NUMERICAL MODELLING OF THE BEHAVIOR OF THERMOPLASTIC COMPOSITE SANDWICH STRUCTURES UNDER LOCALISED IMPACT LOADING

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ABSTRACT

Thermoplastic composite sandwich structures are being considered for increased application in automotive crash structures. The objective of this study is to develop an accurate and reliable finite element modelling procedure for simulating the elastic and failure response of thermoplastic sandwich structures under localised indentation loading. Experimental characterization of the indentation response of the sandwich structure was undertaken for both static and dynamic loading. The LS-DYNA finite element code was used to model the indentation response of the beam. The thermoplastic composite skins are modelled with the advanced MAT 162 material model that has been implemented in the LS-DYNA software. The foam core was modelled with an elastic-plastic material model. The calibration strategy that was developed for the material models is presented. The finite element sandwich indentation model was validated by comparing the experimental results with the simulation predictions. The model was able to successfully predict the non-linear force-displacement response and localised deformation in addition to the damage modes in the sandwich structures.

1. INTRODUCTION

Composite sandwich constructions are being given increased consideration for application in vehicle front-end structures. The high energy absorbing capability of sandwich structures makes them an attractive passive solution for meeting crashworthiness countermeasure requirements . Sandwich structures typically consist of two thin, stiff, high strength skins that are separated by a thick, low density, low strength core [1, 2]. In a sandwich, the skins carry both in-plane and bending loads while the primary purpose of the core is to provide spacing between the skins and carry the transverse shear loads to which the sandwich may be subjected. Sandwich constructions offer several advantages over monolithic composite laminates such as high stiffness to weight ratio, high bending strength to weight ratio, high energy absorption potential and good thermal and acoustic insulation. Furthermore, thermoplastic composite (TPC) sandwich structures offer the potential for rapid, low cost mass production as the single thermoplastic polymer used in the skin and core allows for combined forming and joining in a one-step process [3]. Additionally, the all thermoplastic feature of the sandwich permits the production of shaped structures from flat plates by thermoforming techniques and also allows for recycling. Despite these advantages, research into the development of a predictive modelling procedure for simulating the elastic and damage modes of TPC sandwich structures under localised impact loading still remains limited.

This paper presents the results of a numerical and experimental study conducted with the aim of developing a modelling methodology for accurately simulating the behaviour of TPC sandwich structures under localised indentation loading. This type of loading is relevant to passive safety structures designed for energy management applications.

2. MATERIALS AND MANUFACTURE

The TPC sandwich structures described in this study were manufactured from 60 wt% 0/90 woven fabric commingled glass/polypropylene face-sheets supplied by OCV Reinforcements under the trade name, Twintex™. The core of the sandwich consists of an anisotropic crushable polypropylene foam named Strandfoam™, having a nominal density of 64 kg/m^3. Strandfoam™ was supplied by Dow Automotive and has a high energy absorption efficiency due to its extruded honeycomb like structure [4].

Sandwich panels of dimensions 800 mm x 70 mm were manufactured using an optimised one-step vacuum moulding process [5, 6]. A picture of the process is shown in Figure 1. The vacuum moulding process involved the stacking of preconsolidated layers of Twintex™ (0.5 mm thick) on two aluminium transfer plates. The stacks of Twintex™ were preheated to 200 °C in a hot air oven. The first stack, along with the transfer plate is transferred to the vacuum table. The cold foam core is placed on the stack followed quickly by the second stack which is placed on top of the foam to complete the sandwich assembly. The vacuum membrane is then clamped over the sandwich and a vacuum is applied. Sandwich beam specimens were cut from the moulded panels using a band saw.

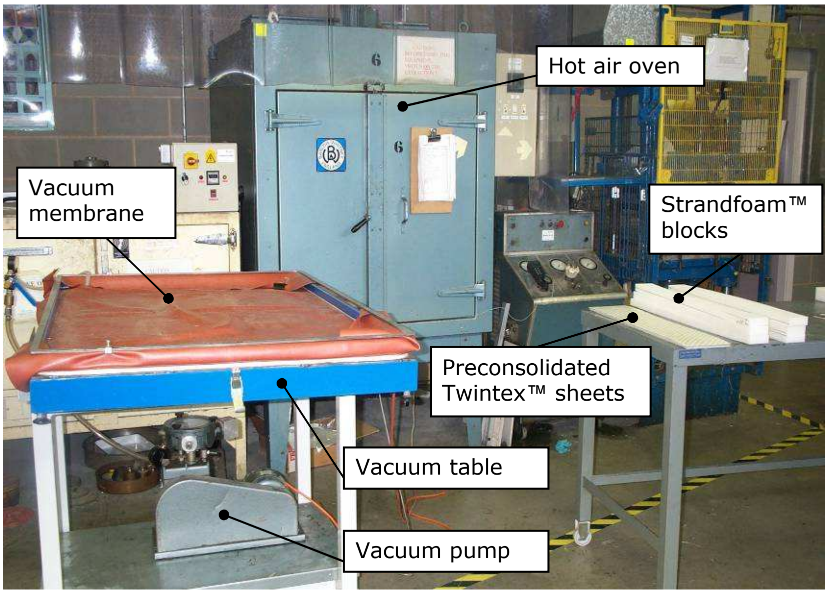


Figure 1. The vacuum moulding process.

