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Deformation and energy absorption of aluminum foam-filled tubes subjected to oblique loading

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ABSTRACT

Research to quantify the energy absorption of empty and foam-filled tubes under oblique loading with different loading angles and geometry parameters was carried out. Tests on circular tubes made of aluminum alloy AA6063 under quasi-static axial or oblique loading were performed. The collapse behavior of empty, foam-filled single and double tubes was investigated at loading angles of 0°, 5°, 10° and 15° with respect to the longitudinal direction of the tube. The tubes were fixed at both ends and oblique load was realized by applying a load at the upper end of a pair of specimens. When the foam-filled tubular structures subjected to oblique quasi-static loading, some new deformation modes, such as spiral folding mode, irregular extensional folding mode and irregular axi-symmetric or diamond deformation mode, were identified and ascribed to the bending of tubes and shearing of foam filler, as well as the interaction between the tubes and the foam. The energy absorption characteristics of empty and foam-filled single and double tube structures with respect to the load angle and wall thickness are determined. It is found that the energy-absorbing effectiveness factors of the circular tube structures with aluminum foam core are significant higher than those of the empty tubes and the energy absorption capacity of the foam-filled double tubes is better than that of the empty and foam-filled single tubes.

1. Introduction

The increasingly interest in the safety and crashworthiness of vehicles has resulted in extensive researches on the structural response of thin-walled metallic tubes, which are the most conventional and effective energy-absorbing devices and have been widely employed in the vehicle design and manufacture [1]. It was shown that the energy absorption capacity of the thin-walled tubes is significantly affected by parameters such as the cross-sectional shape, the geometry and size of the tubes, and the loading conditions [1,2]. Alexander [5] pioneered the studies on the energy absorption behavior of circular tubes under axial loading. Reviews of the studies on the axial crushing behavior of thin-walled tubes for the past five decades can be found in Jones [2], Reid [3], Alghamdi [4] and Lu and Yu [1]. Jones [2] discussed the dynamic plastic instability of different circular and square tubes subjected to large axial impact loads. Reid [3] focused on the progressive buckling, inversion and splitting of circular tubes. Alghamdi [4] briefly reviewed the conventional structures of collapsible energy absorbers such as circular tubes, square tubes, frusta, struts, honeycombs and sandwich plates and their most common deformation shapes. At the same time, various researches were tried out to increase the energy absorption of thin-walled tubes with the use of fillers [6–11]. The filling of cellular materials, such as honeycombs and foams, to the tubular structures is a common method which may tremendously improve the energy absorption efficiency of the tubes [1]. Not only the filler itself absorbs energy by plastic deformation, but also the interaction between tube and filler may change the original collapse mode of the tube into a more efficient collapse mode [1]. Seitzberger et al. [12,13] and Nurick et al. [14] 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. Guo et al. [15–18] also carried out experimental and numerical investigations on the performances of this new topological structure under axial crushing and three point bending conditions.

However, thin-walled tubes working as energy-absorbing devices will rarely experience either pure axial or pure bending loads in the real-world, but rather a combination of axial and non-axial loads, especially in actual vehicle crash events. Such loading

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conditions will cause the tubes to collapse via a combination of both axial and global bending modes. If the tubes deform in a global bending mode, there will be a considerable reduction in the energy absorption capability of the tubes, compared to axial crushing. Previously, only limited studies were carried out regarding oblique loading of thin-walled tubes. Han and Park [19] analyzed the crush behavior of square columns of mild steel subjected to oblique loads. In their experiments, the oblique load was realized by impacting the column at a declined rigid wall with no friction. Different angles were tested and the responses were divided into axial collapse, bending collapse and a transition zone. An empirical expression of the critical angle was given as well. Reyes et al. [20–23] carried out extensive studies on thin-walled aluminum extrusions subjected to oblique loading. In these studies, the responses of square aluminum extrusions [20], empty and foam-filled square tubes [21,23] and circular aluminum tubes [22] were examined through quasi-static experiments and numerical simulations. However, few of them have paid attention to the energy absorption characteristics of aluminum foam-filled double tubes subjected to oblique loading, whether through experimental or numerical investigations. A study aimed at the mechanical behavior of obliquely loaded foam-filled double tubes is necessary to give a better understanding of the energy absorption characteristics of this new topological structure.

For this purpose, experiments were carried out to investigate the deformation and energy absorption characteristics of aluminum foam-filled double tubes subjected to oblique loading and the results are reported in this paper. A test rig is designed and manufactured to perform the quasi-static oblique loading experiments. The deformation modes of three types of tubular structures, i.e. empty, foam-filled single and double tubes, subjected to oblique quasi-static loading and their energy absorption characteristics with respect to the load angle and wall thickness are determined and compared.

Fig. 1. The oblique loading rig used in test of tubular structures.

2. Details of experiments

In most situations the bumper is fully clamped in a vehicle. As the present investigation was motivated by the behavior of bumper beams placed in the front and rear ends of vehicles, circular aluminum tubes are studied and fully clamped boundary condition was selected for the present study.

2.1. Test setup

In order to avoid shear force during the oblique loading, which the test system cannot afford, two specimens were tested at the same time in the symmetrical position. That is to say, each experiment result is the combined effect of two identical specimens. Oblique loading was realized by a rig shown in Fig. 1. A pair of test specimens was clamped at both ends and the quasi-static force was applied through a rigid body placed at the top of the tubes.

The details of parts used to fix the tubes and to achieve oblique loading conditions are illustrated in Fig. 2. They consist of a fixing block (Fig. 2a), a fixing ramp (Fig. 2b) with an inclined plane of desired angle, and a fixing collar (Fig. 2c). For different load angle θ, different fixing ramp was chosen. Clamping was insured by the fixing block within the specimen and the fixing collar outside the specimen. For foam-filled double tubes, different fixing block was used for different inner tubes. For foam-filled single tubes, the fixing block was unnecessary. Two different assemblies, with or without the fixing block, are shown in Fig. 3.

