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Crashworthiness of foam-filled thin-walled circular tubes under dynamic bending

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ABSTRACT

The bending crashworthiness of empty and foam-filled thin-walled circular tubes was investigated through dynamic three-point bending experiments. Three types of tubular structures with different configurations, including empty tubes, foam-filled single tubes and foam-filled double tubes, were tested. The load-deformation characteristics, failure modes and energy absorption capacity of different structures under dynamic loading were investigated and compared with the results of quasi-static tests. Several key parameters related to their crashworthiness were evaluated, including the specific energy absorption and the energy-absorbing effectiveness factor, thus the bending crashworthiness merits of foam-filled double tubes are identified. Due to their high dynamic bending resistance and energy-absorbing effectiveness, foam-filled double circular tube structures are recommended as crashworthy structures.

1. Introduction

Crashworthiness studies devote a great deal of attention to the behavior of thin-walled structures, which have been widely used as load bearing structures as well as energy absorbers in engineering practices such as in automobile and aeronautical applications [1]. The increasing interest in safety and crashworthiness of structures has led to a comprehensive research on the crashing responses of thin-walled tubes with different cross section geometries analytically [2,3], numerically [4,5] and experimentally [6,7]. Optimization studies on thin-walled structures for the crashworthiness design have also been carried out [8–10]. Studying the crashworthiness of thin-walled tubes subjected to bending is relatively new, because to date the investigations have mainly been focused on the collapse of thin-walled circular tubes under axial loading [11–14]. However, a previous study on real world vehicle crashes showed that up to 90% structural members involve failure in a form of bending collapse [15]. Moreover, it has been pointed out that axial progressive folding is easily reproducible only in laboratory experiments and thin-walled tubes working as energy-absorbing devices will rarely experience pure axial loads in a real crash event [16].

While the axial crushing of thin-walled circular tubes has been thoroughly investigated, the bending behavior of thin-walled circular tubes still needs to be determined. A comprehensive study on the deep bending collapse of thin-walled rectangular columns was first carried out by Kecman [17] and a simple failure mechanism consisting of stationary and rolling plastic hinge line was proposed. In order to investigate the potential for further structural weight savings, the earliest researches into the bending of aluminum foam-filled hollow sections were given by the numerical work by Santosa and Wierzbicki [18] and the experimental work by Santosa et al. [19]. They concluded that filling of foam improved the load carrying capacity by offering additional support from inside and increased the energy absorption. It was also pointed out that partial filling of foams increased the energy absorption to weight ratio of the structure. In the past few years, our group [20–22] have carried out systematic experimental and numerical investigations into the performance of different topological thin-walled structures under axial crushing, three-point bending as well as oblique loading conditions. However, the dynamic crashworthiness assessment of thin-walled structures subjected to three-point bending has been less documented.

In the present study, dynamic three-point bending behaviors of three types of thin-walled circular structures, i.e. empty tubes, foam-filled single tubes and foam-filled double tubes, are studied experimentally in detail and compared with the results of quasi-static tests. The deformation behavior and corresponding energy absorption of different thin-walled structures are investigated. Several key parameters related to the crashworthiness of thin-walled structures are assessed.

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2. Materials and experiments

Empty circular tubes and foam-filled single and double circular tubes were tested. The cross-sections of different structures used in the present study are shown in Fig. 1b–d, which are the same as those in our previous study on the oblique loading behavior [22]. The outer and inner circular 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 [23] are summarized in Table 1, where the wall thickness of the tubes are arranged in a sequential manner respectively.

The closed-cell aluminum foam used as filler material in the experiments is also the same as that used in our previous study [22]. The nominal density of the aluminum foam is $\rho_f = 0.45$ g/cm^3 and the average cell size is about 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.

