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Bidirectional Thermo-Mechanical Properties of Foam Core Materials Using DIC

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ABSTRACT
Polymer foam cored sandwich structures are often subjected to aggressive service conditions which may include elevated temperatures. A modified Arcan fixture (MAF) has been developed to characterize polymer foam materials with respect to their tensile, compressive, shear and bidirectional mechanical properties at room and at elevated temperatures. The MAF enables the realization of pure compression or high compression to shear bidirectional loading conditions that is not possible with conventional Arcan fixtures. The MAF is attached to a standard universal test machine equiped with an environmental chamber using specially designed grips that allow the specimen to rotate, and hence reduces paristic effects due to misalignment. The objective is to measure the unidirectional and bidirectional mechanical properties of PVC foam materials at elevated tempreature using digital image correlation (DIC), including the elastic constants and the stress-strain response to failure. To account for nonhomogeneity of the strain field across the specimen cross sections, a "correction factor" for the measured surface strain is determined using nonlinear finite element analysis (FEA). The final outcome is a set of validated mechanical properties that will form the basis input into a detailed finite element analysis (FEA) study of the nonlinear thermo-mechanical response of foam cored sandwich panels.

1. INTRODUCTION

Polymer foam cored sandwich structures are often subjected to aggressive service conditions which may include elevated temperatures. The mechanical properties of polymer foam cores degrade significantly with elevated temperatures, and significant changes in the properties may occur well within the operating range of temperatures. The material properties of foam cored sandwich structures depend on the temperature field imposed, and this is usually ignored in engineering analysis and design. As an example, the thermal degradation problem for wind turbine blades is especially associated with the use of polymer foam cores in the wing shells when these are exposed to high temperatures. This occurs most severely under hot climate conditions, but can also occur in temperate climates. An example would be very high gusting winds increasing on a warm/hot summer day, for instance due to the development of a thunder storm. This scenario may generate large structural loads in combination with hot conditions in the outer sandwich face sheet (70-80°C or more even under temperate climate conditions [1]). At such temperatures a significant stiffness reduction occurs in typical PVC or PET foam cores (40-50% stiffness reduction) [2, 3], and when high mechanical loads act at the same time, nonlinear interaction effects may occur and subsequently lead to a loss of structural integrity [4-6].

Furthermore sandwich core materials may experience multidirectional mechanical stress states. In a conventional sandwich panel the in-plane and bending loads are carried by the face sheets, while the core resists the transverse shear loads. A well known failure mode of such sandwich panels is 'core shear failure' in which the core fails due shear stress overloading. However, although the shear stress is often the main core stress, there are conditions in which the normal stresses in the core are of comparable size or even higher than the shear stresses. Such conditions may occur in the vicinity of concentrated loads or supports and also in the vicinity of geometrical and material discontinuities. Under such condition a material element in the core is subjected to a multidirectional state of stress. Therefore, proper design of sandwich structures requires the characterization of the core material response under multi-directional stress states. Previously, the Arcan test rig has been used to measure mechanical properties of polymer foams and other light materials used for sandwich core, especially in the bidirectional tensile-shear stress region [7, 8].

In this work a modified Arcan fixture (MAF) has been developed to characterize polymer foam materials with respect to their tensile, compressive, shear and bidirectional mechanical properties at room and at elevated temperatures, and including the elastic coefficients and the full stress-strain response to failure. The MAF enables the realization of pure compression or high compression to shear bidirectional loading conditions that are not possible with conventional Arcan fixtures. The MAF is

attached to a standard universal test machine equipped with an environmental chamber using specially designed grips using universal joints that do not constrain the specimen rotation, and hence reduces parasitic effects due to misalignment.

The present paper focuses on characterizing the orthotropic material behaviour of Divinycell cross linked PVC foam at room temperature and to describe the design of the test setup to be used for testing at elevated temperatures. Eventually, the overall outcome will be a set of validated mechanical properties that will form the basis input into a detailed FE analysis study of the nonlinear thermo-mechanical response of foam cored sandwich structures that will in turn be compared with full scale experimental results obtained for sandwich beams subjected to thermo-mechanical loading.

2. EXPERIMENTAL SETUP

2.1 MATERIAL
Fully cross-linked PVC closed-cell cellular foam manufactured by DIAB (Laholm, Sweden) was investigated. In particular the core grade Divinycell H100 with a nominal density of 100 kg/m^3 (PVC foam relative density ≈ 8%) was investigated. Other PVC foam densities will be investigated in future work. A PVC foam sheet of 60 mm thickness and with the rise direction of the cells orientated in the thickness direction was used for the manufacturing of the specimens.

