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Effect of adhesive on the strengthening of aluminum foam-filled circular tubes

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Studies of the crushing behavior of closed-cell, aluminum foam-filled aluminum and steel tubes have shown an *interaction effect* between tube wall and foam filler [1, 2, 3]. The crushing loads of foam-filled tubes are, therefore, found to be higher than the sum of the crushing loads of foam (alone) and tube (alone) mainly due to this effect. Santosa *et al.* [1], based on FEM results, proposed the following equation for the average crushing load of foam-filled square tubes of length b,

$$P_f = P_e + C\sigma_f b^2 \quad (1)$$

where P_f, P_e and σ_f are the average crushing loads of the filled and empty tubes and plateau stress of the filler, respectively. The constant C in Equation 1 is considered to be the *strengthening coefficient* of the foam filling. The values of C were proposed and experimentally shown to be 1.8 and 2.8 for foam-filled tubes without and with (epoxy) adhesive, respectively [1]. The study of Santosa and Wierzbicki has also shown that the use of adhesive, although resulting in a relatively small increase in the total weight of the tube, $<16\%$, raised the crushing load of the tube by as much as the foam crushing load. There has, however, been only this one study on the use and effect of adhesive in foam-filled tubes and the effect of adhesive in circular tubes has not been investigated yet. The present report is a further investigation of the strengthening effect of foam filling with a bonding layer in circular tubes.

The drawn aluminum tubes studied (3003-H14) were 15.88 mm in diameter with a wall thickness of 0.9 mm. 20 mm long empty tubes for compression testing were cut using a slow speed diamond saw. The foam core samples, with a diameter of 14 mm, were prepared by core-drilling. The inner diameter of the tube was almost the same as the diameter of the foam core so that foam samples fitted tightly inside the tubes. The average density of the foam varied between 0.2–0.5 $g\,.\,cm^{-3}$. The weight and dimensions of the tubes and foams were measured before and after filling in order to calculate density of the foam and weight of the polyester layer for each individual sample. The empty tube was filled with polyester resin-curing agent mixture and the foam sample was then inserted inside the tube. Finally, the excessive bonding material was removed, then foam and bonding material were cured at room temperature. The thickness of the polyester layer was predicted to be about 0.1 mm and its weight was about 5% of the weight of the tube. Quasi-static compression tests on empty and filled tubes and foam samples were conducted using a Testometric Test Machine with a displacement rate of 0.01 mm s^{-1}.

The plateau stress as a function of density for the foams is shown in Fig. 1. The plateau stress (σ_{pl}) was found to be well-fitted by the power-law of strengthening equation,

$$\sigma_{pl} = K\rho^{n} \quad (2)$$

where K and n are constants and ρ is the foam density in $g\,.\,cm^{-3}$. The values of K and n are ~22.4 (MPa) and ~1.99, respectively. The foam-crushing load of the 14 mm diameter foam filling of filled tube samples was calculated using the above equation by simply inserting the values of the filler density and the cross-sectional area.

The deformation modes of the empty and filled tubes were progressive and axisymmetric (concertina) and typical compression load-displacement curves of the empty and filled tubes, with various filler densities, are shown in Fig. 2. Compressed empty tubes folded into 3-lobes and each lobe had a length of ~5 mm. Filled tubes were only compressed to the completion of the second fold and, because of the limited number of folds formed, the effect of foam filling on the fold length was not precisely determined.

Corresponding average crushing loads (P_a) of the tested tubes were calculated using the following relation:

$$P_a = \frac{\int P\,d\delta}{\delta} \quad (3)$$

where P and δ are the load and displacement, respectively. The average load-displacement curves of the empty and foam-filled tubes are shown in Fig. 3 for

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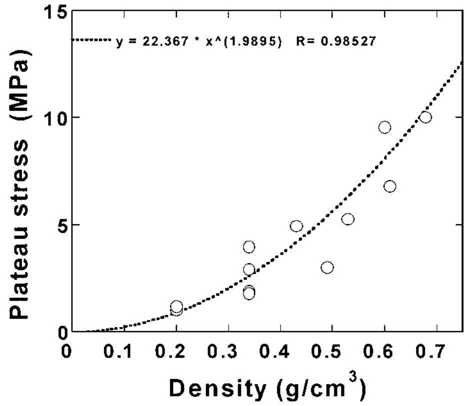

Figure 1 Plateau stress as a function of density of Al-foam.

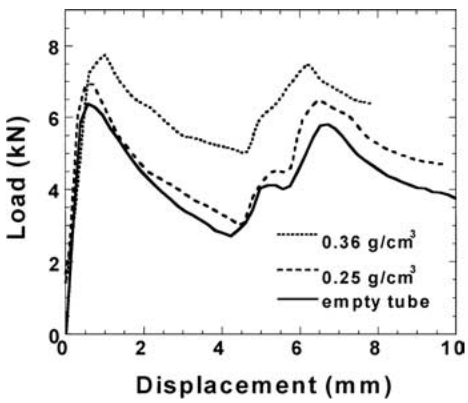

Figure 2 Load vs. displacement curves of empty and foam filled tubes.