Low-velocity impact three-point bending tests were conducted on a drop weight machine. The diameters of the cylindrical punch and the two supports are 10 mm. The total length L of a specimen depends on the ratio of the span L_0 to the outer tube diameter D, see Fig. 1. We chose $L = 190$ mm when $L_0/D = 4$ while $L = 270$ mm when $L_0/D = 6$. The crushing force–displacement response was recorded. The impact mass was approximately 24.23 kg and the drop height was 1418 mm which gave an initial kinetic energy of about 337 J, enough to crush the specimens in the experiments. An accelerometer was embedded inside the hammer just above the projectile tip to obtain the velocity and displacement history. For more details, the readers can refer to [24]. A test identification system was adopted where the sample name "D6S12a" has the following meaning: the first letter D stands for dynamic tests and S for quasi-static tests, the number 6 following the first letter denotes the ratio of the span L_0 to the outer tube diameter D. The second letter S stands for foam-filled single tubes (E for empty tubes and D for foam-filled double tubes), and the following two numbers 1 and 2 correspond to the profile number of outer tube and inner tube listed in Table 1, respectively. The last letter (a, b, c, ...) represents the repetition experiments of identical specimens in alphabetical order. In some cases, these repetition numbers are omitted with the denomination as "D6S12" stands for a kind of tube structure for comparison purpose.

3. Results

3.1. Load response

Typical load–displacement curves for dynamic three-point bending tests of thin-walled tubes are shown in Fig. 2a, together with the quasi-static curves for comparison. Three curves for each dynamic case are obtained and visual inspection of the curves revealed a good reproducibility of the experiments (data not shown). Thus, an average and standard deviation of the total energy absorption, the specific energy absorption and the energy-absorbing effectiveness factor with three repeated tests for every loading case are determined for comparisons purpose in Section 4. It can be seen from Fig. 2a that the load-carrying capacity of the thin-walled structures subjected to dynamic three-point bending is roughly at the same level as that in the corresponding quasi-static cases, though a little higher for some of the tests. However, the maximum displacements of the foam-filled structures subjected to impact bending are much larger than those of the corresponding tubes in the quasi-static tests. In contrast, the differences for empty tube cases are hard to distinguish.

Fig. 2a also reveals that the filling of aluminum foam increases the load-carrying capacity of the thin-walled tubular structures significantly. For both quasi-static and dynamic cases, the load-carrying capacity of empty tubes is the lowest, while that of foam-filled double tubes is higher and that of foam-filled single tubes is the highest, which is different from the results of thin-walled tubes under oblique loading [22]. It shows that the bending resistance of the foam-filled structures is enhanced due to the filling of aluminum foam because that aluminum foam plays a significant role in enhancing the resistance of local indentation. However, the foam-filled structures fail much earlier, especially the foam-filled single circular tubes, although their load-carrying capacity is relatively higher. The foam-filled double tube owns a nearly constant load-carrying capacity before failure and the maximum displacement of foam-filled double tube is about twice as that of the corresponding foam-filled single tube, indicating that more energy can be absorbed. This may be concluded from that local collapse occurs in the foam-filled single tube at a small loading

