

Thermomechanical Interaction Effects in Composite Sandwich Structures – Initial Experimental Analysis and Derivation of Mechanical Properties

J.M. Dulieu-Barton^{1*}, S. Zhang¹, R. Fruehmann¹, and O. T. Thomsen²

¹ School of Engineering Sciences, University of Southampton, Highfield, SO17 1BJ, UK

² Department of Mechanical and Manufacturing Engineering, Aalborg University,

DK-9220 Aalborg East, Denmark

*EMailing Add: janice@soton.ac.uk

ABSTRACT

An experimental study of the effect of increasing temperature on the tensile modulus of PVC foam is presented. The focus is on obtaining reliable measurements of specimen deformation using optical techniques based on digital image correlation (DIC). A FE model that accounts for the 3D strain distribution in the specimen was used to inform the test specimen design. A new testing methodology and test rig design is devised and described in the paper. Firstly, tests are conducted at room temperature using DIC to obtain the strain on two opposite surfaces of the specimen simultaneously, to assess the effect of any specimen misalignment and devise a correction approach referred to as a 'misalignment ratio'. In the elevated temperature test only one face was optically accessible through an optical window in a thermal chamber. Therefore the experiments are performed over a temperature range of 30°C to 90°C using only a single camera and the misalignment ratio applied. It is shown that the proposed methodology provides precise measurements and the thermal degradation of the tensile modulus can be obtained.

KEYWORDS

Sandwich structures, PVC foam, Thermal degradation, Digital Image Correlation (DIC).

1. INTRODUCTION

Polymer foam cored sandwich structures are being used increasingly for a variety of applications including wind turbine blades, boat hulls and ship structures. Sandwich structures are often subjected to aggressive service conditions which may include elevated temperatures. The material properties of foam cored sandwich structures depend on the temperature field imposed, and this is often ignored in engineering analysis and design due to a lack of material property data and poor understanding of the thermomechanical coupling. Polymer foam core materials are particularly sensitive to elevated temperatures [1]. For example, PVC foams (Divinycell® and Airex®) lose all their stiffness and strength at about 100°C [2], while PMI foams

(Polymethacrylimide, e.g. Rohacell®) lose the heat distortion resistance at about 200°C [3]. Moreover, significant reduction of the properties occurs at much lower temperatures than the temperatures where a complete loss of stiffness and strength is experienced. Previous research has shown that thermal degradation (softening) of polymer foam core materials exerts a significant influence on the performance of sandwich structures [4]. However, current studies on the thermal degradation of polymer foam core materials, especially experimental, are still very limited. Foam properties at elevated temperatures are not provided in most of the commercial foam manufacturers' datasheets [2-3]. This is because no specified standard test procedure or well accepted methodology to characterise the temperature dependence of the foam mechanical properties exists.

The present paper aims to develop a new reliable experimental methodology based on non-contact optical measurements to identify the thermal degradation of polymer foam properties. In sandwich panels, it is the through-thickness properties of the foam that are of primary interest, as these withstand the transverse shear and through-thickness compression loadings. Here the through-thickness tensile properties are investigated as a means for developing a new methodology. Once the methodology has been validated, future work will deal with the more complex proposition of obtaining the compression and shear properties. To aid the development of the methodology only one type of foam is investigated: Divinycell H100 PVC foam made by DIAB. Specimens are loaded whilst being subjected to increasing temperatures in an environmental chamber. The DIC (digital image correlation) technique [5-6] is used to obtain the strain on the surface of the specimen. An elastic FEA model [7] is used to assess the 3D strain distribution and aid the specimen design. For the specimen geometry used in this work a correction factor is derived that accounts for departures from the assumed uniform triaxial strain conditions throughout the specimen. The corrected strain values are then used to derive the tensile modulus. Initial tests are firstly performed at room temperature to validate the

methodology, followed by experiments conducted at elevated temperatures.