2.2 MODIFIED ARCAN FIXTURE (MAF)
The standard Arcan testing apparatus can be used to apply bidirectional loading to a butterfly shaped (BS) specimen. Fig.1 (a) shows a standard Arcan rig with circular distribution of griping holes, which is limited to apply only combinations of tensile and shear loadings. A novel modified Arcan Fixture (MAF) has been designed to enable the application of any combination of axial (tension or compression) and shear loadings (Fig.1 (b)) with a quasi-spiral distribution of griping holes. The MAF provides an S-shape fixture that consists of two boomerang shaped arms and a two specimen tabs bonded to the test specimen in the centre of the fixture. The new apparatus appear as a simple fixture that may be simply attached to a test machine, capable of only imparting a tension load, to provide biaxial deformation at different shear to axial deformation ratios. The different shear to axial deformation ratios are provided by selecting different attachment points on the boomerang shaped arms. A load applying double sided fork-lug is connected to each boomerang shaped arm at one end, while at the other end each arm is connected to a universal joint to compensate for any misalignment effect from the loading machine as shown in Fig. 1(c).
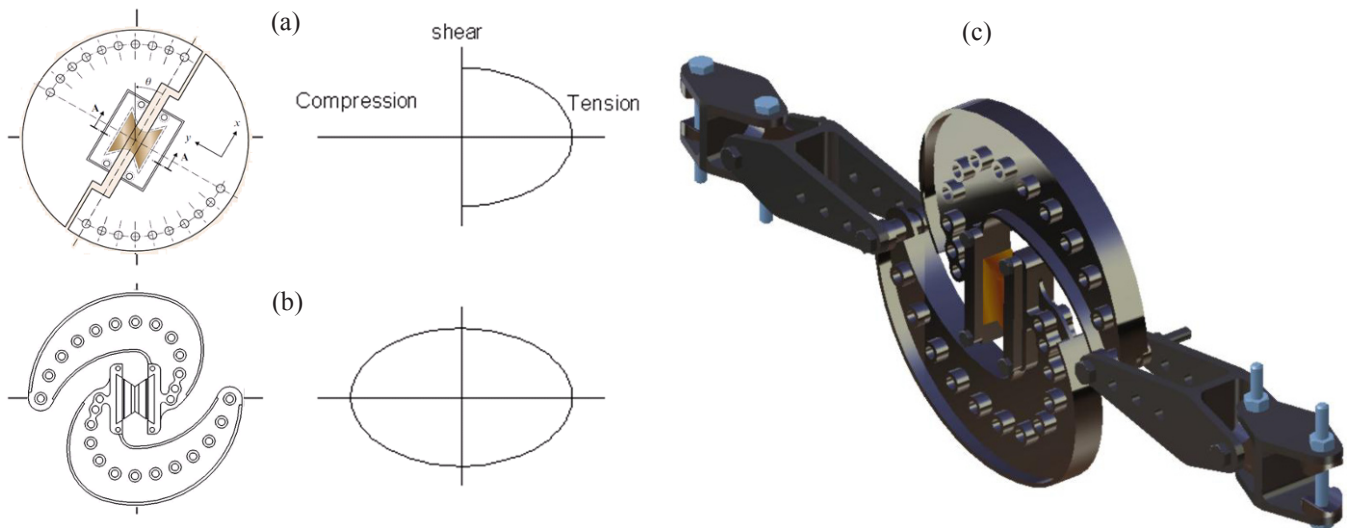
Fig. 1 Bidirectional test rigs: (a) classic Arcan rig with only tension-shear deformation envelope coverage; (b) Modified Arcan fixture (MAF) with full range coverage of the axial-shear deformation envelope; (c) perspective view of MAF

