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Joining of aluminium foams with fasteners and adhesives

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This paper describes methods of joining aluminium foams with mechanical fasteners and with adhesives, and characterises the mechanical properties of the resulting joints. Different techniques of joining were investigated under monotonic and cyclic pull-out and bearing loads. The effects of fastener geometry on pull-out and bearing-load failure are modelled. Cyclic loading reduces the maximum load a fastener can carry without failure to 0.35 of the static failure load. Epoxy adhesive joints are stronger than the foam itself in all modes of loading: failure always occurs remote from the joint.

List of symbols

ρ^*	Density of metal foam
ρ_s	Density of the solid cell wall material
$\bar{\rho}(\bar{\rho} \equiv \rho^*/\rho_s)$	Relative density of metal foam
σ_y	Yield strength of the solid cell wall material
a	Radius of fastener
a_w	Radius of washer
ℓ	Embedded length of fastener
L	Total length of a cylindrical fastener
x	Length of tapered portion of wood screw
t	Specimen thickness for bearing tests
F_{min}	Minimum alternating load
F_{max}	Maximum alternating load
R	The stress or load ratio (i.e. the ratio of the minimum alternating load to maximum alternating load)
ΔF	Load range
N_f	Number of cycles to failure
σ_s^*	Shear yield strength of metal foam
σ_y^*	Yield strength of metal foam in tension and in compression
ε_f	Nominal fracture strain of metal foam
F_p	Pull-out load
F_b	Bearing load
γ	Tear energy
d	Shear zone width

1. Introduction

If metal foams are to be used in engineering structures, ways must be found to join them to other materials. Unlike most engineering materials, foams are plastically compressible. This has advantages: they can be attached by wood screws, nails and the like. But it has drawbacks too: foams indent easily, so that compressive attachments like rivets and through-thickness clamps (nut and bolt assemblies, for example) work loose.

Studies thus far have established the viability of bonding foams with fasteners [1, 2], with adhesives [2] and by welding [2–4], but have not attempted to formulate design equations. This research explores the attachment of metal foams with screws, nails, studs and inserts. The static and cyclic forces these attachments can carry without failure are characterised and modelled.

2. Material and experimental procedure

The foam (trade name *Alporas**) is an aluminium alloy containing 0.2–8% weight of calcium to enhance viscosity and 1–3% weight of titanium hydride as a foaming agent. The relative density $\bar{\rho}$ (the ratio of the density of metallic foam ρ^* to that of the solid cell wall material ρ_s) ranges from $\bar{\rho} = 0.08$ to 0.15.

The density of the cell walls is very close to that of pure aluminium ($\rho_s = 2.7\ \mathrm{Mg\,m^{-3}}$). The yield strength σ_y of the solid cell walls was measured by infiltrating the foam with epoxy and then by micro-indenting the cell edges. An approximate value for the cell wall yield strength is found by dividing the hardness H by 3, giving a value of $\sigma_y = 160$ MPa. Samples of the foams were cut by electro-discharge machining. Details of the microstructure characterisation (cell shape, cell size and cell wall thickness) and relative density $\bar{\rho}$ have been reported elsewhere [5]. The specimens were of rectangular section 150 mm × 50 mm; the height was 50 mm for monotonic pull-out tests, and 25 mm for fatigue pull-out tests. Specimens of dimension 100 × 40 × 15 mm and 100 × 70 × 15 mm were used for monotonic and fatigue bearing-load tests, respectively. All tests were

