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A comparison of mechanical properties of some foams and honeycombs

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The mechanical properties of foams and honeycombs are compared using a normalizing procedure and it is suggested that ideal closed cell foams may be comparable or superior to honeycombs.

1. Introduction
The behaviour of honeycombs has been studied extensively, theoretically as well as experimentally. It is found that with the possible exception of out of plane elastic properties and tensile strength, all the mechanical properties of honeycombs vary non-linearly with density [1] with exponents larger than one. Ideal closed cell foams, on the other hand may display a linear variation of mechanical properties [1]. We may thus expect ideal closed cell foams to exhibit properties which are superior to those of honeycombs and it is of interest to compare their properties as actually obtained in practice. The problem becomes even more interesting because it is generally thought that honeycombs are far better than any foam.

2. An analysis of available data
Ideally, in order to make a perfect comparison we ought to make honeycombs and foams out of identical materials, then test them under identical conditions. It has not been possible for us to do this. Part of the difficulty is that even if we could start with identical raw materials, the various stages of processing needed to make the two structures lead to materials whose properties will be far from being identical.

Another difficulty is that we know of no method by which we could determine the properties of cell walls when they are so thin and small. We have therefore, used an indirect normalizing method for making the comparison. This normalization is based on the observation that strengths and moduli of all cellular solids can be approximated in a general form [1]

$$\sigma/\sigma_s \simeq c(\rho/\rho_s)^n \quad (1)$$

where σ is the property of cellular solid, c a constant that depends on the structure and mechanism of deformation of cellular solid, ρ the density of cellular solid, ρ_s the density of solid material and n an exponent ranging from one to three which depends on the mechanism of deformation as well as the structure of the cellular solid. Usually, σ_s is the same property as σ but it could also be different if the mechanism of deformation operating in the cellular solid is different from the one in dense solid. For example, if σ is the compressive strength of cellular solid σ_s can be the compressive strength of the dense solid if the mechanisms of failure of the two solids are essentially the same. Sometimes they could be different. The dense solid may fail by plastic deformation but the cellular solid may fail by elastic buckling. The appropriate normalizing parameter σ_s then is the elastic modulus of the dense solid and not its compressive strength. Some common properties of cellular solids and related properties of dense solids which can be used as normalizing factors are given in Table I. When correctly normalized Equation 1 allows us to make comparisons of the efficacy of different structures in providing the desired property when under a common mechanism of failure.

We have attempted to compare the properties of seven different cellular solids in order to compare honeycombs with foams. Three of them are commercial aluminium alloy honeycombs made out of 5052, 5056 and 2024 alloys. The data are the ones given as typical by Hexcel [2]. One is a polyaramide honeycomb with the data quoted by Good Fellow Metals [3]. Another is aluminium alloy foam for which we read the data from the paper by Thornton and Magee [4]. Two others are polymeric foams, Rohacell and Ethafoam. Rohacell is a high strength polymethacrylamideimide closed cell foam [5]. Ethafoam is a flexible low density polyethylene foam produced by Dow Chemical Company. Among the three foams used in this comparison, Ethafoam and Rohacell are closed

TABLE I Dense material properties which may be used to normalize properties of cellular solids

Property in cellular solid	Normalizing properties in dense solids
Compressive strength	Compressive strength, elastic modulus
Shear strength	Shear strength, elastic modulus or shear modulus
Shear modulus	Shear modulus, elastic modulus
Elastic modulus	Elastic modulus
Fracture toughness	Fracture toughness
Density	Density

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TABLE II Mechanical properties

Rohacell*					
Density ($kg\,m^{-3}$)	30.4	49.6	70.5	110	299
Tensile strength (MPa)	0.98	1.56	2.15	3.62	10.25
Compressive strength (MPa)	0.39	0.88	1.4	3.52	15.5
Shear strength (MPa)	0.39	0.96	1.3	2.4	7.8
Modulus of elasticity (MPa)	35	73	103	176	365
Shear modulus (MPa)	13.7	19.5	32.3	56	290
Ethafoam†					
Density ($kg\,m^{-3}$)	29–40	48–58	83–93	105–115	
Tensile strength (MPa)	0.33	0.46	0.53	0.85	
Compressive strength (MPa)	0.05	0.08	0.12	0.21	
7075 aluminium foam‡					
Relative density	0.1	0.125	0.15	0.175	0.2
Compressive strength (MPa)	2.2	4.4	7.0	9.7	12.5