The foam specimens were fabricated with high precision using a 3-axis CNC milling machine to cut the foam specimens symmetrically relative to centre plane of the PVC foam sheets. Since PVC H100 has a higher stiffness in the rise direction of the foam cells, both in-plane and through-thickness specimens were prepared for the tests as shown in Fig. 2(a). After machining the specimens were bonded to "dove" tailed aluminium tabs using Araldite epoxy adhesive as shown in Fig 2(b). Three different specimen shapes were used for different loading conditions. Fig. 2 (c) shows the three different shapes of test specimens designed for the MAF test rig: a butterfly shaped (BS) specimen geometry for shear and bidirectional loading, a short dogbone (SD) specimen geometry for tensile loading, and a block specimen geometry for compression loading. The BS type specimens were initially machined with three different notch radii 6.67, 4.5 and 2.5 mm. All specimen types were manufactured with a constant thickness of 15 mm.
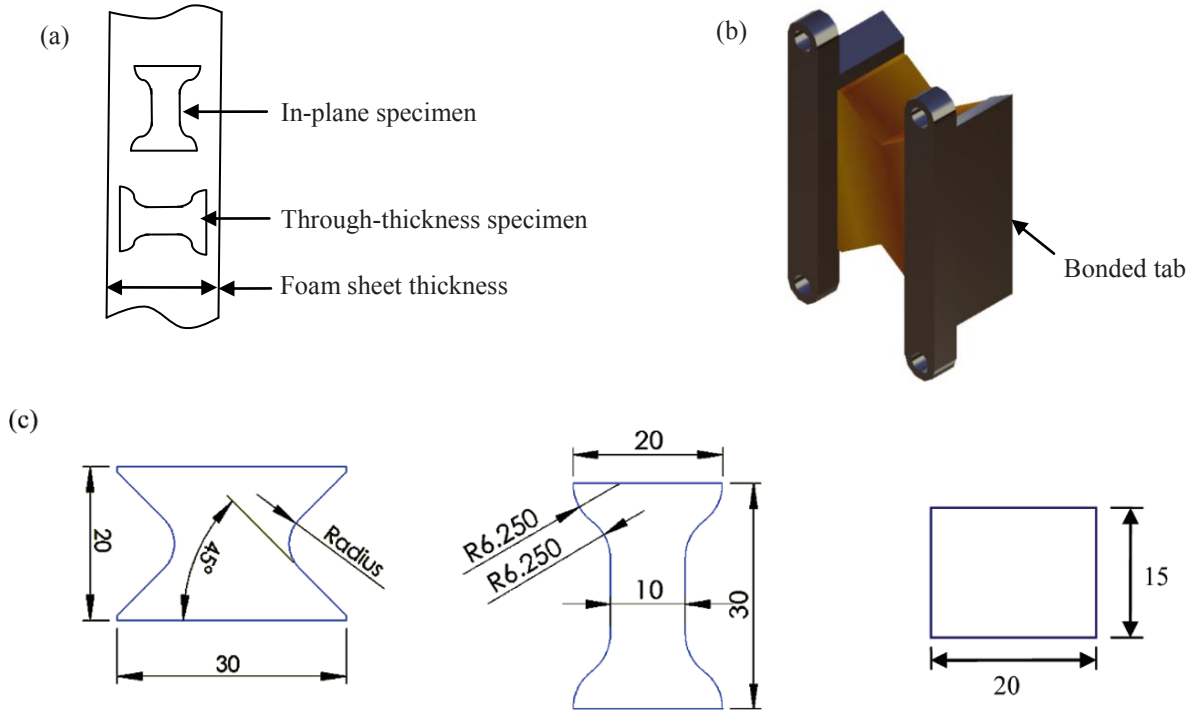

Fig. 2 Specimen preparation and geometries: (a) manufacturing of in-plane and through-thickness short dogbone (SD) specimens; (b) perspective view of a butterfly shaped (BS) specimen bonded to "dove" tailed tabs; (c) dimensions of butterfly shaped (BS), short dogbone (SD) and block specimen shapes.

2.3 DIGITAL IMAGE CORRELATION (DIC) SETUP

The non contact optical full field Digital Image Correlation (DIC) method was used to obtain the strain field over the gauge area of the test specimens. An ARAMIS 4 M system (from GOM GmbH) was used for the measurements and the further processing of the recorded displacement field. Two cameras (1 inch, CMOS chip) with a resolution of 2048×2048 pixels were placed perpendicular to and on both sides of the specimen to provide simultaneous 2D strain measurements of the specimen surfaces. Both cameras and the load cell were synchronized and connected to the computer interface as indicated in Fig. 3(a). Fig. 3(b) shows the MAF rig in a pure shear test setup using double sided DIC measurement. Low heat lights provided the required light without heating the specimen.

