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On the elastic and mixed-mode fracture properties of PVC foam

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ABSTRACT:

Sandwich structures are widely used for the design and fabrication of lightweight structural systems, due to their capability to exhibit excellent structural and thermal performances at low material usage. Understanding the phenomena of propagation of macro-cracks in the core and delamination at the face-to-core interface are aspects of great computational interest. Linking sophisticated models with the actual characterisation of their mechanical properties is essential in view of real engineering applications. The elastic and fracture characterisation of the materials composing the core is particularly relevant because its cracking affects the capacity of the sandwich structures to carry out transverse loads. In this work, PVC foams typically used as the inner core in structural applications are investigated over a range of foam densities. Firstly, the elastic properties of foams under compressive uniaxial loading are measured using a full-field methodology. Subsequently, Semi-Circular specimens are tested in bending varying the position of supports to generate all range of mixed fracture modes. Suitable fracture criteria are also considered in order to assess their capability to evaluate fracture parameters in PVC foams. Finally, the parameters experimentally determined have been used to validate the response provided by a numerical model developed by the authors.

Keywords: Sandwich Structures, PVC foam, DIC, Crack Path, ASCB.

1. Introduction

Due to their excellent mechanical and physical properties (low density, energy absorption and high insulation), cellular polymeric foams are extensively used in many industrial applications. In particular, PVC foams are currently adopted for manufacturing different engineering structures and products such as cores of sandwich panels. In most common applications, sandwich panels are subject to transverse loads and need to resist stresses caused by bending with negligible membrane action. The skin or face sheets (i.e. the external layers) of the panels are usually made of metals or fibre-reinforced composites, materials that are showing an increasing success in civil engineering applications [1-6].

In sandwich panels, the main role of the core is in transferring shear forces between the face sheets when the panel is subject to bending. The intensive loading conditions to which sandwich structures are subjected might produce the skin/core debonding [7-11] and crack kinking propagation in the core region [12-14]. Regarding the crack kinking propagation in the core region, the assessment of the elastic and fracture properties of 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.

The macroscopic elastic characterisation of cellular foams is a challenging problem because of the localised deformation effect caused by the local collapse of cells under compression and of the material anisotropy [15]. With the aim to detect the elastic properties of foam panels, many experimental procedures have been proposed in the last decade. Viana and Carlsson [16] investigated

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the elastic properties of cross-linked PVC with nominal densities of 36, 80, 100, 200 kg/m³. In order to define the degree of anisotropy, they performed tensile tests oriented in both in-plane and through-the-thickness of the foam panels, in which the uniaxial strains were detected by using an extensometer. The behaviour of the PVC was found to be nearly isotropic. Wang et al. [17] and Taher et al. [18] developed a modified Arcan fixture to characterise 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. [19] 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 geometry of the samples was selected in accordance with the prescriptions defined by the ASTM standards [20]. 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 found that the material is highly anisotropic with a ratio between in-plane and through-the-thickness stiffnesses about 0.5. Similar tests were conducted by Colloca et al. [21], in which PVC foams with varying densities were investigated by employing both quasi-static and impact tests.

Several experimental attempts to measure the fracture toughness under pure mode I loading [16, 22-25] used the Single Edge Notch Bend (SENB) specimens. Mathematical correlations between the detected fracture toughness and the density of materials were proposed [24, 26]. Poapongsakorn and Carlsson [24] studied the fracture toughness of a large range on PVC foams. They found out that the fracture toughness measured using a four-point bending test significantly exceeds that measured through a three-point bending test. Furthermore, they examined the influence of different cell size and crosshead rate on the measure of fracture toughness. Noury et al. [26] investigated the mixed-mode fracture in rigid cellular PVC foam based on experimental and numerical analyses. Their tests were performed on CTS specimens in association with a loading device and an appropriate apparatus for mixed-mode fracture analysis. They obtained a ratio of fracture toughness between Mode II and Mode I in the range of 0.4 to 0.65 depending on the foam density.