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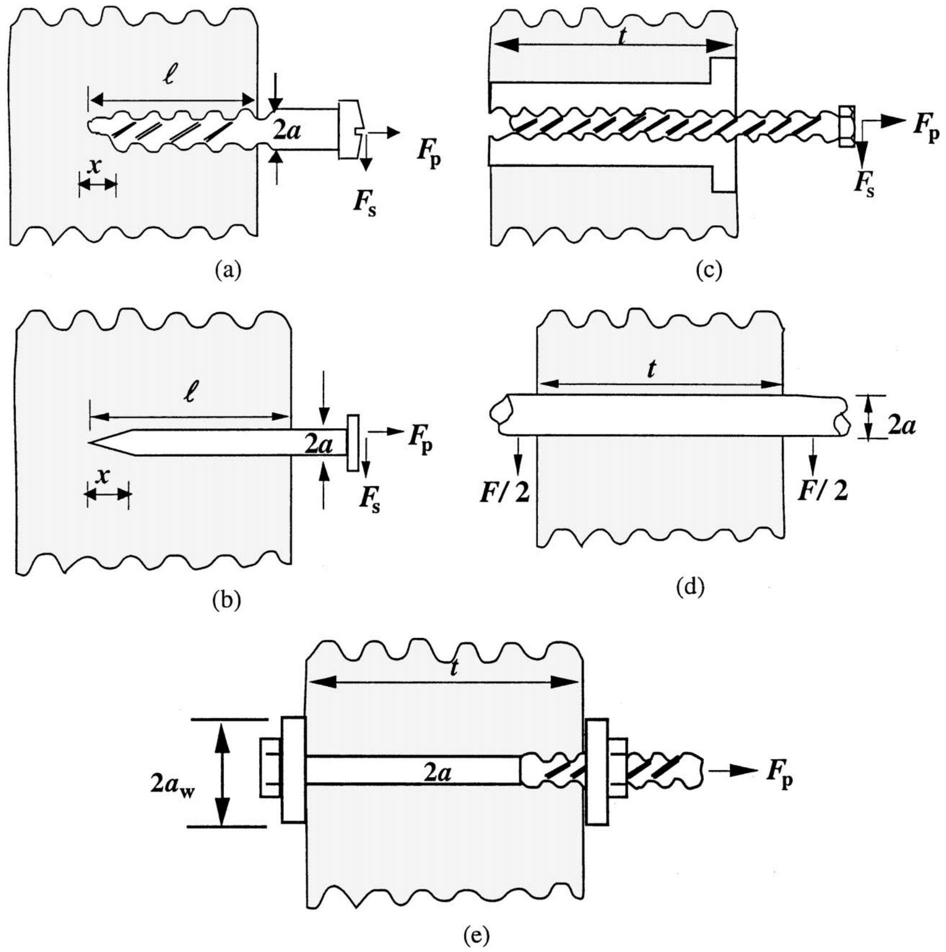

Figure 1 Fasteners: (a) screw; (b) nail; (c) insert; (d) stud; (e) bolt and nut.

performed at room temperature on a servo-hydraulic test machine.

Four types of mechanical fasteners were studied: wood screws, nails, threaded inserts and studs (Fig. 1). Two sets of investigation were carried out. In the first, dry fasteners were driven directly into the foam; in the second, fasteners were embedded in epoxy adhesive ("Araldite Rapid" cured 24 hours at room temperature) in pre-drilled pilot holes in the foam giving a combination of mechanical and adhesive attachment.

Tensile pull-out tests were performed in displacement control at a rate of 5 mm/min, and the load and load-line displacement were recorded. The parameters of interest are:

- the diameter $2a$ of the fastener
- the embedded length ℓ of the fastener in the foam

The bearing-load tests were performed in displacement control at a rate of 5 mm/min, using 6 mm diameter high tensile-strength (HTS) studs, and the load and load-line displacement were noted. The influence of both stud diameter, $2a$, and relative density, $\bar{\rho}$, upon bearing strength were studied.

Cyclic tests were performed in load control at constant load amplitude, at a frequency of 20 Hz and at a load ratio, $R = 0.1$, defined by

$$R = \frac{|F|_{\min}}{|F|_{\max}} \tag{1}$$

The number of cycles, the peak and trough values of the displacement and the load were monitored.

In addition, adhesively bonded butt-joints, lap joints and T-joints were made between flat panels of the foams listed above, using "Araldite Rapid" epoxy cured 24 hours at room temperature. The panel were tested in tension and bending.

3. Experimental results

3.1. Monotonic pull-out behaviour of mechanical fasteners

A typical load-displacement curve for the pull-out of a threaded fastener is shown in Fig. 2. Those for nails, studs and inserts are similar. The load F increases approximately linearly with displacement u up to the peak F_p, beyond which it falls, reaching zero when the fastener is completely withdrawn. Threaded inserts shear the foam; smooth ones pull out by sliding. Epoxy-bonding greatly increases the pull-out force. For example, epoxy-bonded threaded fasteners are still coated with epoxy containing embedded fragments of foam when they are fully withdrawn. Smooth fasteners debond from the epoxy and emerge clean.

Figs 3 and 4 summarise the effect of relative density on maximum pull-out load F_p as non-linear with a power of about 1.5, that is

$$F_p = A\bar{\rho}^{3/2} \tag{2}$$

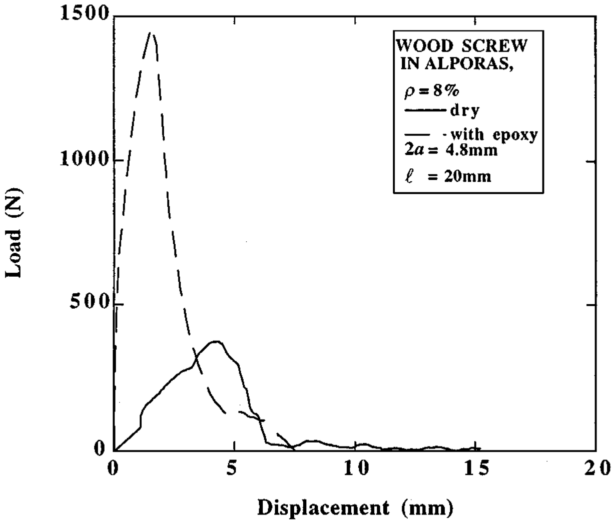

Figure 2 Load-displacement curves for both dry and epoxy-bonded wood screws, in Alporas with relative density $\bar{\rho} = 8\%$. Diameter $2a = 4.8$ mm, embedded length $\ell = 20$ mm.