To generate an appropriate surface pattern for the DIC black ink was smeared onto the surface of specimen after which zinc oxide powder (white) was spread on the surface. After this the top of the surface was cleaned carefully to visualize the foam cell walls. A facet size of 60×60 pixels and a step size of 30 pixels in the X and Y directions were chosen. Each camera recorded a first image before the loading sequence was started, and about 150-300 images were recorded during loading up to the fracture point.
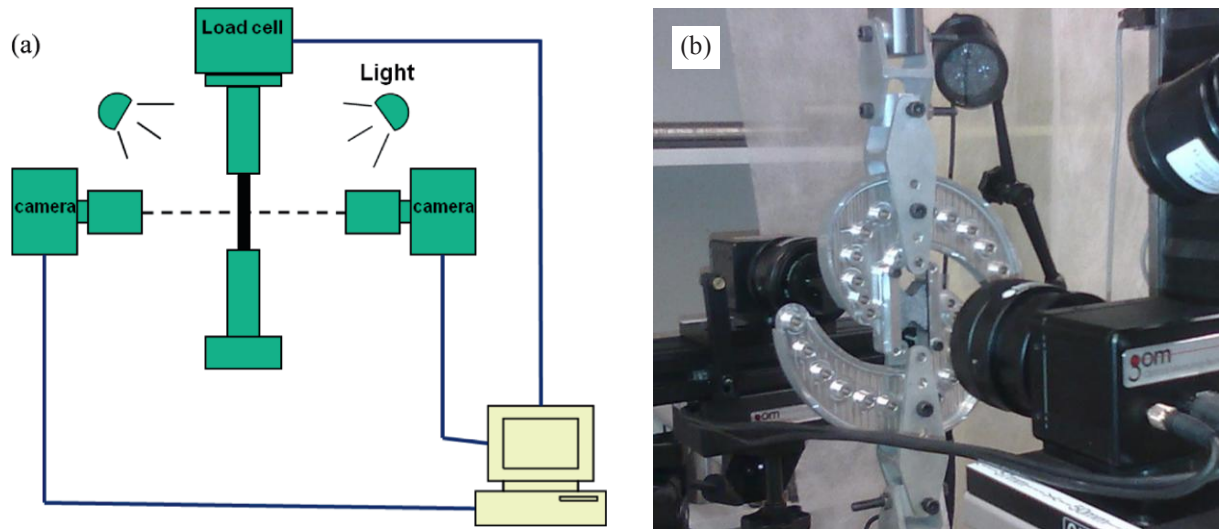
Fig. 3 DIC setup in room temperature configuration: (a) Schematic of synchronized cameras and load cell connected to control system; (b) Photograph of MAF rig and DIC setup for a pure shear test
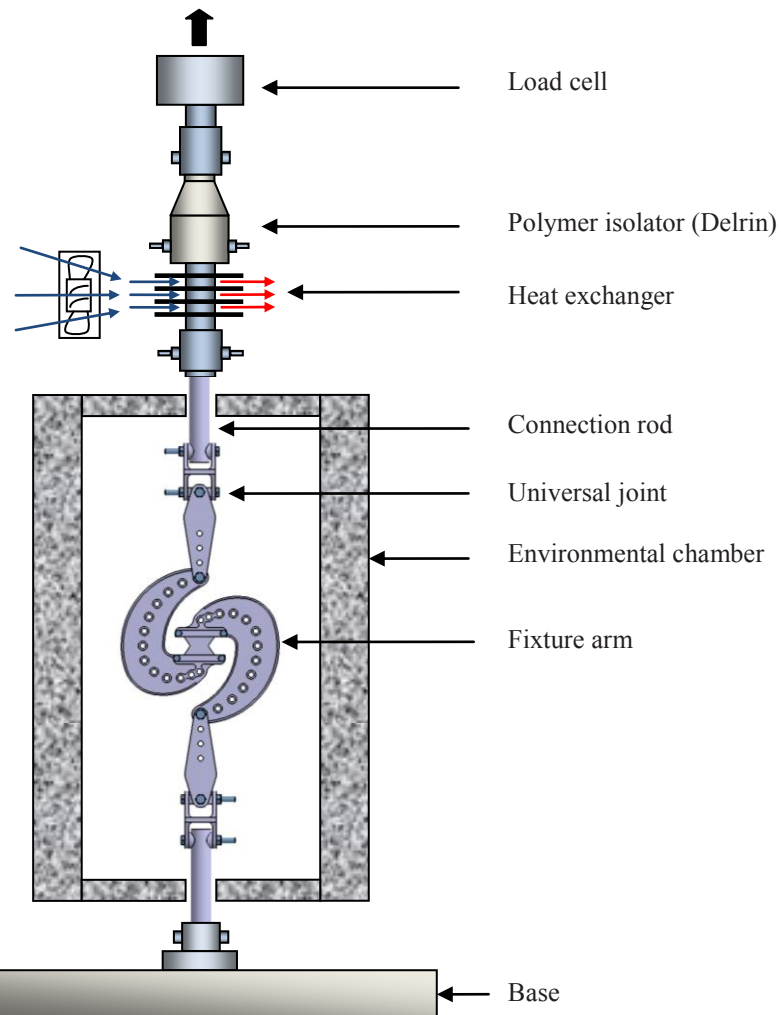

Fig. 4 Test setup for elevated temperatures

2.4 ELEVATED TEMPERATURE TEST SETUP

Extensive experimental core characterisation is being planned at elevated temperatures. The elevated temperature tests will be carried out using an Instron environmental chamber. The specimens will be allowed to equilibrate inside the chamber before testing. The environmental chamber includes a window in the access door, and DIC measurements will be conducted through the window on the front side of specimen. It has been established recently that DIC through the window is indeed feasible [9]. A double 2D DIC setup as shown in Fig. 3(a) will be applied for each specimen prior to the elevated temperature testing, and a small mechanical load will be applied to verify the symmetry of the strain response on both sides of the specimen. After this initial mechanical test the back side camera will be removed and the environmental chamber will be inserted around the MAF rig and the front camera will be used to acquire images through the environmental chamber window.

