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Mechanical behaviour of conventional and negative Poisson's ratio thermoplastic polyurethane foams under compressive cyclic loading

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Abstract

This work presents a comparative analysis between the cyclic loading compressive behaviour of conventional, iso-density non-auxetic and auxetic (negative Poisson's ratio) thermoplastic polyurethane foams. While the three types of foam share the same base material (open cell rigid PU), one batch is transformed into auxetic (i.e., negative Poisson's ratio) using a special manufacturing process involving moulding and exposure to particular temperature profiles to stabilize the microstructure transformation. The specimens have been loaded in cyclic compression with a sinusoidal waveform in displacement control. The static tests show the specific stress–strain compressive mechanical behaviour of these auxetic thermoplastic foams, opposite to conventional ones and other similar data on auxetics available in open literature. The effect of the load loss, stiffness degradation, the evolution of dynamic rigidity and accumulation of energy dissipation versus the number of cycles are discussed for different loading levels. The analysis of the results shows that the fatigue behaviour until failure occurs in two stages, subjected to cyclic loading, depends on the loading level. The hysteresis loop tends to close itself as function as the number of cycles *N*, while the slope of the dynamic stiffness decreases with increasing *N*, therefore with decrease of dissipated energy. The energy dissipated by the auxetic foams is significantly higher than the one from conventional parent phase and the iso-density foams at every number of cycles and loading level.

Keywords: Fatigue; Foam; Auxetic; Polyurethane; Compression

1. Introduction

The mechanical properties of open and closed-cell foams can be described in first approximation by considering the density properties of the cellular solids [1]. This approach is valid for most conventional foamed materials. However, cell shape of foams could provide a significant contribution to the overall mechanical properties of the cellular solids [1]. When the cells are equiaxed the properties are isotropic, but when the cells become slightly elongated or flattened then the properties will depend on direction, often to a significant extent. Three-dimensional foams, in which the cell walls have random orientations in space, are normally anisotropic, due to the way they are foamed [2]. The cell shape can be modified using special processing techniques to obtain more radical mechanical properties changes, like negative Poisson's ratio (auxetic) characteristics.

Since 1987, when isotropic auxetic foam was manufactured for the first time [3], negative Poisson's ratio materials have created some interest for potential applications in structural integrity compliant structures, sandwich components and, in general, smart passive structural devices [4]. By definition, an auxetic (or negative Poisson's ratio) material expands in all directions when pulled in only one, giving therefore a deformation kinematics opposite to that of

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'conventional' materials. This behaviour does not contradict the classical theory of elasticity: a homogeneous isotropic thermo-dynamically correct 3D solid has a potential Poisson's ratio range between −1.0 and 0.5, while anisotropic solids can also have larger values in magnitude [5]. A negative Poisson's ratio coefficient for a material could lead to an increase in indentation resistance [6], enhanced bending stiffness in structural elements and shear resistance ([7,8]), optimal passive tuning of structural vibration [9] and enhanced dielectric properties for microwave absorbers [10]. The reader can find extensive information on auxetics in references ([11,12]).

The cyclic stress–strain behaviour of polymer foams and elastomers has attracted recent attention, particularly when energy dissipation is concerned. When samples are loaded under strain control and then unloaded, subsequent extension to the same strain requires a lower force. Further cycling results in continued softening at a progressively slower rate and a steady state may be reached. This softening phenomenon is an important indication of the amount of energy that the material can continue to absorb. Polyurethane open cell foam subjected to compressive cyclic until 100 cycles has been investigated by Rehkopf et al. [13]. Shen et al. [14] proposed a model based on the experimental results in [13] which could be applied to express the cyclic stress–strain relationship for conventional polyurethane foam at any given cycle.

In sandwich structures with polymeric foam core and partially with metal-based filler [19], it is expected that the viscoelastic behaviour of the foam play an important role in absorbing and dissipating energy especially during dynamic loading [15,16]. The dynamic-mechanical viscoelastic behaviour of the core and its effect on the performance of the sandwich is so far relatively unexplored. Kolsters and Wennhage [17] determined the loss factor ($\tan\delta$) for a variety of H-grade PVC foams. Recently, Palissery et al. [18] have investigated a PVC foam subjected to a fatigue in tension and compression tests.

This paper describes the static and fatigue properties of auxetic thermoplastic foams made by conventional PU–PE base. The foams have been manufactured following a modification of the manufacturing process route described in [2]. As further comparison, a set of iso-density non-auxetic foams has been manufactured to assess if the overall static and dynamic behaviour is influenced by the density only, and whether the negative Poisson's ratio is playing a role or not. The fatigue tests, in particular, have been carried with varying loading ratios between 0.725 and 0.95, and total number of cycles of 100,000. As it will be clear from the results shown, the auxetic foam shows higher energy absorption characteristics during quasi-static tests and more stable rigidity loss over large number of cycles, compared to the isodensity version. To the knowledge of the authors, data on fatigue loading of auxetic and non-auxetic isodensity thermoplastic foams are not present in literature, and a general assessment of the structural integrity of auxetic materials has not been performed yet.

2. Materials and testing techniques

2.1. Specimens manufacturing

The auxetic thermoplastic PU–PE specimens have been manufactured from conventional grey open cell polyurethane foams having 30–35 pores/in. and density of 0.027 g/cm^3 The parent foam was supplied by McMaster-Carr Co., Chicago, IL. Table 1 provides a summary of the nominal characteristics of the base foam as provided by the manufacturer. The conversion process was obtained using a purpose made mould and applying a combination of radial and axial compressions, and thermal gradients [20].

Processing techniques can control various features of the re-entrant cell shape proper of auxetic foams. The method used for the manufacture of auxetic samples involved four stages: (i) compression, (ii) heating, (iii) cooling and (iv) relaxation ([2,3,20]). The auxetic foam is obtained from cylinders having 30 mm of diameter and 170 mm of length. The samples are then compressed inside the mould obtaining a final nominal diameter of 20 mm and length of 100 mm. The non-auxetic (iso-density) ones are obtained from a cylindrical base foam sample of 19 mm of diameter and 200 mm of length ([21]). After compression and relaxation the resulting samples featured average dimensions of 19 mm of diameter and 55 mm of length. The final measured densities of the auxetic and iso-density non-auxetic foams are 0.118 g/cm^3 and 0.109 g/cm^3, respectively, resulting in the auxetic foam being 7.6% denser than the iso-density one. All measurements were taken at a room temperature of 18 °C. No specific humidity control has been taken.

2.2. Testing techniques

Static and fatigue test in compressive loading were carried out using a MTS 858 servo-hydraulic testing machine. The load unit is fatigue-rated at 10 kN, and can be operated at frequencies up to 30 Hz. The static tests were carried out on samples having different lengths with a constant strain rate of 0.1 mm/s. The compression was performed to reach the 80% of the initial length. The static tests were performed also to measure the Poisson's ratio of the foams manufactured. Poisson's ratio measures were based on a technique outlined in [20,22,24]. As it will be clear in the next paragraphs, a careful selection of the lengths of the samples has been performed, to avoid buckling effects during compressive loading.

The fatigue tests have been performed in displacement control for all types of the foams with a sinusoidal waveform with 3 Hz of pulsation. The samples were preloaded at 70% of the maximal displacement obtained during the static tests, and then subjected to a range of different amplitudes (0.6, 1.2, 2.4, 3.6, 4.8 and 6 mm), leading to different loading levels r (0.725, 0.75, 0.80, 0.85, 0.90 and 0.95), where: