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Experimental studies on the quasi-static bending behavior of double square tubes filled with aluminum foam

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Abstract Quasi-static experiments were performed on empty tubes and aluminum foam-filled single and double tubes to study the effects of different filler arrangements on their three-point bending behavior. The load-carrying capacity and energy absorption of different structures are compared. The results confirm the advantage of the foam-filled structures. In particular, the double tube structure with aluminum foam filler enhances the load-carrying capacity, crashworthiness, and total and specific energy absorptions of the structure, in comparison with the foam-filled single tube. It was also found that increasing the wall thickness of the inner tube improves the performance of the structure within the experimental range, and adhesion between foam and tube has a negative effect.

1 Introduction

In many practical engineering systems, structures are required to absorb energy in the event of impact. During the past two decades, much research has been done to study the axial crushing behavior of thin-walled columns, which work as energy absorption members, in order to improve their capacity [1–3]. On the other hand, a study of the real world vehicle crashes by Kallina [4] showed that up to 90% involved structural members failed in bending collapse mode.

The first comprehensive experimental study of the bending behavior of prismatic columns was done by Kecman [5] in 1983. The bending resistance of an empty thin-walled column typically declines very significantly after reaching the peak force at a small rotation. The decrease of load-carrying capacity is due to the inward fold which significantly reduces the cross-section area of the crush zone. In order to achieve higher bending resistance and weight efficiency in energy absorption, ultra-light metal fillers such as aluminum foams were introduced into the thin-walled structures. The bending behavior of such structures was studied by many researchers in the past. Santosa and Wierzbicki [6] and Santosa et al. [7] studied the effect of foam filling on the bending resistance of thin-walled prismatic columns through numerical simulations and quasi-static experiments. It was shown that filling of foam improved the load-carrying capacity by offering additional support from inside and increased the energy absorption, and partial filling of foam increases the energy absorption to weight ratio of the structure. Chen et al. [8] performed an optimization for minimum weight on foam-filled sections under bending conditions. It showed the potential of thin-walled columns with aluminum foam filler for weight-efficient energy absorbers. Chen [9] studied the bending behavior of hat profiles filled with aluminum foam and found that filling of aluminum foam increased the specific energy absorption of the structures.

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Kim [10] studied the bending collapse behavior of a thin-walled cylindrical tube filled with several pieces of foams experimentally and numerically. He pointed out that the bending resistance of the tube with three pieces of filler is higher than that with one piece of filler.

Although filling of aluminum foam increases the bending resistance of thin-walled columns, it was found that columns filled with aluminum foam fail much earlier than those without filler, which limits the energy absorption of the structures. This is a common problem in the previous bending experiments. In order to improve the energy absorption of foam-filled structures while keeping high bending resistance, the quasi-static bending behavior of a new composite structure, i.e., a double square tube structure filled with closed-cell aluminum foam, is studied in this paper. Quasi-static experiments are performed to study the bending resistance and energy absorption of this new structure. The results are compared with those of empty tubes and foam-filled single tubes.

2 Experimental setup

2.1 Specimens

The specimens are divided into two groups by material of the outer tube as follows.

Serial AL: the material of empty tubes and the outer tube of foam-filled single and double tube structures is aluminum alloy. Different materials and wall thicknesses of the inner tube are considered. The effect of bond in foam-filled single and double tubes is also considered.

Serial SS: the material of empty tubes and the outer tube of foam-filled single and double tube structure is stainless steel.

Table 1 gives the dimensions of the square tubes used in the experiments. The parameters of specimens are listed in Table 2 where m_t denotes the mass per unit length. Figure 1 shows the section of the specimens investigated. The specimens are named according to the following rule. For example, the first letter S in specimen named “SMS12a” means square tubes, followed by the arrangement or filling status that E means empty tubes, S means foam-filled single tubes and M means foam-filled double tubes. The third letter S means quasi-static. The first number denotes the material type of outer tube, where type 1 is aluminum alloy and 2 is stainless steel. The second number denotes the wall thickness type of the inner tube which is shown in Table 1. The last letter is a serial number of each specimen type. In the above definition, the material of the inner tube is identical to the outer tube. When different material of the inner tube is considered, the specimen is denoted as “SMS AL0.9/SS0.6a” where AL0.9 is the outer tube and SS0.6 is the inner tube listed in Table 1. Unless clearly described in the test, no glue was used between the tube and the foam for foam-filled specimens. If the foam and tube were stuck with glue, specimens are defined like “SMS12aGlue”.

