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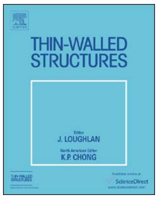

Full length article

Comparative analysis of crashworthiness of empty and foam-filled thin-walled tubes

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ABSTRACT

Quasi-static axial compression tests were conducted on two types of empty aluminum alloy tubes (circular and square) and five types of aluminum ex-situ foam filled tube structures (foam-filled single circular and square tubes, foam-filled double circular and square tubes, and corner-foam-filled square tube). The load-deformation characteristics, deformation mode and energy absorption ability of these structures were investigated. Several parameters related to their crashworthiness were compared, including the specific energy absorption, the energy-absorbing effectiveness factor, etc. The influence of physical dimension on the crashworthiness of these structures was explored. Dimensions of the inner tube were found to have significant influence on the structural crashworthiness of foam-filled double tubes. The averaged crush force, specific energy absorption, energy absorption per stroke and energy-absorbing effectiveness factor of thin-walled circular structures are higher than those of thin-walled square structures, respectively. Foam-filled single and double circular tube structures are recommended as crashworthy structures due to their high crush force efficiency and energy-absorbing efficiency.

1. Introduction

Structure crashworthiness is the ability to prevent excessive and injurious acceleration forces from being transmitted to the occupants and minimize the severity of injuries under the crash impact conditions [1]. The less damaged the vehicle and its occupants and contents after the given event, the higher the crashworthiness of the vehicle or the better its crashworthy performance. The increasingly interest in the safety and crashworthiness of vehicles has resulted in extensive researches on the structural response of thin-walled metallic tubes [2–5], which are the most conventional and effective energy-absorbing devices and have been widely used in applications such as aerospace and transportation.

Thin-walled structures are preferable in vehicles because they are excellent at dissipating impact energy by a progressive deformation when subjected to axial compressive loads. However, when the empty thin-walled tubes are subjected to non-axial loadings, the collapse mode may be relatively unstable globally with the tendency to Euler-type buckling, which is an undesirable energy-dissipating mechanism. Lightweight materials such as aluminum honeycomb, metallic foam and polymeric foam are used to fill the tubular structures to enhance their crashworthiness [6–10]. Metallic foams have excellent energy-absorption behavior, with an almost constant stress plateau and long stroke. Besides, the interaction between the foam and tube walls provides additional enhancement in energy dissipation. In order to improve the crashworthiness of thin-walled tubes, several alternative approaches have been examined, including the design of tube cross-section. Seitzberger et al. [11,12] and Nurick et al. [13] used a double-cell profile (two tubes with similar cross-section and one placed concentrically inside the other) arrangements, empty or filled with aluminum foam, to increase the energy absorption capabilities of thin-walled tubes. Li et al. [14–16] studied the bending and oblique loading of different tube structures experimentally, revealing that the energy absorption efficiency of foam-filled double tubes is superior. Meanwhile, foam-filled double tubes gains increasing attention from the researchers due to the advantages on crashworthiness under both axial and oblique loading [17–21]. The results demonstrate that the foam-filled bitubal configuration has more room to enhance the crashworthiness and can be an efficient energy absorber.

Different types of energy absorber systems have been proposed and efforts need to be devoted to more thorough understanding of the crashing behaviors and energy absorption characteristics of different structures. It is necessary to perform a comprehensive comparative analysis on the crashworthiness of empty and foam-filled thin-walled tubes and to present a set of well-accepted criteria to appropriately evaluate the energy absorption capacity of different kinds of tubular

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Table 1
Mechanical property of profile materials.

Specimen type		Specimen number	Specimen Size (mm)	Wall thickness t (mm)	Young's modulus E (GPa)	Yield stress σ_y (MPa)	Ultimate stress σ_u (MPa)	Uniaxial tensile rupture strain ε_r
Circular	Outer tube	3	Φ38 × 90	2.0	47	126	138	0.070
	Inner tube	1	Φ20 × 90	1.2	42	128	140	0.070
		2	Φ22 × 90	1.4	42	134	146	0.070
		3	Φ24 × 90	1.2	42	128	140	0.070
Square	Outer tube	1	38 × 38 × 114	0.9	53	160	192	0.089
	Inner tube	2	25 × 25 × 114	0.9	53	160	192	0.089
		4	25 × 25 × 114	2.0	52	203	227	0.089

structures. In the present study, quasi-static axial compression tests are conducted on two types of empty aluminum alloy tubes (circular and square) and five types of aluminum foam ex-situ filled tube structures (foam-filled single circular and square tubes, foam-filled double circular and square tubes, and corner-foam-filled square tube). The load- displacement characteristics, deformation mode and energy absorption ability of these structures are investigated and generally compared.

