

MECHANICAL CHARACTERIZATION OF POLYMER AND NANOCOMPOSITE FOAMS USING A MODIFIED ARCAN FIXTURE

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Abstract

A modified Arcan fixture is used to determine stiffness and strength properties of cellular polymers and cellular nanocomposites. Digital image correlation is employed to measure surface deformation and strain, and finite element analysis is used to correct for non-uniformity of the strain field in the gauge section. The experimental protocol is verified on cross-linked PVC foams (DIAB Divinycell H), the results of which are in good agreement with published data. The technique is also applied to rigid polyurethane foams that have been chemically formulated or modified with nano-fillers in an attempt to meet specifications relevant to wind power and marine transportation applications. The results suggest that the addition of nano-fillers influences the mechanical properties of cellular nanocomposites via changes in the cellular structure and reinforcement of the solid polymer.

1 Introduction

1.1 Motivation

The development of new cellular materials with improved structural performance and reduced cost and weight is an active area of research that has been driven by an increasing demand for these materials in the energy and transport industries. There is a corresponding need for characterization techniques that enable the rapid and reliable determination of the mechanical properties of these materials. Conventional testing techniques require large material volumes, often fail to provide reliable data beyond the elastic range, and can introduce edge effects that induce premature failure. In this study, a modified Arcan fixture (MAF) [1] is employed, along with non-standard compact specimen geometries to determine the stiffness and strength of cellular polymers and nanocomposites. The MAF allows the application of tensile, compressive, shear, biaxial tensile-shear, or biaxial compressive-shear loads through the spiral distribution of loading holes. The present study focuses on the pure shear loading configuration in order to supplement compressive data already available for these materials. In conjunction with mechanical models of cellular materials, the results of mechanical testing provide an estimate of the reinforcing effect of nanofillers and of their impact on the cellular microstructure.

1.2 Mechanical Behavior of Cellular Solids

The mechanical properties of cellular materials are highly dependent upon the properties of the solid material making up the foam, as well as the relative density and the cellular structure of the foam [2]. The addition of nanofillers to polymer foams can impact the mechanical properties of the foam by affecting the mechanical properties of the solid (i.e. the Young's modulus and ultimate strength of the solid), by affecting the cellular structure (i.e. the density, cell size, and cell shape), or both [3, 4].

The mechanical properties of foams can be described as a function of the relative density (ρ_f/ρ_s) according to the expression [2]:

$$\frac{P_f}{P_s} \approx C \left(\frac{\rho_f}{\rho_s} \right)^n \quad (1)$$

where P is the mechanical property of interest, ρ is density, the parameters C and n depend on particulars of the foam (including the foam microstructure and deformation mode) [5-7], and the subscripts s and f indicate properties of the fully dense solid and of the foam, respectively.

In conjunction with equation (1), the parameters in Table 1 describe the Shear modulus (G), Young's modulus (E), and tensile strength (σ_u) of open-cell foams [8, 9]. These parameters were derived by assuming an open, cubic unit-cell with bending as the dominant deformation mode yields.

Property, P	C	n
Shear Modulus, G	3/8	2
Young's Modulus, E	1	2
Tensile strength, σ_u	0.65	1.5

Table 1. The parameters C and n from equation (1) for properties of an open cell foam.

The parameters in Table 1 are adequate for describing experimental modulus data from a variety of open-cell foams that cover a range of relative densities. In closed-cell foams, n is generally reduced from the open-cell case of $n = 2$ to the range $1 < n < 2$ as a result of the combination of plate-stretching (in the cell faces, corresponding to $n = 1$) and bending (in the cell struts, corresponding to $n = 2$) deformation modes [2, 5-9].

1.3 Anisotropy of Cellular Solids

In general, foams are mechanically anisotropic, with the axisymmetric case depicted in Figure 1 typical of thermosetting polymer foams.

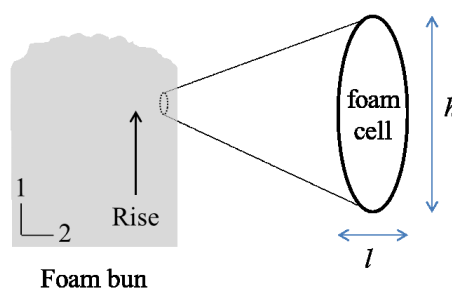


Figure 1. Block of foam with inset showing an individual cell elongated in the rise direction.

Huber & Gibson [10] modified equation (1) to explicitly include the effect of elongated cells on the mechanical properties of foams:

$$\frac{P_f}{P_s} \approx C \left(\frac{\rho_f}{\rho_s} \right)^n f(R) \quad (2)$$

where $f(R)$ is one of several functions of the shape anisotropy ratio ($R = l / h$) of the unit cell, which are tabulated for the Young's and shear moduli in each material direction in Table 2.

Property	$f(R)$
E_1	R
E_2, E_3	$\frac{1}{2R} \left[1 + \left(\frac{1}{R} \right)^3 \right]$
G_{12}, G_{13}	$\frac{2}{R(R+1)}$
G_{23}	$\frac{1}{R}$

Table 2. The function $f(R)$, from equation (2), for the Young's and shear moduli in each material direction.