The tube materials used in the experiments are AA6063 T6 and stainless steel 202A. Their uniaxial tension test results are shown in Fig. 2. There are slight differences in material AA 6063 T6 with different wall thicknesses, which may be due to different extrusion ratios.

The closed-cell aluminum foam was provided by Zhaosheng Aluminum Foams Co. Ltd in Taixing, China. It was produced by liquid state processing using TiH_2 as foaming agent, similar to the method of Alporas [11]. However, the local scatter in density exceeds 25%. Uniaxial compression tests of the foam material were performed with the specimen dimensions of $\Phi 50\,\text{mm} \times 60\,\text{mm}$. Examples of results are shown in Fig. 3 where $\rho_{f.}$ denotes the apparent density of the tested samples. The shearing strength of the glue is 22–25 MPa at 20°C.

2.2 Experimental details

The arrangement of three-point bending tests is shown in Fig. 4. MTS809 Material Test System was used for the experiments. The diameter of the cylindrical punch and supports is 10 mm. The angle between the two

Table 1 The dimensions of the tubes (in mm)

	Outer tube-AL	Inner tube-AL	Outer tube-SS	Inner tube-SS
Outer width	38 × 38	25 × 25	38 × 38	25 × 25
Wall thickness1	0.9			0.6
Wall thickness2		1.2	0.6	
Wall thickness3		2.0		

Table 2 The measured specimen parameters

Specimen	Profiles (outer tube/inner tube)		Aluminum foam		m_t (g/mm)	S_{max} (mm)	E_{smax} (J/g)	D_{ind} (mm)	Remark[a]
	Thickness (mm)	Mass (g)	Mass (g)	Density (g/cm^3)					
Series AL									
SES10a	0.9/0	97.2/0	–	–	0.32	–	–	12.8	Y
SES10b	0.9/0	96.9/0	–	–	0.32	–	–	11.9	Y
SSS10a	0.9/0	96.9/0	142.9	0.36	0.80	22.9	0.45	5.3	Y
SSS10b	0.9/0	97.0/0	152.7	0.39	0.83	22.0	0.43	4.9	Y
SMS12a	0.9/1.2	97.2/93.9	84.2	0.43	0.92	37.2	0.84	10.6	Y
SMS12b	0.9/1.2	97.2/93.7	79.0	0.40	0.90	37.0	0.86	10.1	Y
SMS13a	0.9/2.0	97.2/144.2	88.8	0.44	1.10	33.5	0.98	7.6	Y
SMS13b	0.9/2.0	96.9/144.5	88.6	0.44	1.10	35.2	1.02	7.2	Y
SSS10aGlue	0.9/0	97.3/0	124.0	0.31	0.83	6.12	0.16	1.2	N
SSS10bGlue	0.9/0	97.6/0	132.5	0.34	0.91	5.97	0.14	1.5	N
SMS12aGlue	0.9/1.2	97.2/93.4	84.6	0.44	1.02	23.9	0.53	6.7	N
SMS12bGlue	0.9/1.2	97.0/93.8	86.3	0.43	1.05	25.4	0.58	7.0	Y
SMS AL0.9/SS0.6a	0.9/0.6	97.2/130.3	85.7	0.43	1.04	45.2	0.75	12.5	Y
SMS AL0.9/SS0.6b	0.9/0.6	97.0/129.5	84.2	0.43	1.04	44.3	0.72	11.8	Y
Series SS									
SES20a	0.6/0	231.5/0	–	–	0.77	–	–	10.4	N
SES20b	0.6/0	230.8/0	–	–	0.77	–	–	10.1	N
SSS20a	0.6/0	232.6/0	152.9	0.39	1.29	37.2	0.44	8.0	N
SSS20b	0.6/0	232.7/0	146.9	0.37	1.27	36.1	0.45	7.8	N
SMS21a	0.6/0.6	231.5/131.1	67.5	0.34	1.43	40.7	0.50	10.4	Y
SMS21b	0.6/0.6	232.2/131.5	72.0	0.35	1.45	41.8	0.52	11.4	Y