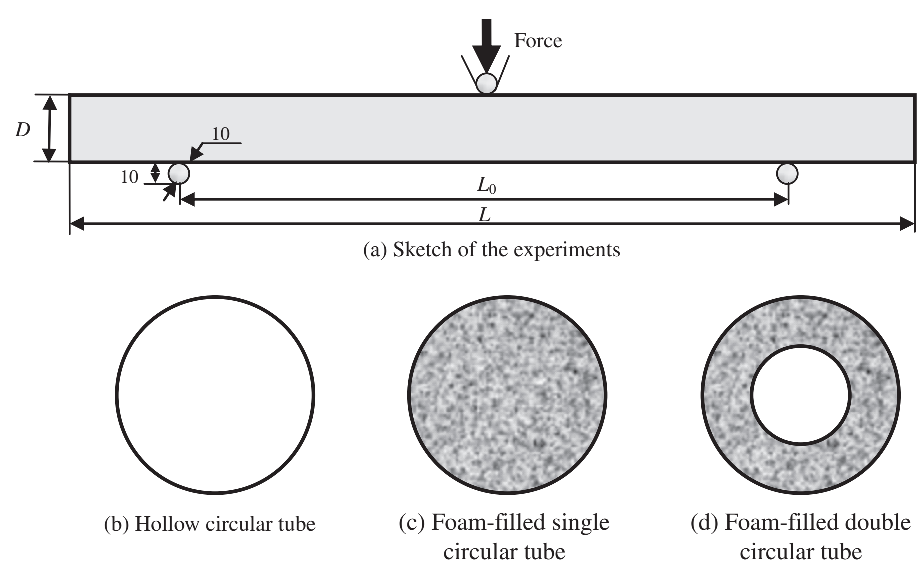

Fig. 1. The sketch of the experiments and the cross-sections of different structures.

Table 1
Geometric parameters and mechanical properties of profile materials.

Specimen type	Profile number	Section size(mm)	Wall thickness t (mm)	Young's modulus (GPa)	Yield stress $\sigma_{0.2}$ (MPa)	Ultimate stress σ_u (MPa)	Uniaxial tensile rupture strain ε_r
Outer tube	1	Φ38	1.0	45	135	140	0.070
	2	Φ38	1.6	45	145	152	0.066
	3	Φ38	2.0	45	130	138	0.070
Inner tube	1	Φ20	1.2	45	135	140	0.044
	2	Φ24	1.2	45	135	140	0.044
	3	Φ22	1.4	45	145	152	0.066

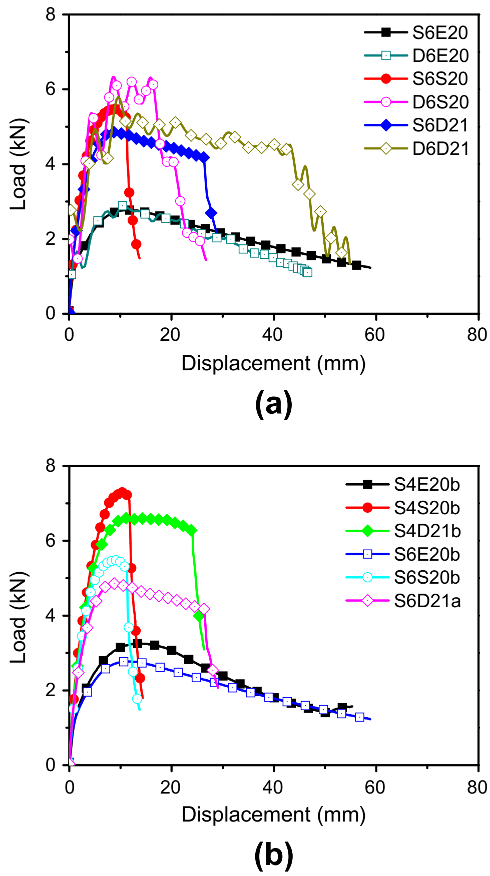

Fig. 2. (a) Typical load–displacement curves of dynamic and quasi-static three-point bending tests of thin-walled tubes and (b) comparison of load-carrying capacity of different structures subjected to quasi-static bending with different L_0/D.

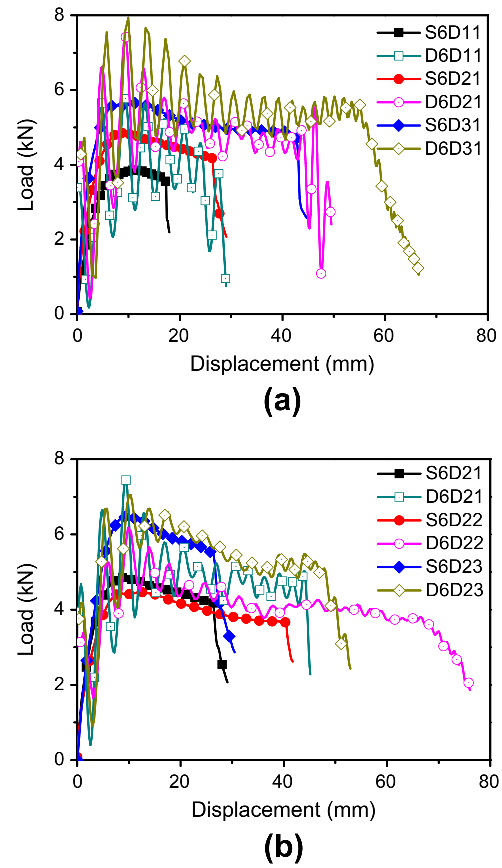

Fig. 3. Comparison of load-carrying capacity of foam filled double tubes (a) with different outer tubes thickness and (b) with different inner tubes.

