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Tension, compression and shear fatigue of a closed cell polymer foam

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ABSTRACT

A closed cell foam of polymetacrylimide (Rohacell) with three different densities is studied. The foam is tested quasistatically in tension, compression and shear. The tensile properties scale very well with the relative density of the foam, but the compression and shear properties do not scale the same way. It is believed to be due to cell edge and cell wall buckling being the dominated deformation mechanism in compression and shear for lower densities that does not occur for higher densities. Fatigue testing is then performed in tension, compression and shear. It is seen that for all load cases and densities, the fatigue life can be plotted using Basquin's law. The results also show that the different failure mechanisms found in the static tests are the same in fatigue. This means that the fatigue life for different load types exhibit different failure mechanisms. This shows not only as a clear difference in the stress levels for fatigue failure, but also on the slope in the fatigue life relation.

1. Introduction

Rigid cellular foams are extensively used as a structural core in load carrying sandwich structures. The usage stretches over applications in aerospace, automotive, marine, transportation and infrastructure. There are numerous examples of applications and a few worth noticing here are the new Swedish Navy Corvette Visby, wind-mill blades, and novel train car structures. In all of these and many other sandwich applications, the core is typically closed cell polymer foam, designed to carry a substantial part of the load. More and more has been focused on the core material recently due to increased demands for material properties and models to use in the design of sandwich structures. Fracture and fatigue of load carrying foam cores remains to a large extent unknown. The reason for this is the inherent structure of foams, constituted of a complicated three-dimensional network of thin membranes (cell walls), enclosing each cell. At the intersection of cell walls, edges with concentrated mass build up rods or beams. A foam is not just a material, but also a micro-structure – homogeneous continuum or heterogeneous cell structure, depending on the scale of interest.

Not much has been reported on fatigue of foams. A good summary of what has been done can be found in [1]. Some early work was performed by Burman and Zenkert [2,3], Shenoi et al. [4], Buene et al. [5] and Kanny and Mahfuz [6]. Kanny and Mahfuz [7] and Kulkarni et al. [8] performed fatigue testing of foam core sandwich beams with polymer foam cores. The testing set-up was in all these cases such that the core would be subjected mainly to shear stress and the intention was to find the stress-life curve for shear stress. McCullough et al. [9] tested aluminium foams in both tension–tension and compression–compression fatigue. Although the results therein are not given in terms of a Basquins' law, it was found that the slope of the S–N curve is considerably lower in the compression–compression fatigue case. Harte et al. [10] performed fatigue testing of an open and a closed cell aluminium foam with one aim of finding the fatigue limit. Olurin et al. [11] performed crack propagation measurement on two closed cell aluminium foams. Shipsha et al. [12,13] used both compact tension (CT) and cracked sandwich beams specimens to measure crack propagation rates in polymer foams. In both cases, it was found that the crack rates were considerably higher than for homogeneous solid materials. By using micro-mechanics Huang and Lin [14] performed the first attempt to model crack propagation in foams and were able to density normalise the data into one single generic relation for all density phenolic foams. Zenkert et al. [15] used an initial flaw approach model through which the crack propagation data could be transformed to stress-life curves. The model gave excellent agreement with measured crack propagation data and tension–tension fatigue testing results for two closed cell polymer foams.

The present study is an extension of the work performed in [15], where only tension fatigue was studied. The aim of this paper is to compare fatigue testing data in tension, compression and shear loading. All the tension data presented here are directly reproduced from [15] but needs to be included in order to make proper comparisons.

2. Materials

The high performance closed cell rigid polymer foam Rohacell WF-grade was used. Rohacell is a polymetacrylimide (PMI) foam

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with predominantly closed cells, which is a rather brittle foam with a tensile strain to failure of approximately 2–3%. Details on this material can be found in [16]. Three different densities were used; WF51, WF110 and WF200, with nominal densities of 52, 110 and 205 kg/m^3, respectively.

3. Static properties

Static properties of the foams used herein were tested in tension, compression and shear. The tension and compression tests were performed using the same specimen geometry as used in the fatigue testing (described below) at a prescribed displacement rate of 1 mm/min. The static shear properties were obtained from the same four-point bending test as later used in the fatigue testing. In this test, the shear strength can be obtained, though, the complete stress–strain relation cannot be acquired. However, by reducing the load–displacement relation from the test to shear stress (transverse load per unit width divided by core thickness) and readjusting the displacement values so that the initial slope equals the known shear modulus we can get the complete curve, at least approximately. Shear tests performed by the core material manufacturer using the standard block shear test according to ASTM-C273 were used for comparison. The reason for using the bend test primarily is that block shear test, because of its design, often gives a non-conservative value, at least in strain to failure, and for high density foams.

In tension, the material yields, though very little. We have chosen to use the yield stress as the governing parameter rather than the stress at rupture. The yield point in tension has been defined as a standard 0.2% offset stress, a value being very close to the ultimate strength. In subsequent use of this property, we will refer to this as the yield strength in tension. The values of yield strength are also given in Table 1. There are many interpretations of the compressive strength of foams. As seen from Fig. 1, the compressive stress–strain relation can be defined by a linear part, followed by a slight non-linear part, a distinct peak followed by a small stress drop and then a so called plateau level. The manufacturers almost always supply this peak stress in the stress–strain relation as the compressive strength. The material also yields in compression and shear. We have chosen the yield points in compression as a 1% offset stress and in shear as the 0.5% offset stress. There is no particular rationale behind this choice except that these points provide good cut-off stress limits for the fatigue results described in the following sections.