[a] Indicating whether the tube fold touched punch or not: *Y* yes, *N* no

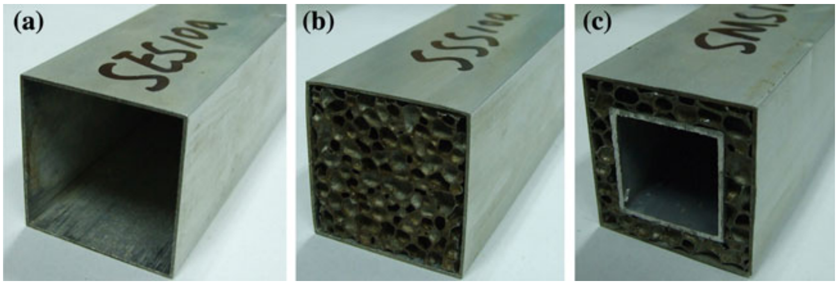

Fig. 1 **a** Empty tube, **b** foam-filled single tube and **c** foam-filled double tube

wedged sides of the upper punch is about 60 degrees. The length of specimens is 300 mm and the ratio of the span L_1 to the side length of out profile D is $L_1/D = 6$. A constant loading velocity of 0.2 mm/s was applied to the specimens.

2.3 Definitions

In order to make comparisons of experimental results easier, the following definitions are used in the paper.

$E(S) = \int_0^S F\mathrm{d}s$ denotes the energy absorbed by the structure up to a displacement of S. When the maximum displacement S_{max} at failure is used, the associated E_{max} represents the total energy the structure can absorb. Here, S_{max} is defined as the displacement when the force of the structure falls sharply at the end stage, as shown in Fig. 5 by the vertical dash line.

$E_s = E/m_t$ denotes the specific energy absorption to describe the mass efficiency of the structure, where m_t is the total mass of a specimen. Again, when E_{max} is used, then E_{smax} represents the maximum specific energy absorption of the structure.

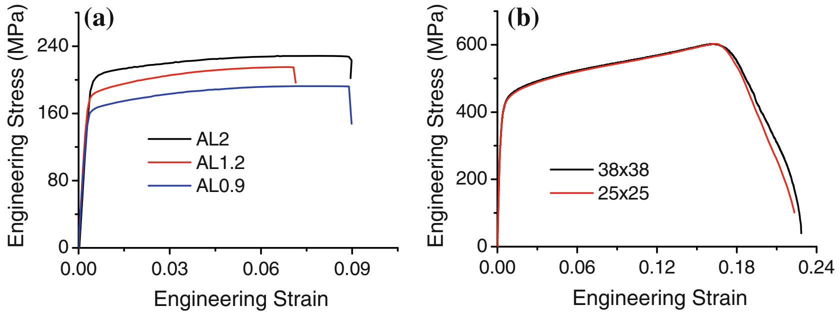

Fig. 2 The uniaxial tensile stress–strain curves of samples cut from the tube materials (**a**) AA 6063 T6 of different wall thickness and (**b**) stainless steel of different tube sizes