displacement and thus its resistance drops significantly, which would then result in low energy absorption efficiency. Hence, the foam-filled double tube seems to be much better than the empty tube and foam-filled single tube in load-carrying capacity.

The effects of some key parameters, such as the outer tube thickness, the type of inner tube (different wall-thickness and diameter) and the ratio of the span to the outer tube diameter, on the bending responses of foam-filled double tubes are plotted and compared in Figs. 2b and 3. Although the effects of these parameters on the bending responses are similar between dynamic and quasi-static loading cases, the force–displacement curves are very different. In all cases, the curves of structures subjected to impact loading exhibit strong oscillation due to inertial effect, mostly resulted by the bending wave propagation. Thus, the curves of quasi-static loading are given for comparison in Fig. 2b. It can be seen from Fig. 3 that increasing the outer tube thickness will increase both the load-carrying capacity and maximum displacement. Enlarging the inner tube will increase the maximum displacement, and thickening the inner tube will increase the load-carrying capacity but may reduce the maximum displacement. As for different spans, the load-carrying capacity drops when L_0/D increases from 4 to 6 while the maximum displacement remains at the same level.

3.2. Deformation and failure modes

The deformation and failure patterns of empty and foam-filled tubes from dynamic bending tests are shown in Fig. 4 while Fig. 5 shows the quasi-static results for comparison purpose, in which all the outer tubes have the same diameter of 38 mm as shown in Table 1. The figures indicate that in all cases the deformation pattern and fold formation obtained from dynamic tests are similar to those observed in the quasi-static experiments. The

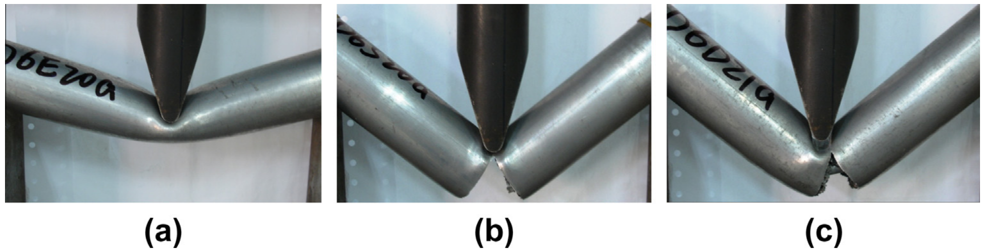

Fig. 4. Deformation patterns of thin-walled structures obtained from impact tests: (a) an empty tube, (b) a foam-filled single tube and (c) a foam-filled double tube.

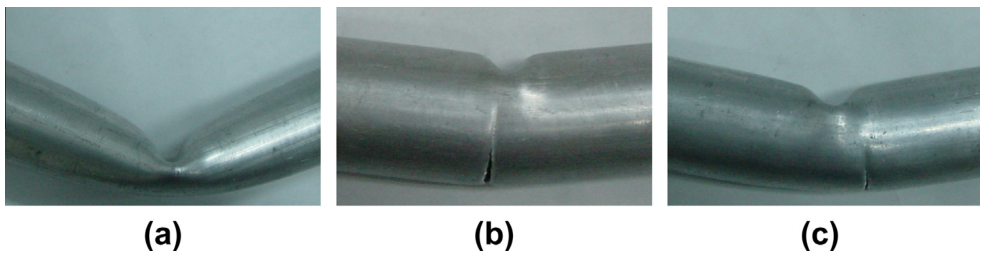

Fig. 5. Deformation patterns of thin-walled structures obtained from quasi-static tests: (a) an empty tube, (b) a foam-filled single tube and (c) a foam-filled double tube.

experimental results of loading and energy absorption characteristics together with collapse modes observed are tabulated in Table 2.