*Source: Rohacell Cyro Industries Data Sheet (1986).
†Source: "Ethafoam" data sheet, Dow Chemical Co (1983) 7.
‡Source: Thornton and Magee [4].

cell foams and the aluminium foam is an open cell foam.

In this comparison we have used all foam and honeycomb properties as quoted by the manufacturers. For easy reference the data on aluminium foams, Rohacell and Ethafoam are given in Table II. The base material properties are mainly taken from standard references and are given in Table III along with their source. In order to obtain the strengths of polymers in the two foams, Rohacell and Ethafoam, we have employed an indirect method. It is known that in tension the cell walls become aligned toward the tensile axis and the tensile strength may be approximated by the relation [1]

$$\sigma = \sigma_s(\rho/\rho_s) \quad (2)$$

where σ is the strength of the foam, σ_s the strength of the solid material and ρ/ρ_s is relative density of the foam.

Fig. 1a shows the variation of tensile strength of Rohacell and Ethafoam as a function of density plotted on a logarithmic scale. It may be seen that the variation is nearly linear as expected. We estimate the strength of the base material as present in the foam by extrapolating these lines to the estimated full densities, $1200\,kg\,m^{-3}$ for methacrylimide and $920\,kg\,m^{-3}$ for low density polyethylene. The elastic modulus of polymethacrylimide was also obtained by a similar plot of modulus against density shown in Fig. 1b. We may mention that this method of estimating the base material properties eliminates the effect of any non-contributing material which may be present in the foam and brings the comparison nearer to those with idealized closed cell foams, rather than the ones actually compared here.

The strength data quoted by the manufacturers are practically attained values and include in them some effects of the process and structural variables. Results on aluminium foam might have been affected not only by the experimental nature of the samples but also while reading the data from the published paper. Ethafoam uses a low density polyethylene in it. We have assumed its specific gravity to be 0.92 as an estimate. Specific gravity of polyethylene may typic-

TABLE III Properties of dense solids

Material	Density ($kg\,m^{-3}$)	Elastic modulus (GPa)	Compressive strength (MPa)	Tensile strength (MPa)	Shear strength (MPa)	Reference and comment
5052 Al Alloy	2680	70.3	255	–	165	[10, p. 943]
5056 Al Alloy	2640	71.0	344	–	220	[10, p. 943]
2024 Al Alloy	2770	73.0	393	–	289	[10, p. 938]
7075 Al Alloy	2800	71.7	342	–	–	[10, p. 948]
Polyamide	1040–1130	1.5–3.3	–	44–82	–	[8]
Polyethylene	920	0.1–0.3	–	5–25	–	[6]
Polymethacrylate	1200	2.4–3.3	–	45–85	–	[7]
Polyaramid	900	5.5	–	70–120	–	[3]
Rohacell Material	1200	1.51	40	40	20	Compressive and shear strengths estimated from tensile strength data on foam.
Ethafoam Material	920	0.2	10.7	10.7	5.4	Compressive and shear strengths estimated from tensile strength data on foam.

