

INFLUENCE OF MATERIAL NONLINEARITY ON THE THERMOMECHANICAL RESPONSE OF FOAM CORED SANDWICH STRUCTURES – FE MODELLING AND PRELIMINARY EXPERIMENTAL RESULTS

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1 Introduction

Lightweight sandwich structures are being used increasingly in the aerospace, naval and transportations industries due to their excellent stiffness-to-weight and strength-to-weight ratios. Sandwich structures are often composed of a low stiffness (compliant or "soft") core material made of polymeric foam or a honeycomb that is flexible in the thickness direction, and laminated composite or metallic face sheets. Sandwich structures are subjected to mechanical loads while exposed to aggressive environmental conditions that may be associated with elevated temperatures. Traditionally, the typical design process of such structures examines the responses due to the mechanical loads and the thermal loading, i.e. treating the deformations induced by either thermal or mechanical sources, separately. However, the interaction between the mechanical and thermal loads may lead to an unsafe response with loss of stability and structural integrity, especially when the deformations are large and the mechanical properties (e.g. stiffness and strength) reduce as the temperature level is raised [1-3]. This is particularly pronounced for polymer foam core sandwich materials, where a significant reduction of the mechanical properties may occur well within the operational temperature range [1-3].

2 Model definition

The research reported in [1-3] is based on the High order SANDWICH Panel Theory approach (HSAPT), and includes the transverse core flexibility as well as geometrically nonlinear effects. However, the

HSAPT approach is valid only in the linear elastic material range, and does not account for the material nonlinearity that occurs when the sandwich constituent materials are loaded to failure.

In the present paper, polymer foam cored sandwich structures with aluminium face sheets and cross linked PVC foam cores are analyzed. The approach uses finite element (FE) analysis that incorporates both material and geometrical nonlinearities. The commercial FE code ABAQUS/Standard[®] is used for the FE analyses. The large difference in stiffness between the face and core typically encountered in sandwich structures leads to numerical instabilities and significant element distortions of the FE models [4]. Also the reduction of core stiffness with increasing temperature results in the face/core stiffness ratio increasing, making a convergent solution for the FE analysis more elusive. To account for the geometric nonlinearity large deformations are permitted in the FE analysis. Complete stress-strain curves to failure for the core material over a range of elevated temperatures are incorporated into the analysis to account for the material nonlinearity. Cross linked PVC core materials typically exhibit orthotropic behaviour and accordingly an appropriate anisotropic yield hypothesis is required.

3 Experimental setup

A test rig that enables full control of the constraints on both the mechanical and thermal boundary conditions is designed (see Fig. 1). This is used to conduct three point bending tests of foam cored sandwich panels subjected to combined mechanical and thermal loading [5]. The two end fixtures were

designed to enable a range of mechanical boundary conditions to be applied to the specimen ends. The mid-span displacements and through thickness strains are derived using digital image correlation (DIC) applied to images taken from the specimen sides. The temperature of the hot surface is controlled using an infrared radiator mounted above the beam while the lower face sheet is maintained at ambient temperature by forced convection. The top face sheet is heated to a specified temperature and once the equilibrium temperature is achieved a mechanical load is applied. During the heating phase, the specimen sides are insulated using the same H100 foam as used in the core. This insulation is removed shortly before the application of the load to enable line of sight access to the specimen side for the DIC. The tests reported in this work are conducted at four discrete top surface temperatures, namely 24, 50, 72 and 97 °C. The temperature on the surfaces is obtained using an infrared camera. Prior to mechanical testing, the top face sheet displacement due to the differential thermal expansion of the top and bottom of the beam is obtained using a single specimen that is heated to each of the four predetermined temperatures. This displacement is subsequently added to the displacements obtained during the mechanical loading which were obtained relative to the equilibrium condition (this step is necessary for comparison with the FE model). The specimens are loaded until failure. A sandwich panel of 450 mm length and 50 mm width is fabricated with 1 mm thick facesheets and 25 mm thick foam core. The core is Divinycell H100 PVC foam and the face sheets are of aluminium. The sandwich panel is simply supported at both ends, i.e. the specimen is free to rotate about its ends and to translate in the horizontal direction; only vertical displacements are constrained.