2. EXPERIMENTAL METHODOLOGY

Specimen design

In designing the specimen, the ideal geometry is one that provides a large region of uniform axial stress and uniform triaxial strain in the specimen. As mentioned above, it is the through-thickness properties of foam materials that are important in sandwich construction. In the case of the PVC foam used in this work, the bulk material is supplied in the form of sheets with a maximum available thickness of 68 mm. Due to the manufacturing process, the material density increases towards the surface of the sheet. Therefore it was decided to use only the central 40 mm of the 68 mm thick sheet, as by visual inspection it could be seen the density in the central region is fairly uniform. The load cell used in this work has a range of ± 5 kN. It is standard recommended practice to use a minimum of 1% of the total range to ensure a stable load when using servo-hydraulic test machines. To stay well below the quoted elastic limit of the foam (3.5 MPa [2]), a cross-sectional area of 25×25 mm was defined. Hence specimens with dimensions of $40 \times 25 \times 25$ mm (length x width x thickness) were used. This was implemented in an elastic FE model which has been presented in reference [7] to estimate the strain uniformity. The FE model also provides a correction factor (1.04 for the specified specimen dimensions) to enable the surface strain to be used to establish the bulk material stiffness [7]. This represents an improved specimen dimension design by comparison to [7] in which 30 mm long specimens were used and the correction factor was 1.09.

Experimental apparatus design

An Instron servo-hydraulic test machine (8802) with a 100 kN actuator and a 5 kN load cell was used to apply a tensile load to the specimen. An Instron EC2061 environmental chamber was used to apply controlled temperatures. The chamber has a viewing window in the door, and circular openings in the top and bottom through which a mechanical link to the actuator is installed allowing the load to be applied. A thermal isolator was designed to link the actuator and load cell to the rigs inside the chamber to prevent heat transfer. In the thermal isolator, a set of PTFE washers and spacers were utilised to provide the heat insulation.

The load was imparted into the specimen via two steel universal joints as recommended in the ASTM standard [8] as shown in Figure 1. The inner block was bonded to specimen using Araltide 2000. The universal joint served to accommodate rig misalignments and ensure a pure tensile loading. A further consideration is the differential expansion of the rig versus that of the specimen. To accommodate this, at each temperature increment the load was applied only after the entire set-up had reached the required temperature.

A LA Vision VC-Imager E-Lite 5M pixel digital camera was used to capture the specimen surface images during the deformation process, and the camera was positioned with the view direction perpendicular to the specimen surface. The specimen surface was prepared with sprayed white-black speckle and a light illumination was applied that provided sufficient contrast to facilitate the use of the DaVis 74 2D DIC software to extract the specimen surface displacement and strain. Initial validation tests took place at room temperature. Here it was possible to capture images from two of the specimen surfaces simultaneously. Thus any bending caused by specimen asymmetry or test rig misalignment could be identified. In the elevated temperature tests, the viewing window allows only images from the front surface of the specimen to be captured by a camera positioned as shown in Figure 1 (The viewing direction of the camera is perpendicular to the specimen surface.)

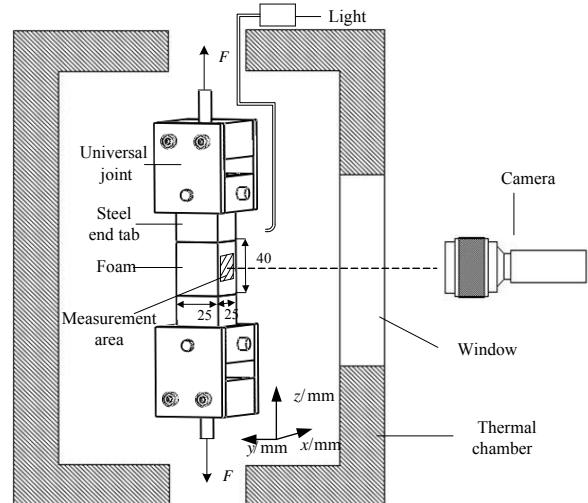


Figure 1: Experimental set-up

3. EXPERIMENTAL RESULTS

Experiments at room temperature

To validate any possible misalignment or bending alongside the tension load introduced to the foam specimen, initial validation tests were conducted at room temperature. The thermal chamber was removed, and thereby the front and back surfaces of the specimen could be viewed simultaneously using two cameras. The tensile moduli were derived using the strain obtained from images of the front and back surfaces. A tensile load was introduced with an extension rate 0.1 mm/min, and the maximum load was set as 400 N to ensure that only elastic deformation occurred. The load data were recorded synchronously with the image capture, and corresponding stress data were derived from the load and the specimen cross-section area. Using the recorded images, the average strain over an area of 20×20 mm positioned centrally on the surface was derived using DIC as shown in Figure 1, and then it was corrected by multiplying the correction factor 1.04 (see section 2).