2 Materials and testing methods

Rigid, closed-cell polyvinylchloride (PVC) foams were obtained from DIAB (Divinycell H80, H100, and H130 grade). A rigid, closed-cell polyurethane (PU) foam system was developed by corporate partners at Recticel¹. Nanocomposite PU foams were produced by incorporating nano-particulate fillers into the polyurethane precursors before the foaming process. Effective incorporation and dispersion of the nanofillers was carried out by colleagues at Aalborg University (AAU) and is described elsewhere [11]. Two types of nanofillers (designated A and B) consisted of nanoclay platelets with carbon nanotubes (CNTs) grown on the clay surface, and differed only in the processing route for grafting of the CNTs. Several different nanocomposite foams were produced by incorporating quantities of each type of nanofiller ranging for 0.25 – 1.0 wt%. Pure polyurethane foams (with no particulate fillers) were produced both at Recticel's manufacturing facilities and under lab conditions at AAU.

The shear specimen geometry in Figure 2(a) was adopted from Taher et al. [1], along with the modified Arcan fixture in Figure 2(b). Foam specimens were produced using a CNC router to plane and shape the foam slabs.

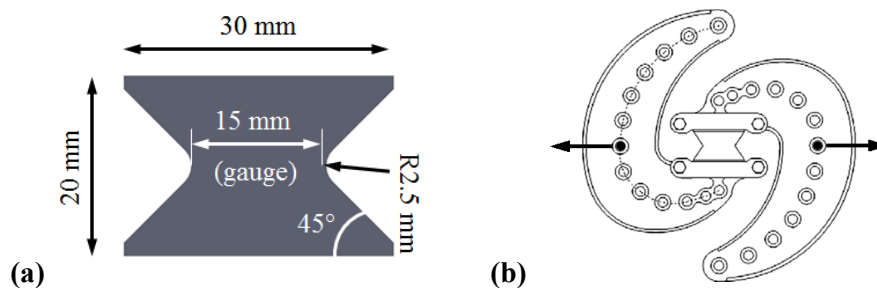


Figure 2. (a) Shear specimen geometry (15 mm thickness). (b) MAF with pure shear loading configuration indicated. Reprinted from [1], with permission from Elsevier.

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Load was applied as shown in Figure 2(b), resulting in shear-dominated deformation in the gauge section of the specimen. A constant displacement rate of 0.6 mm/min. was applied using a screw-driven load frame that was fitted with a 2 kN load transducer to record the applied force. The state of strain on the front and back surfaces of the specimen was measured using Aramis digital image correlation (DIC) software (GOM mbH).

Stress-strain curves were constructed using the average strain measured along the gauge section. Stress was computed using load data and the nominal cross-sectional area. The difference between the surface strain obtained from DIC and the strain through the full thickness of the gauge section was estimated by performing a finite element analysis using the commercial FEA code Abaqus 6.10-2. The measured strain was corrected based on this estimated difference, as described in [1]. The shear modulus was computed within the linear portion of the stress-strain curve, which was taken as $0 < \gamma < 0.02$.

3 Results

3.1 DIAB Divinycell PVC Foams

Representative stress-strain curves for Divinycell PVC H80, H100, and H130 foams are shown in Figure 3(a). As expected, all curves exhibit yielding and significant plastic deformation before failure. The average shear moduli are plotted as a function of the average apparent density in Figure 3(b), along with the upper- and lower-bounds specified by the manufacturer [12]. The measured values fall within the specified range and a power law curve fit of the form in equation (1) fits the data well with $n \approx 1.28$.

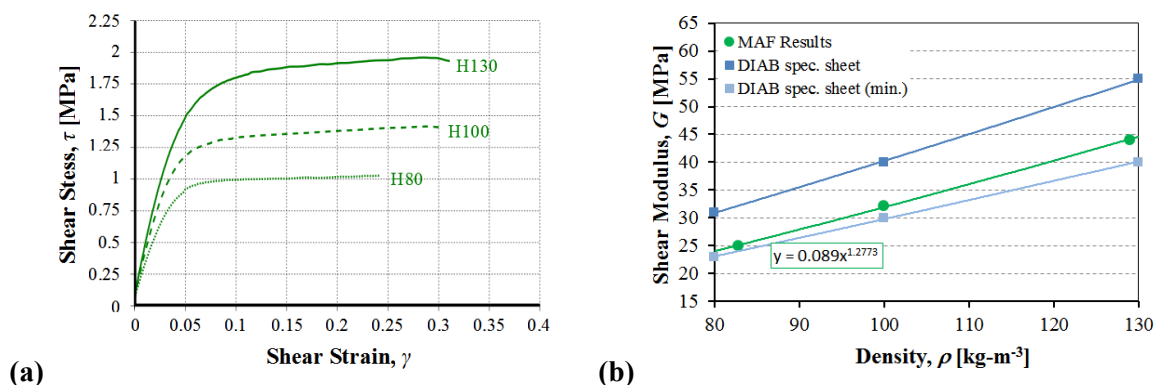


Figure 3. (a) Representative shear stress-strain curves, and (b) shear modulus as a function of apparent density for H80, H100, and H130 Divinycell PVC foams.