An MTS810 test system was used for the experiments. Four load angles were applied in the tests: axial loading $\theta_1=0^\circ$ and oblique loading $\theta_2=5^\circ$, $\theta_3=10^\circ$ and $\theta_4=15^\circ$.

2.2. Terminology

A typical force–displacement curve for oblique crushing of a thin-walled tube is shown in Fig. 4. In order to have a better understanding of the experiment results, some parameters are defined in the following.

The total energy absorption E_t, which describes the energy absorption capacity of each pair of specimens, is defined as the

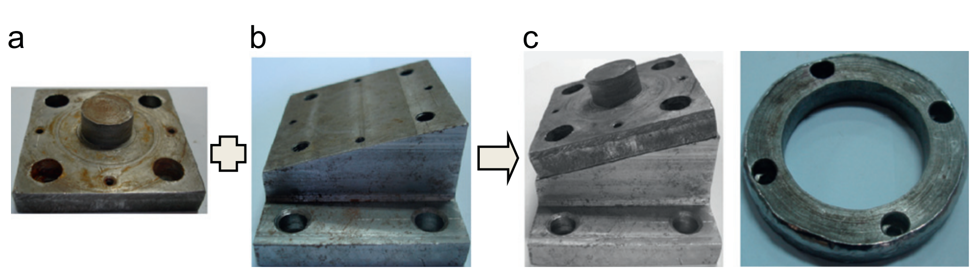

Fig. 2. The parts to clamp specimens in oblique crushing experiments.

integration of the force vs. deformation curve:

$$E_t = \int_0^S F(u)du, \tag{1}$$

where $F(u)$ is the crushing force as a function of crush distance u, and S is the displacement before the end point as shown in Fig. 4.

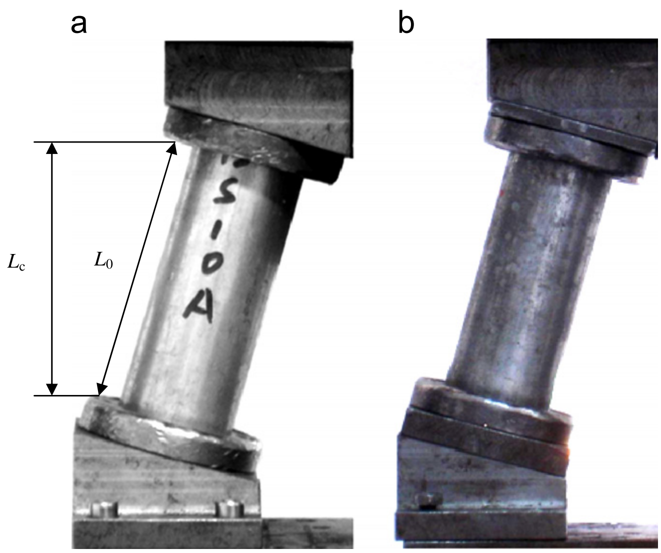

Fig. 3. Two different assemblies in the oblique crushing experiments: (a) without the fixing block and (b) with the fixing block.

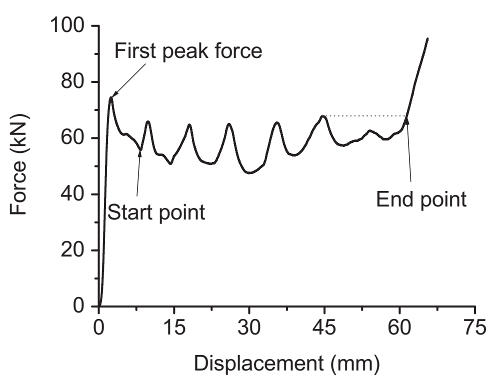

Fig. 4. A typical force–displacement curve for oblique crushing of a thin-walled tube.

Table 1
Mechanical property of profile materials.

Wall thickness t (mm)	Young's modulus E (GPa)	Yield stress $\sigma_{0.2}$ (MPa)	Ultimate stress σ_u (MPa)
1.2	56.2	166.5	193.3
1.6	60.2	184.4	215.5
2.0	53.5	203.7	229.2

The specific energy absorption, E_s, which is defined as the energy absorbed per unit mass, provides a way of comparing energy absorption capacity of structures with different masses and is given by

$$E_s = E_T/m, \tag{2}$$

where m is the total mass of the pair of specimens.

The geometric efficiency, S_{te}, also referred to as the stroke efficiency, is defined as

$$S_{te} = S/L_c, \tag{3}$$

where L_c is the projected length in the compressive direction (see Fig. 3).

2.3. Material properties

The material of the circular tubes used in the present study is aluminum alloy AA6063 T6. Uniaxial tensile tests were carried out to obtain the stress–strain curves under the guidance of China Standard GB/T 228-2002. The test specimens were taken out from the sidewall of circular tubes parallel to the extrusion direction. Table 1 summarizes the average values of mechanical properties obtained from the quasi-static tensile tests for the tubes of three different wall thicknesses. It is noted that there are slight differences in yield stress and ultimate 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 aluminum foam used as filler material in the experiments is a closed-cell foam provided by Luoyang Ship Material Research Institute, CSIC, China, and produced by liquid state processing using TiH2 as a foaming agent. The nominal density of the aluminum foam is $\rho_f = 0.45$ g/cm^3 and the average cell size is 3 mm. Cylindrical specimens were used in the uniaxial compression tests, which were cut from a block using an electric discharge machine. The diameter and height of the test specimens are 50 and 60 mm, respectively. The average values of mechanical properties obtained in the material tests are: Young's modulus $E = 625$ MPa, compressive strength $\sigma_c = 9.74$ MPa and plateau stress $\sigma_p = 8.12$ MPa.