Table 1 gives the parameters for the four different experiments carried out using the test rig. Fig. 2 shows the experimentally obtained plots of applied force vs. mid-span deflection of the top face sheet at the different thermal loading profiles considered in Table 1. In the experiments, the sandwich beams fail due to a combination of local indentation at the mid-span and interface failure between the core and the face sheet. It is observed that the interface failure dominates at the lower temperatures while indentation is the primary failure mode at the higher temperatures. The failure is associated with significant plastic deformation in the top face sheet

and in the vicinity of the core below the applied point load.

4 FE Modelling

Using the sectioning tool available in ABAQUS®, perfect bonding between the facesheets and the core is ensured. The face sheets are assumed to be isotropic and the foam core is assumed to be orthotropic in the elastic range, and as a first approximation to be isotropic in the plastic deformation range. In the continuation of this work an orthotropic plasticity model will be implemented in the nonlinear FE analysis.

Fig. 3 gives the geometry of the FE model including the imposed boundary conditions and the FE meshing used. Due to the symmetry of the problem, only one half of the sandwich beam configuration is modelled. The 8 node plane stress bi-quadratic element CPS8R with reduced integration available in ABAQUS® is used for the analyses. Detailed convergence studies showed that a minimum of 8 elements are required through the thickness of the face sheets, and that a minimum of 28 elements are required through the core material thickness to obtain a fully converged solution.

A relatively simple material modelling approach is considered where a multi-linear elasto-plastic material model is assumed for the foam core and the face sheets. Young's modulus (E) of the face sheets is 70 GPa and Poisson's ratio (ν) is 0.33. The stress-strain curves given in Fig. 4 show the behaviour of the Divinycell H100, PVC polymer foam core at a temperature of 24°C obtained using a newly proposed modified Arcan test fixture [6].

With respect to the material input, the aluminium is approximated using a bi-linear elasto-plastic model in which a yield stress of 130 MPa corresponding to a strain of 0.01 is specified, and where the limit state is given by a strength of 340 MPa corresponding to 0.15 strain. Fig. 5 shows the temperature dependent stiffness properties of the PVC foam core [7]. The full nonlinear stress strain curve of the PVC foam core material has so far only been determined at a temperature of 24°C [6]. In the FE modelling, the full nonlinear stress curves for the PVC foam are implemented using a multi-linear approximation.

5 Experimental vs. FE results

The results from the experiment [5] are simulated using ABAQUS/Standard® to determine the elastic limiting point loads at the different thermal profiles

shown in Table 1. Material nonlinearity is not taken into account at this stage, i.e. only geometrical nonlinearity is accounted for. To obtain the limit point loads, Riks' arc-length solver is used. The converged FE model includes 11070 bi-quadratic CPS8R elements. The FE model for the elastic analysis of the sandwich panel is modelled by imposing the thermal loading profiles shown in Table 1, and with the boundary conditions used in the experimental setup explained in section 3. From Fig. 6 it is seen that the predicted range of limit point loads for the different thermal loading profiles is between 2000-3500 N, whereas the experimental results indicate "apparent" limit point behaviour at loads in the range of 850-1200 N. However, in the experiments significant indentation associated with face sheet and foam core plasticity is observed, thereby explaining the deviations between the modelling results and the experimental observations. It can be seen from Fig. 6 that by eliminating the indentation effect in the experiments, the nonlinear interactions between the thermal and mechanical loads may be observed more clearly. For an improved comparison, these need to be included in the modelling.

6 Effect of material nonlinearities

To introduce material nonlinearity into the model, the materials are assumed to be elasto-plastic. Instead of bilinear elasto-plasticity, the multi-linear elasto-plasticity option available in ABAQUS[®] is utilised for the foam core material to obtain greater accuracy. In all these cases, geometric nonlinearity is incorporated by allowing large deformations and moderate rotations. The complete stress-strain curves up to failure are available only at room temperature i.e., at 24°C. Thus, the material nonlinearity effect is studied only for the first thermal loading profile shown in Table 1, and the corresponding stress-strain curves shown in Fig. 4 are used for the polymer foam core [6]. Fig. 5 represents the temperature dependent stiffness properties of the polymer foam core [7]. Three different FE models are considered to investigate the effects of face sheet and core nonlinearities individually and in combination.