To acquire accurate load data from the load cell of the test machine, any heat transfer into the load cell should be restricted. To ensure temperate operation of the load cell, an intermediate isolating connection that can operate up to 200°C has been designed and manufactured (see Fig. 4); it includes an air cooled heat exchanger and a heat isolator made of Delrin polymer. The connecting rod, heat exchanger and polymer isolator have standard connection pins that are compatible with the Instron test machine connection. Fig. 5(a) shows a photograph of the isolating connector including the aluminium connection rod, the steel heat exchanger and the Delrin polymer isolator. A finite element analysis (FEA) has been conducted to analyse the heat transfer of isolating connector using the commercial FEA package ANSYS 12.1. The FEA steady state simulation included conduction, radiation and convection over the constituent components. As shown in Fig. 5(b) the FEA results predict a reduction of temperature from 200°C in the connection rod to 150°C in the Delrin isolator corresponding to the maximum operation temperature for the Delrin polymer material. The final temperature at end of the isolator is predicted to be about 26°C which is sufficiently low for safe and accurate operation of the load cell.
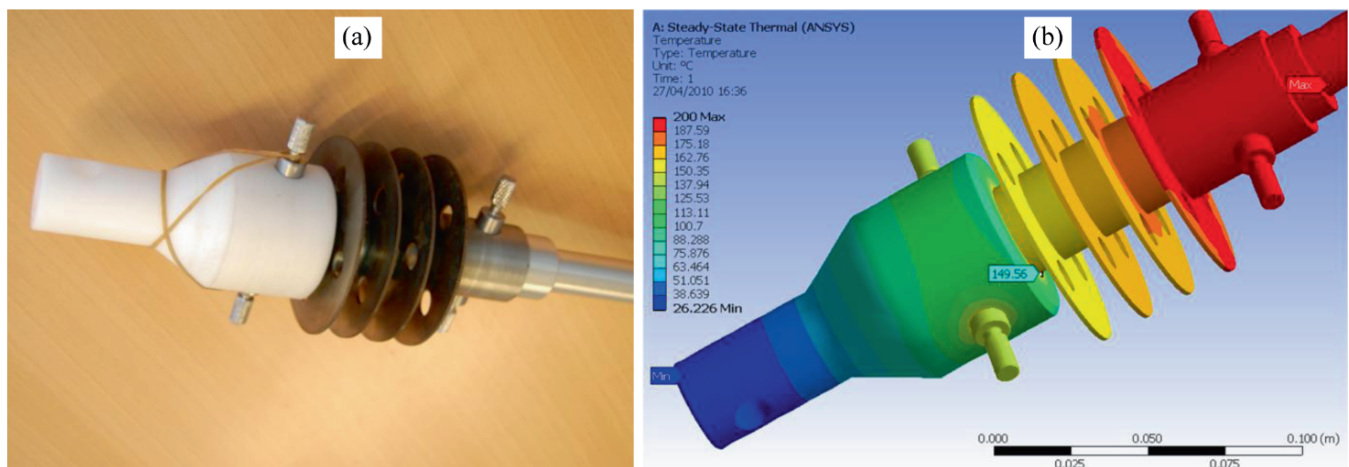

Fig. 5 Thermal isolating connection for separation of MAF rig and load cell: (a) photograph of thermal isolator including heat exchanger and polymer isolator; (b) temperature contour map over thermal isolator predicted using FEA

## 3. EXPERIMENTAL RESULTS OBTAINED AT ROOM TEMPERATURE

Fig. 6 shows examples of the full stress vs. strain curves for uniaxial tension and shear loading recorded at a strain rate of 6×10^{-4} s^{-1}. Each data point on the stress-strain curves is computed from an average of the measured strain on the specimen surface gauge line (DIC measurements) that is multiplied by a "correction factor" derived from nonlinear FEA to compensate for the inhomogeneity of the strain field across the specimen cross sections (to be further described ahead). A specially developed MATLAB code reads each image DIC result data file to extract the all the data points on the stress vs. strain curves, and a robust local polynomial regression approach is used to generate a smoothed stress vs. strain curve for each tested specimen.

Fig. 6(a) shows an in-plane (core plate direction) tensile test response up to the fracture obtained for a short dogbone (SD) test specimen. The curve displays a characteristic nonlinear behaviour up to fracture, where after an initially linear region, the curve show a substantial nonlinear softening response until fracture occurs.