2.4. Specimens

Empty tubes and foam-filled single and double tubes were tested. The sections of different structures are shown in Fig. 5. Two parallel tests were done for each combination. The diameter of the outer tubes used in most experiments is $d_1 = 38$ mm, and the thickness is $t_1 = 1.2$ mm. Two kinds of inner tubes are used in the foam-filled double tubes, of which the dimensions are listed in Table 2.

In order to analyze the effect of the outer tube, some further experiments were carried out with the other two kinds of outer tubes in Table 2. A test identification system was adopted where the sample name "15D12AB" has the following meaning: 15 is the load angle $\theta = 15^\circ$, D stands for foam-filled double tubes (E for empty tubes and S for foam-filled single tubes), 1 and 2 correspond

Fig. 5. Section view of empty and foam-filled structures.

Table 2
Dimensions of cylindrical tubes.

	Outer tube		Inner tube	
	Diameter (mm)	Thickness (mm)	Diameter (mm)	Thickness (mm)
1	38	1.2	–	–
2	38	1.6	22	1.6
3	38	2.0	24	1.2

to the type of outer and inner tube listed in Table 1, respectively. The last two letters A and B is the repetition number of each specimen in pair. The total length of the specimens is $L_0=90$ mm and the projected length in the compressive direction, L_c, varies with the load angle. All tests were quasi-static and a constant loading speed of 0.09 mm/s was applied.

3. Experimental results

3.1. Deformation mode

The deformation mode of tubular structures depends on the geometry parameters as well as the loading angle. The details of experimental results are summarized in Table 3. Typical photographs of deformed empty tubes are presented in Fig. 6. When a circular thin-walled tube is crushed axially, it collapses either axi-symmetrically or non-symmetrically, depending primarily on the ratio of diameter and thickness (d/t) [1]. For the value of d_1/t_1 in this study, when subjected to a small angle loading (load angle $\theta_1=0^\circ$ or $\theta_2=5^\circ$), the tubes may collapse in the axi-symmetric mode A_E (Fig. 6a). Due to the interaction between the two specimens tested at the same time, diamond mode D_E (Fig. 6b) was also observed. However, when subjected to a relatively large angle load the tubes may collapse with an irregular diamond mode, which is in an oblique way and possibly accompanied by overall buckling instead of the typically progressive buckling mode, here called mode I_E for short, see Fig. 6c. For the tubes with a larger wall thickness, $t_2=1.6$ mm or $t_3=2.0$ mm, only the axi-symmetric mode A_E occurred when subjected to pure axial loading and only the irregular diamond mode D_E with fewer lobes formed was found when subjected to oblique loading.

The main effect of aluminum foam filling of 38 mm-diameter empty aluminum tube is to shift the deformation mode from diamond mode to axi-symmetric mode, regardless the loading angle. Due to the interaction between foam and tube, the formation of folds is no longer typically progressive, and the axi-symmetric mode here is an irregular extensional folding mode E_F with all lobes moving outwards and the folds forming at different locations, generally not in a sequential manner, which is depicted in Fig. 7a. Although the specimens have the same deformation mode in the sense that compression wall buckled outward, one can see that there are some differences in the extent of the lobes. Also, the number of folds decreased with foam filling and hence the fold length increases accordingly.

When the foam filled tube is subjected to a large-angle oblique load, bending force acting on the tube will significantly affect the deformation of the tube that the lobes are formed easier on the compression side than on the tensile side. On the other hand, the foam, which acts as an elastic–plastic foundation for the sidewalls and affects their buckling distances, was subjected to a shearing force. Due to these factors, some folds were not complete, i.e. only part of the circumferential plastic hinge occurred out of the shearing zone. And the irregular axi-symmetric mode accompanied by the overall buckling mode, I_F mode (Fig. 7b) occurred. A new deformation mode, the spiral folding mode

Table 3
Details of the oblique loading experiments.

Sample	S_e	E_t (J)	E_s (J/g)	m (g)	Deformation mode	ψ
0D12AB	0.70	3524	26.7	131.9	E_F and D_F	32.61
0D12CD	0.69	3476	25.3	137.3	E_F and D_F	32.83
5D12AB	0.67	3331	24.6	135.4	E_F and D_F	32.39
5D12CD	0.71	3423	26.0	131.8	S_F and D_F	32.74
10D12AB	0.69	3515	25.4	138.4	I_F and I_F^*	31.27
10D12CD	0.75	3383	25.5	132.5	I_F and I_F^*	33.80
15D12AB	0.79	3286	24.8	132.1	I_F and I_F^*	27.91
15D12CD	0.77	3467	24.5	129.4	I_F and I_F^*	27.94
0S10AB	0.64	2272	16.9	133.8	E_F	30.66
0S10CD	0.64	2221	17.0	130.8	E_F	30.68
5S10AB	0.62	2283	16.8	135.8	S_F	32.11
5S10CD	0.58	2212	16.0	138.4	E_F	32.51
10S10AB	0.61	2323	16.7	139.3	I_F	34.15
10S10CD	0.64	2261	16.8	134.7	I_F	31.97
15S10AB	0.65	2130	15.8	134.9	I_F	30.79
15S10CD	0.65	2200	16.1	136.7	I_F	30.99
0E10AB	0.75	1169	21.1	55.4	A_E and D_E	22.68
0E10CD	0.75	1160	20.9	55.6	A_E and D_E	22.71
5E10AB	0.76	1203	21.6	55.6	A_E and D_E	23.71
5E10CD	0.78	1247	22.5	55.6	A_E and D_E	23.72
10E10 AB	0.81	1239	22.3	55.6	I_E	22.67
10E10CD	0.83	1254	22.6	55.5	I_E	22.69
15E10AB	0.89	1286	23.2	55.5	I_E	22.05
15E10CD	0.87	1215	21.9	55.5	I_E	22.25
0D13AB	0.65	2291	17.8	128.8	E_F and D_F	24.37
0D13CD	0.62	2143	15.8	135.6	E_F and D_F	24.58
5D13AB	0.60	2283	16.8	136.2	E_F and D_F	26.18
5D13CD	0.66	2279	18.0	126.4	S_F and D_F	26.32
10D13AB	0.66	2543	18.1	140.7	I_F and D_F	24.74
10D13CD	0.66	2325	17.8	130.6	I_F and D_F	24.89
15D13AB	0.74	2309	17.8	129.9	I_F and I_F^*	22.81
15D13CD	0.72	2327	17.6	132.5	I_F and I_F^*	23.01
0S30AB	0.63	3665	20.6	177.9	E_F	21.43
0S30CD	0.62	3587	20.4	176.1	E_F	21.26
5S30AB	0.63	3491	20.1	173.7	E_F	20.43
5S30CD	0.64	3612	20.9	173.0	E_F	20.05
10S30AB	0.59	3308	18.7	176.5	I_F	20.93
10S30CD	0.61	3405	19.4	175.4	I_F	20.90
15S30AB	0.67	3640	20.9	173.8	I_F	20.39
15S30CD	0.63	3403	19.3	175.9	I_F	20.27
0E30AB	0.67	2784	27.2	102.3	A_E and D_E	19.67
0E30CD	0.67	2737	26.8	102.3	A_E and D_E	19.77
5E30AB	0.72	2899	28.3	102.0	A_E and D_E	20.37
5E30CD	0.70	2952	28.9	101.9	A_E and D_E	20.42
10E30AB	0.80	3002	29.3	102.3	I_E	14.25
10E30CD	0.75	2214	21.6	102.3	I_E	14.30
15E30AB	0.81	2557	25.0	102.3	I_E	17.39
15E30CD	0.81	2831	27.7	102.3	I_E	17.38
0S20AB	0.62	3047	19.0	160.4	E_F	23.16
0S20CD	0.63	3106	19.5	159.1	E_F	23.08
5S20AB	0.63	2945	19.1	162.4	S_F	22.56
5S20CD	0.63	3002	18.9	159.1	E_F	22.66
10S20AB	0.62	2959	18.5	160.4	I_F	23.18
10S20CD	0.63	3006	18.8	159.5	I_F	23.39
15S20AB	0.69	3062	19.4	157.6	I_F	21.66
15S20CD	0.67	2963	18.7	158.2	I_F	21.79
10E20AB	0.79	2306	27.7	83.1	I_E	18.99
10E20CD	0.80	2176	26.2	83.1	I_E	19.50

(typical samples are shown in Fig. 7c), namely, S_F for short, was also observed but just a few times, in agreement with the findings of Guo et al. [24]. The spiral folding mode was characterized by spiral formation of lobes along the tube wall, rather than one by one folding in the axi-symmetric mode. This can be traced back to the heterogeneity of the foam filling, which causes the buckling of the sidewall to take place not along the same cross section, and thus leads to the dislocation formation of folds, especially when the tubes are subjected to oblique loads.

For the foam filled double tubular configurations investigated, the outer tube deformed in irregular extensional folding mode E_F