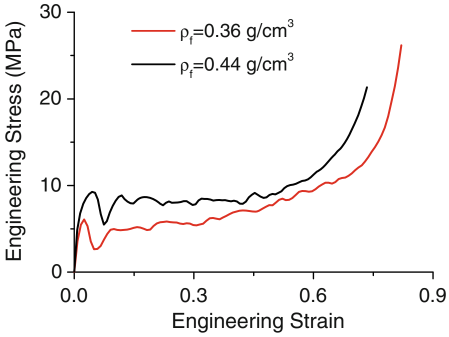

Fig. 3 The uniaxial compressive stress–strain curves of aluminum foams

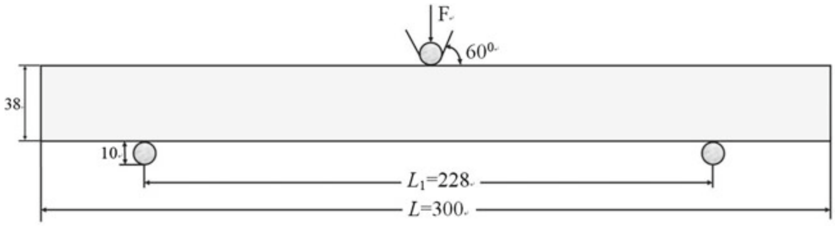

Fig. 4 The arrangement of three-point bending tests

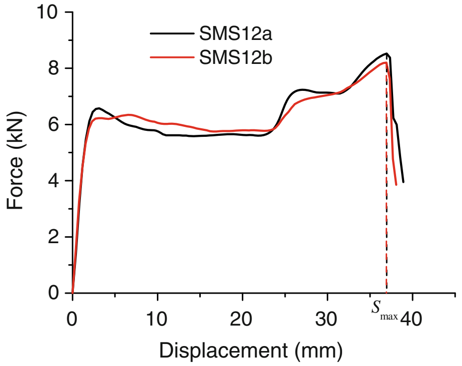

Fig. 5 The force-displacement curves of SMS12 specimens showing the reproducibility of experiments

3 Experiment results and discussion

3.1 Reproducibility of experiments

The force-displacement curves of two SMS12 foam-filled double tube specimens are shown in Fig. 5, indicating a good reproducibility of experiments. Since the experiments are repeatable, only one curve for each structure is used in the following figures.

3.2 Deformation mode

The final deformation of different structures is shown in Fig. 6. The deformation patterns of these structures are very similar, but the fold sizes are different. The fold size of the foam-filled single tube is the smallest, while that of the foam-filled double tube is larger, and that of the empty tube is the largest. Comparing with foam-filled structures, the indentation of the empty tubes is obvious. The indentation depth D_{ind}, defined as the vertical distance from the highest point to the lowest point of the indentation, was measured and listed in Table 2 for comparison.

Since the foam did not adhere to the tube, slide could happen between the foam and the tubes. As shown in Fig. 6, only the sliding in the foam-filled single tube is obvious and the foam ruptured into two separate parts at the center part, which affects the energy absorbed by the structures.

All the foam-filled structures failed with cracks but no crack was found in the empty tubes. The major difference between Series SS and Series AL is that the indentation depth of the former is less than that of the

Fig. 6 Final deformations of specimens of (**a**) Series AL and (**b**) Series SS

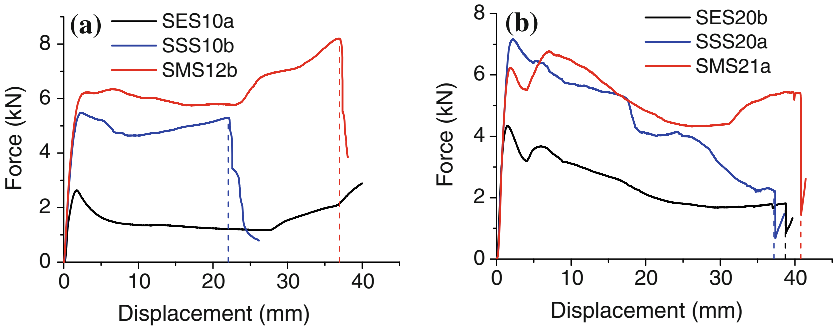

Fig. 7 Comparisons of the force-displacement curves of different structures: **(a)** Series AL and **(b)** Series SS

latter, while the fold width of the former is larger than that of the latter. The reason may be that the strength of SS is much higher than that of AL. This is also the cause of serious slide between the foam and the tube found in Series SS.

3.3 Load-carrying capacity

The punch force-displacement curves for different structures of Series AL and Series SS is shown in Fig. 7. A sharp final drop in some curves is associated to the fracture of the specimen. It should be noted that a rising of force at a late stage happened in some specimens because the specimen surface comes into contact with the wedged sides of the upper punch due to large rotation, which is indicated in Table 2 as a remark.

From Fig. 7a it can be seen that foam fillers in Series AL increase the load-carrying capacity of structures significantly. The load-carrying capacity of an empty tube is the lowest, and after an initial stage, it decreases rapidly because of serious indentation. The filling of aluminum foam restricts the indentation and enhances the bending resistance of the structure. So the load-carrying capacity of foam-filled structures decreases much slower, especially for foam-filled double tubes which have nearly a constant force level and the highest load-carrying capacity. The maximum displacement $S_{\max}$ of the foam-filled double tube is much larger than that of the foam-filled single tube. Hence the foam-filled double tube is much better than the foam-filled single tube in crashworthiness.

