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Joining of Metal Foams with Fasteners**

By *Olujide B. Olurin*,* *Norman A. Fleck*, and *Michael F. Ashby*

Recent developments in manufacturing methods have given rise to a wide range of recyclable foams made from aluminum alloys. Aluminum foams have low density and are attractive as cores of sandwich panels, shells, and tubes. They have high energy absorption, high acoustic damping, relatively low thermal conductivity, and good electric conductivity. Commercially available foams include the open cell Duocel and the closed cell Alporas, Alulight, and Cymat. For the successful application of metallic foams, effective and efficient ways must be found for joining them. Since they are plastically compressible, they can been joined by wood screws and the like; however, as they indent easily, compressive attachments like rivets and through-thickness clamps (nut and bolt assemblies, for example) can work loose.

The load-carrying capability of a joint depends upon: joint design, the manner in which the joint is loaded, and the environment the joint experiences in service.

With proper precautions, metal foams can be joined using welding, mechanical fasteners and/or adhesives. This communication explores the static and cyclic load a joint can withstand prior to failure. Models to explain the failure mechanisms are presented.

The aluminum foam investigated (Alporas[1]) is an 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 ρ (the ratio of the density of metallic foam ρ_f to that of the solid cell-wall material ρ_s) is in the range 0.08–0.15.

The density of the cell walls is very close to that of pure aluminum ($\rho_s = 2.7$ Mg m^{-3}). The yield strength σ_y of the solid cell walls was measured by infiltrating the surface of the foam sample cut by spark machining 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 electrodischarge machining. Details of the microstructure characterization (cell shape, cell size, and cell-wall thickness) and relative density, ρ, have been reported elsewhere.[2] The specimens were of rectangular section 150 × 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 performed at room temperature on a servohydraulic test machine, and the load and load-line displacement recorded on computer.

Four types of mechanical fasteners were studied: wood screws, nails, threaded inserts, and studs. Figure 1 shows a sketch of a wood screw and a stud. 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 h 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 0.08 mm s^{-1}, and the load and load-line displacement were recorded. The parameters of interest, see Fig-

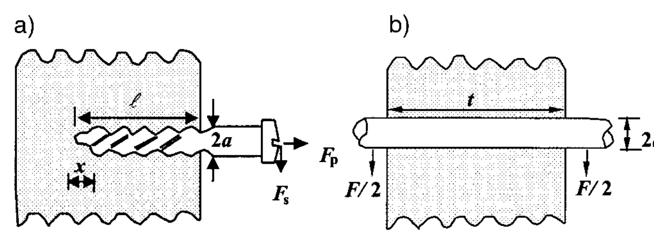

Fig. 1. Typical fastener joints: a) wood screw, b) stud.

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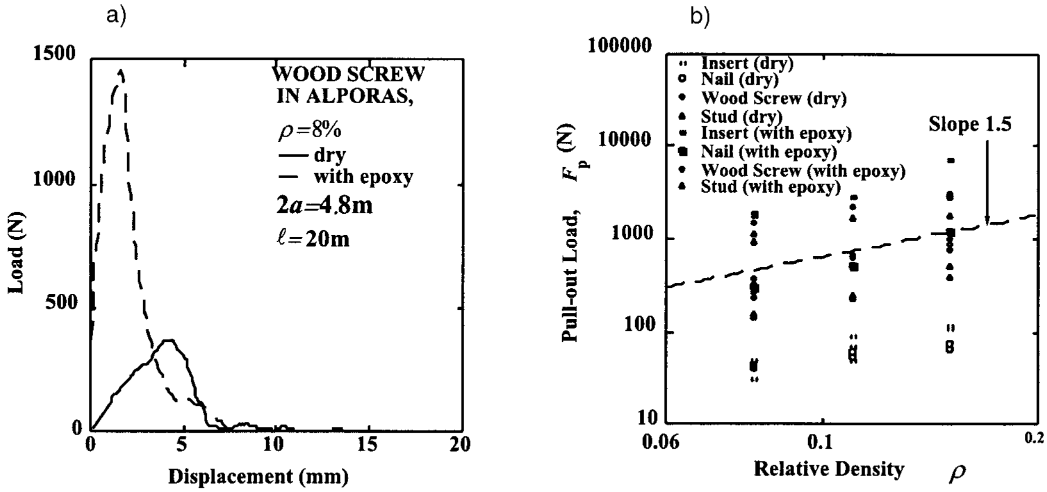

