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In situ mechanical characterization during deformation of PVC polymeric foams using ultrasonics and digital image correlation

T.H. Kidd, S. Zhuang, G. Ravichandran *

Graduate Aerospace Laboratories, California Institute of Technology, Pasadena, CA 91125-5000, USA

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ABSTRACT

Cellular solids such as polymeric foams are finding increasing applications including its use as a core material for sandwich structures. In this study, a novel method is used to measure both the longitudinal and shear wave speeds of a material simultaneously while applying a compressive load in four different densities of polymeric foams made from the same base polymer, polyvinyl chloride (PVC). The study showed that there was a significant difference in evolution of the wave speeds and hence in the apparent modulus during deformation of the lower density foams in comparison to the higher density foams. The non-contact full-field method of digital image correlation (DIC) is used to gain insights into the failure modes during deformation. The lower density foams undergo heterogeneous deformation and failed due to buckling of cell walls. In contrast, the higher density foams undergo nominally homogeneous deformation due to plastic collapse. The failure mode transition is shown to be governed by the relative density of the foams and the mechanical properties of the polymer.

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1. Introduction

Cellular materials such as polymeric foams are finding increasing structural applications including sandwich structures (Gibson and Ashby, 1999; Nemat-Nasser et al., 2007; Vaziri et al., 2006). Due to their high stiffness-to-density ratio, sandwich structures are used in many applications from aerospace structures to high speed naval craft, as well as in automotive industry. Apart from this well-known stiffness advantage that is mainly governed by the properties of the face sheets, sandwich structures offer several attractive properties depending on the proper choice of core material such as improved crash behavior, fire and noise insulation, and good vibration damping characteristics.

With the advent of new core materials, sandwich structures are becoming important in many new areas of applications and there are many issues that need to be resolved such as their deformation response and failure behavior. Also, the deformation behavior of these core materials is important because their failure behavior directly affects the stress state at the interface between core and face plate in sandwich structures. Hence, the material properties of foams are needed not only about its initial elastic state (Christensen, 1986; Gibson and Ashby, 1999) but also damage accumulation during deformation (Gong et al., 2005; Papka and Kyriakides, 1998; Steeves and Fleck, 2004; Subhash et al., 2006). Reliable mechanical characterization data for the foams as a function of deformation are needed to validate micromechanical and phenomenological models, which are used in modeling and analysis of structures.

Ultrasonic wave speed measurement is an ideal technique used to track the property changes of a material due to damage accumulation during deformation. However, foam materials in general have very high attenuation to the propagation of waves, which is exploited in acoustic shielding and noise reduction applications. Therefore, the common method of pulse echo mode ultrasonic measurements is generally inadequate. A better choice to make

* Corresponding author. Tel.: +1 626 395 4525; fax: +1 626 449 2677.
E-mail address: ravi@caltech.edu (G. Ravichandran).

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use of ultrasonic wave speed measurements is to use the transducers in the transmission mode. Ultrasonics has been used to infer the elastic properties of carbon foam (Rizzo et al., 2005). In the present study, a recently developed technique for simultaneously measuring longitudinal and shear wave speeds (Kidd et al., 2007) and digital image correlation are used to characterize the mechanical properties and failure modes of PVC foams while being subjected to deformation.

Digital image correlation (DIC) is a non-contact full-field optical technique which is used to measure displacements on the surface of a deforming specimen and is widely used to characterize material behavior over a wide range of length scales (Sutton et al., 2009). DIC has been used to study the heterogeneous nature of deformation in polymeric foams (Wang and Cuitino, 2002; Jin et al., 2007) and the non-uniform deformation in an aluminum alloy foam (Bastawros et al., 2000).

The foam materials used in the investigation and the experimental techniques (*in situ* ultrasonics, digital image correlation (DIC)) are described in Section 2. In Section 3, results for PVC foams of four different densities in the form of stress-train curves, wave speeds during deformation, and full-field deformation at various stages of compression of the foam are presented. The apparent elastic modulus and Poisson's ratio as a function of deformation is calculated using the measured wave speeds. Analytical models for two distinct failure modes are used in Section 4 to understand the observed failure mode transition.