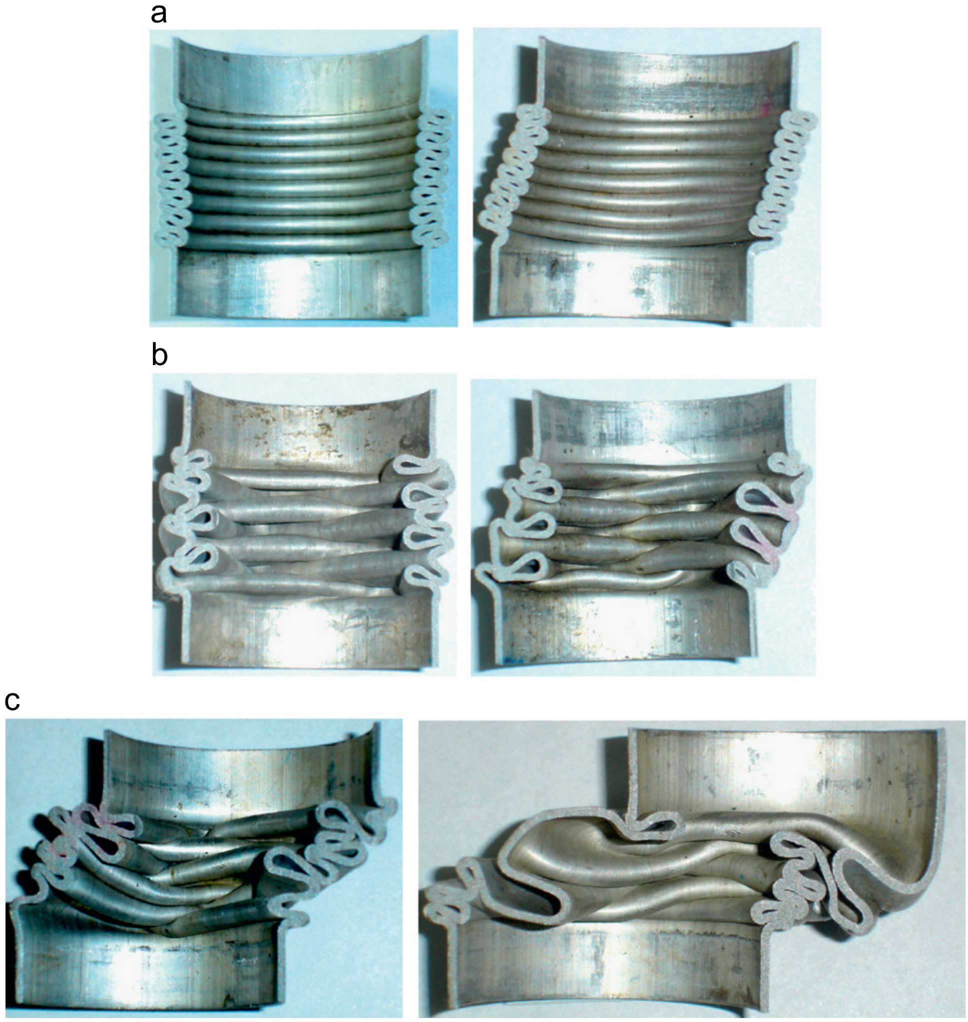

Fig. 6. Photographs of deformed empty tubes after tests: (a) axi-symmetric mode A_E, (b) diamond mode D_E and (c) irregular diamond mode I_E.

when subjected to small angle load, and irregular axi-symmetric mode I_F when subjected to larger angle load. In some rare cases, the spiral folding mode S_F was also observed, similar to the foam filled single tubes. However, two typical deformation modes were observed in the interior tubes, here called the diamond mode D_F (Fig. 8a-left) and the irregular diamond mode accompanied by the overall bending mode I_F^* (Fig. 8a-right). Progressive buckling was initiated in the inner tube but the interaction between the inner tube and foam would change its mode. When subjected to a relatively large angle load, the overall crush mode of the foam filled double tubes was influenced by the crush of the foam core which appeared mainly in shearing. In both of the two failure modes observed in the interior tubes, the inner tubes buckled in such a way that the lobe formation matched that of outer tubes through the shear band in foam, as highlighted in Fig. 8b. It can be found that the inner tube deformed in the irregular diamond mode, and the lobes moving outwards extruded the aluminum foam core. It is worth mentioning that the influence of geometrical parameters of tubes is less pronounced for the deformation modes of foam-filled aluminum tubes subjected to oblique quasi-static loading according to the experimental results.

3.2. Crushing force and energy absorption

The force–displacement curves of different tubular structures with outer tube wall thickness $t_1 = 1.2$ mm are compared in Fig. 9. Due to the good reproducibility of experiments, only one of the curves in two repetitions of tests is given. For all loading angles tested, the crush force of foam-filled tubes is significant higher than that of empty tubes. Moreover, the crush force of foam-filled double tubes is greater than that of foam-filled single tubes. On the other hand, the foam-filled structures become less compressible. Therefore, the stroke efficiency of foam-filled structures is smaller than that of empty tubes. Nevertheless, it was found that the relative reduction of the stroke efficiency of foam-filled double tubes is less than that of foam-filled single tubes.

In spite of the reduction in strike efficiency, the crush force of foam-filled structures is enhanced, especially for double tubes. The energy absorption of the foam-filled tubes is higher than that of the empty structures because of their high crushing resistance, as shown in Table 3. With the inner tube taking the place of some of the foam core, the compressibility of the foam-filled double tubes is much greater than that of the foam-filled single ones. And at the same time, due to the introduction of inner tube, the load carrying capacity of the structures is improved. As a result, the energy absorption of the foam-filled double tubes is higher than that of the single ones.

As can see from Table 3, the total mass of foam-filled double and single tubes are roughly the same, thus the specific energy absorption of double structures is higher than that of single ones under identical loading angle. And the experiment results have shown that the energy absorption efficiency of the traditional

