Composite Structures 135 (2016) 205–216

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Identification of the mechanical moduli of closed-cell porous foams using transmitted acoustic waves in air and the transfer matrix method

Erick Ogam [a,*,1], Z.E.A. Fellah [a], Géry Ogam [b]

[a] Laboratoire de Mécanique et d'Acoustique UPR7051 CNRS, 31 chemin Joseph Aiguier, 13402 Marseille cedex 20, France
[b] Télécom Physique Strasbourg, Pôle API – Parc d'Innovation, Bd Sébastien Brant – BP 10413, 67412 Illkirch cedex, France

ARTICLE INFO

Article history:
Available online 26 September 2015

Keywords:
Closed-cell cellular foams
Physical properties
Elastic moduli
Acoustic waveguide
Transfer matrix

ABSTRACT

Closed-cell cellular polymer foams are the most efficient insulating materials commercially available. Their lightweight and mechanical resistance also make them ideal materials for packaging protection in the transport industry. A new method using guided *acoustic waves in air* transmitted through samples of cellular foam panels, has been developed to recover their P-wave moduli and Poisson's ratios. These parameters were recovered from measured transmission coefficients of the foams through fitting to an elastodynamic transfer matrix method (TMM). The TMM integrates both the P and shear waves propagating in the layer. It was shown by using a finite element fluid–solid (elastic) interaction and an analytic P-waves-only model, that the two types of waves should be modeled to give a more precise representation of the data. The retrieved values were validated using vibration spectroscopy and from the measured velocity of a transient mechanical stress wave propagating in thin, long rod specimens cut from the panels. The problems inherent to these simple 1D characterization methods were pointed out and solved.

1. Introduction

This study focuses on the acoustic characterization to recover the elastic moduli of cellular closed-cell polymer foams (CCCPF): the expanded polystyrene (EPS) and extruded polystyrene (XPS) foams. These foams are mostly employed in the building trade as thermal insulators. The EPS foam also serve as protective packaging material for goods in the transport industry. Their popularity is due to their excellent thermal and mechanical resistances and lightweight. The EPS foam is made from pre-expanded beads.

The most common mechanical parameter provided by manufacturers for closed-cell polymer foams is the compressive strength determined using the ASTM D6817 standard [1,2]. Data provided by different manufacturers show that this property and also the thermal resistance are directly proportional to the foams' densities (Table 1) except for the XPS foam whose thermal resistance properties are constant for the tabulated densities. The elastic modulus given in the table for the EPS has no theoretical basis. The compressive resistance was measured according to the ASTM D6817 standard. The Young's modulus was then obtained by multiplying by a 100, the compressive resistance at 1% deformation. This relation does not apply to the XPS foam for which there are no tabulated data providing its elastic modulus. Giving a theoretical background to the mechanical moduli recovered using the new method was one of the aims of this paper. Measuring a parameter like Young's modulus can give an indication of the values of the thermal or compression resistances especially in cases where the equipment for measuring the other parameters are not available or not at one's disposal.

A better knowledge of the characteristics, mechanical and thermal behavior of CCCPF can be important for their use in new applications whose aims are to improve the functionalities of thermal insulation, mechanical and acoustic absorption packages. Improving thermal insulation of buildings will have a positive impact on global warming and preserve the valuable and finite energy resources. According to the United States Environmental Protection Agency (EPA) [3], buildings, account for an estimated 36% of total energy use, and 30% of greenhouse gas emissions. A solution to the reduction of carbon dioxide (CO_2) levels originating from emissions due to fossil fuel combustion for heating homes and commercial buildings, is to construct energy-efficient dwellings and edifices.

In this study, a new experimental method and model has been developed to recover without ambiguity the P-wave modulus (where P stands for primary) using acoustic waves in air. Closed-cell foams are light weight and have low elastic Young's moduli. These characteristics make them good candidates for characterization using *acoustic waves propagating in air*.

* Corresponding author.
E-mail address: ogam@lma.cnrs-mrs.fr (E. Ogam).
1 Principal corresponding author.

http://dx.doi.org/10.1016/j.compstruct.2015.09.029

Table 1
Manufacturer characteristics of EPS and XPS foams (ACH Foam Technologies, Denver, CO USA), Geofoams (AFM Corporation, Lakeville, MN USA). Thermal resistance of specimens of 25.4-mm thickness and compression at 1% (EPS) and 10% (XPS) deformation using the ASTM D6817 standard [1,2].