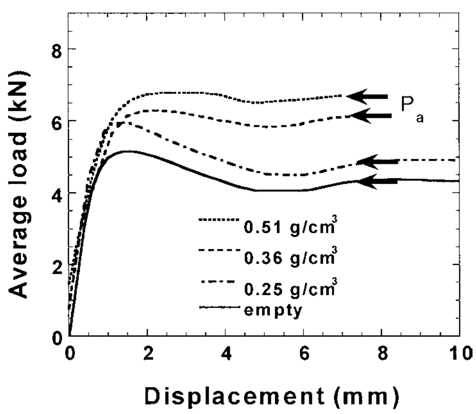

Figure 3 Average load vs. displacement curves of empty and foam-filled tubes.

different foam densities. The strengthening (ΔP) resulting from foam filling was calculated by subtracting the average load of the filled tube from that of empty tube. The variation of ΔP as a function of foam load is shown in Fig. 4 and linear interpolation to the data in this figure results in a calculated interaction coefficient of 2.74, which is very similar to previously proposed interaction coefficient for square tubes [1].

Three plastic hinge models of Alexander [4], Singace *et al.* [5] and Wierzbicki *et al.* [6] were used to predict the average crushing load of the empty tubes as a function of the tube wall thickness. These models are given

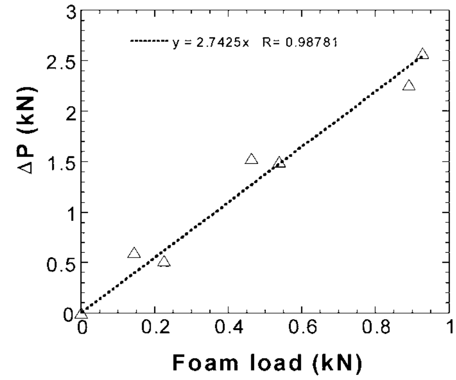

Figure 4 Strengthening vs. foam load.

sequentially as:

$$P_a = \sigma_o t^2 \left[8.462 \left(\frac{R}{t} \right)^{1/2} + 1.814 \right] \quad (4)$$

$$P_a = \sigma_o t^2 \left[7.874 \left(\frac{R}{t} \right)^{1/2} + 1.408 \right] \quad (5)$$

$$P_a = 11.22 \sigma_o t^2 \left(\frac{R}{t} \right)^{1/2} \quad (6)$$

where σ_o, t and R are the mean stress from yield point to failure, thickness and mean tube radius, respectively. The value of σ_o for the studied tube material is taken to be 150 MPa [7]. In the calculations, the inner diameter of the tube was taken as constant (14.08 mm) while the thickness of the tube increased from 0.85 to 2 mm. The calculated specific energy of empty tubes, using Equations 4–6 is shown in Fig. 5, as a function of total mass of the tube.

For the tested empty tube, Equation 6 estimates well the specific energy absorption and, therefore, calculations of the filled tube specific energies were based on the average crushing load of the tube estimated by Equation 6. Using Equations 1 and 2 with C values corresponding to bonded (2.8), unbonded (1.8) conditions, and only axial deformation of the tube and foam (1), the specific energy absorptions of the filled tubes were calculated and also plotted as function of total mass in Fig. 5. The higher values of specific energy of

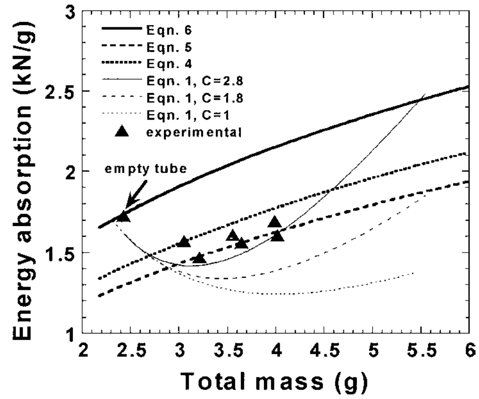

Figure 5 Comparison of the energy absorption behavior of the empty and foam-filled tubes.