In the first case, the face sheets are assumed to be elasto-plastic and the core to be elastic. In the second case, the core is assumed to be elasto-plastic while the face sheets are elastic. In the third case, both the face sheet and the core are assumed to be elasto-plastic. The three cases are summarised in Table 2.

Fig. 7 shows the load vs. displacement curves for the three different cases shown in Table 2 as well as the elastic analysis results showing the limit point load. Table 3 gives the range of stresses that materials are experiencing in the three different cases. The computational approach is to use the anisotropic yielding law using Hill's potential which is available in ABAQUS[®] by writing a subroutine with user specified material properties (UMAT). This allows for the anisotropy of the polymer. As the UMAT is still in the construction stage, the critical stress in the different directions of the polymer foam is derived by checking manually which stress is more dominant in the polymer foam core.

7 Discussion and conclusions

The initial stiffness predicted by the elastic FE analysis agrees well with the experimental results as seen in Fig. 6. From the parametric study with material model laws explained in Table 2 and Fig. 7 it can be concluded that the material nonlinearity of the face sheets in the present scenario is more pronounced and dominating than the material nonlinearity of the polymer foam core. Thus, the mid-span indentation observed experimentally is the reason for the early failure of the sandwich panel. This also explains the deviations between the experimental results and the linear elastic and geometrically nonlinear FE simulation results displayed in Fig. 6. The mid-span indentation can be reduced by extending both ends of the sandwich beam beyond the end supports of the test by approximately one sandwich beam thickness. This will be assessed in the continuation of this work where also the application of distributed loading will be investigated.

Acknowledgements

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Load case	A	B	C	D
Top facesheet	24 °C	50 °C	72 °C	97 °C
Bottom facesheet	24 °C	26 °C	26 °C	27 °C

Table 1. Different thermal loading profiles applied to the sandwich beam

FE Modelling Assumptions for	I	II	III
Top and bottom facesheets	Elasto-plastic	Elastic	Elasto-plastic
Central core	Elastic	Elasto-plastic	

Table 2. Three different FE modelling material assumptions considered to study the influence of plasticity

Range of stresses in (in MPa)	I	II	III
Facesheets	250	450	200
Central core	20	9	9

Table 3. Range of the stresses in the core and facesheet for the different FE modelling considered

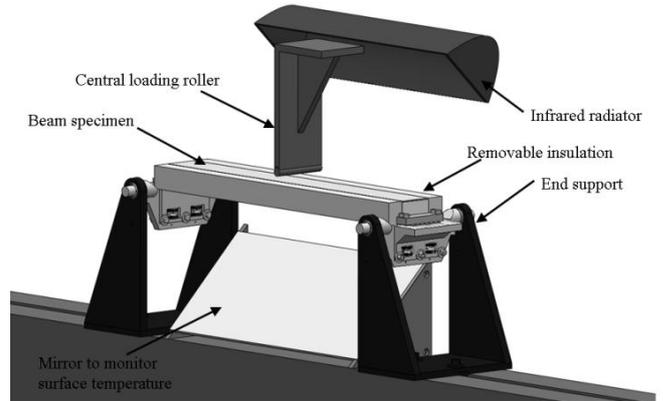


Fig. 1. Schematic arrangement of the specially designed test rig [5]

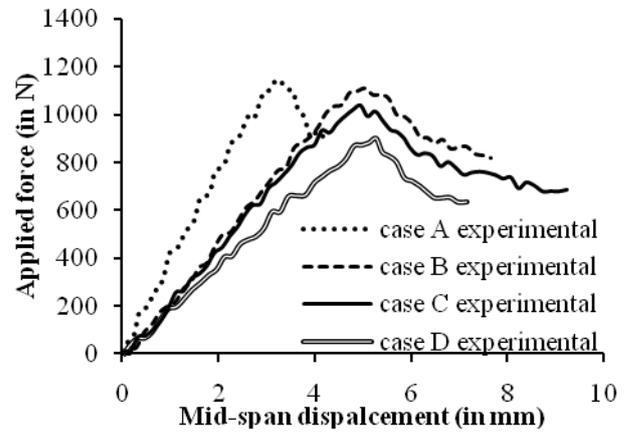


Fig. 2. Experimental results – applied force vs. mid-span deflection of top face sheet [5]

