An Experimental and Numerical Study to Evaluate the Crack Path Under Mixed Mode Loading on PVC Foams

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Abstract. Being able to provide outstanding performances under out-of-plane loading, sandwich structures offer great flexibility for the design of lightweight structural systems. However, they can be affected by macroscopic and microscopic damages, which may trigger catastrophic failure modes. As a consequence, a detailed understanding of the propagation of macro-cracks in the core as well as of delamination phenomena at face-to-core interfaces are aspects of great computational interest. Moreover, linking sophisticated numerical models with the measurement of the mechanical properties of materials is fundamental in view of actual engineering applications. The elastic and fracture characterization of the core is particularly relevant because its cracking strongly reduces the capacity of the sandwich structures to carry out loads. To this end, PVC foams typically used as inner core in structural application are investigated over a range of foam densities. Firstly, the elastic properties of foams under compressive uni-axial loading are measured using the full-field methodology. Subsequently, Asymmetric Semi-Circular Bend (ASCB) specimens are tested varying the position of supports to generate all range of mixed fracture modes. Finally, some of the mostly recognized fracture criterions have been considered, and their capability to compute the crack propagation angles in PVC foams have been evaluated. The parameters experimentally determined have been used to test the accuracy of the response provided by a numerical model developed by the authors.

Keywords: Sandwich structures · PVC foam · DIC · Crack path

1 Introduction

Due their excellent mechanical and physical properties (low density, energy absorption, high insulation), cellular polymeric foams are extensively utilized in many industrial applications. In particular, PVC foams are currently adopted for manufacturing

A. Carcaterra et al. (Eds.): AIMETA 2019, LNME, pp. 378–388, 2020.
https://doi.org/10.1007/978-3-030-41057-5_31

different engineering structures and products such as cores of the sandwich panels. Skins can be made of metals or fiber reinforced composites, materials that are showing an increasing success in civil engineering applications [1–4].

In particular, the core has the task to transfer shear between the sheets when the panel is subject to bending loads. The intensive loading conditions to which sandwich structures are subjected might produce failure modes such as the skin/core debonding [5–9] and the crack kinking propagation in the core region [10, 11]. With reference to the crack kinking propagation in the core region, the assessment of the elastic and fracture properties of the PVC foams is an essential prerequisite to correctly implement a numerical model, which will be able to simulate deviation of crack trajectory from the initial direction.

As a matter of fact, macroscopic elastic characterization of cellular foams is a challenging problem because of their hyperelastic behaviour and tendency for deformation localization due to local collapse of cells under compression [12]. With the aim to detect the elastic properties of foam panels, many experimental procedures have been proposed in the last decade. Viana and Carlsson [13] investigated the elastic properties of cross-linked PVC with nominal densities of 36, 80, 100, 200 kg m^{-3}. In order to define the degree of anisotropy, they performed tension tests oriented in both in-plane and through-the-thickness of the foam panels, in which the strain field was detected by adopting a MTS extensometer. The behaviour of the PVC was found to be nearly isotropic. Wang et al. [14] and Taher et al. [15] developed a modified Arcan fixture to characterize all the elastic coefficients of an orthotropic polymeric foam material carrying out one single test where the Digital Image Correlation (DIC) and the Virtual Fields Method (VFM) were used. Zhang et al. [16] defined an experimental setup to measure the material properties of polymeric foam at elevated temperatures. They focused on Divinycell PVC H100 foams carrying out tensile and compressive tests in a temperature controlled chamber with temperatures ranging from 20 °C to 90 °C. In this case, the samples geometry was selected in accordance with the prescriptions defined in the ASTM standards [17]. In order to remove the parasitic effects intrinsically presented in the experimental setup, a full-field methodology to detect the strain fields (DIC) was adopted. They obtained that the material is highly anisotropic with a ratio between the stiffness in plane and in the through-thickness directions approximately equal to 0.5. Similar tests were conducted by Colloca et al. [18], in which PVC foams with varying densities were investigated by employing both quasi-static and impact tests.

