin-walled structures filled with foams and composite skeleton

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ABSTRACT

This study investigated crashworthiness characteristics of a circular aluminum tube internally reinforced with a composite skeleton and aluminum foams subjected to quasi-static axial crushing load. For a comparative purpose, an empty tube and tubes with single reinforcement (aluminum foams or composite skeleton) were tested as well. The deformation patterns and several key parameters related to the crashworthiness of these structures were investigated and compared. The experimental results showed that the proposed design offered the best energy absorption characteristics, and the specific energy absorption increased by 32% compared to the empty tube. In order to explore the mechanisms of enhancement in energy absorption, the composite skeleton and the tube filled with separated foams were tested, and the strong interaction between foams and the skeleton has been found to have a very remarkable contribution to total energy absorption. Additionally, numerical models were built based on different material constitutive relationships and validated by experimental results. Further parametric studies were performed to investigate the effects of tube thickness, skeleton thickness and foam density on crashworthiness. It is found that tube thickness is more important to affecting crashworthiness, which provides a basis for structural optimization.

1. Introduction

Thin-walled structures have been widely used as energy-absorbing structures to protect occupants from injury in automotive manufacturers while collision occurs. The studies of the energy absorption of thin-walled steel tubes can be traced back to 1960s when Alexander [1] developed the theoretical formula to predict the mean crushing force of circular tubes. Wierzbicki and Abramowicz [2,3] extended the solution to square tubes. The accuracy of the theoretical predictions was validated by the experiments in the 1980 s and 1990s with a series of works by Abramowicz and his co-workers e.g. [4–7]. Guillow et al. [8] detailed the results of axial quasi-static compressive tests on thin-walled circular tubes based on aluminum (6060-T5), and they presented an empirical relationship, which can be applied to axisymmetric, non-symmetric and mixed modes of collapse. Al Galib and Limam [9] investigated collapse behaviour of circular aluminum tubes subjected to axial compressive loading and explored the influences of geometrical imperfections and material strain rate on the crashworthiness characteristics through experimental and numerical approaches. To sum up, the thin-walled circular metal tubes can be compressed in an axisymmetric, non-symmetric or mixed mode under an axial crushing load, with the formation of a series of progressive plastic folds. Additionally, the thin-walled tubes based on aluminum materials have superior specific energy-absorbing capability compared with steel materials.

More recently, the vehicle crash safety and environmental change due to exhausted gas emission have caused much more concerns. These issues drive the idea of developing better crashworthy structures which should be able to absorb maximum energy with minimum mass. Therefore, in order to further improve the energy absorption of crashworthy structures without adding too much weight, cellular materials such as metallic foams are usually taken as the filler inside thin-walled columns for their superior energy-absorbing capability. Also, it has been proven that the energy absorption of foam-filled column exceeds the sum of energy absorptions of the filler and the column due to the complex interaction effect [10–12]. There have been substantial studies available regarding the crushing behaviour of foam-filled column. Hanssen et al. studied the axial collapse behaviour of the foam-filled tubes under both quasi-static and dynamic loading conditions, and they proposed the theoretical formulas to predict average force, maximum force and effective crushing distance [13,14]. A comparative study of bending crashworthiness on different thin-walled structures, including empty tubes, foam-filled single tubes and foam-

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filled double tubes, were carried out by Li et al. [15]. They indicated that the foam-filled double tube had superior crashworthiness characteristics and therefore was recommended as an excellent crashworthy structure. Santosa et al. [16] explored the crushing behaviour of foam-filled squared tubes subjected to axial compressive loading by experimental and numerical approaches. The results showed that the mean crushing force of foam-filled column was positively related to the foam compressive resistance and cross-sectional area of the column. In fact, the energy absorption of foam-filled structures was found to be highly dependent on the foam density, where the higher the foam density, the higher the energy absorption. However, filling the thin-walled tube with high-density foam may lead to a lower specific energy absorption compared with the empty tube [17]. Therefore, the selection of the appropriate foam density is critical to optimise the crashworthiness of such structures.

Carbon fiber reinforced plastic (CFRP) composite materials, as a promising class of lightweight materials, have been recently used to replace the metallic materials in automobile engineering field for improving fuel economy and structural safety [18–21]. Continuing efforts have been devoted to the investigation into the crashworthiness characteristics for a range of CFRP applications [22–27]. The crushing behaviours of CFRP structures, not like metal materials, are dominated by fracture, inter-ply delamination and extensive microcracking development. Besides, three distinct failure modes, classified as mode I (progressive end-crushing mode), modeII (unstable local tube wall buckling mode) and mode III (mid-length collapse), respectively, can be observed in the compression tests of CFRP structures, and mode I is associated with the highest energy absorption [25]. Notwithstanding the lightweight feature and advantages in specific energy absorption (SEA) capacity, the CFRP materials are too much expensive to completely replace metallic components in the entire structure due to high material cost. Considering the material cost and weight reduction, the metal/composite hybrid structures were introduced by combining the low density and high strength of CFRP materials with low cost and high plasticity of metallic materials (e.g. aluminum) in crashworthy structures. There have been a number of published studies available regarding the crushing behaviour of various metal/composite hybrid structures [28–30]. In review of aforementioned literatures, these existing studies have largely focused on those hybrid structures that were made from an inner thin-walled column wrapped CFRP. It is less common to take the CFRP structure as the inner filler of thin-walled column, and there have been very limited studies available specifically addressing the crashworthiness characteristics of such structures.