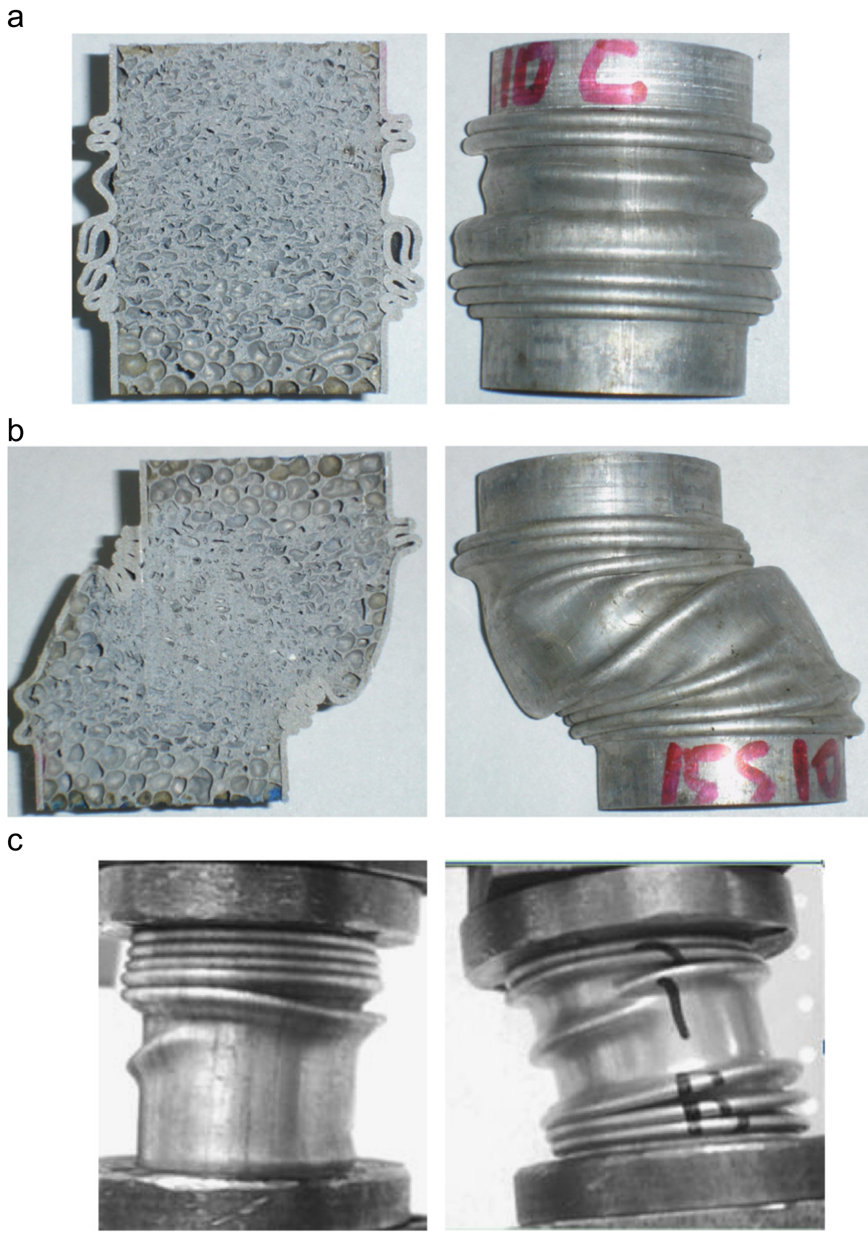

Fig. 7. Photographs of deformed foam-filled single tubes after tests: (a) irregular extensional folding mode E_F, (b) irregular axi-symmetric mode I_F and (c) spiral folding mode S_F.

single structures is lower than that of the corresponding empty outer tube, which agrees well with the previous conclusions. However, the new type of foam-filled structure is more efficient and the energy absorption efficiency can be higher than that of empty tubes under the fully clamped boundary condition.

3.3. Energy-absorbing effectiveness

To evaluate the efficiency of novel structures and new materials, an energy-absorbing effectiveness factor was introduced and defined as the quotient of the total energy, which can be absorbed in a system, to the maximum energy up to failure in a normal tensile specimen, which is made from the same volume of material [25]. And extensive studies have been carried out on the energy-absorption effectiveness factor [26]. In this study, all test specimens are of the same materials and of the same constraints so that this dimensionless energy-absorption effectiveness factor can be adopted to compare the effectiveness of the energy absorber for different combinations. The energy-absorption effectiveness factor ψ might be written in the form of

$$\psi = \frac{3P_m}{4\varepsilon_r(\sigma_{0e}A_e + \sigma_{0i}A_i + \sigma_f A_f)} \quad (4)$$

where P_m is the mean axial crushing force, ε_r is the uniaxial tensile engineering rupture strain, σ_{0e} and σ_{0i} are the static flow stresses of materials for the external and internal tubes, respectively. Similarly, A_e and A_i are the cross-sectional areas of the external and internal tubes, respectively, σ_f is the plateau crushing stress of the foam and A_f is the cross-sectional area of the foam infilling.

Table 3 presents the results from Eq. (4) for the empty tubes, foam filled single and double tubes subjected to oblique loads. These results reveal that the values of the static energy-absorbing effectiveness factors of the foam filled single and double tubes are larger than those of the empty circular tubes. Incidentally, the results show that ψ are similar for foam filled single tubes and double ones with an inner tube of type 2. In other words, from the

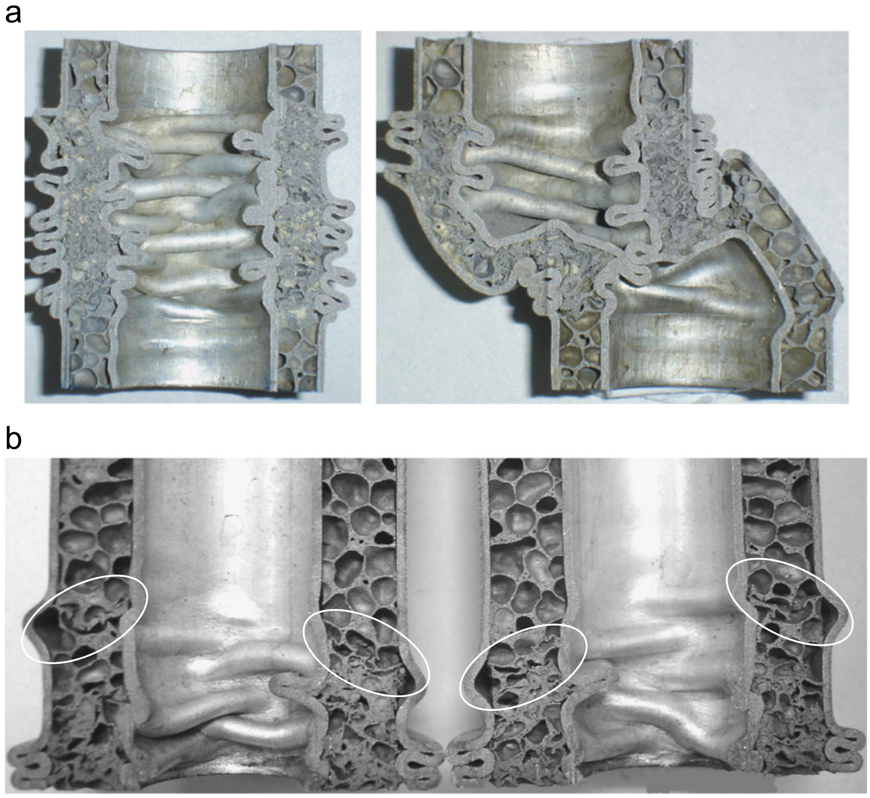

Fig. 8. Photographs of deformed interior tubes of foam-filled double tubes after tests. The deformation modes of inner tube are (a) diamond mode D_F (left) and irregular diamond mode I_F^* (right). Highlight of shear zone in the foam is shown in (b).

viewpoint of the static energy-absorbing effectiveness factors, it is advantageous to fill the thin-walled aluminum alloy circular tubes with aluminum foam. On the other hand, ψ decrease significantly with the increase in the wall thickness of the empty tubes and foam filled single tubes, as shown in Table 3. As for the foam filled double tubes with the same type of external tubes, a reduction in ψ occurs when replacing the internal tube of type 2 with type 3. This observation suggests a further study on the optimization of the foam filled tube structures.