The main trend of Series SS is the same as Series AL, as shown in Fig. 7b. Although the peak force of Series SS is higher than that of Series AL, the load-carrying capacity decreases very fast afterwards. Even the foam-filled double tube of Series SS is not good. So, Series SS is not suitable for energy absorption structures in bending and only Series AL is discussed hereafter.

3.4 Energy absorption

The energy absorption E of Series AL is shown in Fig. 8a. The vertical and horizontal dash lines at the ends of curves in this figure and later denote the maximum displacement of the punch and the energy absorption of the structure before failure, respectively. The energy absorption E of the foam-filled double tube is higher than that of the other structures because of its high bending resistance. The total energy absorption of the foam-filled double tube $E_{\max}$ is much higher than that of the other structures owing to its high load-carrying capacity and large displacement before failure ($S_{\max}$).

To make the comparison more meaningful, Fig. 8b shows the specific energy absorption E_s and $E_{s\max}$ of different structures. It is obvious that the foam-filled double tube has higher values of E_s and $E_{s\max}$ than those of the other structures. In other words, foam-filled double tubes are more weight-efficient than the other structures in energy absorption.

3.5 Effect of inner tube wall thickness

In order to further improve the performance, the effect of inner tube wall thickness is studied experimentally. A comparison of the force-displacement curves between two foam-filled double tubes with different inner tube

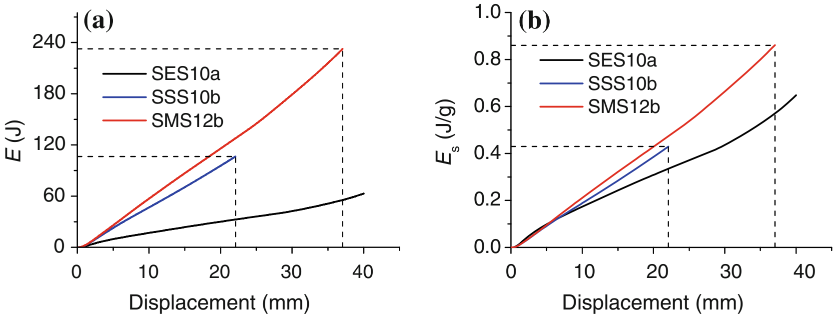

Fig. 8 Comparisons of (**a**) the energy absorption E and (**b**) the specific energy absorption E_s of different structures in Series AL

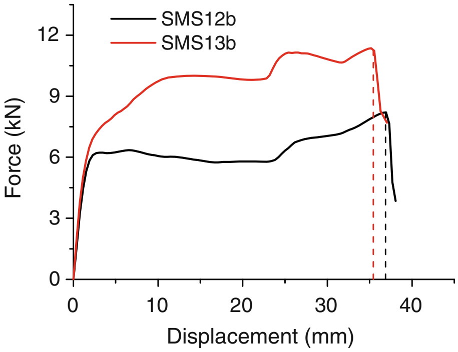

Fig. 9 The force-displacement curves of foam-filled double tubes with different inner tube wall thicknesses

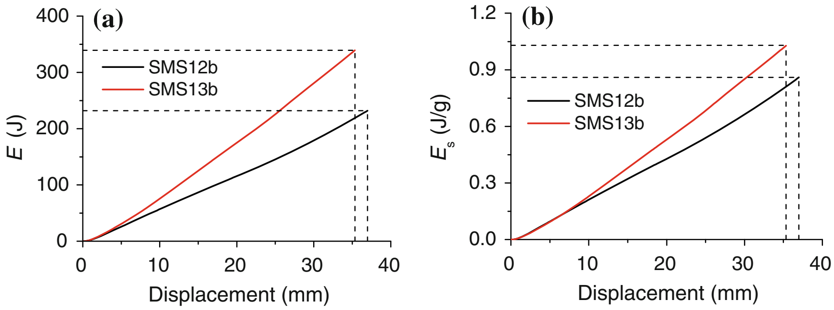

Fig. 10 Comparisons of (**a**) the energy absorption E and (**b**) the specific energy absorption E_s of foam-filled double tubes with different inner tube wall thicknesses

wall thicknesses is shown in Fig. 9, and a comparison of their energy absorption is shown in Fig. 10. Within the range of the experiments, thickening the inner tube increases the load-carrying capacity of the foam-filled double tube, and meanwhile maintains nearly the same maximum displacement before failure. Also, thickening the inner tube increases the total energy absorption and the weight-efficiency of the structure.

