Bending Response of Sandwiched Double Tube Structures with Aluminum Foam Core

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Abstract. Three point bending response of sandwiched double cylindrical tube structures with aluminum foam core was studied numerically using the explicit finite element method. The numerical results are in good agreement with the corresponding experimental results and display the advantage of this new structure in load carrying capacity and energy absorption efficiency over the traditional foam-filled single tube structure. The deformation and failure mechanism is revealed by comparisons of the strain and stress distributions and the history of the maximum strain. The influence of the inner tube diameter for the structure was explored. It is found that increasing the inner tube diameter enhances the maximum deflection at failure of the foam-filled double tube within the diameter range considered. With a proper inner tube diameter, a steady load carrying capacity of the foam-filled double tube structure can be achieved, which shows an excellent crashworthiness with high energy absorption efficiency.

Keywords: Foam-Filled Structure, Three Point Bending, Finite Element Method, Optimization.
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INTRODUCTION

During the past two decades, many research works have been done to study the axial crushing behavior of thin-walled columns, in order to improve their capacity as energy absorption members [1-3]. On the other hand, a study on the real world vehicle crashes by Kallina [4] in 1994 showed that up to 90% involved structural members failed in bending collapse mode.

Many research works have shown that empty tubes are not suitable for bearing three point bending loads due to their very low resistance to indentation. In order to achieve a higher bending resistance and weight efficiency in energy absorption, ultra-light metal fillers such as aluminum foams were introduced into thin-walled empty structures. The bending behavior of such structures was studied experimentally and numerically by many researchers in the past decade. Santosa and Wierzbicki [5] and Santosa et al. [6] 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 increases the energy absorption. Chen et al. [7] performed an optimization for minimum weight on foam-filled sections under bending condition. It showed the potential of thin-walled columns filled with aluminum foams as weight-efficient energy absorbers. Chen [8] studied the bending behavior of hat profiles filled with aluminum foams and found that filling of aluminum foams increased the specific energy absorption of the structures. Kim et al. [9] studied the bending collapse of thin-walled cylindrical tubes filled with several pieces of foams experimentally and numerically. The results showed that the aluminum alloy foam filling offered remarkable increase of bending resistance and enhanced the crashworthiness of the structure.

Although filling of aluminum foams increases the bending resistance of thin-walled columns, it was found that columns filled with aluminum foams failed much earlier than those without fillers, which limits the energy absorption of the structures. In order to increase the energy absorption of the structures while keeping high bending resistance, we developed a new structure, i.e., a sandwiched double tube structure with metal foam filler. Our quasi-

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static experiments have shown that the performance of the new structure is much better than that of empty or foam-filled singe tube structures. In this paper, numerical simulation of the bending response of the aluminum foam filled double tube structures are carried out to reveal the mechanism and to optimize the inner tube diameter of the structure.

SIMULATION DETAILS

The explicit finite element code of ABAQUS was used in the simulation. The basic model is shown in Figure 1. The diameter of the rigid punch and two supporters is 10mm. The angle between the two wedged sides of the upper punch is about 60 degree. A constant velocity of 10mm/s is assigned to the punch.

According to the parameters in the experiments, the diameter D_1 and thickness T_1 of the outer tube is fixed as 38mm and 1.6mm respectively. The inner tube thickness T_2 is fixed as 1.2mm and the diameter D_2 varies with samples. The ratio of the span length to the outer tube diameter, L_0/D, equals 6, and the total length of the structure is fixed as 270mm.

The samples in the simulation are named with the following rule. In the sample "6-38-20", the first figure means the ratio L_0/D, followed by the outer tube diameter and the last figure is the inner tube diameter.

The uniaxial stress-strain curves of the tube material AA 6063T6 and the closed-cell aluminum foam core are shown in Figure 2. The parameters of these materials are detailed in Table 1.