A subset size of 64×64 pixels with no overlap was used to perform the image correlation. With this set-up, the manufacturer quotes a maximum precision of $50\mu\epsilon$ for the strain of each subset [9]. Since the 20×20 mm measurement area consisted of 225 subsets, the theoretical precision of the average strain should be $0.2\mu\epsilon$. To verify this, 20 specimen surface images were captured from an unloaded specimen and the average strain derived over the measurement area. A precision of less than $50\mu\epsilon$ was obtained, which equates to 5% of the total tensile deformation applied in the test. Therefore, this approach to obtaining strain values from the image data is robust and should allow reliable derivation of the tensile modulus. Strain values were derived for each of the 225 subsets and an average value obtained for each load increment. The tensile modulus was obtained from the stress-strain curve as shown in Figure 2 using a linear fit; the error bars represent the standard deviation of the full-field strain map derived over the measurement area. At lower values of strain, the scatter is about that predicted in the zero strain test, but increases to approximately $100\mu\epsilon$ at $1000\mu\epsilon$. The reason for this is yet to be established, but is possibly associated with the non uniform strain on the specimen surface. The gradient of the curve represents the tensile modulus (E_t) and the R^2 value is the linear correlation coefficient. It can be seen that the R^2 value is quite near to unity, which indicates a very good linear relationship between the stress and strain and hence confirming the tensile deformation is in the elastic region [1]. The standard deviation (STD) of E_t is equal to $E_t((R^2 - 1)/(N - 2))^{1/2}$, where N is number of data points. For the data given in Figure 2, the tensile modulus E_t is derived as 131.02 ± 1.59 MPa, i.e. approximately 1% scatter.

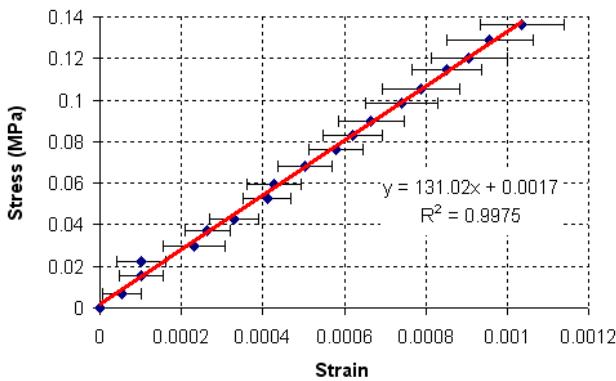


Figure 2: Linear fit of stress-strain data

To assess the repeatability of the test rig alignment and the procedure, nine tests were performed in total. For each test, the test rig was removed from the test machine and refitted. The tensile moduli derived using the strain from the front surface, back surface and the average of the two surfaces are shown in Figure 3, with the precision represented by the error bars. In each test plots similar to that given in Figure 2 were derived with similar amounts of scatter in the linear fit. It can be seen

that the tensile moduli derived using only the front or back surface strain can deviate significantly (143.02 ± 20.09 MPa and 126.21 ± 13.31 MPa, respectively), while the modulus derived by the average strain is rather stable (132.43 ± 2.61 MPa) and agrees well with the value of 130 MPa given in the manufacturer's datasheet [2]. These results indicate that a bending moment is being developed that results from an eccentric loading alongside the tensile load. It appears that even though universal joints were used as recommended by the ASTM standard some parasitic effects are still occurring. It can be concluded that misalignment in this type of testing is inevitable and may be caused by the asymmetry in the specimen or friction in the universal joints. Therefore, the tensile modulus derived using the strain on only one surface may be inaccurate. However, by performing an initial alignment test, the misalignment can be quantified and subsequent data obtained from only one surface can be corrected, hence providing a means for utilising the chamber in the elevated temperature tests.