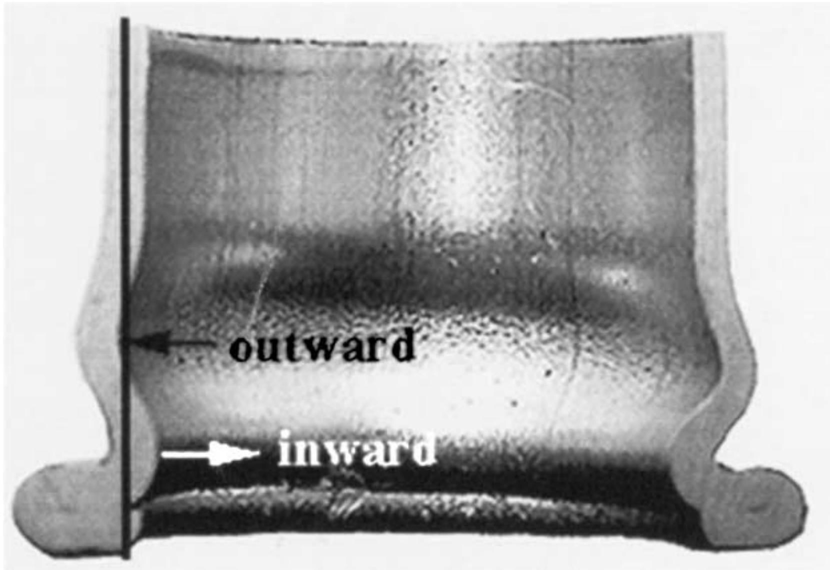

Figure 6 Cross-section of a deformed empty tube with axisymmetric folding.

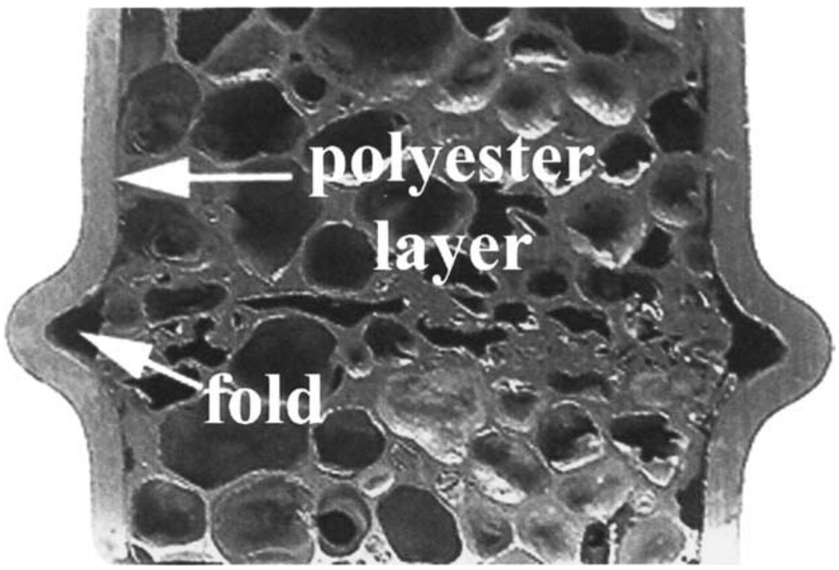

Figure 7 Cross-section of the deformed foam-filled tube with axisymmetric folding.

foam filling in this figure, as compared with the sum of the specific energies of the foam alone + tube alone (Equation 1, $C = 1$), confirmed again the existence of the interaction effect between tube wall and filler. It can also be inferred from Fig. 5, that there is a critical total mass (or foam density) above which foam filling is more favorable than thickening of the tube wall and that the effect of use of the adhesive, i.e. as C increases, is to decrease this critical mass. A similar critical total mass has been previously proposed for Al foam filled tubes [8]. The present results clearly demonstrate that, although foam filling resulted in a higher specific energy absorption than the sum of the specific energies of the tube alone and foam alone, it might be not always be more effective in increasing the specific energy than simply thickening the tube walls. Therefore, for effective foam filling, an appropriate tube-foam combination must be selected.

One of the advantages of foam filling along with an adhesive might be an ability to tailor the specific energy absorption capacity of the filled-tubes by increasing the level of interaction coefficient. In filled tubes, the interaction effect is partly due to the resistance of the filler to the inward and/or outward folding of the tube (see Fig. 6) and partly due the interfacial friction stress between foam and tube wall. Numerical studies of Al foam filled tubes have shown a negligible effect of interfacial frictional stress on the crushing strength of tubes [1]. The use of adhesive can contribute to the specific energy absorption of the tube by two mechanisms, namely, increased load transfer from tube wall to the foam core and peeling of the adhesive. The latter mechanism occurs mainly due to the outward folding of the tube as shown in Fig. 7 for the foam filled tubes studied here. It is also noted that the use of the adhesive also changed the place of the first fold. In foam filled tubes, folding started in regions where local inhomogeneities favor fold formation (see Fig. 7). This is in contrast to the deformation of empty tubes, in which folding always started at the end of the tube. The similarity between the interaction coefficients found in this and the previous study [1] is probably due to the similar fracture strength of the adhesives used, epoxy and polystyrene.

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