In the simulation, the friction factor is 0.3 for the interface between tube and foam, and the self-contact of the tube. Shell and continuum solid elements are used for the tubes and foam respectively, and a global mesh size 2mm is identified by the mesh convergence analysis of the structure in the simulation.

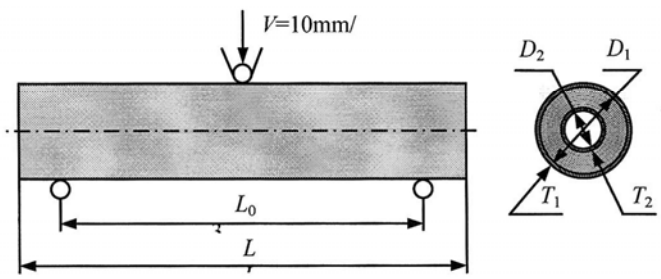


FIGURE 1. The model of the structure in the simulation.

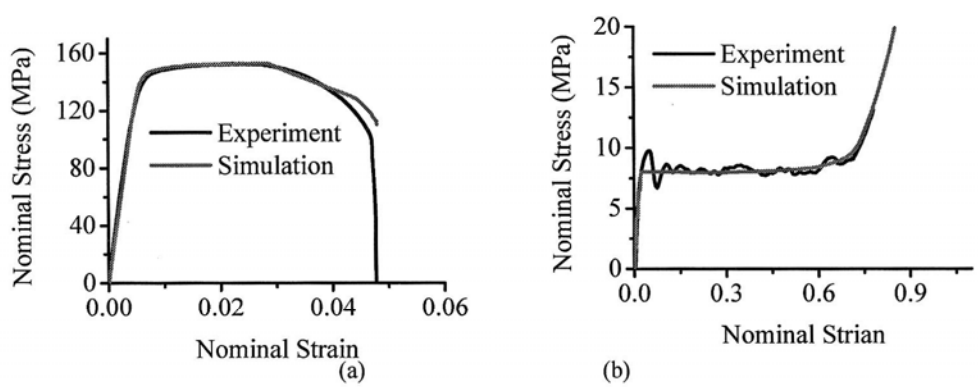


FIGURE 2. The quasi-static stress-strain curves of materials (a) AA 6063T6 and (b) Closed-cell aluminum foam.

TABLE 1. The material parameters in detail

	ρ (g/cm^3)	E (GPa)	ν	ν_p	k
Tube	2.7	59	0.3		
Foam	0.43	0.625	0.1	0	1.732

DEFINITIONS

In order to investigate the mechanism of the new structure easily, the following parameters are defined and will be discussed later, refer to Figure 3.

ε_m: The maximum axial tensile strain of the lowest part of the foam-filled structure.

U_u: The displacement of the upper punch.

U_{iu}: The maximum displacement of the inner surface of the upper part of inner tube just underneath the punch.

U_{il}: The maximum displacement of the inner surface of the lower part of inner tube just underneath the punch.

U_{dd}: The maximum displacement of the lowest part of the foam-filled double tube.

U_{ds}: The maximum displacement of the lowest part of the foam-filled single tube (not shown in Figure 3).

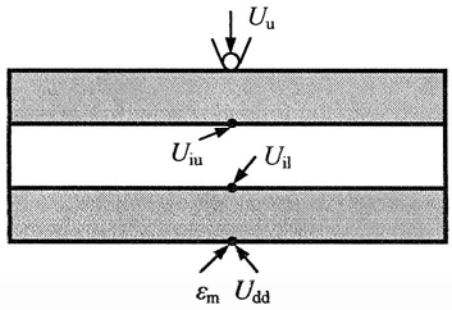


FIGURE 3. The locations of parameters discussed in the foam-filled structures.

RESULTS AND DISCUSSION

A comparison of the force-displacement curves of foam-filled single and double tubes obtained experimentally and numerically is shown in Figure 4. It can be seen that the numerical results are in good agreement with the experimental results except at a late stage after failure of the structures, since no fracture mechanism was incorporated in the simulation. Figure 4 also indicates that the maximum displacement and the energy absorption capacity of the foam-filled double tube structure are enhanced, in comparison with the foam-filled single tube.