A series of preliminary shear tests were carried out on butterfly shape (BS) shaped specimens with three different notch radii (6.67, 4.5 and 2.5mm). Only the specimen with minimum radius displayed fracture initiation at the (shear) gauge section, and accordingly only specimens with a notch radius of R=2.5mm were subsequently considered for the shear tests. The shear stress vs. shear strain curves displayed a distinctly nonlinear behaviour as shown in Fig. 6(b).
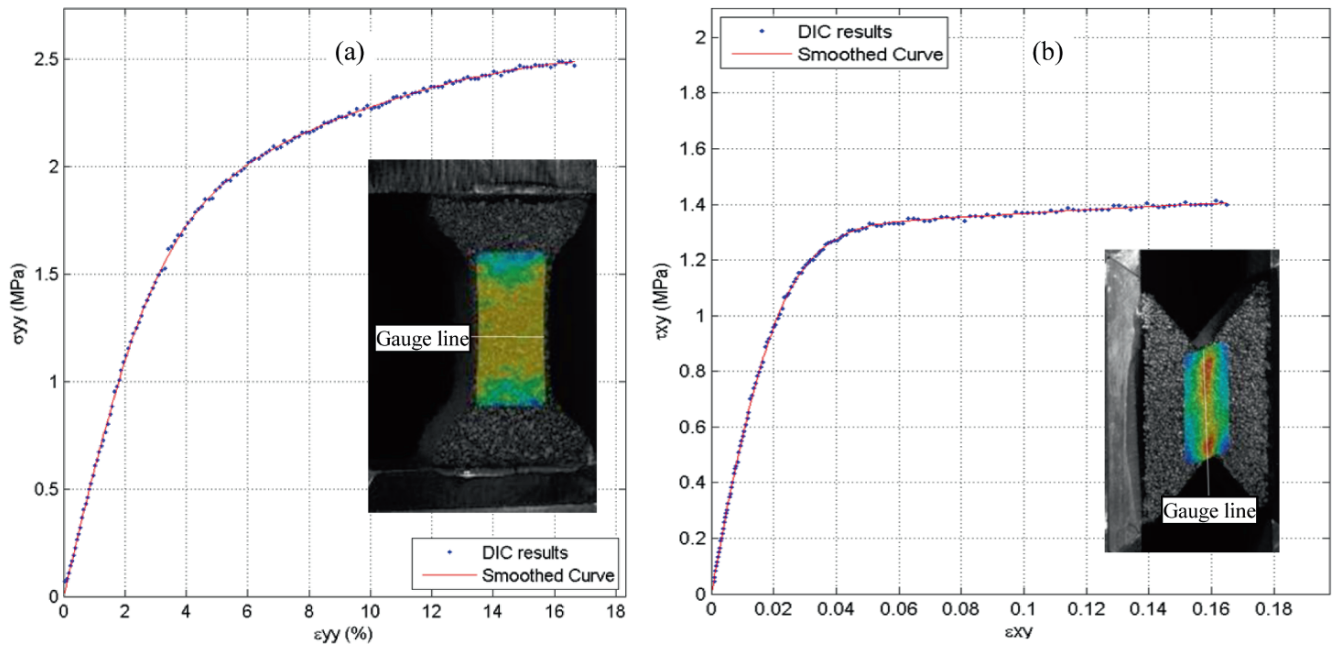
Fig. 6 Tensile and shear material behaviour of H100 foam: (a) SD tensile normal stress vs. normal strain response up to fracture (in-plane core material direction); (b) BS shear stress vs. shear strain behaviour of material (transverse core material direction)
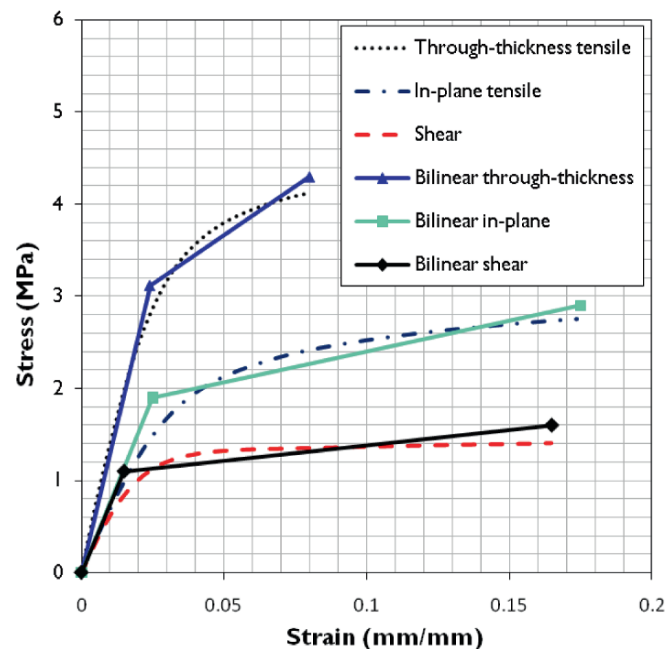
**Fig. 7** Bilinear material approximation for nonlinear FEA modelling