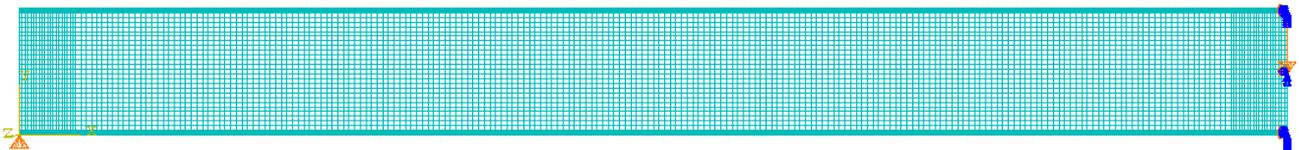


Fig. 3. FE model geometry and boundary conditions with element distributions in the sandwich beam considered for the analysis

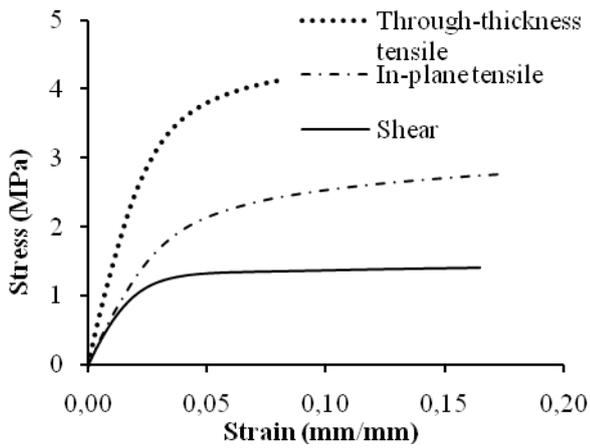


Fig. 4. Nonlinear stress-strain curves for Divinycell H100 PVC foam at 24 °C [6]

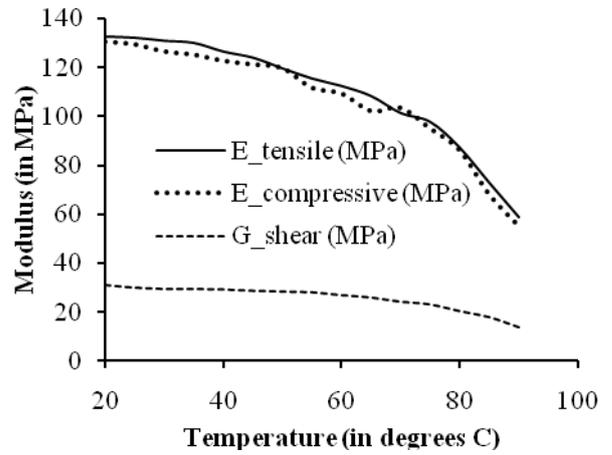


Fig. 5. Elastic stiffness of Divinycell H100 PVC foam core vs. temperature [7]