Meanwhile, it is worth noticing that the energy absorption of CFRP filler may be significantly improved by filling some confinement system into the gaps between the tube wall and the filler. This is due to the fact that the confinement system can make the CFRP filler fracture progressively, which leads to a higher energy absorption. The present study proposed a new structural configuration to meet increasing lightweight and crashworthiness requirements in the automobile industry. Fig. 1 shows the combination configuration of the proposed design, in which the inner reinforcements of CFRP skeleton and aluminum foams were together filled into a circular aluminum tube. In order to investigate the crashworthiness characteristics, the axial quasi-static compression test was performed. To understand how each material was working in the proposed design, material characterization tests were also carried out. Additionally, a comparative study on the proposed design, the empty tube and the tubes with single reinforcement (foam or composite skeleton) was conducted to further explore the advantage in crashworthiness of the proposed design. The deformation patterns and several key parameters related to the crashworthiness of these structures were investigated and compared. The CFRP skeleton and the tube filled with separated foams were tested to explore the interaction effects between different materials. Furthermore, numerical models were built based on different material constitutive relationships and validated by experimental results. Finally, parametric studies were performed to provide a guideline for the best-performing configuration.

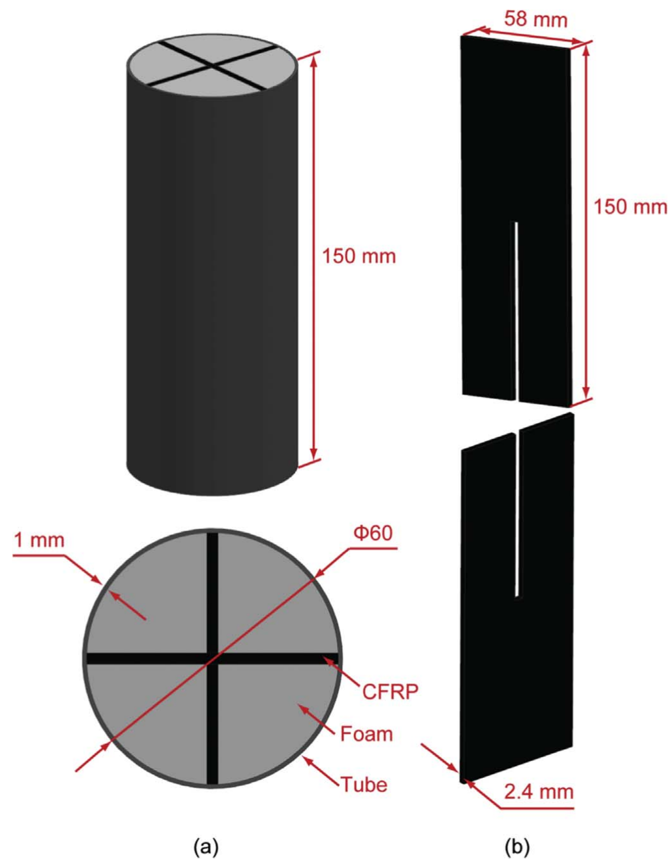

Fig. 1. The proposed crashworthy structure made of aluminum tube with inner reinforcements of aluminum foams and CFRP skeleton: (a) Crashworthy structure and its cross-section; (b) CFRP skeleton assembly.

2. Experimental testing

2.1. Specimens preparation

As illustrated in Fig. 1, the proposed design consists of a circular aluminum tube (60 mm in external diameter, 150 mm in length and 1 mm in wall thickness), a CFRP skeleton (2.4 mm in thickness, 150 mm in length and 58 mm in width) and aluminum foams. The CFRP skeleton was composed of two CFRP plates, which were cut and assembled in the way shown in Fig. 1(b). The CFRP plate was fabricated from plain woven carbon fiber produced by Toray industries with a stacking sequence of $[(0^\circ, 90^\circ)/(90^\circ, 0^\circ)]_6$ and epoxy resin by using a vacuum-assisted resin transfer molding (VARTM) process. Generally, the VARTM process consists of five steps, which include: (1) mold preparation and fabric lay-up; (2) sealing of the mold and creating a vacuum bag; (3) resin preparation and degassing; (4) resin impregnation; (5) curing of fabricated panels. The schematic diagram of the present VARTM setup is shown in Fig. 2.

In addition, another reinforcement consisted of four separated foams, which were inserted between the CFRP skeleton and the tube wall, as shown in Fig. 1(a). The foam considered in this study was closed-cell aluminum foam with the cell size of 5 mm. It was produced by a direct foaming technique, which include: (1) aluminum is melted; (2) calcium is added to thicken and stabilise the foam; (3) titanium hydride is added as a blowing agent. Electro Discharge Machining (EDM) was used to cut the foam materials to avoid cell-wall distortion.

For comparative purposes, the CFRP skeleton (C0), the tube filled with four separated foams (TF-S), the tube filled with CFRP skeleton (TC), the tube filled with an intact foam (TF-I) and an empty circular