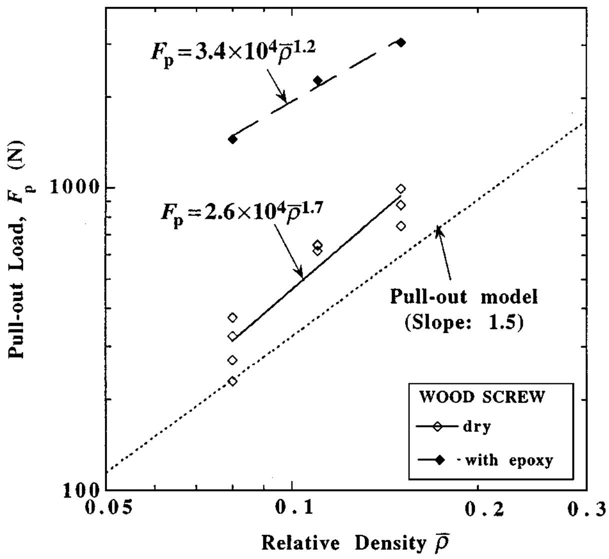

Figure 4 Effect of relative density on pull-out load of wood screw (diameter $2a = 4.8$ mm, embedded length $\ell = 20$ mm), from Alporas metallic foams—comparison of experimental and predicted results. (Open symbols: dry; full symbols: epoxy-bonded).

where A is a constant. Figs 5 and 6 show the dependence of pull-out load on fastener radius and embedded length. The trends are analysed in Section 4.

3.2. Monotonic bearing-load response of studs

Typical force-displacement curves for bearing-load are shown in Fig. 7. The initial portion of the load-displacement curve is nearly linear until a displacement of about 1 mm, where initial yielding by compressive crushing occurs. Thereafter the load climbs to a plateau value, beyond which it falls because of interaction with the free edges of the sample. Figs 8 and 9 show the dependence of initial-yield load and plateau load on relative density and stud radius.

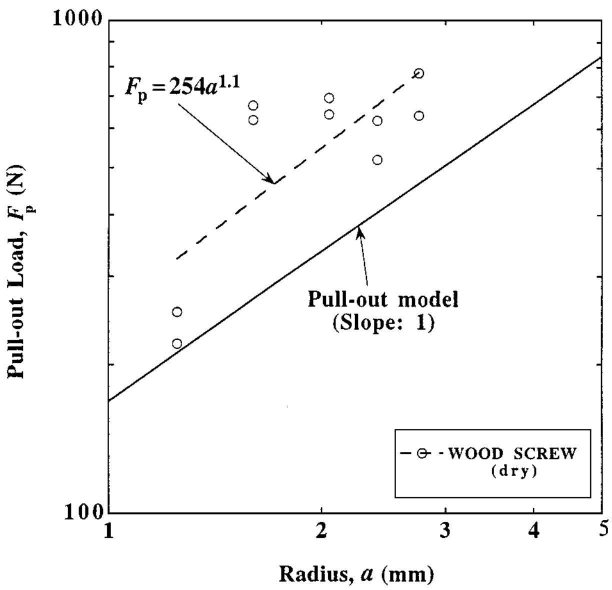

Figure 5 Effect of radius of wood screw (dry), of embedded length $\ell = 35$ mm, on the pull-out load from Alporas metallic foam, relative density $\bar{\rho} = 8\%$.

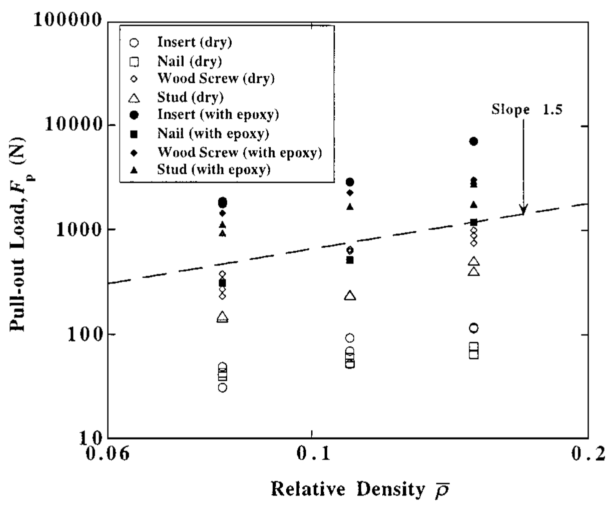

Figure 3 Effect of relative density on pull-out load for fasteners. Physical dimension of fasteners are: (a) wood screw, diameter $2a = 4.8$ mm, embedded length $l = 20$ mm; (b) nail, diameter $2a = 4.5$ mm, embedded length $l = 20$ mm; (c) stud, diameter $2a = 6$ mm, embedded length $l = 20$ mm; (d) insert, diameter $2a = 20$ mm, embedded length $l = 20$ mm.