Besides, the assessment of the fracture toughness of the PVC foam is something that has not completely addressed yet. Several experimental attempts to measure the fracture toughness under pure mode I loading [13, 19, 20] used the Single Edge Notch Bend (SENB) specimens. Some authors found out that the fracture toughness is independent of the initial crack length whereas others proposed mathematical correlations between the detected facture toughness and the density of materials under investigation. It is worth noting that the mixed mode fracture of polymeric foam is rarely instigated. Aliha et al. [21] used the ASCB loading scheme, which is able to generate all range of mixed fracture modes in fragile materials, to measure the fracture properties of Polyurethane (PUR) foams. Conversely, there are not similar works in the literature investigating the fracture behaviour of PVC foam under the mixed mode loading.

The present study aims at proposing an experimental method to measure both elastic and fracture properties of PVC foams featured by different densities, ranging from 100 to 200 kg m^{-3}. The parameters experimentally determined are subsequently employed as input values into a numerical model previously developed by the same authors [22–25]. The work is organized as follows. Section 2 describes the compression and the fracture tests, respectably. Section 3 illustrates a numerical investigation aimed to simulate crack kinking phenomena in the core region of a sandwich structure. Finally, some remarkable conclusions are discussed in Sect. 4.

2 Experimental Tests

In the following subsections, the compressive and fracture tests of the Divinycell H series of PVC foams, with a range of density ranging from 100 to 200 kg m^{-3}, are described.

2.1 Compression Tests

According to ASTM standards D1621-10 (Standard Test Method for Compressive Properties of Rigid Cellular Plastics) [17], cubic samples with side length equal to 60 mm were tested to detect the elastic properties of the foams in compression. The samples were cut from 60 mm Divinycell panels in the two main directions using a Denford CNC router with a 0.1 mm resolution equipped with a 3 mm drill bit. Uniaxial tests were performed along the three main directions of the panel to investigate on the expected transversally isotropy of the material, which is due to the manufacturing method.

The experimental setup consists of an Instron 4204 electromechanical universal testing machine equipped with a 50 kN load cell. As shown in Fig. 1, the load was applied by mean of a compression device embedding a spherical seating mechanism and two aluminium plates to apply the load uniformly on the specimen. Furthermore, in order to detect the specimen deformation by-passing the compliance of the load application system, a displacement transducer (DT) was used to measure the distance between the two plates. A Digital Image Correlation (DIC) system, consisting of a high-res digital camera employed in manual mode and two high frequency led lights (Fig. 1) was also employed. A picture every 0.5 s (2 Hz) was taken during the test with purpose to monitor he front surface of the cube during testing phases, whereas LED lights were used to provide the necessary image contrast. A stream of black paint was preventively applied on the monitored specimen face as to obtain a random b/w speckle pattern, the ideal reference system for DIC purpose [19].

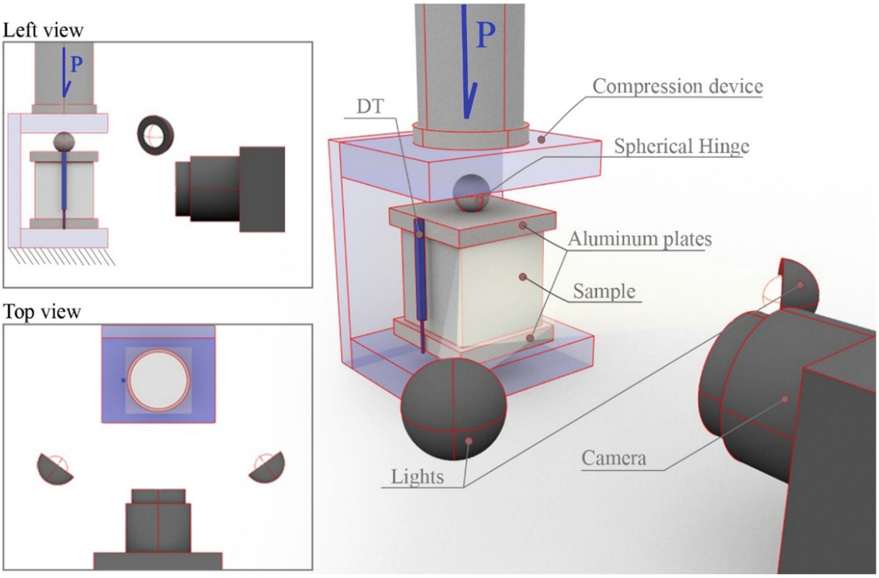

Fig. 1. Compressive tests: experimental setup.