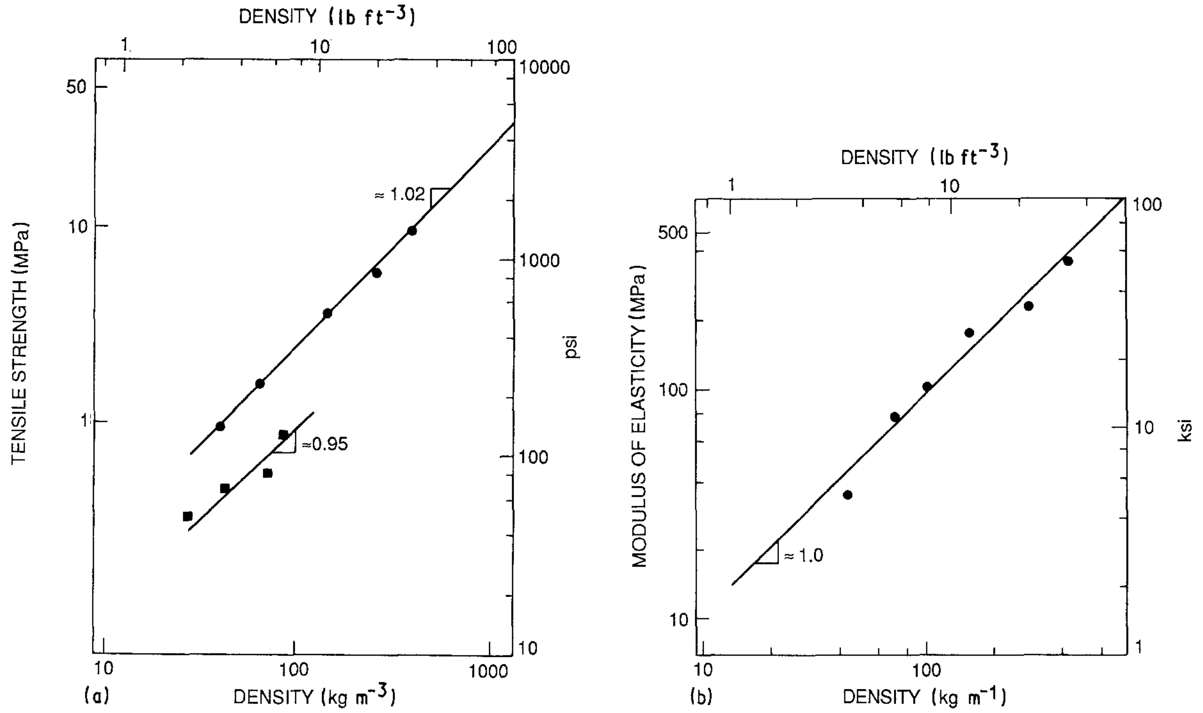

Figure 1 Variation of tensile properties for Rohacell and Ethafoam with density. (a) Tensile strength for Rohacell (●) and for Ethafoam (■) (b) Modulus of elasticity for Rohacell.

ally vary from 0.9 to 0.95 and 0.92 may be a reasonable value. Tensile strength data of polyethylene showed a linear variation with density with a slope of 0.95 on a log–log plot. Tensile strength of polyethylene was estimated to be 10.68 MPa. Typically the strength of polyethylene may vary from 5 to 25 MPa [6] and the 10.68 MPa may not be unreasonable. Elastic modulus of polyethylene may typically be 0.1 to 0.2 GPa [6]. We have assumed it to be 0.2 GPa. We have assumed the compressive modulus to be the same as tensile modulus and the shear modulus to be directly related to tensile modulus, and be about 0.4 times the tensile value. We have taken the shear strength to be about half the tensile strength. We have also assumed the compressive strength to be the same as the tensile strength.

The data used for Rohacell are also not accurate. Rohacell is a polymethacrylamide–imide foam. Typical specific gravity of polymethacrylate is about 1.2 [7], for polyamide is about 1 to 1.15 [8] and for polyamideimide it is about 1.4. We have assumed a value of 1.2 for the Rohacell material. The strength is deduced from the tensile strength data for the foams. From the linear plot of density against tensile strength it was found to be about 40 MPa. This value resembles that expected out of polymethacrylate (45 to 85 MPa) [7] and polyamide (40 to 80 MPa) [8]. Some loss in strength may be due to the possible presence of some non-contributing material in the foam. It may also be because the foam is not so flexible and suffers brittle fracture before the average stress reaches the tensile strength. We have used the tensile data to estimate the compressive strength as well as the shear strength. Since in brittle polymers compressive strength may be higher than tensile strength by as much as a factor of two, it is possible that the compressive strength used for this foam is in error by the same margin. For compressive modulus of Rohacell material we extrapolated the modulus-density data, to full density and obtained a value of 1.51 GPa. This is near to the lowest value expected for polyamides [8] and lower than the value for polymethacrylates [7] and polyamide–imides [9]. Though the estimated strength and modulus may be lower by a factor as high as 2, they may actually be nearer to correct value to be used for our idealized foam in which the material distribution is uniform and all faces contribute fully. In an ideal foam which has uniform wall thickness we can eliminate the problem of non-contributing material thus making them nearer to this idealization.