3.3. Response to cyclic pull-out loads of mechanical fasteners

The axial displacement of a screw fastener caused by a cyclic pull-out load range ΔF is shown in Fig. 10 at a load ratio $R = 0.1$. The maximum load of the fatigue cycle F_{max} is normalised by the plateau value of the pull-out load F_p in the monotonic test. The response is essentially elastic up to a critical number of cycles, beyond which it increases dramatically and the fastener pulls out. The fatigue life N_f is defined by the knee of the curve. Fig. 11 shows how the safe cyclic load, normalised in this figure by the static pull-out load, depends on number of cycles. The safe load falls to less than 0.4 of the static load when the number of cycles is large.

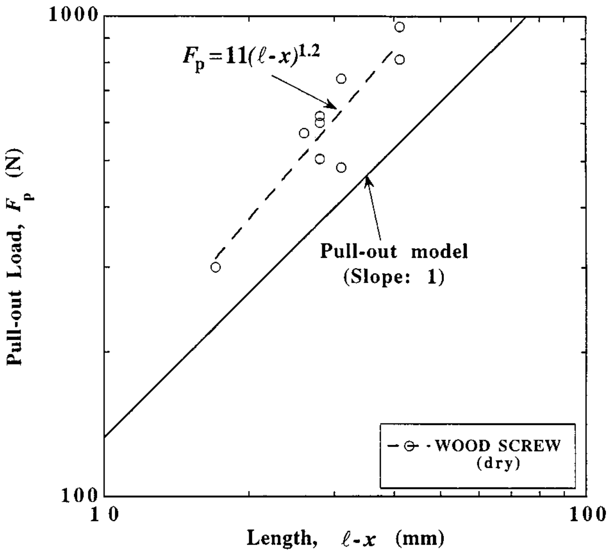

Figure 6 Effect of embedded length ℓ of wood screw (dry), with diameter $2a = 5.5$ mm, on the pull-out load from Alporas metallic foam, relative density $\bar{\rho} = 8\%$ (x = length of the tapered portion of wood screw).

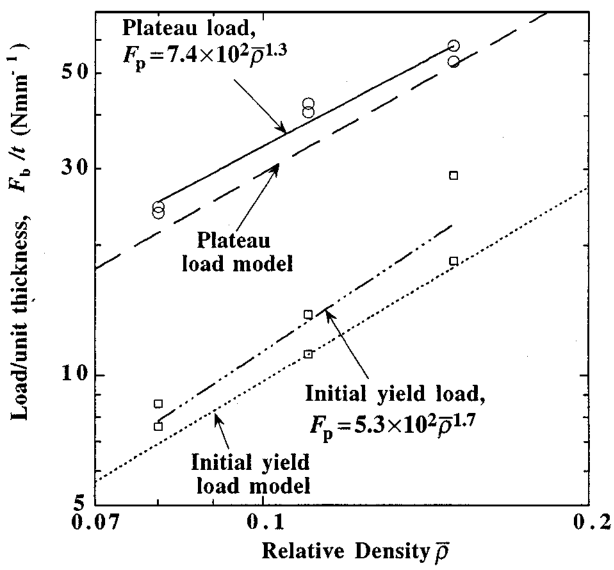

Figure 8 Plateau bearing load and initial yield load per unit thickness against relative density for Alporas metallic foam , for a 6 mm diameter stud.

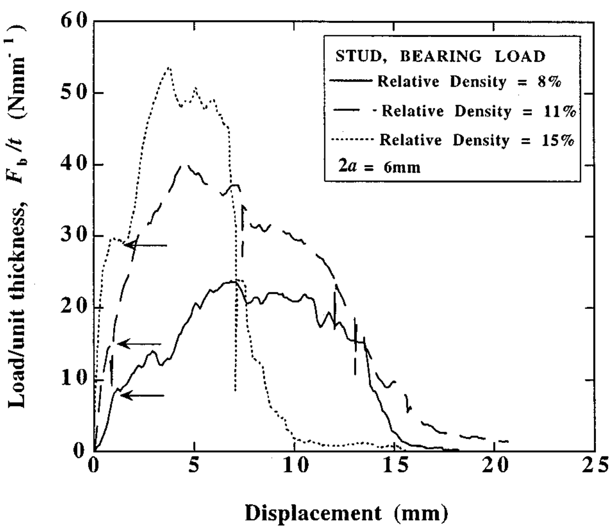

Figure 7 Pull-through of a 6 mm diameter stud through Alporas metallic foam (specimen dimension 100 × 40 × 15 mm), for three densities of foam. The arrows in the figure show initial yield load.