The propagation of mixed-mode fracture in Polyurethane (PUR) foams has been extensively investigated by various authors [27-29]. Aliha et al. [30] used the Asymmetric Semi-Circular Bend (ASCB) loading scheme, which is able to generate all ranges of mixed fracture modes in fragile materials, to measure the fracture properties of PUR foams. Conversely, there are no similar works in the literature investigating the fracture behaviour of PVC foam under 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/m³. The

parameters experimentally determined are subsequently employed as input values into a numerical model previously developed [2, 31, 32]. The work is structured as follows. Section 2 describes the compression and fracture tests. Section 3 illustrates a numerical investigation aimed to simulate crack propagation in PVC foam. Finally, conclusions are discussed in Section 4.

2. Experimental Analysis

In the present section, the experimental behaviour of Divinycell H series of PVC foams with a range of density from 100 to 200 kg/m³ is investigated. The elastic properties of the materials are first characterised through compressive tests. Subsequently, their fracture properties are experimentally determined.

2.1 Compressive Tests

2.1.1 Experimental Method

According to ASTM standards D1621-16 (Standard Test Method for Compressive Properties of Rigid Cellular Plastics) [20], cubic samples with side length equal to 60 mm were tested to obtain the elastic properties of the foams in compression. Furthermore, cylindrical samples with height and radius equal to 60 mm were tested (only through-the-thickness directions) to assess the shape effect that can be observed on PVC foam samples under uniaxial compressive loading. The samples were cut from 60 mm Divinycell panels in two orthogonal directions (casting direction and in-plane direction) using a Denford CNC router with a 0.1 mm resolution equipped with a 3 mm drill bit. Such specimens allow the material to be tested in three different orthogonal directions: the first is through-the-thickness of the panel, whereas the other two are embedded in the panel plane (Fig. 1).

Figure 1: Schematic representation of the testing directions.

An Instron 4204 electromechanical universal testing machine equipped with a 50 kN load cell was employed to perform the tests. As shown in Fig.2, the load was applied by mean of a compression device embedding a spherical seating mechanism and two parallel metallic plates, suited to apply the load uniformly in the faces of the specimen. Furthermore, in order to accurately detect the specimen deformation by-passing the compliance of the load application system, a displacement transducer (DT) was mounted to measure the variation of distance between the two plates.

A Digital Image Correlation (DIC) system, consisting of a high-resolution digital camera, and two high frequency led lights (Fig. 2) was also employed to monitor the displacement field distribution on the external surface of cubic samples. Matt black paint was preventively applied on the front specimen face as to obtain a random b/w speckle pattern, the ideal reference system for DIC purposes [19]. A picture every 0.5 sec. (2 Hz) was taken during the testing phase, whereas LED lights were used to provide the necessary image contrast. The freeware MATLAB script Ncorr, developed by Blaber et al. [33] was utilised to process the acquired images. This allowed obtaining an estimate of the local strain in the core of the specimen. Considering that the front face surface of the samples is 60×60 mm, the measurement area has been set to a centred 30×30 mm portion, in order to remove the edge effects. The average deformations obtained through the DIC in the area of interest were then coupled with the loading values measured through the load cell, using time as the sorting variable. Three different loading stages were considered in the elastic range to estimate the elastic modulus of the material under uniaxial compression.

Three types of PVC foams, characterised by different densities (H100 - 100 kg/m³, H130 - 130 kg/m³, H200 - 200 kg/m³), were analysed along the through-the-thickness and the in-plane directions. Five specimens were tested for each foam and direction, accounting for a total of ten specimens for each foam typology. The tests were performed in displacement control at a constant rate of $5 \cdot 10^{-4} \text{ m s}^{-1}$.

Figure 2: Compressive tests: Experimental setup.

2.1.2 Results and Analysis

Fig. 3a shows the stress-strain curves obtained on both cubic and cylindrical shapes for different foams (H100, H130, H200), along the through-the-thickness direction.

The engineering stresses reported on the vertical axis are computed as the applied load divided by the contact cross-section of the samples. The generalised axial strains depicted on the horizontal axis are obtained as the ratio between the detected shortening and the initial length of the sample, which is equal to 60 mm.