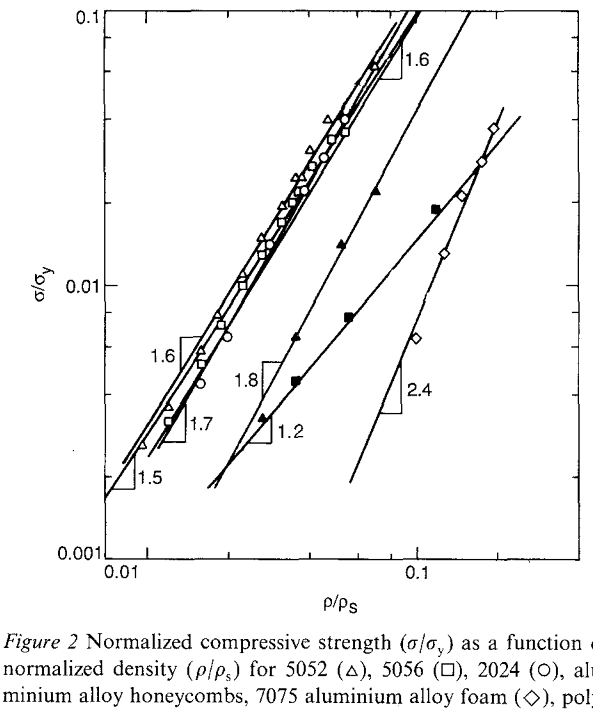

Figure 2 Normalized compressive strength (σ/σ_y) as a function of normalized density (ρ/ρ_s) for 5052 (△), 5056 (□), 2024 (○), aluminium alloy honeycombs, 7075 aluminium alloy foam (◇), poly-aramid honeycomb (▲) and for Rohacell (——) and Ethafoam (■). Normalizing factors for strength are the base materials' strength at full density (Table III).

In Fig. 2 we have shown the normalized compressive strength of 5052, 5056 and 2024 honeycombs in the direction of the cell axis along with the normalized strength of Rohacell and Ethafoam. Also shown in Fig. 2 are the normalized compressive strength of a polymer honeycomb [3] and 7075 aluminium foam. All normalizing factors are the base material strengths or densities and are shown in Table III. It may be seen that when normalized the strength of Rohacell foam nearly approaches the strength of aluminium honeycombs. Ethafoam is weaker and aluminium open cell foam is ranked lowest and is more than an order of magnitude weaker than honeycombs.

In Fig. 3 we have shown the compressive strengths when they are normalized by the elastic modulus. This comparison is perhaps more appropriate when the failure is initiated by elastic buckling rather than by plastic buckling as is often the case with low density foams and honeycombs of all materials. In this comparison, the polymer and metal honeycombs fall near one another and both Ethafoam and Rohacell emerge superior. Ethafoam appears to be superior by a factor of about 2 at low densities. Rohacell is superior at all densities by a factor of about 5. The metal foam 7075 is once again inferior to honeycombs by a factor of about 10.

In Fig. 4 we have shown the normalized compressive modulus of aluminium honeycombs along with that of Rohacell. The foam shows a slope close to 1 while honeycombs show a slope near 1.5. In addition the elastic moduli of the foam are at least comparable if not superior to those of the honeycombs.