3.4. Effect of load angle

Fig. 10 presents the crushing force–displacement responses of empty tubes with wall thickness $t_1=1.2$ mm under varying load angle. The mean crushing force remains fundamentally unchanged as the load angle increases, but the structural stroke efficiency increases as well. This is because that the possibility and extent of lateral shear deformation of the tubes become greater when the load angle increases. The compressibility and plastic deformation of the structure became larger, and so was the stroke efficiency. Thus, within the current range of load angles studied, the energy absorption capacity is enhanced as the load angle increases. This should be ascribed to the changes in deformation modes. When subjected to small angle loading, overall buckling occurred after folds were formed in the axial direction, hence the plastic deformation of structures became easier and more energy was absorbed. However, if the load angle is too large, the crushing force may decrease significantly, and so is the energy absorption efficiency.

Fig. 11 shows the crushing force–displacement responses of foam-filled single tubes under varying load angles. As the load angle increases, the mean crushing force of single tubes remains basically unchanged and the oscillation of crushing force is small, which is conducive to the stability of the structural load carrying capacity. This is mainly due to the special deformation mode of foam-filled tubes under small-angle oblique loading, i.e. irregular axi-symmetric deformation mode I_F. Under this deformation mode, the overall bending is obvious, and the aluminum foam is fully compressed. In particular, the regular periodic collapse is strangled and deformation becomes more complex, so the oscillation of crushing force is reduced significantly, but the load bearing capacity does not decrease. When subjected to small-angle oblique loading, the stroke efficiency and specific energy absorption of foam-filled single tubes remain nearly unchanged, but the energy absorption efficiency decreases slightly when the load angle is too large, at $\theta_4=15^\circ$. Moreover, the same conclusions can be reached for foam-filled single structures with outer tube wall thickness $t_2=1.6$ mm and $t_3=2.0$ mm under varying load angle.

Typical force vs. displacement curves of foam-filled double tube structures under varying loading angles are given in Fig. 12. Under small-angle oblique loading, the stroke efficiency and specific energy absorption of foam-filled double tubes remain unchanged, but the oscillation of crushing force is reduced gradually due to the special irregular diamond deformation mode I_F^*, especially for the case of load angle $\theta_3=10^\circ$. As a result, the load bearing stability is enhanced. But if the angle is too large, say, $\theta_4=15^\circ$ in this study, the overall bending is so serious that it degrades the load bearing and energy absorption capacities.

3.5. Effect of inner tube

In the current study, foam-filled double structure involves two types of inner tube, which have been shown in Table 2 as inner tube of type 2 and type 3. The inner tube of type 3 is larger than type 2 in diameter, but thinner. Outer tube of type 1 is selected, which is 38 mm in diameter and 1.2 mm in wall thickness. Fig. 13 depicts the crushing force–displacement response of foam-filled double structures with different inner tubes. Results show that

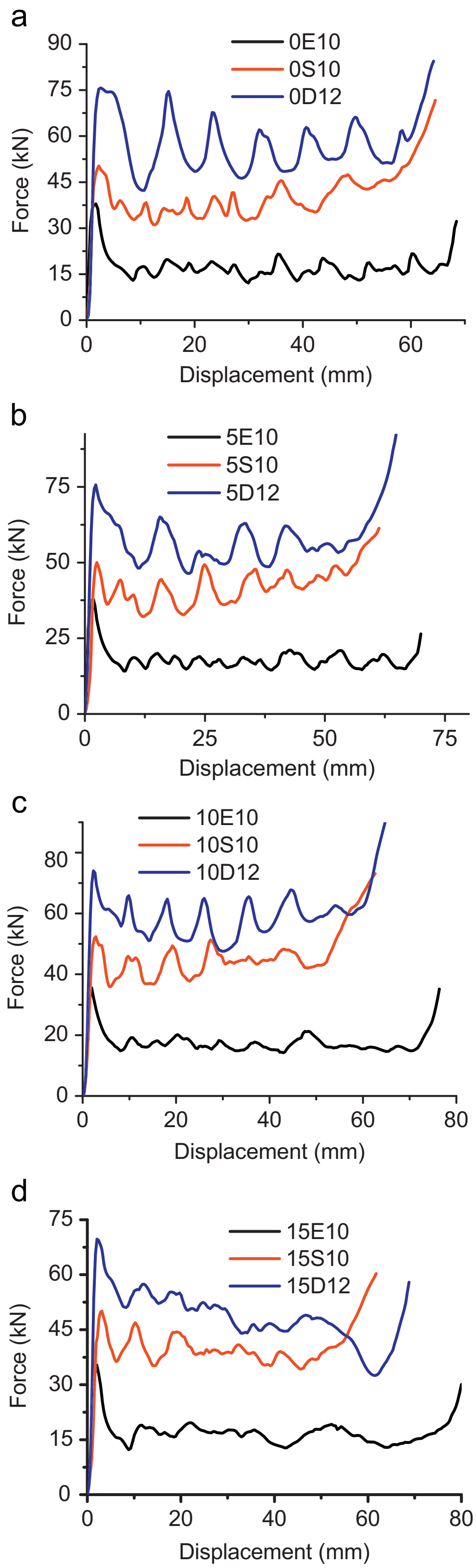

Fig. 9. The force–displacement curves of different structures under oblique loading condition: (a) $\theta=0^{\circ}$, (b) $\theta=5^{\circ}$, (c) $\theta=10^{\circ}$ and (d) $\theta=15^{\circ}$.