The tests were performed in displacement control at a constant rate of $5 \cdot 10^{-4}$ m s^{-1}.

Figure 2 shows the envelope of stress–strain curves obtained on five samples for all type of materials investigated (H100, H130, H200), for both through-the-thickness and in plane directions. The engineering stress reported on the y-axis is computed as the measured load divided by the contact surface of the foam (60 × 60 mm), whereas the strain reported on the x-axis is obtained as the ratio between the detected shortening and the initial length of the sample.

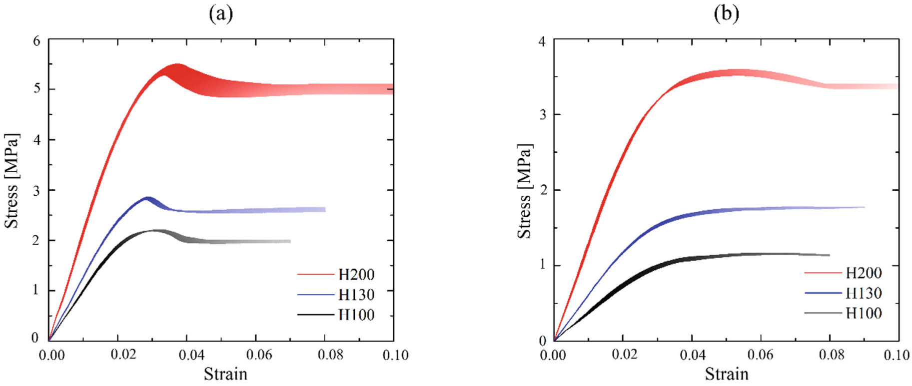

Fig. 2. Compressive tests: uni-axial tests: through-the-thickness (a) and in plane (b) Stress-Strain curves.

Table 1. Elastic properties Divinycell H 100, 130 and 200: through-the-thickness.

PVC foam	DIAB		DT		DIC	
	E_{th} [MPa]	ν_{xy}	E_{th} [MPa]	ν_{xy}	E_{th} [MPa]	ν_{xy}
H100	135	–	102	–	141	0.42
H130	170	–	127	–	172	0.43
H200	310	–	223	–	312	0.43

Table 2. Elastic properties Divinycell H 100, 130 and 200: in-plane.

PVC foam	DIAB		DT		DIC	
	E_{ip} [MPa]	$\nu_{xz} = \nu_{yz}$	E_{ip} [MPa]	$\nu_{xz} = \nu_{yz}$	E_{ip} [MPa]	$\nu_{xz} = \nu_{yz}$
H100	–	–	39	–	56	0.38
H130	–	–	60	–	83	0.39
H200	–	–	130	–	154	0.41

As a matter of fact, elastic moduli and compressive strengths exhibit increasing values with the increasing of the foam density. The average experimental strengths are in good agreement with the ones declared by the producer data sheet, whereas some differences in terms of the elastic moduli obtained based on the data shown in Fig. 2 are visible.

DIC was also employed to monitor the displacements field and consequently to compute strain on the monitored specimen face. The freeware Matlab script Ncorr, developed by Blaber et al. [26] was employed to process the acquired images. This technique was employed to work out a good estimate of the local strain in the core of the specimen. Considering the total surface of the sample is 60 × 60 mm, the measurement area has been set to 30 × 30 mm in order to remove the edge effects. Average deformations obtained through DIC in the measurement area were linked to loading values measured through the load cell, using time as sorting variable. Three different loading stages were finally considered in the elastic range to estimate the elastic modulus of the material under uni-axial compression.