4. NONLINEAR FINITE ELEMENT MODELLING

3D nonlinear finite FE analyses, including both material and geometric nonlinearity, have been conducted using the FE code ANSYS 12.1 to estimate the "correction factors" that are used to compensate for the difference between the measured surface field and the inhomogeneous strain field over the specimen cross section. Higher order solid twenty nodded hexahedral elements (solid186) were used for both the PVC foam and the aluminium fixture materials. Different FE meshes, ranging from 5,000 to 35,000 elements, were used. A bilinear approximation of the experimentally obtained nonlinear shear stress-strain curves (see Fig. 7) has been implemented in the nonlinear FEA model for each specimen type (SD and BS specimens),

and an iterative solution procedure is used to "correct" the material model in the FE analyses until convergence of the derived "correction factor" is achieved after typically 2-4 iterations.

Fig. 8(a) shows the shear stress field in a butterfly shaped (BS) shear test specimen as predicted by nonlinear FE analysis. The distribution of the shear strain on the specimen gauge cross section and the specimen surface gauge line are shown in Fig. 8(b) and Fig.8(c), respectively. The "correction factor" is then used to "correct" the stress-strain response measured on the surface gauge line to obtain the average shear strain on the whole gauge cross section.

Fig 8(a) displays the variation of the calculated strain "correction factor" as a function of the average strain on the gauge cross section. As expected, the strain "correction factor" displays it highest values in the linear (elastic) region of the PVC foam material. However, it decreases with increasing gauge section strains where the specimen gauge section undergoes increasing plastic strains that will smooth the strain distribution, becomes almost uniform before specimen fracture occurs. The "correction factor" appears to increase again just before fracture (see data point to the outermost right in Fig. 9(a)), but this behaviour is believed to be nonphysical and caused by numerical instability in the nonlinear numerical solution. Original data obtained from the shear testing of Divinycell grade H100 PVS foam at room temperature and the corrected shear stress vs. shear strain curve (core through-thickness direction) are shown in Fig. 9(b).
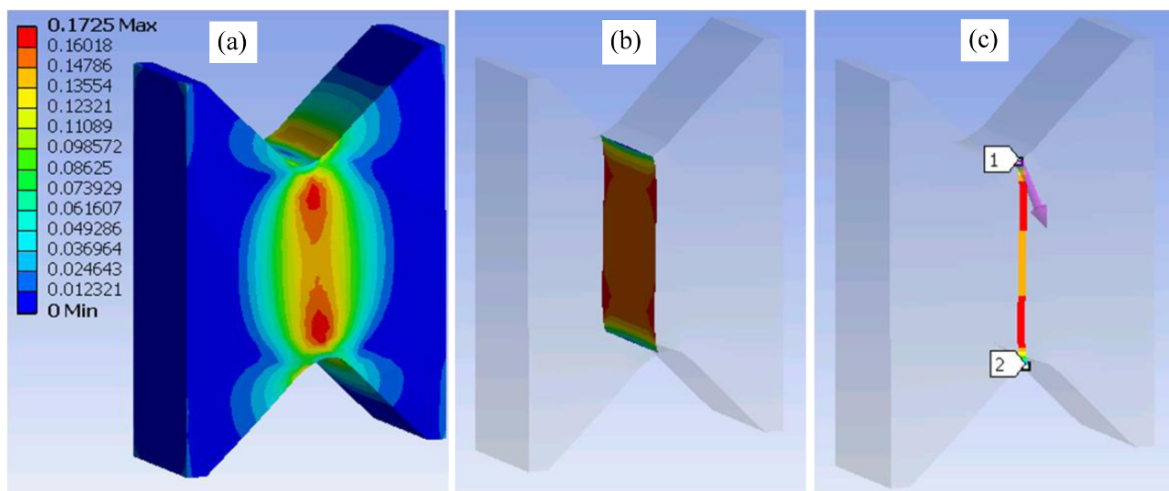
Fig. 8 Nonlinear FEA results: (a) shear strain distribution; (b) gauge section shear strain distribution; (c) defined gauge line on external specimen surface of FEA model
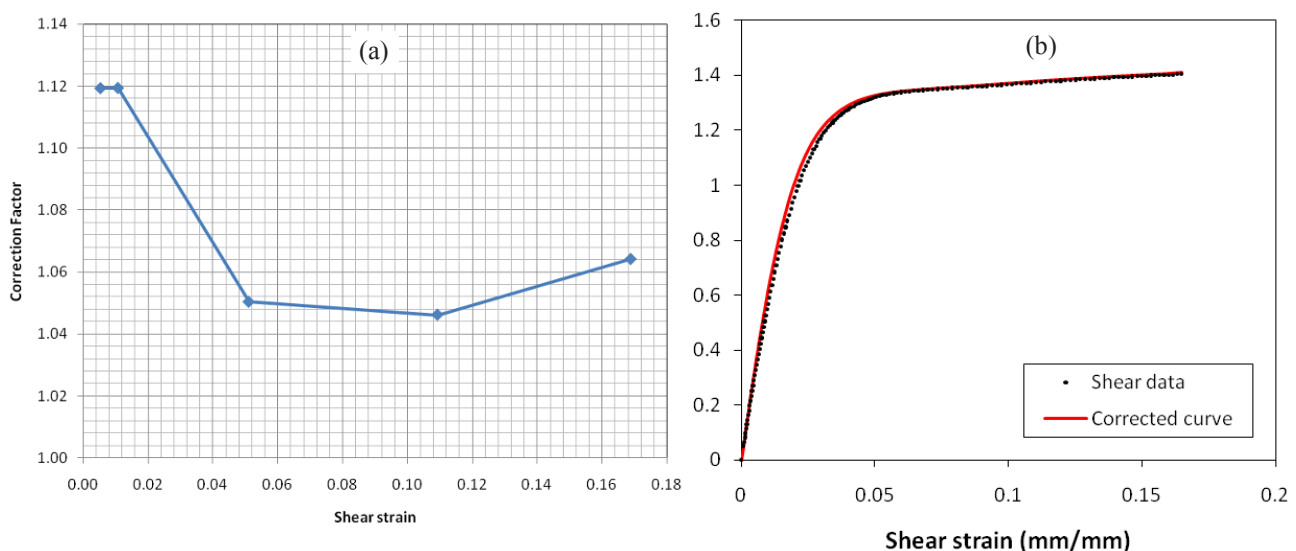
Fig. 9 Nonlinear FEA correction results for shear test: (a) shear strain "correction factor" computed as a function of total shear strain; (b) shear data and corrected shear stress vs. shear strain curve for Divinycell H100 (through-thickness direction)