Fig. 5 shows the shear strength of Rohacell normalized by the shear strength of the solid material compared with normalized W direction shear strength of aluminium alloy honeycombs. The W direction is taken as the direction transverse to the general direction of the ribbons of honeycomb cell walls. Rohacell appears to be substantially superior. Fig. 6 compares

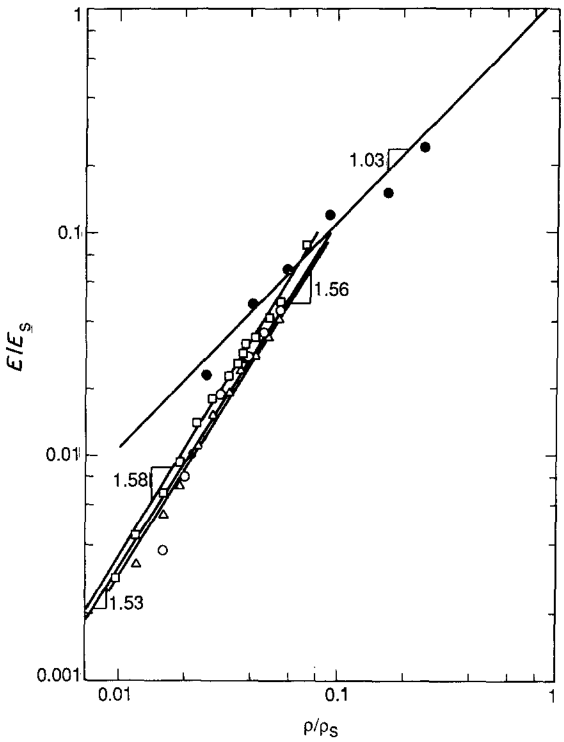

Figure 4 Normalized compressive modulus (E/E_s) of Rohacell (●) and honeycombs as a function of relative density (ρ/ρ_s). (□ 5056,

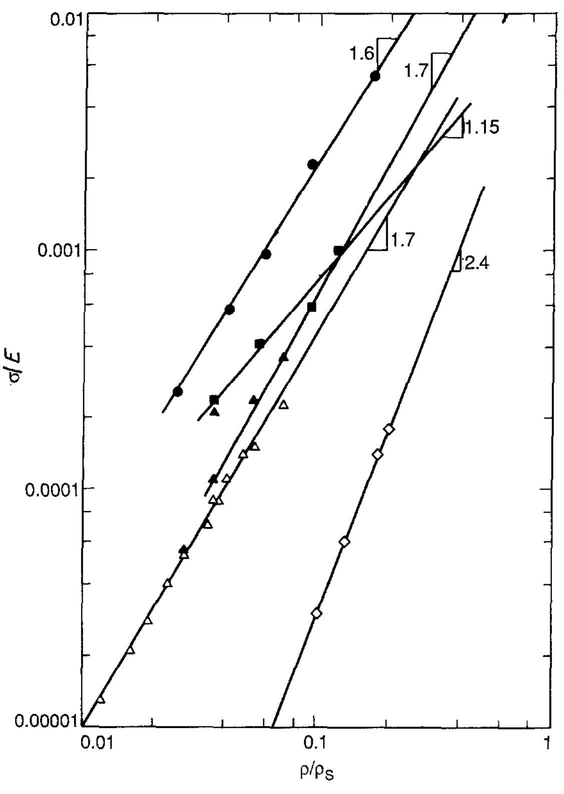

Figure 3 Compressive strength (σ/E) of five different cellular materials normalized by the elastic moduli of the dense materials and shown as a function of relative density (ρ/ρ_s). Both Rohacell (●) and Ethafoam (■) appear superior to polymer (▲) and aluminium alloy 5052 (△) honeycombs. (◇ 7075 foam).