Table 1
Material data for Rohacell WF51, WF110 and WF200 (manufacturer's data within parenthesis)

	WF51	WF110	WF200
ρ [kg/m3]	52 (52)	114 (110)	207 (205)
E [MPa]	75 (75)	185 (180)	395 (350)
G [MPa]	27 (24)	71 (70)	152 (150)
$\hat{\sigma}_{tension}$ [MPa]	1.6 (1.6)	3.5 (3.7)	7.4 (6.8)
$\hat{\sigma}^{tension}_{yield}$ [MPa]	1.51	3.20	6.45
$\hat{\sigma}_{compression}$ [MPa]	0.95 (0.8)	3.3 (3.60)	8.9 (9.0)
$\hat{\sigma}^{compression}_{yield}$ [MPa]	0.90	3.2	8.0
$\hat{\tau}_{shear}$ [MPa]	0.75 (0.8)	2.5 (2.4)	6.0 (5.0)
$\hat{\tau}^{shear}_{yield}$ [MPa]	0.66	2.4	5.8
$\hat{\sigma}_{compression}/\hat{\sigma}_{tension}$	0.50	0.97	1.32
$\hat{\tau}_{shear}/\hat{\sigma}_{tension}$	0.50	0.73	0.77
$E/\bar{\rho}^n$	2370	2550	2760
$G/\bar{\rho}^n$	760	990	1050
$\hat{\sigma}_{tension}/\bar{\rho}^n$	50	51	48
$\hat{\sigma}_{compression}/\bar{\rho}^n$	25	50	63
$\hat{\tau}_{tension}/\bar{\rho}^n$	25	33	35

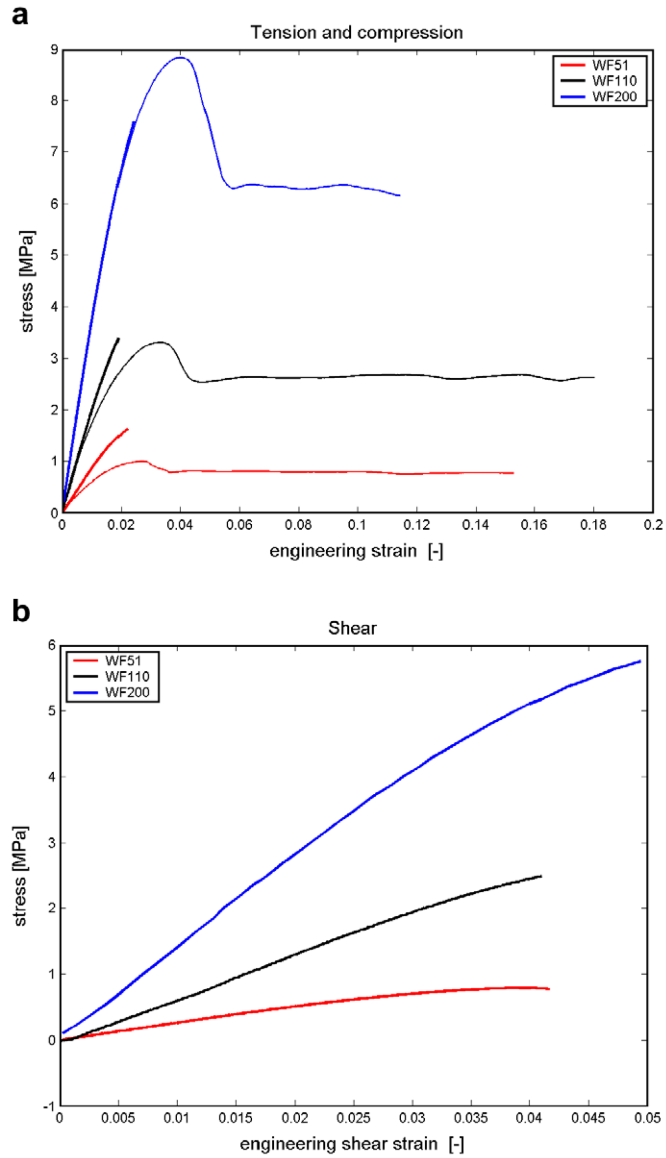

Fig. 1. Typical stress–strain relations for WF51, WF110 and WF200 in (a) tension/compression and (b) tension/shear. Tension curves are in thick lines and compression in thin lines.

In [15] the tensile stress–strain relations were normalised with the density and shown to form a generic relation. The density normalisation was performed using

$$\bar{x} = \alpha\bar{\rho}^n \qquad (1)$$

where $\bar{x}$ is some mechanical property of the foam normalised with its value for the fully dense material (bulk property) of which the cell edges and faces are made of, and $\bar{\rho}$ is the foam density normalised with the bulk density of the material, the latter taken as 1200 kg/m^3. This scaling works well when having $n = 1.1$ for properties like elastic modulus and tensile strength. The actual numbers are included in Table 1. In [15] it was shown that other properties, like fracture toughness, also scale similarly well.

Typical stress–strain relations are given in Fig. 1. For reasons of discussion these are plotted in two graphs. In Fig. 1a the tensile and compression relations are shown together and in Fig. 1b the shear relations are shown. By density normalizing according to Eq. (1) using $n = 1.1$, the tensile stress–strain relations will almost perfectly overlap for all three densities, as seen in Fig. 2a. One can also see from Table 1 that both the elastic modulus and the tensile