In order to explore the mechanism, the evolutions of the maximum tensile strain ε_m for foam-filled single and double tubes are compared in Figure 5a. The axial strain distributions along the downside of the out tube in the foam-filled structures are also compared, as shown in Figure 5b. Note that the curves are obtained at a fixed time before failure of the individual structures but associated with different deflection. It can be seen that the increase in ε_m of the foam-filled double tube is much slower than that of the foam-filled single tube. Hence the maximum deflection of the former is larger than the latter before failure.

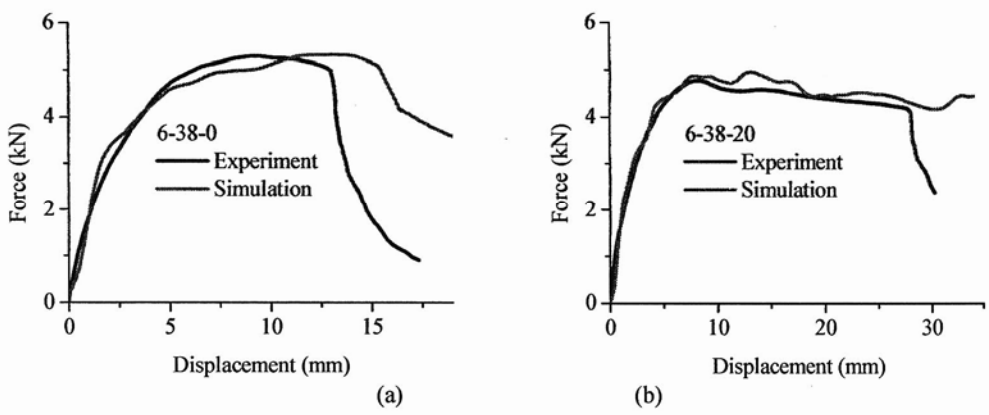


FIGURE 4. A comparison of force-displacement curves of (a) foam-filled single tube and (b) foam-filled double tube obtained experimentally and numerically.

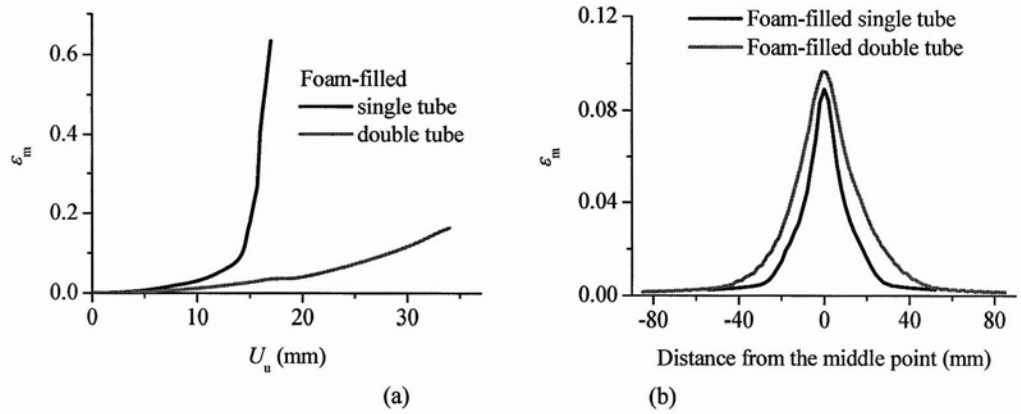


FIGURE 5. (a) the evolution of ε_m and (b) axial strain distribution along the downside of the out tube in foam-filled structures.