2. Experimental methodology

The thin-walled tubes used in the present study were made of aluminum alloy AA6063-T6. The average values of geometric dimensions and the mechanical properties obtained from the quasi-static tensile tests in accordance with Chinese Standard GB/T 228.1–2010 [22] are summarized in Table 1. As can be seen from Table 1, the yield strength of the circular tube material is slightly lower than that of the square tube. It is noted that there are slight differences in flow stress among the samples with different thickness, and this is probably caused by the variation of extruding ratio in the process of extrusion forming. The Young's moduli of aluminum alloy 6063 are a little lower than the reference value and this may due to the heat treatment. The difference in the Young's modulus of different tubes is probably caused also by the variation of extruding ratio in the process of extrusion forming.

A closed-cell aluminum foam used as filler material in the experiments, which is produced by liquid state processing using titanium hydride (TiH_2, 1–3 wt%) as a foaming agent, is the same as that used in our previous study [15]. The nominal density of the aluminum foam is $\rho_f = 0.45$ g/cm^3 and the average cell size is approximately 3 mm. The average values of the Young's modulus, compressive strength and plateau stress of the aluminum foam are $E_f = 625$ MPa, $\sigma_c = 9.74$ MPa and $\sigma_{pl} = 8.12$ MPa, respectively. Here, compressive strength (denoted with the subscript of c) is the plastic collapse strength of the aluminum foam, corresponding to the first peak load that reflects the initiation of the cell band collapse. For the calculation of plateau stress (denoted with the subscript of *pl*), the readers could refer to Ref. [23].

Two types of empty aluminum alloy tubes (circular and square) and five types of aluminum foam ex-situ filled tube structures (foam-filled single circular and square tubes, foam-filled double circular and square tubes, and corner-foam-filled square tube) were tested. The cross-sections of different structures used in the present study are shown in Fig. 1. Detailed information of the inner and outer tubes used is shown in Table 1. Aluminum foam fillers are cut from a block by wire-cutting technology and inserted into the tubes without any bonding. A test identification system was adopted where the sample name “CD32a” has the following meaning: the first letter C stands for circular tubes and S for square tubes. The second letter D stands for foam-filled double tubes (E for empty tubes, S for foam-filled single tubes, and C for corner-foam-filled tubes), and the following two numbers 3 and 2 correspond to the profile number of outer tube and inner tube listed in Table 1, respectively. Repetition experiments of identical specimens are distinguished by the last letter (a, b, c, …) in alphabetical order. However, these repetition numbers are usually omitted for comparison purpose with the denomination as “CD32” stands for the statistical results of identical tube structures.

Quasi-static compressive tests were performed on specimens to study their deformation modes and obtain their load displacement curves, from which energy absorption could be calculated. A MTS universal testing machine was used and no special fixtures (such as clamping devices) were used for the tests apart from the flat crossheads. The specimens were subjected to axial compressive loads at a constant velocity of 0.1 mm/s.

3. Experimental results

3.1. Load response

Tests were conducted twice at least under each identical test conditions to check variability of the experimental results and the load-displacement curves match very well. A typical load-displacement curve for quasi-static axial compression tests of thin-walled tubes is shown in Fig. 2a, together with some parameters. The curves of thin-walled tubes with different cross sections are given for comparison in Fig. 2b. It can be seen from Fig. 2b that the filling of aluminum foam increases the load-carrying capacity of the thin-walled tubular structures significantly. However, the strokes of the structures are reduced due to the filling of aluminum foam in the meanwhile.

3.2. Deformation and failure modes

Deformation modes of different thin-walled structures are shown in Fig. 3. Note that for empty square tubes (SE), the compact collapse mode [1] occurs, while the collapse mode of empty circular tubes (CE) depends primarily on the ratio of diameter and thickness (D/t). The empty circular tube collapses either axi-symmetrically (*the ring/concertina mode*) or non-symmetrically (*diamond mode*), see Fig. 3a.

For the foam-filled single square tubes (SS), some of them undergo progressive collapse when subjected to axial loading. Nevertheless, the foam filler provides constraint when the tube wall buckles inwardly and may cause tearing of the tube corners owing to the excessive tensile strain. Hence, the *split mode* occurs (Fig. 3b). When the tube splits along the corners, the end strips are bent outwards into curls. However, this mode is inefficient and difficult to control. Due to the introduction of inner tubes for foam-filled double square tubes (SD), the load carrying capacity and collapse stability of the structures are improved for that the inner tube undergoes successive deformation (Fig. 3c). Thus, with the inner tube taking the place of some of the foam core, the crush force of the structure is enhanced, even though the outer tube may still undergo the *split mode*. With some of the foams that provide constraint removed, the corner-foam-filled square tubes (SC) undergo the *progressive folding collapse mode* (Fig. 3d). As a result, the collapse stability and controllability of foam-filled tubes are greatly improved.

For the foam-filled single circular tubes (CS), the foam filler which prohibits inward bending of the outer tube changes the collapse mode from the diamond mode of the outer tube to the ring mode (Fig. 3b). Meanwhile, the plastic fold decreases and the number of folds increases with the presence of foam. A kind of spiral folding, characterized by