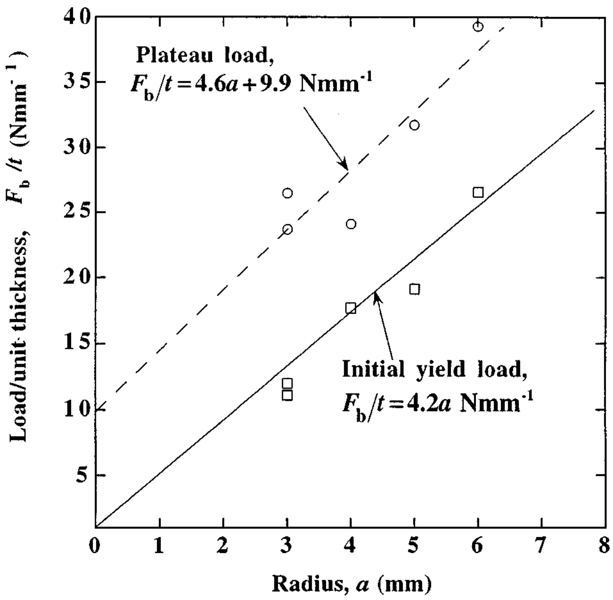

Figure 9 Effects of stud radius on bearing load: Alporas, relative density $\bar{\rho} = 8\%$. The lower line describes initial yield load; the upper one describes the plateau load.

3.4. Response to cyclic bearing loads of studs

Figs 12 and 13 show the response of the foam to cyclic bearing loads. The results parallel those for pull-out (Section 3.3). The safe load falls to 0.35 of the static bearing load when the number of cycles is large.

3.5. Adhesive joints

Adhesively-bonded joints were loaded in tension and bending. In all cases the load deflection response and failure load were the same as those of the foam itself, and final failure was remote from the joint.

4. Models for the mechanics of attachments

Here we seek more general descriptions for the pull-out, the bearing and the shear response of attachments in metal foams.

4.1. Pull-out

We think of the fastener as a circular cylinder, of radius a, embedded over a length ℓ in the foam. A force F is applied parallel to the axis of the cylinder and in a direction which will pull the fastener out. Consider first the case of a fastener inserted without an adhesive. Pull-out is opposed by the shear-resistance σ_s of the fastener-foam interface. The pull-out force is

$$F_p = 2\pi a(\ell - x)\sigma_s \tag{3}$$

where x is a length-correction to allow for the poor grip between the conical tip of the screw fastener and the foam. If the fastener is smooth (as the inserts are) σ_s is determined by friction; but more usually fasteners are threaded, keying them into the foam. When the threaded

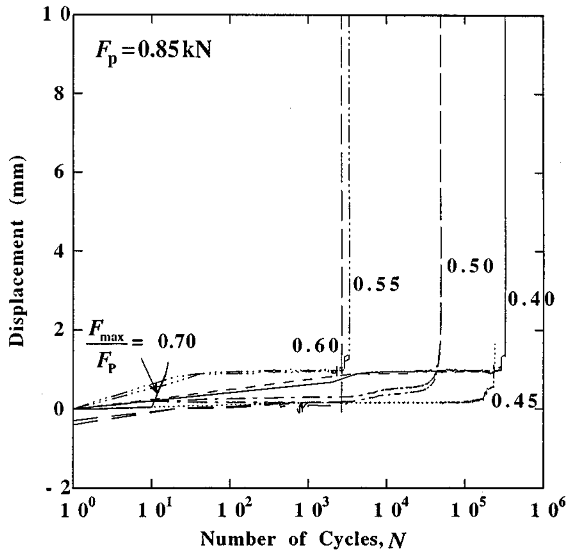

Figure 10 Accumulated displacement under tension-tension cyclic loading of a dry wood screw, diameter $2a = 4.8$ mm, embedded length $\ell = 20$ mm (Alporas, relative density $\bar{\rho} = 15\%$, at $R = 0.1$). Pull-out is progressive with increasing cycles.