The evolution of displacement at different positions of the foam-filled structures is shown in Figure 6. It can be seen that the maximum displacement of the lowest part of the foam-filled double tube U_{dd} increases slower than that of the foam-filled single tube U_{ds}. For the foam-filled double tube, U_{iu} increases much slower than U_u at the early stage due to the indentation of the upper part. When the foam is sufficiently compressed, the two values increase nearly at the same rate. On the other hand, displacements U_{il} and U_{dd} are almost the same, indicating that the down part of the structure mainly bears bending loads. Since there is no indentation, the lower part deforms more homogeneously, so it can keep its capability longer.

The interesting findings in the quasi-static bending experiments are the difference of the crack number and location of the two structures shown in Figure 7. It can be seen that two cracks exist in the foam-filled double tube. This is not consistent with Figure 5 since we did not consider fracture in the simulation. However, if we check Figure 7b carefully, there is evidence that the formation of cracks in the foam is earlier than that in the out tube. So it is the cracks in the foam which lead to the final failure. In order to study the mechanism of this behavior, the stress distribution of the foam along the downside (the red line in Figure 8) for the foam-filled double tube structure is investigated. The deviatoric stresses along the path are shown in Figure 9a. It transpires that the peak value of the axial deviatoric stress component S_{33} is not located at the middle but at a distance from the middle in both sides with some spread. The minimum distance between the two peaks is about 30mm, in accordance with the distance between two cracks found in the experiments. This provides the reason for the two symmetrical cracks in the foam-filled double tube structure. The distribution of the Mises equivalent stress shown in Figure 9b also gives the same explanation for the behavior.

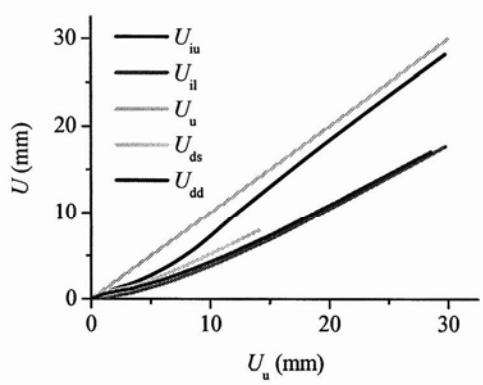
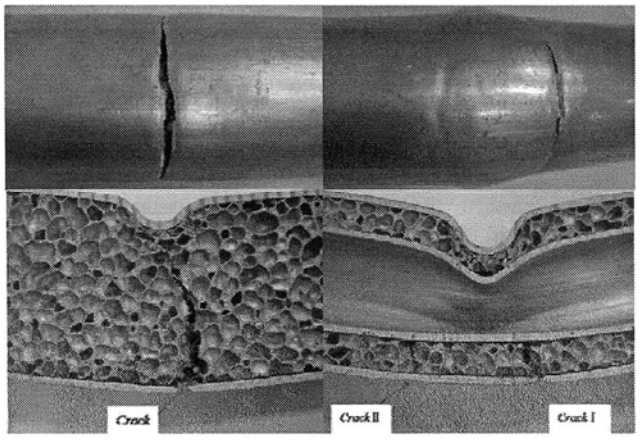


FIGURE 6. The evolution of displacement at different positions in foam-filled structures.



(a) (b)

FIGURE 7. Cracks found in (a) foam-filled single tube and (b) foam-filled double tube.

