Effect of tube length on the bucking mode and energy absorption of Al foam-filled tubes

S. ASAVAVISITHCHAI, D. SLATER, A. R. KENNEDY
Advanced Materials Research Group, School of Mechanical, Materials, Manufacturing Engineering and Management, University of Nottingham, UK
E-mail: Andrew.kennedy@nottingham.ac.uk

Aluminum foam components have a high capacity to absorb energy during compressive deformation. It is thought that by filling thin-walled metal tubes with Al foam, the energy absorption and crushing resistance of the tube can be improved. These structures are targeted for enhancing the crashworthiness of automotive components, with reduced weight compared to an equivalent steel tube [1]. The high-energy dissipation capability of these hybrid structures should also make them more stable against buckling.

Hassen *et al*. [2] observed two distinctive deformation modes, axisymmetric (concertina effect) and non-axisymmetric mode (diamond effect), during the axial compression of empty tubes. It was also observed that for foam-filled tubes, a noticeable shift in buckling mode occurred from diamond to concertina when the foam filler density increased. It has been reported that increasing the tube wall thickness results in an improvement in energy absorption, but this can lead to large load fluctuations during the buckling process and large increases in mass compared to foam-filled structures [3]. In this study, the effects of tube length on buckling mode and energy absorption have been investigated by axially compressing Al foam-filled stainless steel tubes of three different lengths.

Foamable precursors were made by mixing Al powder, with an average size of 66 μm, and 0.6 wt% of TiH_2, with an average size of 33 μm, in a tubular mixer for 20 min. The mixture was compacted in a 22-mm-diameter die, lubricated with lithium stearate powder suspended in acetone, to a pressure of 650 MPa, using uniaxial cold compaction. Densities between 99–100% of the theoretical density were achieved in all precursors, ensuring successful foaming [4]. The precursors were placed inside a boron nitride coated stainless steel mold and heated to 800 °C in a preheated furnace for approximately 450 s. Foamed samples were sectioned to a length of 27 mm, using a Struers Accutom-5 saw. The density of each sample was determined by measuring its dimension and mass. The foams used had densities of 0.6 ± 0.01 g cc^{-1}.

Three different lengths of stainless steel tubes, 27, 54, and 81 mm, identified as short, medium, and long, were prepared. The outer diameter and thickness of the tubes were 25.5 and 1.5 mm, respectively. The tubes were push-fitted with multiple foam samples which were 27 mm in length. The push-fitted, foam-filled tube samples were compressed axially, between two flat plates, to approximately 70% of their original height using a Mayes mechanical testing machine at a cross-head speed of approximately 1 mm min^{-1}. The load–displacement data were recorded with a computer. The compressive tests were repeated at least 3 times to confirm the reliability of the data.

Fig. 1a presents a typical load-displacement plot for axial compression of a closed-cell Al foam of similar length to the short tube. It shows the three stages of plastic deformation typical of these materials; linear-elastic behavior, plateau regime, and densification. The deformation behavior of this foam is in a good agreement with that observed by other authors which are well described elsewhere [5, 6]

Fig. 1b–d show load-displacement plots for short, medium, and long, empty tubes and Al foam-filled tubes. The plots for empty tubes show a typical wavelength for progressive buckling with a high initial peak, corresponding to the formation of the first lobe. In all cases, the first peak is higher than the subsequent peaks. The load-displacement plots for the foam-filled tubes show similar first peaks to those for the empty tubes, followed by peaks with similar or increasing heights for subsequent lobes. Irrespective of the sample size, the first peak, in all cases, occurs at similar strains and is of similar magnitude. For foam-filled tubes there is a rapid increase in load at roughly 50–60% strain which corresponds to the onset of densification of the foam. The number of lobes, produced in both empty and

TABLE I Summary of the energy absorbed for different tubes

	L/D	No. of lobes	Overall energy absorption to 70% strain(J)	Energy absorption (J/mm)	Improved energy absorption (%)
Al foam	–	–	103	3.81	–
Short empty tube	1.06	2	601	22.26	–
Short foam-filled tube	1.06	2	773	28.63	28.62
Medium empty tube	2.12	4	1163	21.54	–
Medium foam-filled tube	2.12	4	1725	31.94	48.28
Long empty tube	3.18	5	1716	21.19	–
Long foam-filled tube	3.18	6	2590	31.98	50.92

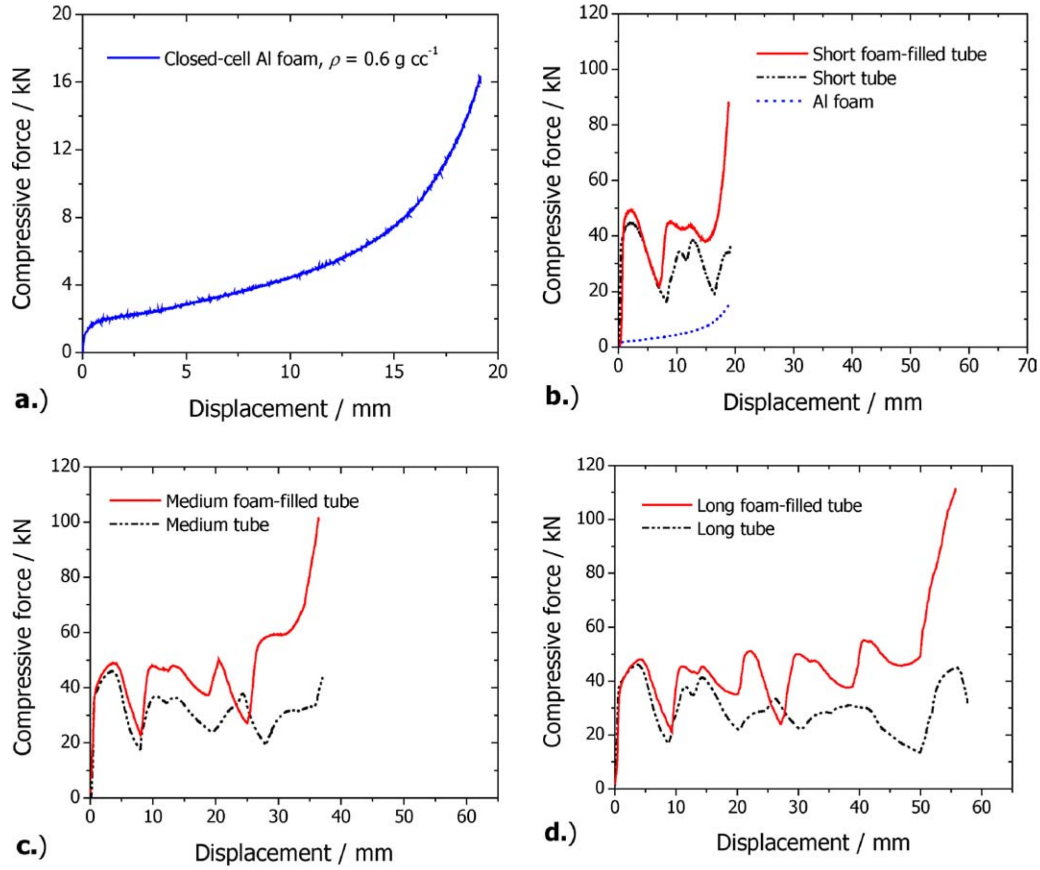

Figure 1 Load-displacement plots for (a) Al foam, (b) short, (c) medium and (d) long Al foam-filled tubes in comparison with empty tubes of equivalent length.

foam-filled compressed tubes, corresponds to the number of peaks in the load-displacement plots.

Table I shows that the foam-filled tubes absorb more energy than their unfilled counterparts and the sum of the empty tube and the foam. The empty tubes of different lengths absorb similar energies per mm deformed whereas the medium and long foam-filled tubes absorb more energy than the short one. Fig. 2 shows foam-filled and empty tubes after compression. The concertina effect is observed in all the foam-filled tube samples. This failure mode is also observed in the short empty tube, because the length to width ratio (L/D) is low [2]. For larger empty tubes, where $L/D > 1.06$, the diamond deformation mode is observed, producing erratic folds, during compression. It is clear that for tubes with $L/D > 1.06$, the presence of the foam stabilises the tube wall, enabling it to resist the folding process, changing the buckling mode from the diamond mode to the more stable concertina mode. With this, a significant improvement in energy absorption is observed, as a result of this change in deformation mode.

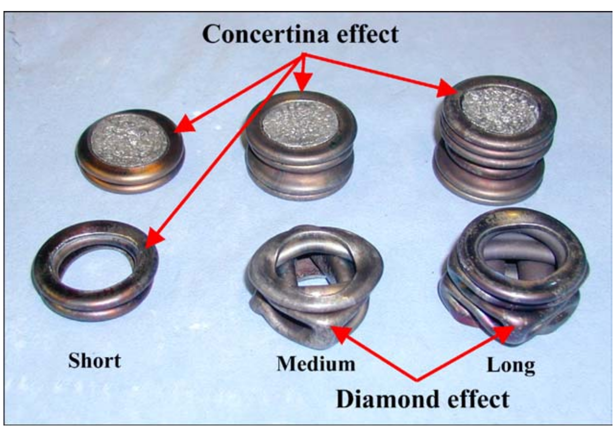

Figure 2 Compressed foam-filled tubes and empty tubes, of three different lengths, showing concertina and diamond buckling modes.

Acknowledgments

The author would like to acknowledge the Royal Thai Government for the financial support. The supply of Al powders by the Aluminum Powder Company (ALPOCO) is also appreciated.

References

1. M. SEITZBERGER, F. G. RAMMERSTORFER, H. P. DEGISCHER and R. GRADINGER, *Acta Mech.* **125** (1997) 93.
2. A. G. HANSSEN, M. LANGSETH and O. S. HOPPERSTAD, *Int. J. Impact Eng.* **24** (2000) 475.
3. C. HABERLING and H. G. HALDENWANGER, in Proceedings of the 2nd International Conference on Metal Foams and Porous Metal Structures, Bremen, June 1999, edited by J. Banhart, M. F. Ashby and N. A. Fleck (MIT-Verlag, Bremen, 1999) p. 37.
4. A. R. KENNEDY and S. ASAVAVISITHCHAI, *Mater. Sci. Forum.* **396**(4) (2002) 251.
5. J. BANHART and J. BAUMEISTER, *J. Mater. Sci.* **33** (1998) 1431.
6. I. W. HALL, M. GUDEN and C.-J. YU, *Scripta Mater.* **43** (2000) 515.

*Received 27 February
and accepted 3 June 2004*