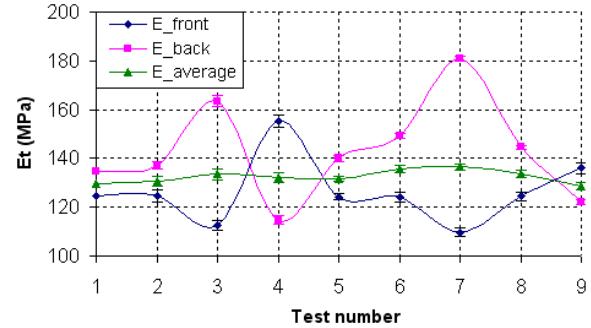


Figure 3: Tensile modulus at room temperature

Experiments at elevated temperatures

For the tests at elevated temperatures, the rig was positioned in the thermal chamber. As the thermal chamber has only one optical window, the strain on the back surface of the foam specimen cannot be obtained using optical techniques. Hence only images from the front surface could be gathered while conducting tests at elevated temperatures. Therefore, a procedure for identifying the misalignment is required as follows:

- (1) Obtain a reliable room temperature E_t from multiple measurements from the front and back surfaces as described in section 3.
- (2) Obtain the tensile modulus of the foam specimen using only the front surface strain at room temperature in the set-up that is used for the elevated temperature tests.
- (3) Calculate the ratio between the result from (2) with the result from (1).
- (4) Use the 'misalignment ratio' derived in (3) to correct the tensile modulus obtained from images of the front surface in the elevated temperature tests.

Initial tests were conducted and gave a misalignment ratio of 1.05. Then tests were conducted at temperatures

from 30°C to 90°C with increments of 2°C. Between each temperature increment the specimen temperature was allowed to stabilise (taking approximately 15 minutes). The load was applied as in the room temperature tests in position control at a rate of 0.1 mm/min with a maximum load of 400 N. Strain values were determined from the images gathered from the specimen front surface for each test and corrected using the correction factor 1.04 (see section 2). Typical stress-strain curves are shown in Figure 4 for temperatures of 30, 60 and 90°C. It can also be seen that the R^2 values remain fairly near to unity at different temperatures, which shows that the tensile deformation is linear. The tensile modulus at each temperature was obtained from a linear fit as before. The tensile moduli were then corrected using the misalignment ratio.

The tensile modulus is plotted against each 2°C temperature increment from 30°C to 90°C in Figure 5. The reduction in tensile modulus with temperature is nonlinear and fitted with a 4th-order polynomial curve which is similar to that obtained in [7]. A significant change in the rate of modulus reduction occurs around 45 and 75°C; at 90°C, the tensile modulus is only half of its original value.

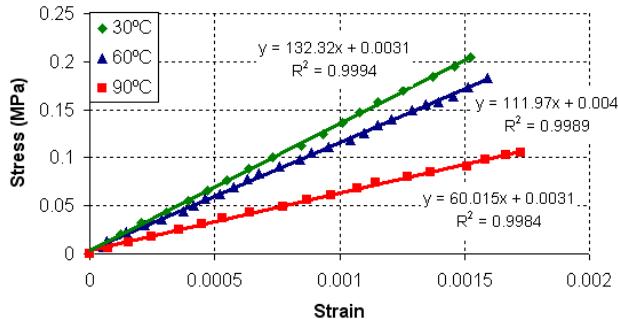


Figure 4: Stress-strain data at different temperatures

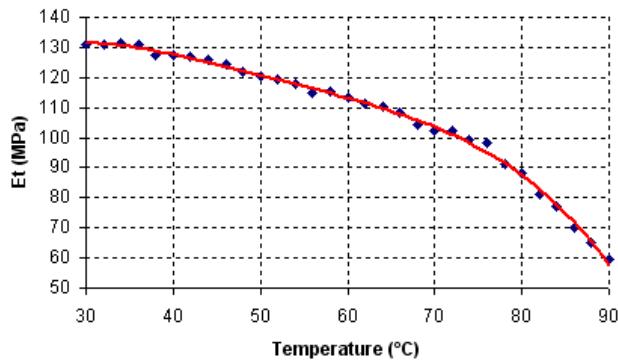


Figure 5: Change of the E_t of PVC H100 with temperature

4. CONCLUSIONS

The work in the paper has shown that it is possible to quantitatively characterise the thermal degradation of the tensile modulus of PVC foam using optical techniques such as DIC. It has been demonstrated that inevitable misalignment can be accounted for by taking measurements from opposite faces of the test specimen

at room temperature and incorporating a correction approach to elevated temperature tests. Neglecting the correction approach for the case shown in the paper would result in a combined error of 9.2% resulting from the misalignment and geometric effects. Thereby, this work lays the foundation for a complete characterisation of the elastic properties of foam materials at elevated temperatures, which will be the object of future work. The methodology will also be applied for other foam core materials and it will be demonstrated that the data are vital to assess the performance of sandwich structures in elevated temperature conditions.

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