3.2 Pure Polyurethane and Nanocomposite Foams

The shear modulus of PU foams was measured on the 2-3 plane (G_{23}), according to the coordinate system in Figure 1. The results are plotted for pure PU foams (red circles) and PU nanocomposite foams (blue diamonds and squares) in Figure 4. The data points for pure PU are fitted with a power law (solid red line), with $n \approx 1.82$. Young's modulus (E_I) in the 1-direction was measured in compression for pure PU (lab) and nanocomposite foams according to ASTM D1621 [13] by the producers of the foams.

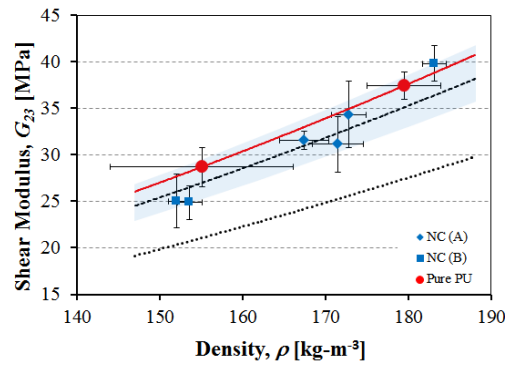


Figure 4. Shear modulus as a function of apparent density of polyurethane (PU) and nanocomposite (NC) foams. Model predictions account for: relative density (red solid line), cell shape (black dotted line), cell shape & reinforcement (black dashed line).

The addition of the nano-fillers resulted in foams with a range of apparent densities from approximately 150–185 kg/m³. While the shear moduli of the nanocomposite foams were at or below the power law predictions for pure PU foams, the reported Young's moduli (E_I) of the nanocomposite foams were significantly increased above the power law prediction (36.6% average increase).

The average increase in E_I for nanocomposite foams above the power law prediction can be predicted using equation (1) by assuming a corresponding increase in the Young's modulus of the solid PU nanocomposite (E_s), but the predicted shear modulus also increases which is not supported by the data in Figure 4. This discrepancy suggests that the increase in E_I cannot be solely attributed to mechanical reinforcement of the PU. Alternatively, the increase in E_I can be attributed to changes in the cell shape (R). Using equation (2) and $f(R)$ for E_I in Table 2, an increase of R by 36.6% predicts the reported increase in E_I , but the shear modulus predicted using equation (2) is significantly below the measured values (dotted line in Figure 4). Combining the effects of mechanical reinforcement (increased E_s) and cell shape (increased R) results in trend lines that span the shaded regions in Figure 4 and encompass the experimental results. The E_I and G_{23} forms of equation (2) may be solved simultaneously for the change in R and in E_s (relative to pure PU) for each of the nanocomposite foams. The results of this calculation are contained in Table 3. Using equation (2) and the average values of ΔR and ΔE_s in Table 3 results in the dashed line in Figure 4, which is in good agreement with the data and predicts the reported 36.6% average increase in E_I .

Foam Material	ΔR	ΔE_s
Pure PU	1	1
NC (A 0.25 wt%)	1.24	1.12
NC (A 0.5 wt%)	1.17	1.15
NC (A 1.0 wt%)	1.19	1.13
NC (B 0.25 wt%)	1.29	1.13
NC (B 0.5 wt%)	1.26	1.14
NC (B 1.0 wt%)	1.09	1.12
NC Average	1.21	1.13

Table 3. Change in R and E_s relative to pure PU calculated for each nanocomposite (NC) foam.

The changes in the cellular microstructure of the nanocomposite foams predicted using equation (2) were partially confirmed by measuring the cell shape anisotropy (R) in pure PU and 0.25wt% B nanocomposite (NC B 0.25wt%) using scanning electron microscopy. Cell

size was measured in the rise (1) and flow (2) directions according to ASTM D3576 [14]. The increase in shape anisotropy measured in this way was 1.09 ± 0.31 , compared with a predicted value of 1.29. Although there is a large degree of uncertainty associated with the microscopically-measured value (as indicated by the large standard deviation), the predicted value is well within one standard deviation and the mean indicates a bias toward increased cell elongation in the nanocomposite foam.

4 Conclusions

The modified Arcan fixture (MAF) was used to characterize PVC, PU, and nanocomposite foams under shear loading conditions. The test methodology was validated on commercially-available PVC foams with well-defined mechanical properties. The test results from nanocomposite foams were used in conjunction with available compressive data and microstructural models for cellular materials to infer changes in the cellular structure.

In future, we expect to utilize the tensile, compressive, and biaxial loading capabilities of the modified Arcan fixture to fully characterize new PU and nanocomposite foams. Measurements of mechanical anisotropy (i.e. E_1 / E_2) should provide a more reliable measure of cell shape anisotropy than microscopy.

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