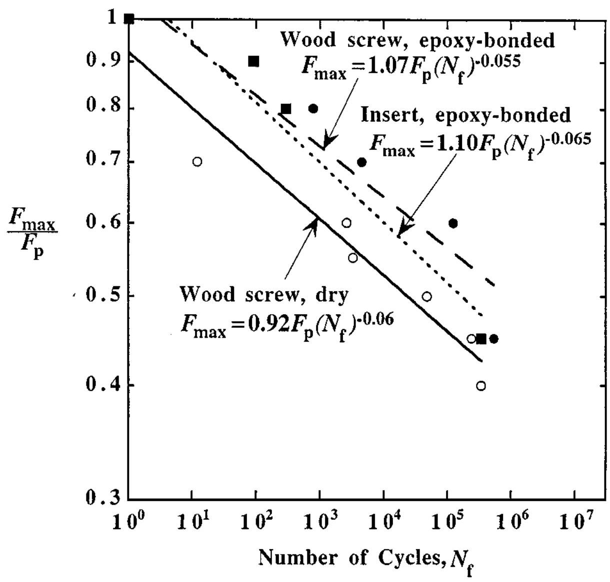

Figure 11 S-N curves for pull-out of fasteners—dry and epoxy-bonded wood screws, and epoxy-bonded insert. Load ratio, $R = 0.1$.

fastener is withdrawn the foam yields in shear and so σ_s is the shear-yield strength, σ_s^*, of the foam itself. The yield strength σ_y^* of a ductile foam in either tension or compression is related to its relative density by [6]

$$\sigma_y^* \approx 0.3 \sigma_y \bar{\rho}^{3/2} \tag{4}$$

where σ_y is the yield strength of the material of the cell walls. The shear-yield strength is approximately $\sigma_s^* = \sigma_y^* / \sqrt{2}$ giving [7]

$$F_p = 1.3 a (\ell - x) \sigma_y \bar{\rho}^{3/2} \tag{5}$$

We thus anticipate a pull-out force which scales linearly with fastener radius a and—but for the end-correction—with the embedded length ℓ, and which increases with foam density as $\bar{\rho}^{3/2}$. Figs 4–6 bear this

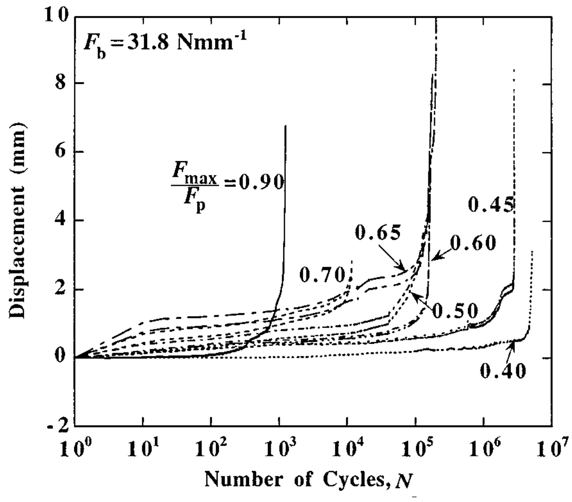

Figure 12 Displacement under cyclic bearing load on a 10 mm diameter stud in Alporas foam (relative density $\bar{\rho} = 8\%$, at $R = 0.1$).

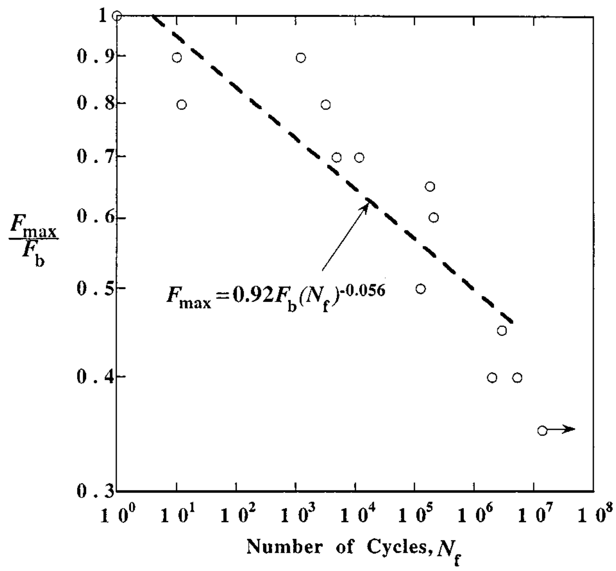

Figure 13 S-N curve—bearing load on a 10 mm diameter stud in Alporas foam (relative density $\bar{\rho} = 8\%$, at $R = 0.1$).

out. The predictions of Equation 5 are plotted on each. The dependencies of F_p on radius, length and density are supported. The absolute value of F_p for dry fasteners is underestimated by a factor of about 1.3, because, we think, the cell wall yield strength is larger than that inferred from the hardness measurements.

The bolt fastener of Fig. 1e will pull-out when the stress beneath the washer, of area $\pi(a_w^2 - a^2)$, exceeds the compressive strength of the foam, giving:

$$F_p = \pi\left(a_w^2 - a^2\right)\sigma_y^* = 0.94\left(a_w^2 - a^2\right)\sigma_y \bar{\rho}^{3/2} \tag{6}$$

The screw fastener described by Equation 5 has a higher pull-out load than the bolt if (assuming $\ell \gg x$)

$$\frac{\ell}{a} > 0.7\left(\left(\frac{a_w}{a}\right)^2 - 1\right) \tag{7}$$

making screw-fasteners the preferred choice if the embedded length is large.