Such experimental curves provide a measure of the compressive strength of the PVC foams, which can be detected at the peak of the curves. The slope of the curves in the elastic range also provides an estimate of the elastic modulus in compression, based on the generalised measure of the axial strain.

It can be observed that the shape of the samples does not produce remarkable response modifications under uniaxial compression. A good agreement in terms of stiffness and peak load were detected. Table 1 summarises the experimental results obtained in terms of compressive strength and modulus of elasticity of both the investigated shapes.

Figure 3a: Through-the-thickness stress-strain curves under uniaxial compression: comparisons between Cylindrical and Cubic samples.

PVC Foam	Modulus of Elasticity E_{th} [M P a]		Compressive Strength f_{th} [M P a]	
	Cylindrical	Cubic	Cylindrical	Cubic
H100	103	102	2.21	2.20
H130	135	127	2.98	2.83
H200	227	223	5.36	5.39

Table 1: Through-the-thickness elastic properties Divinycell H 100, 130 and 200: comparisons between Cylindrical and Cubic samples.

Figs. 3b-c show the envelope of the stress-strain curves obtained from the cubic samples for different foams (H100, H130, H200), along the through-the-thickness and in-plane directions.

Figure 3b: Through-the-thickness stress-strain curves under uniaxial compression.

Figure 3c: In-plane stress-strain curves under uniaxial compression.

Figs. 4a-f show the strain contour maps along the x and y directions obtained using the DIC technique. Here, y indicates the direction of testing (or vertical) and x indicates the direction in the specimen face transversal to testing (or horizontal). Results referring to three different stress levels are shown for each set of tests performed. The stress levels are considered in the range between 10% and 60% of the ultimate compressive strength observed for each set of specimens, with the aim to estimate the material properties in the elastic range.

A 30mm x 30mm subset region located at the centroid of the front face of the specimen is taken into consideration to analyse a portion of the specimen which is not affected by the application of loads. Average values of the strain are numerically extrapolated in the investigated region. These are considered into a linear regression analysis of the stress-strain relations, to obtain an experimental measure of the elastic modulus. Similarly, the Poisson coefficients are determined considering the ratios between the strains in the x and y directions at various load steps.

Figure 4a: Divinycell H100, through-the-thickness analysis: DIC strain maps at different stress levels (0.25, 0.50 and 0.75 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

Figure 4b: Divinycell H100, in-plane analysis: DIC strain maps at different stress levels (0.15, 0.30 and 0.45 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

Figure 4c: Divinycell H130, thorough-the-thickness analysis: DIC strain maps at different stress levels (0.25, 0.50 and 0.75 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

Figure 4d: Divinycell H130, in-plane analysis: DIC strain maps at different stress levels (0.20, 0.40 and 0.60 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

Figure 4e: Divinycell H200, thorough-the-thickness analysis: DIC strain maps at different stress levels (0.67, 0.1.34 and 2.00 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

Figure 4f: Divinycell H200 in-plane analysis: DIC strain maps at different stress levels (0.34, 0.67 and 1.00 MPa). The x-direction is normal to the testing direction in the specimen face; the y-direction is the compression testing direction.

PVC Foam	Modulus of Elasticity E_{th} [M Pa]			Poisson ratio ν_{th}	Compressive Strength f_{th} [M Pa]	
	Datasheet	DT	DIC	DIC	Datasheet	Exp.
H100	135	102	141	0.42	2.00	2.20
H130	170	127	172	0.43	3.00	2.83
H200	310	223	312	0.43	5.40	5.39

Table 2: Elastic properties Divinycell H 100, 130 and 200: through-the-thickness.

PVC Foam	Modulus of Elasticity E_{ip} [M Pa]			Poisson ratio ν_{ip}	Compressive Strength f_{ip} [M Pa]	
	Datasheet	DT	DIC	DIC	Datasheet	Exp.
H100	-	39	56	0.38	-	1.15
H130	-	60	83	0.39	-	1.78
H200	-	130	154	0.41	-	3.54

Table 3: Elastic properties Divinycell H 100, 130 and 200: in-plane.