5. DERIVATION OF MATERIAL PROPERTIES

A set of representative tensile and shear material properties measured for Divinycell grade H100 PVC foam at room temperature is shown in Table 1. The Young´s moduli are 130 MPa and 67 MPa in the through-thickness and in-plane directions, respectively. The in-plane modulus is approximately 55% lower than the through-thickness modulus, and the in-plane strength is about 36% lower than the through-thickness strength. Table 1 shows that the properties obtained using the MAF rig compares well with recent measurements conducted at the University of Southampton, UK [9], as well as with the data sheet valued provided by the manufacturer of the foam core material [2]. It should be noted that the MAF data includes both of the elastic material coefficients as well as the strengths and strains to failure. Also it should be emphasized that all properties have been measured using the same MAF rig. Recent work has shown that the standard rigs used in [9] have limited performance beyond the elastic limit.

Table 1 Divinycell grade H100 PVC foam orthotropic material properties measured using the MAF rig and comparison with measurements using other test methods

	E_1[1] (MPa)	E_2 (MPa)	ν_{12}	G_{12} (MPa)	σ_{1max} (MPa)	σ_{2max} (MPa)	τ_{12max} (MPa)	ε_{1max} (%)	ε_{2max} (%)	ε_{12max}
MAF	130.51 ±1.38	58.90 ±1.53	0.40 ±0.02	32.53 ±0.58	4.0 ±0.15	2.55 ±0.55	1.44 ±0.02	0.073 ±0.01	0.177 ±0.02	0.15 ±0.01
UoS[2]	132.78 ±0.88	58.70 ±0.89	0.41 ±0.01	30.12 ±0.18	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
DIAB[3]	130	N.A.	N.A.	35	3.5	N.A.	1.6	N.A.	N.A.	20

[1] Indices 1 and 2 represent the through-thickness and in-plane directions, respectively.
[2] Linear elastic properties measured using DIC on the tensile and lap shear fixtures at the University of Southampton, UK [9].
[3] Material data sheet data provided by DIAB [2].

6. ONGOING AND FUTURE WORK

Work is presently ongoing to characterize the stress vs. strain curves for PVC foam core materials loaded in compression and at elevated temperatures for tensile, shear and compressive loads. In a further continuation of the work the bidirectional properties of PVC foams at both room and elevated temperatures will be also be investigated.

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