It can be found that a deep collapse occurs in the empty tube at the section along a hinge line just below the punch axis, as shown in Figs. 4a and 5a, while fracture occurs at the lower part of the foam-filled single tube due to excessive tensile stretching, as shown in Figs. 4b and 5b. The aluminum foam filler retards the inward fold formation by providing lateral support to the tube wall, thus the sectional collapse of tube is inhibited and the bending resistance is improved. However, the foam filler will also impede bending deformation of the foam-filled tube structure and increase the tensile stress of the tube just opposite to the loading point. Due to the tensile failure of the foam, the tensile stress in the outer tube will cause early rupture of the outer tube. As a result, thin-walled tubes filled with aluminum foams fail much earlier than those without fillers, which limits the energy absorption of the structures. A crack can be found in Fig. 5b and the maximum displacement of foam-filled single tube decreases dramatically, as can be deduced from Fig. 2a. On the other hand, Figs. 4c and 5c reveal that the foam-filled double tube follows a different deformation and failure pattern from the foam-filled single tube. Since the foam-filled double tube was filled partially while the inner tube was placed concentrically inside to replace some of the foam filling, two or more cracks can be found inside the foam core of the foam-filled double tube, which are located symmetrically on the two sides of the loading point. Numerical simulations have been performed to investigate the deformation and failure mechanism of these structures [20,21]. It shows that for foam-filled double tubes, the localized folding propagates to the adjacent sections rather than to reduce the cross section. Therefore, the foam filler and the inner tube insertion force the tubular structure to form more plastic hinge lines and give rise to bending crush resistance.

4. Discussion

The bending crashworthiness characteristics of thin-walled foam-filled structures, including the total energy absorption E, the specific energy absorption (*SEA*), and the energy-absorbing effectiveness factor ψ, are given in Table 2 in detail. As there is no obvious failure point in the bending responses of empty tubes, the results of empty tubes are not included in the comparisons of crashworthiness. However, previous studies have confirmed that the filling of foams to the tubular structures would tremendously improve the energy absorption efficiency of thin-walled tubes [1].

Three repeatability tests for each dynamic case are performed and the averages of the data of each condition are illustrated in Figs. 6–8 with the results from quasi-static experiments included for comparison purposes. Error bars denote the standard deviations of the results of specimens with the same geometrical characteristics and loading conditions.

4.1. Energy absorption

The area under the load–displacement curve up to failure represents the total energy absorption, E, which can be mathematically defined as

$$E = \int_0^{\delta} F ds \tag{1}$$

where F is the bending force, δ the maximum displacement and s the bending displacement.

Fig. 6 depicts the total energy absorption of different thin-walled structures subjected to dynamic and quasi-static bending. In all cases despite different spans, the total energy absorption of the foam-filled structures in dynamic tests is nearly twice as high as that of the corresponding structures in quasi-static tests. It can be seen that, the foam-filled double tubes 6D22, 6D31 and 4D21 absorb the most amount of energy, and the foam-filled single tubes 6S20 and 4S20 as well as the foam-filled double tube 6D11 absorb the least. The foam-filled double tubes have their own unique configuration, thus high bending resistance is maintained and more energy can be dissipated for foam-filled double tubes by retarding sectional collapse. The energy absorption of foam-filled double tube with a larger and thinner inner tube (inner tube No. 2 in Table 1) is more than those of the foam-filled double tubes with the other two types of inner tube. It is also found that the foam-filled double tubes with thicker outer tube can dissipate more energy within the parameter range of this study. This indicates that the foam-filled double tube configuration has more room to

Table 2
Details of the three-point bending experiments.