Tables 2 and 3 provide a summary of the experimental results obtained in terms of compressive strength, modulus of elasticity and Poisson ratio, along the through-the-thickness and in-plane directions, respectively. Both the elastic modulus and the compressive strength show larger values with increasing foam density, while the Poisson ratio does not seem to vary significantly for the different type of foams analysed.

The elastic moduli provided by the manufacturer for the various class of foams [34] are compared with the ones obtained experimentally based on the two different measures of strain: i) the global

axial strain, measured by means of the displacement transducer (DT) detecting the shortening of the specimen under uniaxial compression; ii) the local strain measure, performed in the core of the specimen using the DIC technique. These are computed along both the through-the-thickness and in-plane direction. A remarkable difference is found between the generalised measures of the elastic moduli and those detected at the core of the specimen, using the DIC technique.

The non-homogenous behaviour of the material can be partially explained by the manufacturing process, which causes the density through the thickness of the foam sheet to vary significantly, especially towards the surface of the sheet. This may explain the variation in stiffness measured through-the thickness of the PVC sheets (Table 2), but does not provide a sound justification for the similar behaviour obtained along the in-plane direction (Table 3). A more reasonable explanation relates to the peculiar constitutive behaviour of the material, whose response at the macro-scale is determined by the local behaviour of the cells micro-structure. The application of compressive load through the metallic plates causes stress concentrations which are responsible for a local collapse of the cells at the edges of the specimen. This phenomenon may generate erroneous evaluations of the elastic properties of the materials if the shortening of the whole specimen is taken into consideration to obtain the measure of the generalised axial strain. Differently, the DIC technique overcomes the problem by allowing monitoring the displacements field in a portion of the specimen that can be considered undisturbed by the edges effect. The values of the modulus of elasticity obtained using the DIC analysis show good agreement with those declared by the producer along the through-the-thickness direction. A maximum error of 5% is observed for the Divinycell H100, while the tests carried out on Divinycell H200 have provided responses within a 1% accuracy.

The ratio between the two elastic moduli (E_p/E_{th}) and the compressive strengths (f_p/f_{th}) are in the ranges of 0.40-0.50 and 0.50-0.65, respectively. Therefore, the panels show material properties that are remarkably superior along the through-the-thickness direction, hereafter referred to as properties along the principal material direction. This transversally isotropic constitutive behaviour is not highlighted in the material datasheet of the tested products and seems to be generally neglected by manufacturers of PVC foams aimed at structural applications. Researchers analysing the compressive behaviour of PVC foam [17, 18] have shown similar results and have justified this phenomenon observing that the characteristic length of the cells structures in the through-thickness direction is approximately twice the size of the cells in the in-plane direction. Indeed, the anisotropy of the material structure relates to the PVC foams manufacturing method, consisting of casting the material in the fluid state.

2.2 Fracture Tests

2.2.1 Experimental Method

In this section, the fracture toughness of different densities of PVC foams is evaluated by Semi-Circular Bend (SCB) and Asymmetric Semi-Circular Bend (ASCB) specimens, featuring a pre-notched crack originating in the centre of the semicircle and perpendicular to the flat edge of the specimens. All samples had identical geometrical features: radius, R , equal to 80 mm; crack amplitude, a , equal 40 mm. As in the previous case, they were cut from 20 mm thick Divinycell panels using a Denford CNC router with a 0.1 mm resolution equipped with a 3 mm drill bit. The same PVC foams analysed in the previous section were tested (H100, H130 and H200), with three different densities. In each specimen, the natural crack onset was initiated by sliding a fresh blade across the notch root before the start of the test.

Figure 5: Fracture tests: Experimental setup.