The use of epoxy increases the effective diameter of the fastener, increasing F_p, but leaving its dependence on a, ℓ and $\bar{\rho}$ unchanged. As a rule of thumb, the effect of adhesive bonding is to increase the radius of the fastener by the cell size of the foam (approximately 5 mm in the case of Alporas foam).

4.2. Bearing load failure

A cylindrical fastener ("stud") of radius a passes through and projects from both sides of a foam panel of thickness t. It is pulled through the panel by two equal forces $F_b/2$ at either end, acting normal to the axis of the cylinder (Fig. 1d). Initial yield (Fig. 14a) occurs when the average bearing pressure exceeds the compressive yield strength σ_y^* of the foam, that is when

$$F_b = 2ta\sigma_y^* \tag{8}$$

or, using Equation 4,

$$F_b = 0.6t\sigma_y\bar{\rho}^{3/2} \tag{9}$$

Further displacement compresses and densifies the material ahead of the stud and tears the cell walls at its sides as sketched in Fig. 14. The force rises to

$$F_b = 2at\sigma_y^* + 2\gamma t \tag{10}$$

where γ is the tear-energy per unit area of the foam itself. In the limit of $a = 0$, Equation 10 reduces to

$$F_b = 2\gamma t \tag{11}$$

allowing the tear energy to be determined from a plot of F_b/t against a. Fig. 9 shows such a plot for a foam of relative density 8%. From it we find the experimental value for the tear energy to be

$$\gamma \approx 5\,\mathrm{kJ\,m^{-2}} \tag{12}$$

This compares with the value $\gamma \approx 5.2$ kJ m^{-2} which can be calculated from the indentation measurements of Andrew *et al.* [8] for a foam of $\bar{\rho} = 8\%$. Both are in agreement with a separate set of deep-indentation tests using flat-ended punches, chamfered to avoid friction on the shank, which allowed the tear energy γ in kJ m^{-2} to be measured as a function of relative density $\bar{\rho}$ (Fig. 15), giving, for Alporas foam,

$$\gamma = 250\bar{\rho}^{1.4} \tag{13}$$

The tear energy can be modelled in the way shown on the right-hand side of Fig. 14. A zone of width d and shear stress σ_s^* shears through a strain ε_f in order to cause tearing. The work done per unit area is

$$\gamma \approx \sigma_s^* \varepsilon_f d \tag{14}$$

Using $\sigma_s^* = 0.2\sigma_y\bar{\rho}^{3/2}$ (as before), $\varepsilon_f = 2$ and $\gamma \approx 5$ kJ/m^2 leads to a shear-zone width, d, of

$$d \approx 3.5\,\mathrm{mm} \tag{15}$$

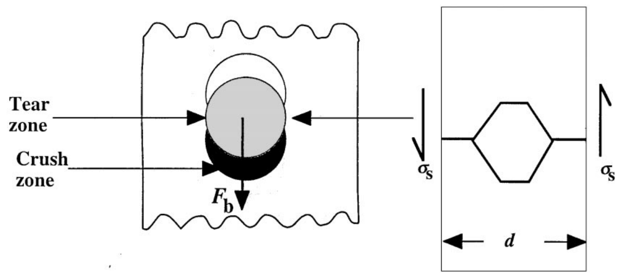

Figure 14 Initial yield due to the start of compressive crushing beneath the stud. A crush zone develops ahead of the stud and tearing occurs on each side, absorbing energy γ per unit area.

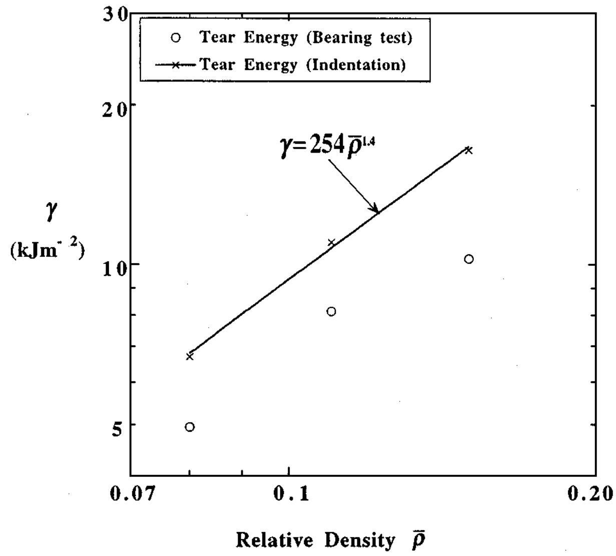

Figure 15 Tear energies for Alporas metallic foams of different relative density. Tear energies determined from bearing and deep-indentation tests.

that is, about one cell diameter. Thus we interpret the peak or plateau load as the load at which the foam beneath the stud crushes and, on either side, tears in a zone of width about one cell size.