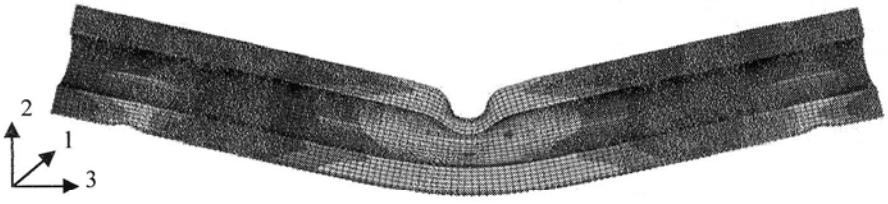
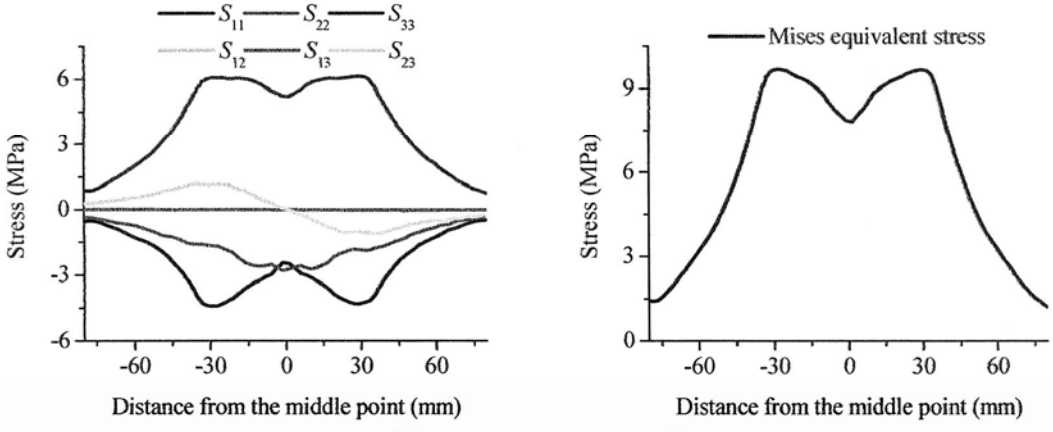


FIGURE 8. The deformation of the foam in the foam-filled double tube structure.



(a) (b)

FIGURE 9. The distributions of (a) deviatoric stresses and (b) Mises equivalent stress along the downside of foam in the foam-filled double tube structure.

Finally, the effect of the inner tube to the foam-filled double tube structure is studied numerically. Different inner tube diameters are considered in the simulation. A comparison of the force-deflection curves is shown in Figure 10. An early drop of the force is found for foam-filled double tubes with inner tube diameter of 14mm and 18mm. It seems that enlarging the inner tube diameter can increase the deflection without significant loss in strength or failure. However, if the inner tube diameter is too large, e.g. 30mm in this case, the load carrying capacity decreases significantly. From Figure 10 it is estimated that the optimal diameter of the inner tube for the foam-filled double tube is roughly half of the out tube diameter.

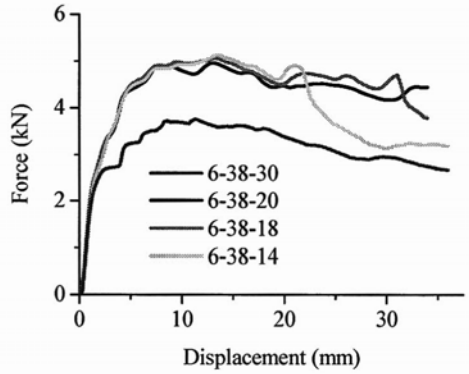


FIGURE 10. The force-deflaction curves of foam-filled double tube structures with different inner tube diameters.

CONCLUSION

The load carrying behavior and failure mechanism of foam-filled double tube structure are investigated numerically and compared with those of foam-filled single tube using the finite element method. It is shown that the maximum strain of the foam-filled double tube increases slower than that of the foam-filled single tube, which makes the maximum deflection of the former before failure much larger than that of the latter. The mechanism is discussed in detail by comparing the displacement at different positions in the structures. It is found that the lower part of the double tube sandwich structure deforms more homogeneously, so it is more efficiency in load bearing and energy absorption. The numerical simulation also provides evidence that two cracks may occur in the lower part of the foam, which explains the findings of different failure modes observed in the three-point bending tests between foam-filled single tube and double tube structures. Finally, the effect of the inner tube diameter to the foam-filled double tube is studied and it is found that the optimal inner tube diameter for the foam-filled double tube is roughly half of the out tube diameter.

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