Fig. 5 shows the experimental setup, which consists of an electromechanical Tinius Olsen testing machine equipped with a 5 kN load cell and a testing rig featuring two adjustable position support pins and one loading pin, all having 20 mm diameter. The testing schemes were designed to simulate five different mixed fracture modes in addition to pure mode I. The loading scheme and the geometrical parameters of the samples are depicted in Fig. 6. Mode I is obtained when the load is applied symmetrically (SCB), i.e. $S_2=60$ mm. Several fracture modes are obtained by varying the position of one of the supports, i.e. $S_2 = 5.22, 8, 12, 16, 24$ mm., mode II corresponds to the support position $S_2=5.22$ mm.

The experimental tests were performed under displacement control, applying a 2 mm/min rate. Five samples were tested according to each scheme, accounting for a total of thirty specimens for each PVC foam density considered.

Figure 6: SCB and ASCB fracture tests: Loading scheme and geometrical parameters.

2.2.2 Results and Analysis

Fig. 7a-c shows the envelope of the loading curves obtained on the H100, H130, and H200 foams under three different loading schemes. These are the ones responsible for generating fracture in pure mode I ($S_2=60$ mm), pure mode II ($S_2=5.22$ mm), and mixed-mode ($S_2=24$ mm). The peak load values obtained on different loading configurations ($S_2= 5.22, 8, 12, 16, 24, 60$ mm) and densities (H100, H130, H200) are shown in Table 4. As expected, the peak loads observed show a gradual rise with an increasing density of the panel as well as while moving from a pure I to a pure II mode of fracture.

	H100	H130	H200
S_2 [mm]	P [N]	P [N]	P [N]
5.22	595	953	1805
8	656	1031	1864
12	688	1062	1952
16	701	993	1850
24	581	836	1505
60	357	529	897

Table 4: Peak load for all the load configurations ($S_2= 5.22, 8, 12, 16, 24, 60$) and all the densities (H100, H130, H200)

Figure 7a: Fracture tests on Divinycell H100: Load-displacement curves.

Figure 7b: Fracture tests on Divinycell H130: Load-displacement curves.

Figure 7c: Fracture tests on Divinycell H200: Load- displacement curves.

The tests carried out under the mode II loading scheme ($S_2 = 6\text{mm}$) show the highest value of the peak load. The peak values decrease when the position of the support is moved apart from the load, with the minimum value obtained for pure mode I ($S_2 = 60\text{mm}$). The mode I loading scheme is also responsible for the minimum stiffness of the system. Maximum stiffnesses are shown when mixed-mode loading schemes are adopted, although this result was expected in the case of pure mode II. It has to be considered that local crushing of the foam occurs in the vicinity of the pins due to the applied point load, and this phenomenon is exacerbated for pure mode II and mixed-mode in the vicinity of the support S_2 due to the higher reactive force. This has a relevant influence on the slope of the force-displacement curves and may generate an erroneous evaluation of the stiffnesses.

According to Ayatollahi et al. [35], the calculation of the Stress Intensity Factors (SIFs), a measure of the fracture toughness, is given by:

$$K_{ic} = \frac{P_{\max}}{2Rt} \sqrt{\pi a} Y_i(S_2/R), \quad i = 1, 2, \quad (1)$$

where $P_{\max}$ is the average value of the maximum load experimentally measured on ASCB specimens, t is the thickness of the specimens, and the functions $Y_i(S_2/R)$ were determined by finite element analysis by Marsavina et al. [36]:

$$Y_I(S_2/R) = 6.235(S_2/R)^3 - 15.069(S_2/R)^2 + 17.229(S_2/R) - 1.062; \quad (2)$$

$$Y_{II}(S_2/R) = 1.884(S_2/R)^5 - 7.309(S_2/R)^4 + 5.037(S_2/R)^3 + 2.77(S_2/R)^2 - 5.075(S_2/R) + 1.983. \quad (3)$$

PVC Foam	K_{Ic} [MPa m ^{0.5}]	K_{IIc} [MPa m ^{0.5}]	K_{IIc} / K_{Ic}
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H100	0.238	0.109	0.46
H130	0.353	0.176	0.50
H200	0.597	0.332	0.56

Table 5: Stress Intensity Factors experimentally determined (H100, H130 and H200).