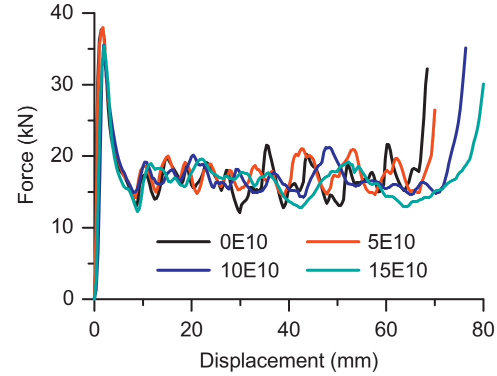

Fig. 10. The effect of load angle on the load carrying capacity of empty tubes with wall thickness $t=1.2$ mm.

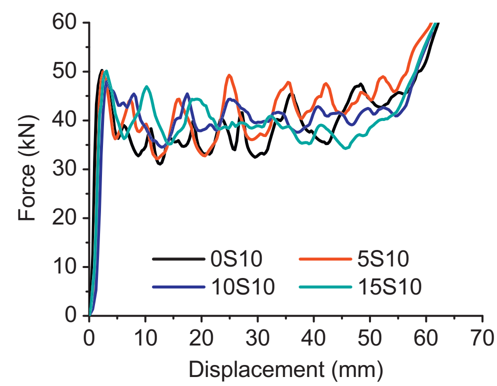

Fig. 11. The effect of load angle on the load carrying capacity of foam-filled single tubes with outer tube thickness $t=1.2$ mm.

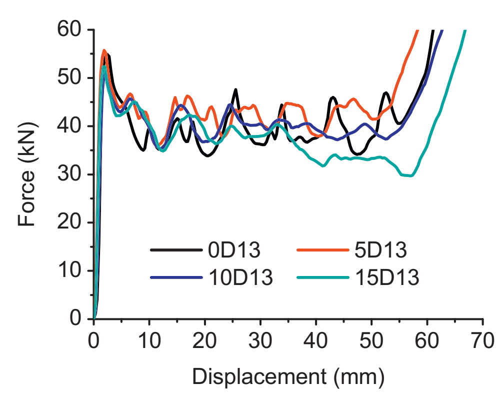

Fig. 12. The effect of load angle on the load carrying capacity of foam-filled double tubes with outer tube thickness $t=1.2$ mm.

the double tube structures with a larger and thinner inner tube of type 3 have a lower crushing force and lower stroke efficiency than the ones with type 2, in spite of that they deform more smoothly. In the case of a smaller inner tube (inner tube of type 2), the aluminum foam core takes a larger proportion in the foam filled structure, and the interference between inner and outer tubes is reduced during deformation. Therefore, the structure is more compressible and the stroke efficiency is relatively higher, in contrast with the case of the inner tube of type 3. With regard to the energy absorption, it is found that the total energy absorption and specific energy absorption of structures with a smaller and thicker inner tube is obviously higher than that of the structures with a larger but thinner inner tube.

4. Conclusions

The crushing behavior of empty, foam-filled single and double circular tubes subjected to quasi-static axial and oblique loads was studied experimentally and new deformation modes, such as

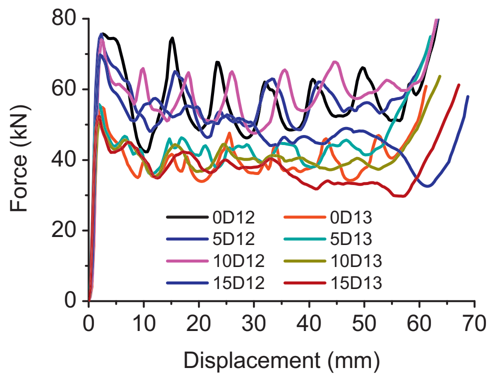

Fig. 13. Effect of inner tube on the foam-filled double tube structure under oblique loading: (a) $\theta=0^{\circ}$, (b) $\theta=5^{\circ}$, (c) $\theta=10^{\circ}$ and (d) $\theta=15^{\circ}$.

spiral folding mode, irregular extensional folding mode and irregular axi-symmetric or diamond deformation mode, were identified. Subjected to small-angle oblique loading, tubes experienced different degree of bending moment while the foam filler bore a larger shear load. These factors, together with the interaction between the tube and the foam, lead to complex deformation of foam-filled tubular structures under oblique loading.

For the specimens studied, the specific energy absorption of conventional foam-filled single circular tubes is not as good as that of empty tubes under current loading conditions, but the specific energy absorption of the foam-filled double tube structures is obviously higher than that of the empty ones.

For empty tubes with both ends clamped, as the load angle increases, the load bearing capacity is enhanced. However, if the load angle is too large, the stability of the structure would be reduced. With the increase of the load angle, empty tubes became more susceptible to bending deformation, and both the stroke efficiency and energy absorption efficiency of the structure are improved. For fully clamped foam-filled single or double tube structures the energy absorption efficiency is essentially unchanged with the increase of load angle, but the oscillation of crushing force is reduced gradually. The load bearing stability is enhanced as a result. However, if the angle is too large, the bending deformation is so serious that it degrades the load bearing and energy absorption capabilities.

An energy-absorbing effectiveness factor was also used to study the effectiveness of the three thin-walled tubular structures subjected to static oblique loadings. The comparison reveals that the energy-absorbing effectiveness factors of the circular tube structures with aluminum foam core are significant higher than those of the empty tubes.

The effect of inner tube diameter and thickness in the double structures is also discussed preliminary. It is found that the total energy absorption and specific energy absorption of structures with a smaller and thicker inner tube is higher than that of the structures with a larger but thinner inner tube.

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