The elastic moduli and the poisson ratio of the investigated foams are shown in Tables 1 and 2. The results show that foam seem to be highly anisotropic with a ratio between the stiffness in plane and in the through-thickness directions $(E_{ip}/E_{th}$ in the range between 0.4–0.5 (depending on the foam density). It is worth of noting that the moduli of elasticity obtained by using the DIC technique are in good agreements with the ones declared by the product datasheet (Fig. 3).

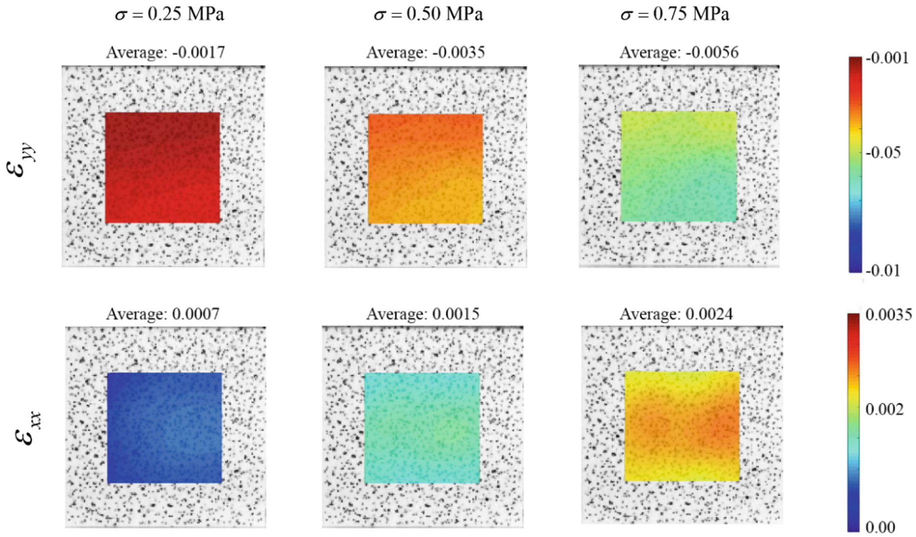

Fig. 3. Divinycell H100 through-the-thickness: Strain Maps obtained by DIC for different load levels (0.25, 0.50 and 0.75 MPa).

2.2 Fracture Tests

In this section, the fracture toughness of different densities of PVC foams is evaluated by Asymmetric Semi-Circular Bend (ASCB) specimens.

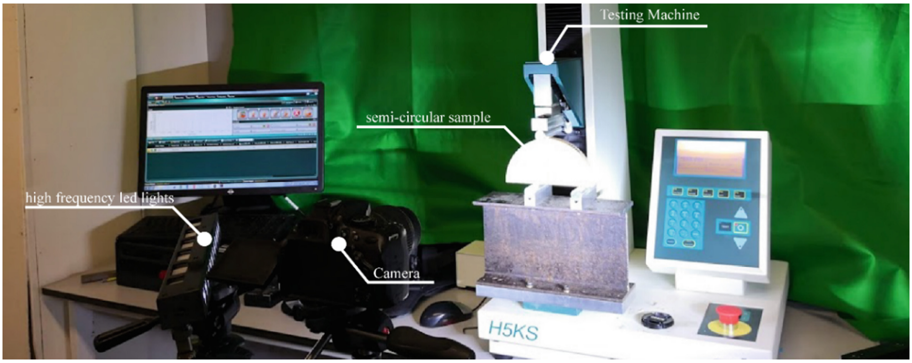

Fig. 4. Fracture tests: experimental setup.

The samples were cut from 20 mm Divinycell panels in the two main directions using a Denford CNC router with a 0.1 mm resolution equipped with a 3 mm drill bit, whereas the initial natural crack was initiated by sliding a fresh blade across the notch root.