3.6 Influence of inner tube material

The effect of material strength of the inner tube is also studied. Comparisons of the load-carrying capacity and energy absorption of foam-filled double tubes with aluminum alloy (AL) and stainless steel (SS) inner tube are shown in Figs. 11 and 12, respectively. Although the strength of SS is much higher than that of AL and the SS inner tube of 0.6 mm wall thickness is as strong as the AL inner tube of 1.2 mm wall thickness, the load-carrying capacity of the foam-filled double tube with the SS inner tube is lower than that with AL. Maybe the effect of the wall thickness is more important. However, the maximum displacement $S_{\max}$ of the structure with SS inner tube is larger, so the total energy absorption $E_{\max}$ of these two structures is almost the same. Since the weight of the SS inner tube is much larger than that of the AL one, the weight-efficiency of

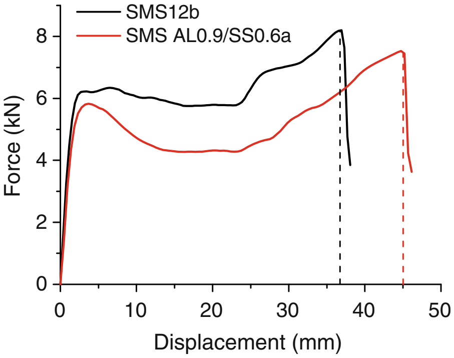

Fig. 11 The force-displacement curves of foam-filled double tube with different inner tube materials

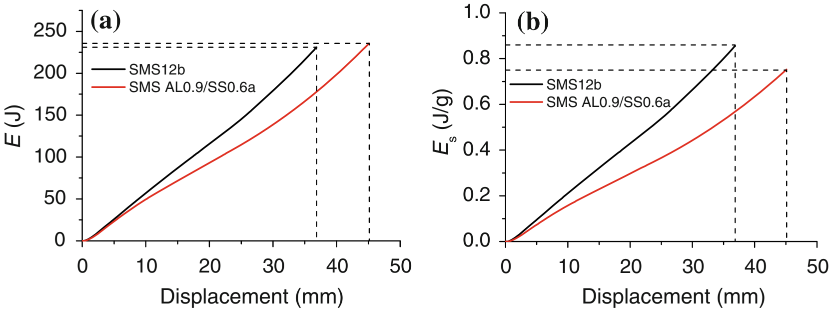

Fig. 12 Comparisons of (**a**) the energy absorption E and (**b**) the specific energy absorption E_s of foam-filled double tubes with different inner tube materials

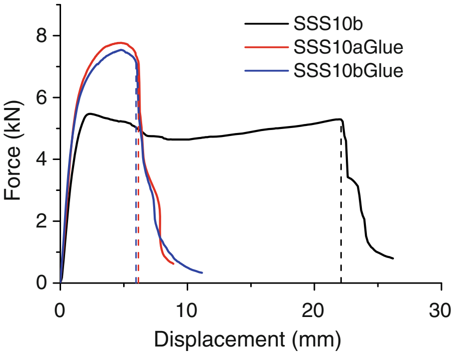

Fig. 13 The force-displacement curves of foam-filled single tubes with or without glue

the foam-filled double tube with SS inner tube is lower than that with AL one. Nevertheless, the effect of inner tube material is not so obvious, in comparison with the inner tube wall thickness.

3.7 Effect of foam–tube interface condition

The effect of adhesion in the foam-filled single tube and double tube is studied in the experiments. Comparisons of the load-carrying capacity and energy absorption of the foam-filled single tubes glued or not glued between the tube and foam are shown in Figs. 13 and 14, respectively. Similar comparisons of the foam-filled double tubes are shown in Figs. 15 and 16.

It transpires that when the tube and the foam adhered together, the load-carrying capacity of the foam-filled single tube is higher but the displacement before failure is very small. So the maximum energy absorption of the glued structure is worse than of that without glue.