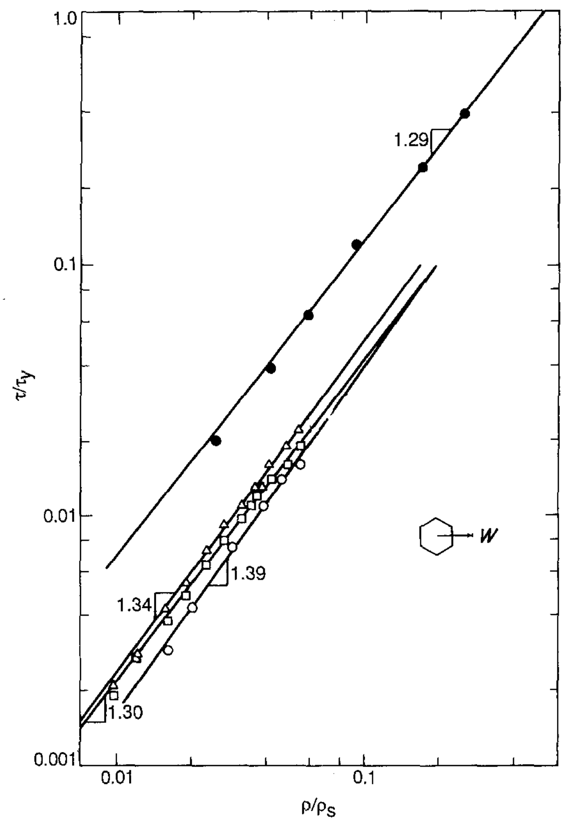

Figure 5 Normalized W direction shear strength of aluminium alloys honeycombs compared with normalized shear strength (τ/τ_y) of Rohacell (●) foam shown as a function of relative density (ρ/ρ_s). (△ 5052, □ 5056, ○ 2024).

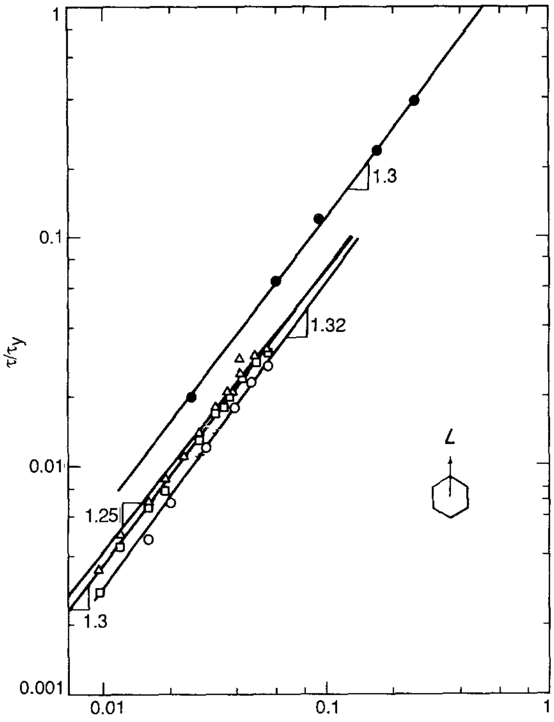

Figure 6 Normalized L direction shear strength of aluminium alloy honeycombs compared with normalized shear strength of Rohacell (●). Normalizing factor for the strength was the shear strength of the base material. (△ 5052, □ 5056, ○ 2024).

aluminium honeycombs, polyaramide honeycombs, and Rohacell for their shear strength in the L direction, the ribbon direction. It appears that the closed cell foam is not inferior to any of the honeycombs with respect to shear strength in both L and W directions.

In Fig. 7 we have shown the normalized L direction shear modulus of aluminium alloy honeycombs with the normalized shear modulus of Rohacell. The data