Figure 4 shows the experimental setup, which consists of an electromechanically Tinius Olsen testing machine equipped with a 5 kN load cell and attesting rig. The loading scheme and the geometrical parameters of the samples are reported in Fig. 5. It should be noted that the experimental setup is designed in order to be able to simulate five different mixed modes, i.e. S_2 = 6, 8, 12, 16 and 24 mm in addition to pure mode I S_2 = 60, just by changing the position of one of the supports. All samples had identical geometrical features: the radius, *R*, of the semi-circular samples was 80 mm, whereas the length of the notch, *a*, was 40 mm. The experimental tests were performed under displacement control, employing a 2 mm min^{-1} rate. Five samples were tested according to each scheme, accounting for a total of thirty tests.

Figure 6a shows the loading curves for the foam with 100 kg m^{-3} under different loading schemes. Mode II configuration shows the highest value of the peak load which tends to decrease when considering pure mode I. According to Ayatollah et al. [27], the average values of maximum forces detected in the experimental tests, as detailed in Table 3, were employed for the calculation of the Stress Intensity Factors (SIFs), which were performed by using the expressions reported in [27]. In Fig. 6b the values of K_{II}/K_{Ic} versus K_I/K_{Ic}, obtained on the foam with 100 kg m^3 are reported for the 6 loading configurations here considered (S2 = 6, 8, 12, 16, 24, 60 mm). The data experimentally predicted are compared with the fracture curves obtained on the basis of both the Maximum Circumferential Tensile Stress (MTS) and the Equivalent Stress Intensity Factor (ESIF) criteria. It is worth noting that ESIF guarantees a good prediction of the experimental results.

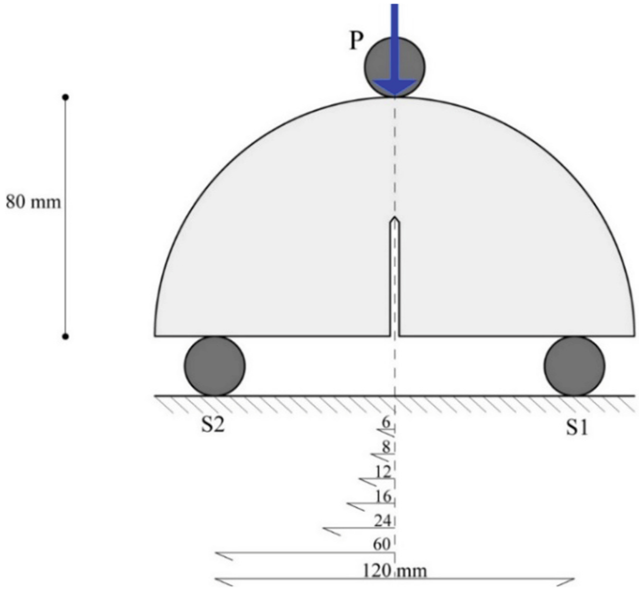

Fig. 5. Fracture tests: loading scheme and geometrical parameters.

Table 3. Fracture toughness results (H100, H130 and H200).

PVC foam	K_{Ic} [MPa m$^{0.5}$]	K_{IIc} [MPa m$^{0.5}$]
H100	0.238	0.109
H130	0.353	0.176
H200	0.597	0.332

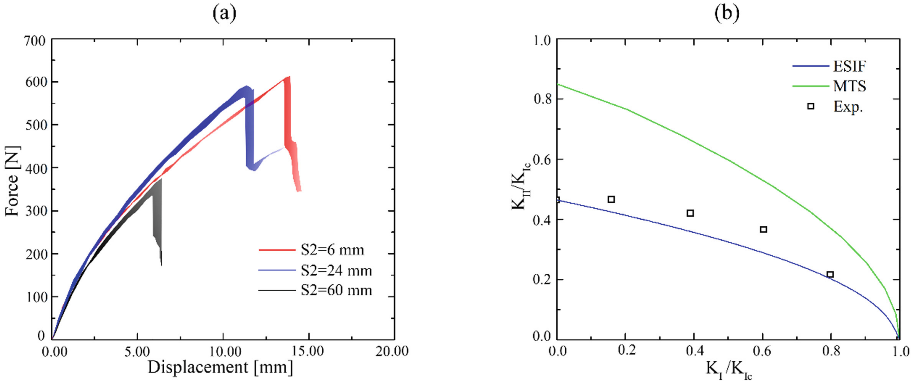

Fig. 6. Fracture tests, Divinycell H100: loading displacement curves (a), comparison between mixed mode fracture toughness of PVC H100 and theoretical fracture criteria (b).