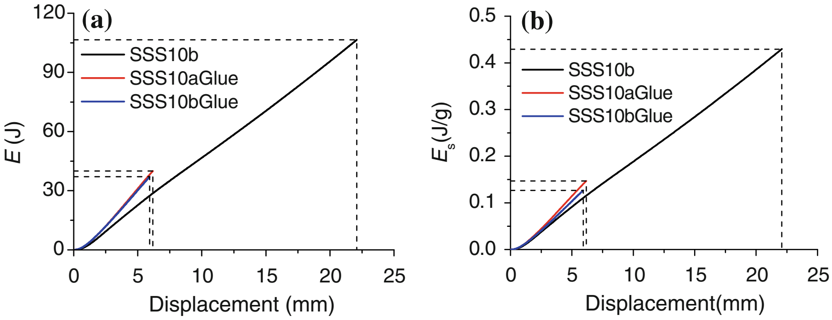

Fig. 14 Comparisons of (**a**) the energy absorption E and (**b**) the specific energy absorption E_s of the foam-filled single tubes with or without glue

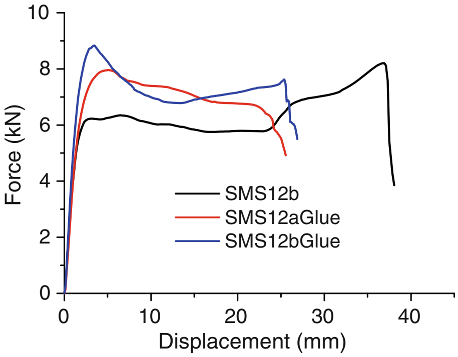

Fig. 15 The force-displacement curves of the foam-filled double tubes with or without glue

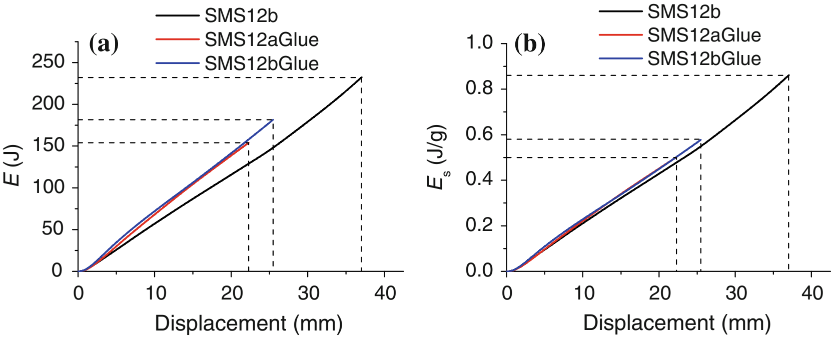

Fig. 16 Comparisons of (**a**) the energy absorption E and (**b**) the specific energy absorption E_s of the foam-filled double tubes with or without glue

The situation of the foam-filled double tube with glue is a little better than that of the foam-filled single tube. With glue, the load-carrying capacity of the structure increases and the displacement before failure is slightly reduced. But the maximum energy absorption and the specific energy absorption with glue is much smaller than that without glue. So, gluing the tube and foam in the foam-filled single tube and double tube does not improve structural crashworthiness.

4 Conclusions

Three-point bending tests of empty tubes and aluminum foam-filled single and double square tubes were conducted. The load-carrying capacity, bending resistance, total energy absorption and weight-efficiency of these three types of structures are compared.

The results show that the load-carrying capacity and bending resistance of empty tubes decrease very fast due to deep indentation. The foam filler can reduce the indentation thus improving the load-carrying capacity.

However, the aluminum foam-filled single tube cracked much earlier, which limits its total energy absorption. On the contrary, the maximum displacement of the foam-filled double tube structure is much larger than that of the foam-filled single tube, so it can absorb more energy before failure. With regard to the specific energy absorption and maximum specific energy absorption, the aluminum foam-filled double square tubes are also the most efficient ones. So this new type of structure is more suitable for bearing bending load and crashworthiness.

The effect of the material and wall thickness of the inner tube was discussed. The results show that the inner tube wall thickness is more important than its material. The negative effect of gluing to the foam-filled single and double tube is confirmed by experiments.

Only quasi-static experiments are performed and reported here. The dynamic behaviors of this new type of structure are more important and will be studied in the near future.

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