4.3. Transverse loading of embedded fastener

A cylindrical fastener of radius a, total length L, with an embedded length ℓ, projects from the face of a foam and is loaded at its end by a load F_s normal to the axis of the cylinder (Fig. 16). The cylinder rotates about a point along its axis at a distance y^* below the free surface. When foam plasticity is fully established along the length of the cylinder, force equilibrium is expressed by

$$F_s + 2a(\ell - y^*)\sigma_y^* = 2ay^*\sigma_y^* \tag{16}$$

where y^* is measured from the point of rotation to the free surface of the foam. Moment equilibrium requires that

$$F_s(L - (\ell - y^*)) = 2a\sigma_y^*\left(\frac{1}{2}y^{*2} + \frac{1}{2}(\ell - y^*)^2\right) \tag{17}$$

Elimination of y^* in (17) by substitution of (16) gives an expression for the shear force F_s, which will cause the

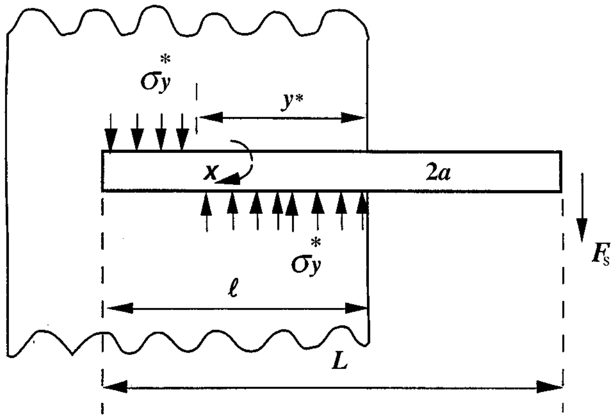

Figure 16 A fastener carrying an end shear load. Rotation occurs about the point X at plastic collapse.

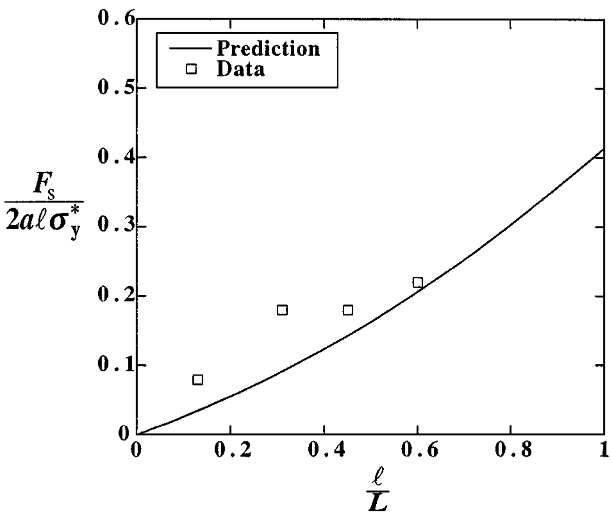

Figure 17 A comparison of the measured and predicted failure load F_s as a function of the embedded length ℓ. The prediction is given by Equations 16 and 17.

fastener to fail. The result is shown in Fig. 17. The horizontal axis is the fraction ℓ/L of the length of the fastener that is embedded in the foam. The vertical axis is the shear force to cause failure, normalised by the bearing load, $2a\ell\sigma_y^*$, that the embedded length could support. Test data (square symbols) confirm the trend and magnitude of the failure load. We conclude that shear loading can be damaging when L is large and ℓ is small.

4.4. Fatigue loading of fasteners

Guided by the results of Sections 3.1 and 4.1, we might anticipate that the safe maximum cyclic pull-out load to allow infinite life (meaning above 10^7 cycles) for the fastener is

$$(F_{\max})_{\text{cyclic}} = 2\pi a\ell(\tau_{\max})_{\text{cyclic}} \tag{18}$$

where $(\tau_{\max})_{\text{cyclic}}$ is the maximum cyclic shear stress the foam can tolerate for 10^7 cycles without failure. Data for $(\tau_{\max})_{\text{cyclic}}$ are given by Harte *et al.* [9]. Our results show that $(F_{\max})_{\text{cyclic}}$ is less than this. The difference arises from a faster rate of damage accumulation.

5. Concluding remarks

Foams can be joined with adhesives, with fasteners and by welding. This paper describes experiments and models for the first two. Standard epoxy adhesives give joints which are stronger than the foam itself. Adhesives, provided that they are compatible with the other requirements of the design, are economical and mechanically effective. Screw-fasteners can provide adequate fastening provided that they are designed according to the models developed in Section 4 of this paper. Improperly designed fasteners can pull-out or fail at low loads.

Acknowledgements

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