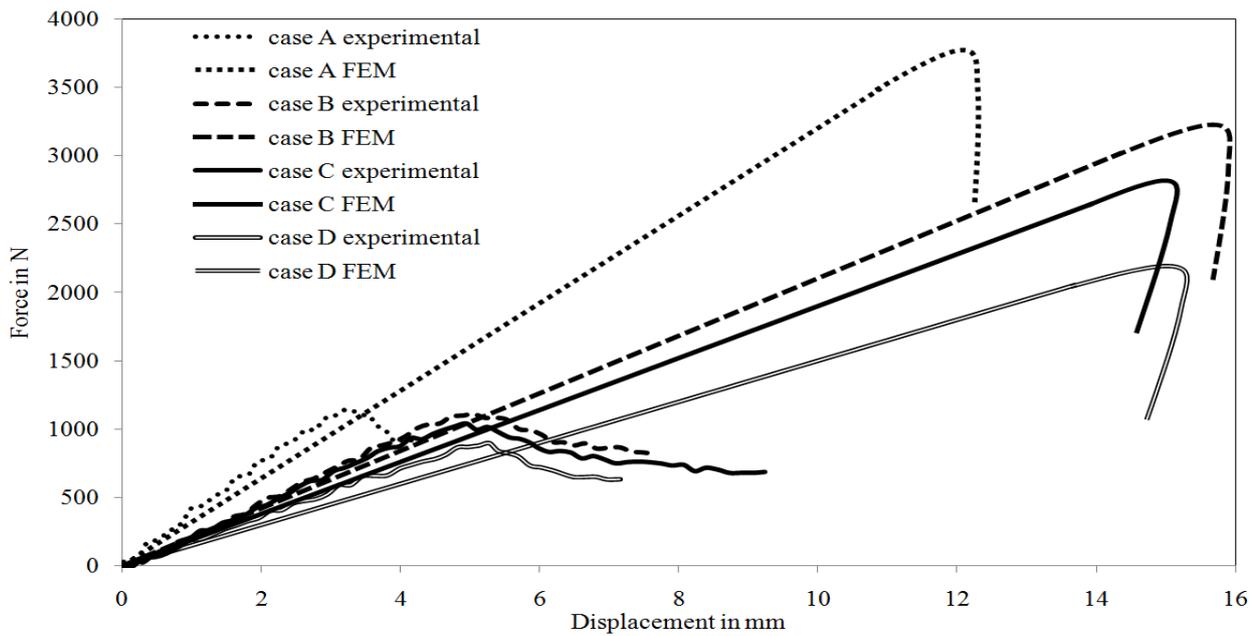


Fig. 6. Comparison of nonlinear elastic FE analysis with experimental results

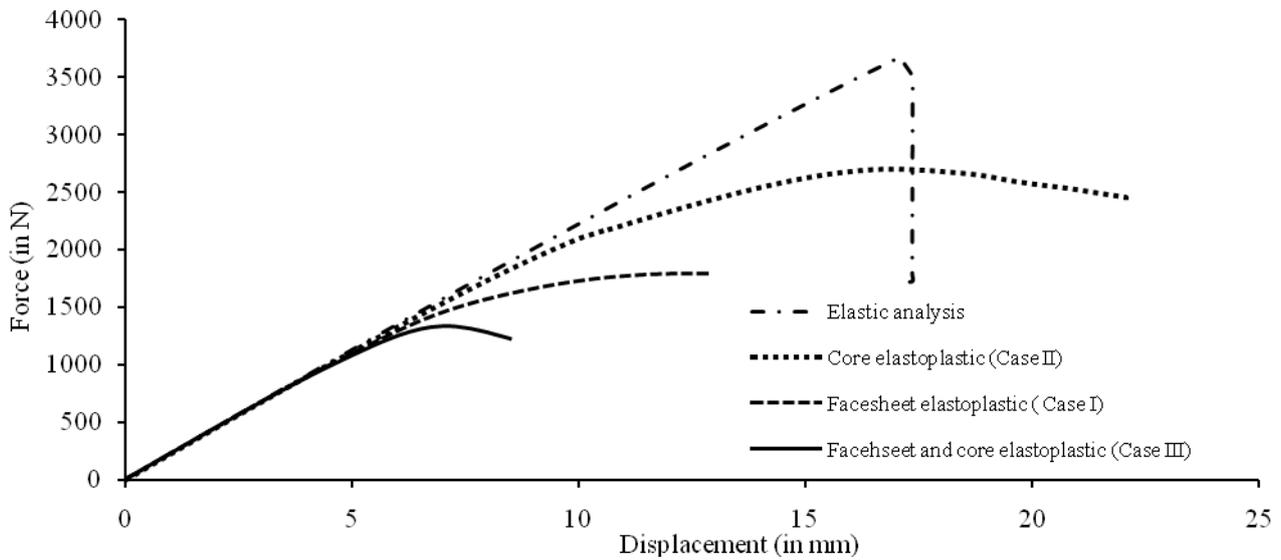


Fig. 7. FE model results showing the influence of material nonlinearity (plasticity) in the face sheets and the core individually as well as in combination

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