Fig. 2. a) Load–displacement curves for both dry and epoxy-bonded wood screws, in Alporas foam with relative density $\rho = 8\,\%$. Diameter 2a = 4.8 mm, embedded length l = 20 mm. b) Dependence of relative density on pull-out load for fasteners. Physical dimension of fasteners are: i) wood screw, diameter 2a = 4.8 mm, embedded length l = 20 mm; ii) nail, diameter 2a = 4.5 mm, embedded length l = 20 mm; iii) stud, diameter 2a = 6 mm, embedded length l = 20 mm; iv) insert, diameter 2a = 20 mm, embedded length l = 20 mm.

ure 1, are the diameter, $2a$, of the fastener and the embedded length, l, of the fastener in the foam.

The bearing-load tests were performed in displacement control at a rate of 0.08 mm s^{-1}, using 6 mm diameter high tensile-strength (HTS) studs, and the load and load-line displacement were noted. The influence of stud diameter, $2a$, and relative density, ρ, 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

$$R = |F|_{\min} / |F|_{\max} \qquad (1)$$

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

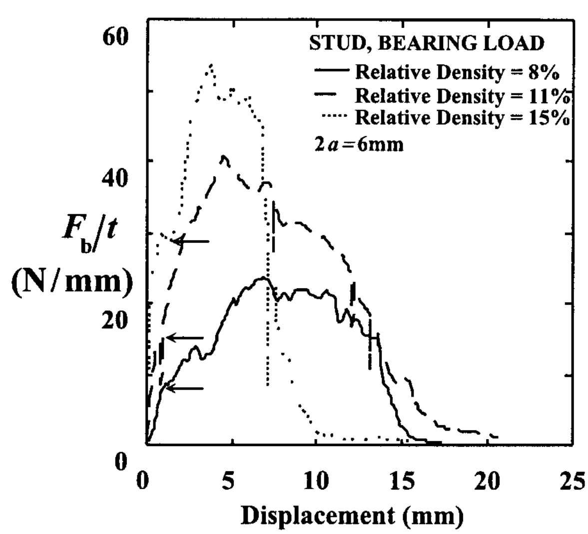

Fig. 3. Pull-through of a 6 mm diameter stud through Alporas metallic foam (specimen dimension 100 × 40 × 15 mm), for three densities of foam. The arrows in the figure show initial yield load.

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

A typical load–displacement curve for the pull-out of a threaded fastener is shown in Figure 2a. 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. 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.

Figure 2b summarizes the effect of relative density on maximum pull-out load, F_p, as nonlinear with a power of about 1.5, that is

$$F_p = A\rho^{3/2} \qquad (2)$$

where A is a constant. Experimental results also show a linear dependence of pull-out load with fastener radius and embedded length. These results are not reported here for the sake of brevity, but details may be found elsewhere.[3]

Typical force–displacement curves for the monotonic bearing-load are shown in Figure 3. 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 due to interaction with the free edges of the sample. Figure 4 shows the dependence of initial-yield load and plateau load on relative density.

The axial displacement of a screw fastener caused by a cyclic pull-out load range, ΔF, is shown in Figure 5a for a load ra-

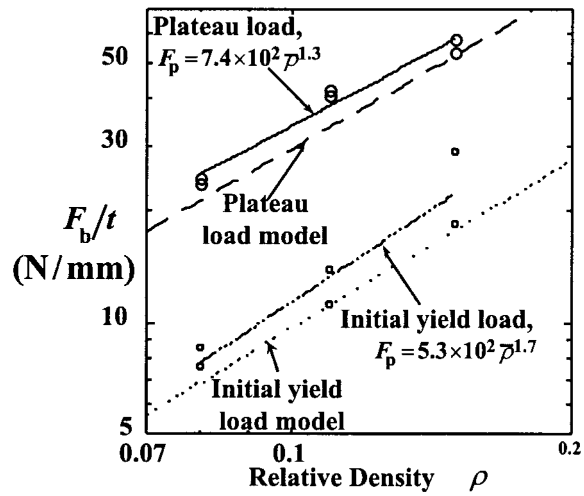

Fig. 4. Plateau bearing load and initial yield load per unit thickness against relative density for Alporas metallic foam, for a 6 mm diameter stud.

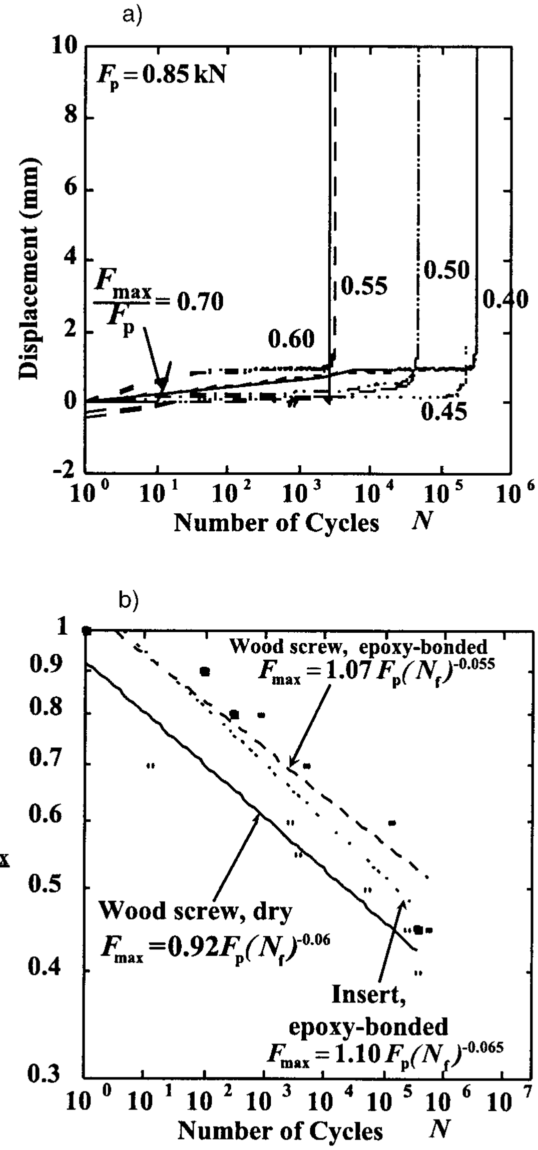

Fig. 5. a) Accumulated displacement under tension–tension cyclic loading of a dry wood screw, diameter 2a = 4.8 mm, embedded length l = 20 mm (Alporas, relative density ρ = 15 %, at R = 0.1). Pull-out is progressive with increasing cycles. b) S–N curves for pull-out of fasteners: dry and epoxy-bonded wood screws, and epoxy-bonded insert. Load ratio, R = 0.1.

tio $R = 0.1$. The maximum load of the fatigue cycle, F_{max}, is normalized 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. Figure 5b shows how the safe cyclic load, normalized in this figure by the static pull-out load, depends on the number of fatigue cycles. The safe load falls to less than 0.4 of the static load when the number of cycles is large.

The results for bearing loads parallel that of pull-out and the safe load at infinite life falls to 0.35 of the static failure load.

Adhesively-bonded joints are in all cases stronger than the foam itself, provided the epoxy penetrates the first layer of surface cells. Final failure is always remote from the joints.

We developed models of the mechanisms of attachment. General descriptions for pull-out and bearing response are presented.

For pull-out, consider the fastener to be 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 that 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

$$F_p = 2\pi a(l-x)\sigma_s \quad (3)$$

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 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[4]

$$\sigma_y^* \approx 0.3\sigma_y\rho^{3/2} \quad (4)$$

where σ_y is the yield strength of the cell-wall material. The shear-yield strength is approximately[5] $\sigma_s^* = \sigma_y^*/\sqrt{2}$, giving

$$F_p = 1.3a(l-x)\sigma_y\rho^{3/2} \quad (5)$$

Thus, we anticipate a pull-out force that scales linearly with fastener radius a and (but for the end-correction) with the embedded length l, and that increases with foam density as $\rho^{3/2}$. Experimental results (Figure 2b) bear this out for relative density. Details about the dependence of pull-out force on l and a is available elsewhere.[3]

The use of epoxy increases the effective diameter of the fastener, increasing F_p, but leaving its dependence on a, l, and ρ 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 3.5 mm in the case of Alporas foam).