Physical properties	EPS12	EPS15	EPS18	EPS22	EPS29
Density (kg/m^3)	12	15	18	22	29
Thermal resistance (K · m^2/W)	0.55	0.63	0.67	0.70	0.74
Compression resistance (kPa)	15	25	40	50	75
Elastic modulus (kPa)	1500	2500	4000	5000	7500

Physical properties	XPS150	XPS250	XPS400	XPS600
Density (kg/m^3)	21	25	29	35
Thermal resistance of (K · m^2/W)	0.88	0.88	0.88	0.88
Compression resistance at yield (kPa)	104	173	276	414
Elastic modulus (kPa)				

Mechanical characterization of rigid cellular plastic materials involves the measurement of the static [1,4–6] and/or the dynamic Young's modulus. The former uses an Electronic universal testing machine (ISO 9001), while the latter is often calculated from velocity measurements of transient elastic waves propagating in the specimen [7,8]. The velocity based methods employ the time of flight (TOF) of the elastic impulse, measured from a temporal pulse signal propagating in a cylindrical or prismatic specimen. The TOF method can be unreliable because of the multimodal and dispersive nature of wave propagation in structures (many modes can propagate simultaneously with velocities depending on frequency) making the identification of specific modes difficult. One way to alleviate this problem is to determine Young's modulus (E_s) from velocity by employing an asymptotic value of the phase velocity in a slender rod [9]. This can be the fundamental longitudinal guided wave mode ($L(0,1)$) [10] of a stress-free isotropic rod of infinite length whose static limit called the bar velocity is $\sqrt{E_s/\rho_s}$ (ρ_s is the density) [11]. This is one of the methods that was employed to validate the moduli retrieved by the new method. The pitfalls of the method were also presented. The subtlety between Young's modulus and the P-wave modulus were also demonstrated.

2. Materials and methods

2.1. Closed-cell cellular foams and their microstructure

The nature of cell morphology, anisotropy and deformation of these cellular materials can be identified through scanning electron microscopy (SEM). The SEM images of the extruded polystyrene (XPS) and expanded polystyrene (EPS) foams are shown in Fig. 1. Their cells are delimited by thin wall membranes. The walls intersect at cell edges where struts [12] are present in the case of the XPS foams (clearly seen on the lower left side of Fig. 1b). In EPS foams, only walls without struts are present. The mechanical properties of foams are greatly improved by the presence of these foam struts.

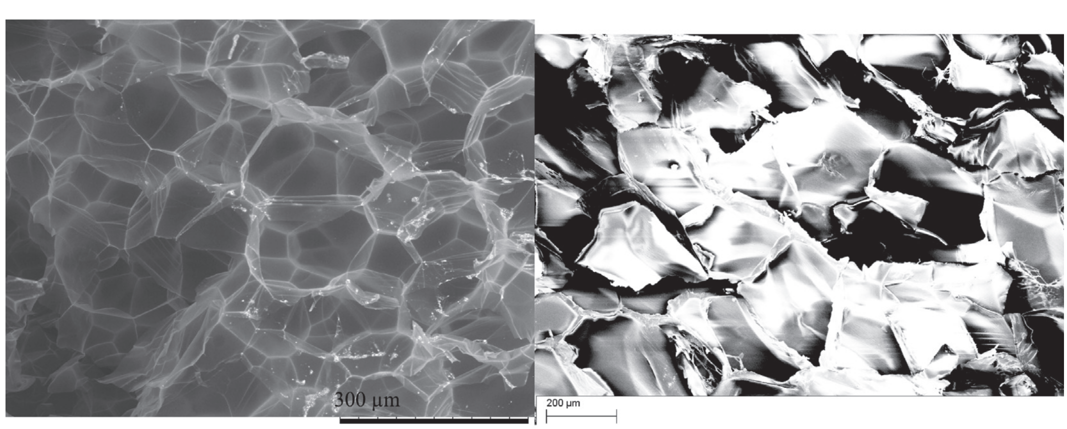
2.2. Acoustic wave transmission by a closed-cell cellular panel – the experimental reality and finite specimen dimensions

The transmission of an acoustic wave by a closed-cell cellular panel of infinite extent bordered on both sides by a fluid of semi-infinite extent is considered. Most studies on transmission of elastic waves in poroelastic/elastic thick plates often involve the modeling of only the compressional wave [13,14]. The absence of shear (SH) waves is often justified by the assumption that the interrogating wave impinges on the panel at normal incidence. However, the size of the transmitter and that of the panel are often limited, therefore the effects of geometric diffraction widen the beam of the incident wave and the wave transmitted by the panel are not similar to plane waves, as they have some divergence. Consequently, at normal incidence, the incident wave can excite a transverse wave mode conversion. It is also possible in experimental measurement reality that the incident beam not be exactly at normal incidence with respect to the panel.

Considering the previous arguments, the combined shear and compressional wave modeling were implemented for the study of the transmission and reflection by a closed-cell cellular panel. It is assumed that the wave impinges on the panel at oblique incidence at an angle, θ. The geometry of the acoustic wave transmission problem by the panel is depicted in Fig. 2. The mode conversions at the interfaces (from compressional to shear and vice versa) of the thick panel are also shown.

2.3. The experimental method for the characterization of closed-cell cellular panels

It would be very expensive to manufacture very large sized panels (the ideal would be one of infinite extent) for low frequency acoustic characterization. However closed-cell cellular panels of finite extent are easily available from most hardware retail stores in most countries where these materials are employed for thermal isolation of buildings or in packaging of goods. The solution chosen was then to take smaller specimens cut from these finite panels and employ a low frequency (plane wave) acoustic waveguide for



(a) (b)

Fig. 1. Scanning electron micrograph images of the closed-pore cells of the characterized cellular panels. (a) Low density expanded polystyrene (EPS) foam (tabletop microscope Hitachi TM1000). (b) Extruded polystyrene (XPS) foam.