Samples	*m* (g)	δ (mm)	*E* (J)	*SEA* (J/g)	ψ	Failure mode
S6E20a	124.5	–	–	–	–	No crack
S6E20b	124.5	–	–	–	–	No crack
D6E20a	124.5	–	–	–	–	No crack
D6E20b	124.5	–	–	–	–	No crack
D6E20c	124.4	–	–	–	–	No crack
S6S20a	238.5	12.9	55.5	0.23	0.112	One crack
S6S20b	248.7	11.3	49.2	0.20	0.099	One crack
D6S20a	227.6	19.0	88.4	0.39	0.178	One crack
D6S20b	245.9	15.6	77.7	0.32	0.157	One crack
D6S20c	243.5	17.8	82.6	0.34	0.167	One crack
S6D21a	247.9	26.4	111.6	0.45	0.219	Multi-crack
S6D21b	246.0	27.7	115.7	0.47	0.227	Multi-crack
D6D21a	249.2	42.3	196.5	0.79	0.386	Multi-crack
D6D21b	244.0	43.1	203.5	0.83	0.399	Multi-crack
D6D21c	238.2	44.0	208.1	0.87	0.408	Multi-crack
S6D22a	249.4	40.3	155.6	0.62	0.298	Multi-crack
S6D22b	246.3	43.1	164.1	0.67	0.315	Multi-crack
D6D22a	237.3	66.9	279.7	1.18	0.536	Multi-crack
D6D22b	247.2	72.3	283.8	1.15	0.544	Multi-crack
D6D22c	240.2	81.2	294.0	1.22	0.564	Multi-crack
S6D23a	269.9	26.4	142.4	0.53	0.173	Multi-crack
S6D23b	268.9	26.3	143.6	0.53	0.174	Multi-crack
D6D23a	259.9	48.0	255.9	0.98	0.311	Multi-crack
D6D23b	259.8	46.3	238.4	0.92	0.289	Multi-crack
D6D23c	261.2	40.3	226.1	0.87	0.275	Multi-crack
S6D11a	220.3	17.3	56.6	0.26	0.149	Multi-crack
S6D11b	217.8	18.8	62.4	0.29	0.165	Multi-crack
D6D11a	224.4	27.3	101.1	0.45	0.267	Multi-crack
D6D11b	222.1	29.7	111.5	0.50	0.294	Multi-crack
D6D11c	222.9	25.0	105.9	0.48	0.279	Multi-crack
S6D31a	279.7	42.1	209.9	0.75	0.384	Multi-crack
S6D31b	281.5	27.6	140.3	0.50	0.257	Multi-crack
D6D31a	281.2	55.2	298.3	1.10	0.546	Multi-crack
D6D31b	279.5	60.2	306.3	1.10	0.561	Multi-crack
D6D31c	282.3	48.6	242.2	0.88	0.444	Multi-crack
S4E20a	87.5	–	–	–	–	No crack
S4E20b	87.5	–	–	–	–	No crack
D4E20a	124.6	–	–	–	–	No crack
D4E20b	124.5	–	–	–	–	No crack
D4E20c	124.4	–	–	–	–	No crack
S4S20a	164.3	13.3	70.4	0.43	0.202	One crack
S4S20b	172.2	11.7	64.0	0.39	0.184	One crack
D4S20a	170.6	23.1	151.1	0.89	0.433	One crack
D4S20b	156.3	21.0	115.0	0.74	0.330	One crack
D4S20c	172.3	19.8	137.7	0.80	0.395	One crack
S4D21a	172.8	26.3	139.8	0.81	0.390	Multi-crack
S4D21b	177.3	24.0	138.7	0.78	0.387	Multi-crack
D4D21a	166.5	51.0	286.7	1.72	0.800	Multi-crack
D4D21b	170.0	38.6	235.6	1.39	0.657	Multi-crack
D4D21c	167.0	56.0	313.1	1.87	0.873	Multi-crack