3 Numerical Simulation

The parameters experimentally determined have been implemented in a numerical model developed by the present authors [22–24] based on a moving mesh approach and capable to predict the crack growth phenomena in sandwich structures. To this end, the case study of a panel featuring a pre-existing horizontal crack located at the core mid-length, was numerically investigated. The panel was considered fixed at bottom skin and subject to in-plane crack opening load at the upper skin. The loading, boundary conditions and geometry considered are illustrated in Fig. 7a. The mechanical properties of the foam PVC are taken in agreement with the data reported in Tables 1 and 2, whereas those referred to face sheets are taken in agreement with [10]. Figure 7b shows the loading displacement curve numerically simulated. The structural response of the sandwich sample shows a linear behaviour, initially. Once the crack growth criterion, defined in [10], is satisfied, the curve shows a decreasing branch characterized by a snap-back phenomenon. It is worth noting that in the sandwich structures the loads are typically applied on the skins, which transmit the tension to the core by means the adhesive component at the skin-core interfaces. The core is consequently greatly affected by the way adhesive interface is numerically modelled. In the present study this obeys to a cohesive law that is taken in agreement with [10].

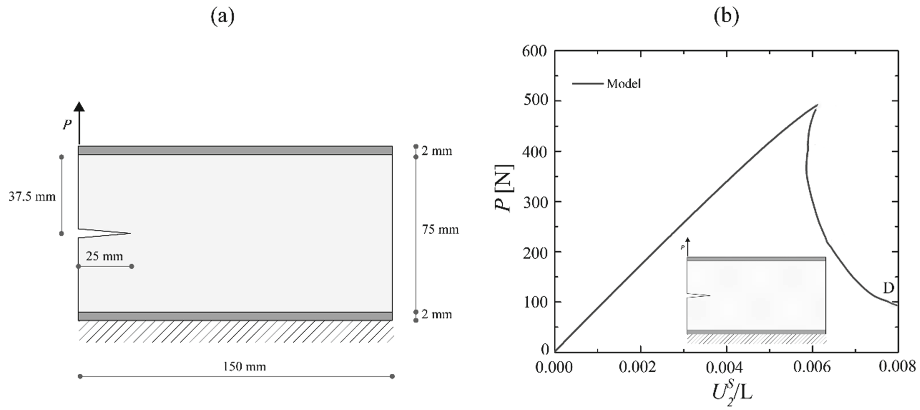

Fig. 7. Loading scheme (a); Loading displacement curve (b).

4 Conclusions

The present paper proposes an experimental procedure aimed to detect both the elastic and fracture properties of three different densities of polymeric foam material. The compression tests are conducted in accordance to [17], which prescribes a methodology to measure the elastic propertied of Rigid Cellular Plastics. However, the experimental tests reveal that PVC foams are affected by the tendency to produce localized deformation due to local collapse of cells under compression. This phenomenon produces an erroneous estimation of the elastic properties which is overcame by using the DIC. The Fracture tests have been conducted on asymmetric semi-circular samples (ASCB tests), which are able to generate all range of mixed fracture modes in fragile materials. The experimental data show that the fracture toughness of PVC foam materials strongly increases together with their density. Furthermore, the theoretical fracture criterion based on Equivalent Stress Intensity Factor seems to be the most suitable for this class of PVC foam because it is the only one taking into consideration the ration between mode I and mode II SIFs by means the parameters $\alpha = K_{Ic}/K_{IIc}$. The numerical model developed in previous author's works is also able to describe crack propagation phenomena in the core region.

Acknowledgements. The authors acknowledge Frank McCauley and Jeremy Moore from Diab Limited UK for kindly providing the foam core material that was employed in the experimental section of this work.

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