The values of mode I and mode II SIFs experimentally obtained on different foam densities, as well as the K_{IIc} / K_{Ic} ratios, are reported in Table 5. The ratio between the SIFs does not show a large variation, being in the ranges of 0.46-0.56 for different densities. This allows observing that, increasing the foam density, the fracture toughness of pure mode II increases more quickly with respect to the one associated with pure mode I. K_{Ic} and K_{IIc} is plotted against the values of foam density in Figs. 8a and 8b, respectively, showing that the fracture toughness of the PVC foam increases approximately linearly with the foam density. Fig 8a includes experimental data obtained by Poapongsakorn and Carlsson [24] testing prismatic specimens made of similar PVC foams under two different symmetric static scheme. The diagram shows that the results obtained on ASCB specimens tested under mode I are in good agreement with the existing results based on four-point bending tests. Contrarily, the results obtained on three-point bending tests always predict the lower value of the fracture toughness of the PVC foam due to the stress concentration in the proximity of the crack. Although ASCB specimens are tested according to a three-point bending scheme, stress concentration is strongly reduced by the increase of the specimen dimension. These results demonstrate the potential of the semi-circular bending test, as a reliable measure for the characterisation of fracture toughness in fragile materials. Furthermore, the semi-circular specimen allows obtaining the stress intensity factor in all ranges of mixed-mode fracture, including pure mode I and pure mode II also.

Figure 8a: Comparisons in terms of fracture toughness vs density of PVC foams for Mode I. SCB ($S_2=S_1=60$ mm)) are the results obtained in the present study, 3PB and 4PB indicate three-point bending and four-point bending, respectively.

Figure 8b: Fracture toughness vs density of PVC foams: Mode II. Results obtained in the present study on ASCB specimens ($S_2 = 5.22$).

Fig. 9a-c depict the K_{II}/K_{Ic} vs K_I/K_{Ic} relations obtained on all the tested foams for the six loading configurations considered ($S_2 = 5.22, 8, 12, 16, 24, 60$ mm), normalising the SIFs by the maximum Stress Intensity Factor found in pure mode I. The data experimentally found are compared with the curves obtained on the basis of the Maximum Circumferential Tensile Stress (MTS) and the Equivalent Stress Intensity Factor (ESIF) criteria. The MTS criterion significantly overestimates the prediction of K_{II} for lower densities, whereas the ESIF criterion guarantees a reasonably accurate prediction of the stress intensity factor for PVC foams.

Figure 9a: Fracture tests on Divinycell H100: Normalised comparison between mixed-mode fracture toughness of PVC H100 and theoretical fracture criteria.

Figure 9b: Fracture tests on Divinycell H130: Normalised comparison between mixed-mode fracture toughness of PVC H130 and theoretical fracture criteria.

Figure 9c: Fracture tests on Divinycell H200: Normalised comparison between mixed-mode fracture toughness of PVC H200 and theoretical fracture criteria.

3. Numerical Modelling

Numerical simulations are presented next to analyse how the mechanical properties of different foams and the material orientation can affect the loading-displacement curves and the crack propagation trajectory. The mechanical and fracture parameters experimentally determined are employed to perform the numerical prediction of crack propagation in the PVC foam using a numerical model formulated by the authors, based on a moving mesh methodology. This was implemented in a unified framework to predict crack growth on the basis of fracture mechanics variables. The evolution of the crack tip is monitored by a refined mesh which adapts to the fracture condition, allowing an accurate prediction at low computational costs. Details about the theoretical formulation and the numerical implementation of the model can be found in [2, 31, 32].

The foam is discretised by means of plane stress triangular elements characterised by cubic interpolation functions. A high number of computational points is condensed around the crack tip region, whereas a coarse discretisation is adopted in the remaining domain (Fig. 10a). The moving computational nodes were modified starting from a fixed referential coordinate system on the basis of a crack growth criterion to predict directionality and displacement of the tip front.