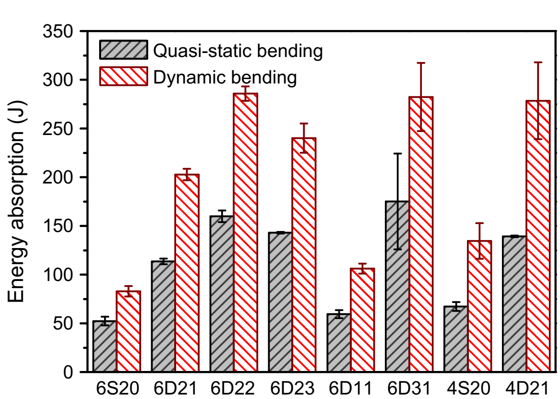

Fig. 6. Total energy absorption of different foam-filled thin-walled structures.

enhance the crashworthiness and can be an efficient energy absorber structure. Moreover, Zhang et al. [3] and Aktay et al. [12] demonstrated that the energy absorption of foam-filled structure is higher than that of the empty column as well as the sum of two separate components of the empty column and foam-filler as their own.

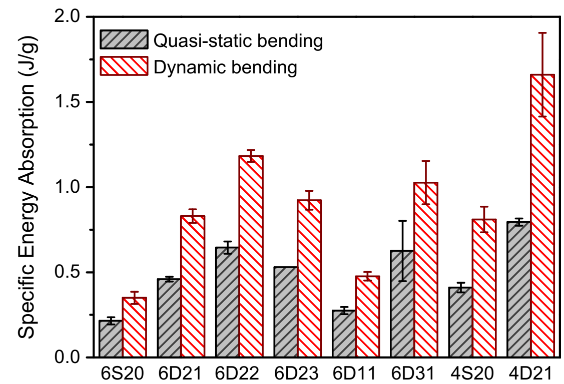

Fig. 7. Specific energy absorption of different foam-filled thin-walled structures.

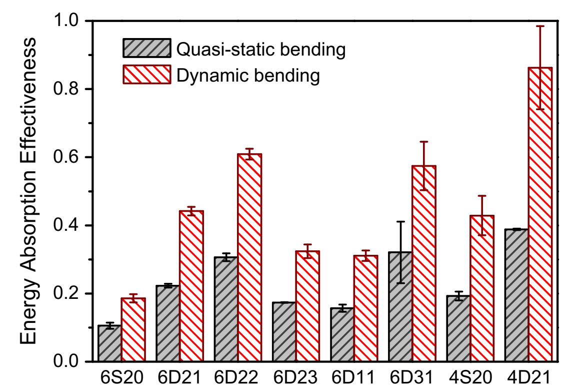

Fig. 8. Energy-absorbing effectiveness of different foam-filled thin-walled structures.

4.2. Specific energy absorption

The specific energy absorption (*SEA*) is one of the most important factors in the design of structures, such as cars, airplanes and motorcycles, where the weight efficiency is the main consideration. For the foam materials or foam-filled thin-walled structures, the *SEA* has been often taken as the design criteria for lightweight requirements in the literature [2–4,10]. It can be calculated by

$$SEA = E/m \tag{2}$$

where m is the total mass of the energy absorption structure.

The specific energy absorption of different foam-filled structures tested is compared in Fig. 7. It is clear from the figure that the specific energy absorption in bending crushing of foam-filled structures in dynamic tests is higher than those in quasi-static tests. Foam-filled double tubes absorb more energy per unit mass than corresponding foam-filled single tubes through bending collapse. In both the static and dynamic cases, the effect of the thickness of outer tube and inner tube on the specific bending energy absorption is almost the same as that on the total energy absorption. According to Table 2, it is worth noting that the gain in *SEA* reaches nearly 100% in bending collapse with an inner tube replacing some of the foam filling for circular tubes 6D21, 6D23 and 4D21, and even can reach up to 300% if the parameters of the foam-filled double tubes are optimized to achieve a higher weight-efficient energy absorption (6D22). Moreover, the experimental results show that the energy absorption efficiency of the foam-filled structures loaded with $L_0/D = 4$ is higher than that of the corresponding tubes loaded with $L_0/D = 6$, which agrees well with the previous conclusions in the present study. This may due to the difference in the hinge formation that corresponds with the bending load. With the same outer tube diameter, structures loaded with a longer span will bow more easily, causing a lower bending resistance. The tubes loaded with a shorter span have higher rigidity and will result in a smaller global deflection of the tube.