2. Materials and methods

2.1. Material

Divinycell H-grade poly-vinyl chloride (PVC) foams used in this study were manufactured by the DIAB Corporation, DeSoto, TX. The foam samples were all semi-rigid foams with a closed cell structure. Fully dense solid PVC has a density of 1420 kg/m^3, Young's modulus (E) of 3 GPa, and yield strength of 49 MPa (Gibson and Ashby, 1999). PVC foam has many desirable characteristics for its use in marine structural applications, including its closed cell structure and hence its imperviousness to water. Four sheets each of size, $12'' \times 12'' \times 0.4''$ ($\sim$30 cm $\times$ 30 cm $\times$ 1 cm) of the PVC foam material, H130, H160, H200 and H250 provided by the DIAB Corporation were used in the study. The number designation following the H represents the density of the material; for example, H130 has a nominal density of 130 kg/m^3. Cubical samples were cut from the foam by a band saw and then polished with 400 grit sand paper. The prepared samples were cubes of 0.95 cm side with highly planar surfaces on the sides of cube. The data for selected physical and mechanical properties of the foams are given in Table 1.

Table 1
Selected physical and mechanical properties of PVC foams.

Grade	H130	H160	H200	H250
Density[a] (kg/m^3)	130	160	200	250
Compressive modulus[a] (MPa)	170	200	240	300
Shear modulus[a] (MPa)	50	73	85	104

[a] DIAB (2009).

2.2. In situ ultrasonics

A fixture for simultaneously measuring the wave speeds (longitudinal and shear) was developed to apply load to a specimen while protecting the transducers themselves from mechanical loading. A casing and spring was used to protect the transducer, while wave speed measurements were performed in the specimen during compression. The details of the loading fixture with *in situ* ultrasonics are described in Kidd et al. (2007).

Two 5 MHz piezoelectric shear transducers with a diameter of 1/8″, manufactured by Panametrics, Inc. (Waltham, MA) were used for making measurements in the transmission mode. The pulse generator model# 5052A, also manufactured by Panametrics, Inc., was used to drive the input transducer with a pulse of $\sim$30 V whose width is $\sim$200 ns. The A/D data acquisition card that acquired the signals from the transducers was Gage model# 8200G (Montreal, Canada), which had a sampling rate of 1 GSamples/s. The software used to control the card was GageScope, Professional Edition 1.0. A servo-hydraulic testing machine (Model# 110.19, Materials Testing System (MTS), Eden Prairie, MN) was used to load the specimen and has a maximum load capacity of 3 kips (13,344 N). The cross-head displacement and the load were recorded continuously. All tests were performed at a nominal strain rate of 10^{-3} s^{-1}. Ultrasonic measurements were initiated 10 s after loading commenced and readings were then taken every 10 s until the end of the experiment.

Instantaneous longitudinal (c_l) and shear (c_s) wave speeds are determined by knowing the current height of the sample and the transit time in the sample measured using the ultrasonic transducers,

$$c_l = \frac{(h_o - \delta h)}{t_l}, \quad c_s = \frac{(h_o - \delta h)}{t_s}, \tag{1}$$

where h_o is the original height of the sample, δh is the change in height (applied displacement) of the sample as determined from the cross-head motion that has been corrected for machine compliance. t_l and t_s are experimentally measured transit times of the longitudinal and shear waves, respectively.

For isotropic materials, the longitudinal and shear wave speeds can be related to its Young's modulus, E and the Poisson's ratio, ν (Achenbach, 1987),

$$c_l = \left[\frac{(1-\nu)E}{(1+\nu)(1-2\nu)\rho}\right]^{1/2}, \quad c_s = \left[\frac{E}{2(1+\nu)\rho}\right]^{1/2}, \tag{2}$$

where ρ is the density of the material.

It is important to note that the density of the foams increase with increasing compressive strain. Structural foams contain significant porosity ($\sim$70–90%), which increases with decreasing density. Under uniaxial deformation, the cross sectional area of a sample does not change since the deformation is accommodated by cell wall buckling and/or collapse of the voids (Gibson and

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