A cylindrical fastener ("studs") 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 (Figure 1b). Initial yield occurs when the average bearing pressure exceeds the compressive yield strength $\sigma_y{}^*$ of the foam, that is when

$$F_b = 2ta\sigma_y{}^* \tag{6}$$

or, using Equation 4,

$$F_b = 0.6ta\sigma_y\rho^{3/2} \tag{7}$$

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

$$F_b = 2at\sigma_y{}^* + 2\psi t \tag{8}$$

where ψ is the tear-energy per unit area of the foam itself. In the limit of $a = 0$, Equation 8 reduces to

$$F_b = 2\psi t \tag{9}$$

allowing the tear energy to be determined from a plot of F_b/t against a. The plots of the predicted bearing loads from Equation 8 show good agreement with the experimental results (Fig. 4). The measured tear energy ψ in kJ m^{-2} is given as $\psi = 260\rho^{3/2}$ for Alporas foam.

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. 6a). 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

$$F_s + 2a(l-y^*)\sigma_y{}^* = 2ay^*\sigma_y{}^* \tag{10}$$

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

$$F_s(L-(l-y^*)) = 2a\sigma_y{}^*(0.5y^{*2} + 0.5(l-y^*)^2) \tag{11}$$

Elimination of y^* in Equation 11 by substitution of Equation 10 gives an expression for the shear force F_s, that will cause the fastener to fail. The result is shown in Figure 6b. 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, normalized by the bearing load, $2al\sigma_y{}^*$, that the embedded length could support. Test data (square symbols) confirm the trend and magnitude of the fail-

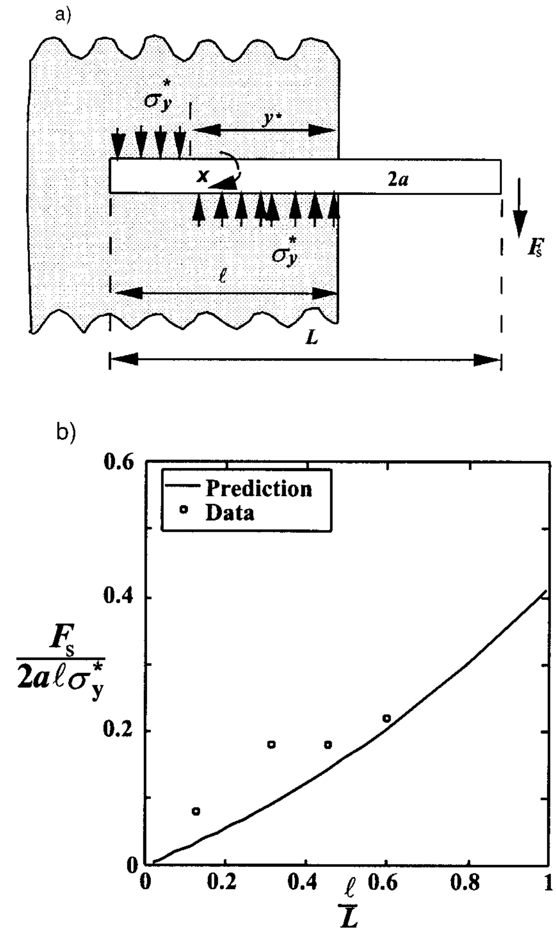

Fig. 6. a) A fastener carrying an end shear load. Rotation occurs about the point X at plastic collapse. b) A comparison of the measured and predicted failure load F_s as a function of the embedded length l. The prediction is given by Equations 10 and 11.

ure load. We conclude that shear loading can be damaging when L is large and l is small.

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

$$(F_{max})_{cyclic} = 2\pi al(\tau_{max})_{cyclic} \tag{12}$$

where $(\tau_{max})_{cyclic}$ is the maximum cyclic shear stress the foam can tolerate for 10^7 cycles without failure. Data for $(\tau_{max})_{cyclic}$ are given by Harte et al.[6] Our results show that $(F_{max})_{cyclic}$ is less than this. The difference arises from a faster rate of damage accumulation. The slope of the lines on Figure 5b are near –0.06; that for uniform cyclic loading of the same foam[6] is about –0.06.

Foams can be joined with adhesives, with fasteners, and by welding. This communication describes experiments and models for the first two methods. Standard epoxy adhesives give joints that are stronger than the foam itself. Adhesives, provided that they are compatible with the other requirements of the design, are economical and mechanically effective.

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