4.3. Energy-absorbing effectiveness

In order to compare the efficiency of tube structures made from different materials, an energy-absorption effectiveness factor has been introduced and extensive studies have been carried out on it [25]. In the present study, this dimensionless energy-absorption effectiveness factor can be adopted to compare the crashworthiness efficiency of different structures. The energy-absorption effectiveness factor ψ is defined as the quotient of the total energy, which can be absorbed in a system, to the maximum failure energy in a normal tensile specimen made from the same volume of materials. In the present study, it might be written in the form of [22]

$$\psi = \frac{E}{\varepsilon_r(\sigma_e A_e + \sigma_i A_i + \sigma_{pl} A_f)L} \tag{3}$$

where ε_r is the uniaxial tensile engineering rupture strain of the tube material. Here it is assumed that the maximum strain reached in the foam is equal to the uniaxial rupture strain of the tube material, though the locking strain of the foam is much larger than the rupture strain of the tubes [25]. σ_{pl} is the plateau stress of the aluminum foam, and σ_e and σ_i are the static yield stresses of the external and internal tube materials (corresponding to $\sigma_{0.2}$ in Table 1), respectively. Similarly, A_e and A_i are the cross-sectional areas of the external and internal tubes, and A_f is the cross-sectional area of the foam filling.

Table 2 presents the results from Eq. (3) for foam filled single and double tubes subjected to quasi-static and dynamic bending. The averaged values of the energy-absorbing effectiveness factors of different structures under different conditions are plotted in Fig. 8 for clarity. It is found that the energy-absorbing effectiveness of structures subjected to impact is generally higher than those subjected to quasi-static bending. Fig. 8 also reveals that when subjected to bending crushing, the energy-absorbing effectiveness factors of foam-filled double tubes are larger than those of the corresponding foam-filled single tubes, and this is consistent with the study in Ref. [3]. Incidentally, the results show that the effect of inner tube on ψ for foam-filled double tube is not simply the same as that on total energy absorption or specific energy absorption discussed in the previous sections. As for the foam-filled double tubes with the same type of outer tubes and identical loading conditions but different inner tubes, to take the tubes of 6D21, 6D22 and 6D23 for example, 6D22 has the highest energy-absorbing efficiency and 6D23 the lowest. However, ψ gradually increases with the increase of the outer tube thickness within the range of tests conducted. It can be concluded that the optimized foam-filled double structure could provide a better crashworthiness performance than a foam-filled single tube or an empty tube [3,22]. In all the cases, the value of energy-absorbing effectiveness factor $\psi < 1$. This is because the bending collapse of thin-walled tubes is localized in a narrow zone near the impact point and other part beyond this area does not work as an energy absorber.

5. Conclusions

The crashworthiness of thin-walled empty and foam-filled tubes subjected to deep bending collapse is studied experimentally in this paper. Three different types of circular tube structures are considered, including empty tubes, foam-filled single tubes and foam-filled double tubes. The load-deformation characteristics, deformation and failure patterns and energy absorption efficiency of these structures are investigated and compared. The foam filler and the inner tube insertion force the tubular structure to form more plastic hinge lines and give rise to bending crush resistance. Several parameters related to crashworthiness are evaluated, including the total energy absorption, the specific energy absorption and the energy-absorbing effectiveness factor. High bending resistance is maintained and more energy can be dissipated for foam-filled double tubes by retarding sectional collapse. Moreover, the foam-filled double tubes absorb more energy per unit mass than the corresponding foam-filled single tubes through bending collapse. The comparative study demonstrates that when subjected to bending, superior bending resistance and crashworthiness of foam-filled double tubes are identified in this study. It is concluded that the foam-filled double tube structure could provide a better bending crashworthiness performance than the foam-filled single tubes. Foam-filled double tubes are strongly recommended as crashworthy structural components for vehicle engineering applications due to their high bending resistance and energy-absorbing efficiency.

Acknowledgements

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