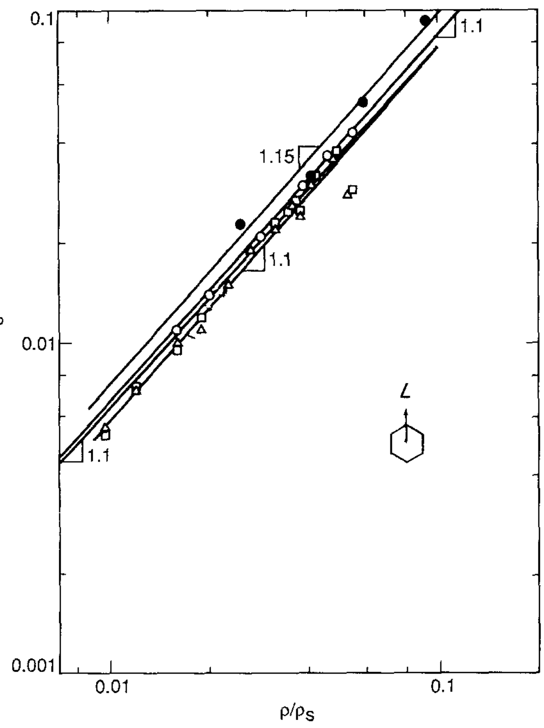

Figure 7 Normalized L direction shear modulus (G/G_s) of aluminium honeycombs compared with normalized shear modulus of Rohacell (●). Normalizing factors were the shear moduli of the base materials. (△ 5052, □5056, ○ 2024).

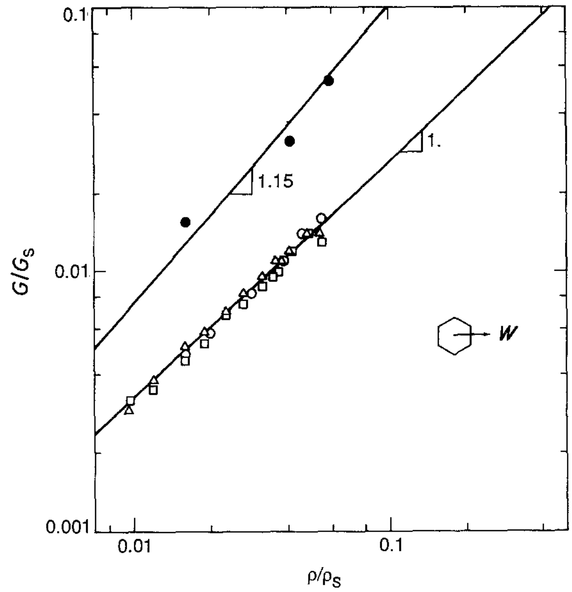

Figure 8 Normalized W direction shear modulus of aluminium alloy honeycombs (○ 5052, △ 2024, □ 5056) and Rohacell (●).

are normalized by the shear moduli of the respective dense solids. The normalized shear modulus of the foam is comparable to the normalized L direction shear modulus of the honeycombs. In Fig. 8 we have shown similar results for the W direction shear moduli of honeycombs compared with the shear modulus of Rohacell. Clearly the closed cell foam appears superior.

3. Discussion of the results

The above analysis seems to indicate that closed cell foams can be superior to honeycombs with respect to shear strength as well as shear modulus. They also suggest that the compressive strength and compressive modulus of the two structures may be nearly equal for the two structures. This is particularly evident when we normalized the compressive strength by the compressive modulus (Fig. 3).

We believe the results of our analysis should be used only to provide a broad assessment of the comparative performance of honeycombs and foams because the data used may have a large margin of error.

We may learn something more from the data on 7075 open cell foam where the data for all the properties are known without significant error. Data on aluminium honeycombs are also known accurately. We find that the open cell foam is weaker than honeycombs by a factor of about 10 in compression. We also find that the slope of plots for foam is about 2.4 whereas those for honeycombs it is about 1.5. Using the relations derived in Chapter 5 [1], it is possible to show that closed cell foams will show lower slopes and can be stronger than open cell foams by a factor of about ρ_s/ρ. For the foam used here, this factor would range from 10 to 5. Considering that a good fraction of the material ($\sim 25\%$) in the inhomogeneous foam used here may not be fully contributing to strength we may conclude that in an ideal closed cell foam where all material participates fully, the strength of a closed cell 7075 foam would be higher by a factor of about 10 to 20 compared to that of the open cell 7075 foam.

This brings the strengths of ideal closed cell foams to levels comparable or superior to those of honeycombs.

4. Conclusions

The conclusions are as follows.

(1) Ideal closed cell foams may provide compressive strengths which are isotropic and yet can be comparable to the compressive strengths of honeycombs in the thickness direction.

(2) Shear strength of ideal closed cell foams may be superior to the shear strength of honeycombs.

(3) Compressive and shear modulus of ideal foams may be nearly equal or superior to those of honeycombs.

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