The numerical formulation is general and may integrate any crack growth and kinking criteria. In the present study, the crack growth and angle requirements are defined based on the ESIF criterion [37]. A good correlation between the experimental results previously presented is demonstrated.

The crack advanced is assumed equal to 0.75 mm. Furthermore, the rezoning mesh method strongly reduces the remeshing events, ensuring small distortions and an unaltered mesh typology. Furthermore, the moving grid is modified from the initial configuration in such a way that the recourse to remeshing procedures has been strongly reduced.

The discretised equations are implemented by using an external subroutine that interacts with a COMSOL MULTIPHYSICS FE software [38]. In particular, the algorithm was developed by means of proper customised script files, which manage the parameters and the results required by the iterative procedure.

The first step consists of validating the numerical method. This is performed by modelling both the SCB (pure mode I, $S_2 = 60$ mm) and the ASCB (mixed mode, $S_2 = 24$ mm) tests. The elastic parameters and the fracture toughness experimentally obtained on PVC H200, as discussed in the previous sections, are employed in the numerical simulations.

In Figs. 10a-b, the crack propagation trajectories obtained using the numerical model are compared with the ones experimentally observed, showing an excellent correlation. In detail, the Pearson correlation coefficient is $r = 0.999$ for the SCB test and $r = 0.998$ for the ASCB test here considered. This comparison demonstrates the capability of the model to accurately simulate the crack pattern

and its propagation in PVC foams for different fracture modes. This is relevant if considering that the experimental values employed to calculate the SIFs (employed to inform the mechanical model) only depend on the peak loads measured under various static schemes. They do not embed any information about the crack pattern observed experimentally.

Figure 10a: SCB configuration: predicted crack path, comparisons between experimental and numerical results.

Figure 10b: ASCB configuration(S2=24): predicted crack path, comparisons between experimental and numerical results.

4. Conclusions

The present paper proposes an experimental procedure aimed at detecting both the elastic and fracture properties in polymeric foam materials. PVC foams typically used as the inner core in sandwich panels with structural function are investigated over a range of foam densities. Firstly, the elastic properties of foams under compressive uniaxial loading are measured in-plane and through-the-thickness of the panels. Subsequently, Asymmetric Semi-Circular Bend (ASCB) specimens are tested varying the position of supports to generate a broad range of mixed fracture modes. Suitable fracture criteria have been considered, in order to assess their capability to assess fracture parameters in PVC foams. The parameters experimentally determined have been successfully employed to validate and test the accuracy of the response provided by a numerical model formulated by the authors, based on a moving mesh methodology.

The study allows drawing the following conclusions.

- The compressive tests show that the PVC foams are characterised by a transversally isotropic constitutive behaviour, with a ratio between the two elastic moduli in the range between 0.4 and 0.5, and orthotropy (transversely isotropic) axis coinciding with the direction of casting.
- Remarkable differences are shown between the local and generalised measurement of the axial strain, demonstrating a non-homogenous behaviour of the material due to local collapses of cells in the load application area. This phenomenon produces an erroneous estimation of the elastic properties, which is overcome by using the Digital Image Correlation (DIC) technique. Allowing to monitor an unperturbed area at the core of the specimen, DIC provides an accurate estimate of the elastic properties of the material.
- The samples' shape does not produce remarkable response modifications under uniaxial compression.
- The bending test carried on semi-circular specimen proved to be a reliable measure for the characterisation of the mode I fracture toughness in fragile materials such as PVC foams. Furthermore, Asymmetric Semi-Circular Bend (ASCB) specimens allow detecting the stress intensity factor in the entire range of mixed-mode, including pure mode I and pure mode II.
- The Equivalent Stress Intensity Factor (ESIF) criterion seems to accurately estimate the values of the stress intensity factor for this class of PVC foam.
- The model proposed by the authors can accurately simulate the crack pattern and its propagation in PVC foams for different fracture modes.
- The numerical application shows the applicability of the parameters experimentally determined and the opportunity to use the experimental methods proposed to empower sophisticated numerical models in view of actual engineering applications.

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