3. EXPERIMENTS

Quasi-static indentation tests were conducted on a Tinius Olsen electromechanical machine at a crosshead speed of 5 mm/min. The TPC sandwich beam specimens were indented with a 25 mm cylinder across the whole width of the beam cross-section. During the test the beam is supported on a rigid steel base plate. The tests were conducted under displacement control up to a maximum indentation of 45 mm. A schematic of the test setup and specimen dimensions are shown in Figure 2. The specimens were 250 mm long with a width of 30 mm and nominal core thickness of 50 mm. Sandwich beams with three different skin thicknesses were investigated, 1, 2 and 3 mm, respectively. All sandwich beam skins had a [090] fibre orientation aligned along the beam longitudinal axis. The foam was assembled between the skins such that the Strandfoam™ extrusion direction was aligned with the impact direction, i.e. vertical.

For the dynamic indentation tests, particular focus was given to analysing one of the primary indentation failure modes, i.e. core crush. Therefore, for simplicity and to suppress other modes of failure, consideration was given to low velocity impacts at an incident energy level of 15 J. Dynamic impact tests were performed in an instrumented drop tower with an impact mass of 8.2 kg and impact velocity of 1.89 ms^{-1}. The specimen dimensions are the same as in the quasi-static tests.

Digital images extracted from high speed camera footage were used to investigate the deformation and failure.

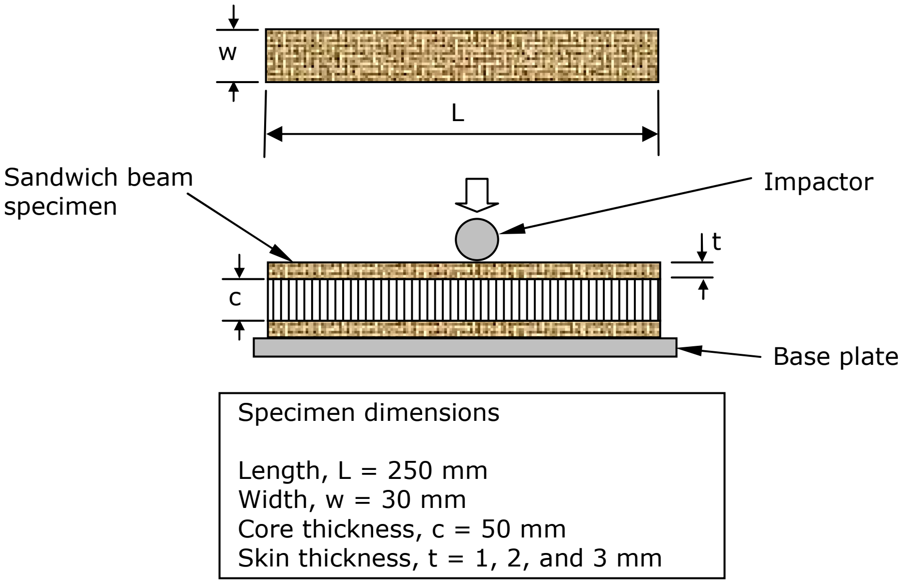


Figure 2. Schematic of indentation test and specimen dimensions.

4. SANDWICH MODELLING METHODOLOGY

Finite element (FE) modelling of the response of TPC sandwich beams under indentation loading was conducted using the LS-DYNA explicit FE code [7]. Figure 3 shows the sandwich beam finite element model and boundary conditions. Taking into account the geometric and material symmetry, only one half of the sandwich beam was modelled in order to reduce solution time. All the components were modelled with single integration point eight node solid elements. A stiffness based hourglass control was applied so as to prevent the occurrence of hourglassing. Each ply in the skin laminates was represented individually by a layer of solid elements. The cylindrical impactor and base plate were modelled as rigid bodies. The base plate was fully constrained while the impactor was only allowed to translate along the global Z axis. For the quasi-static analysis, the impactor was given a prescribed velocity which was much higher than that in the actual test so as to reduce the computational run time. For the dynamic model, the impactor was given an initial velocity equivalent to the actual test.

Contact between the impactor and the top composite skin was modelled using the automatic surface to surface contact algorithm within LS-DYNA. The same contact type was used to model contact between the bottom composite skins and the base plate.

A local coordinate system was used to define the material coordinates of the foam core. The local x-direction was aligned with the foam extrusion axis and the local y-direction is normal to this axis along the beam as shown in Figure 3. The material axes for the skins and all other components are orientated along the global axes.

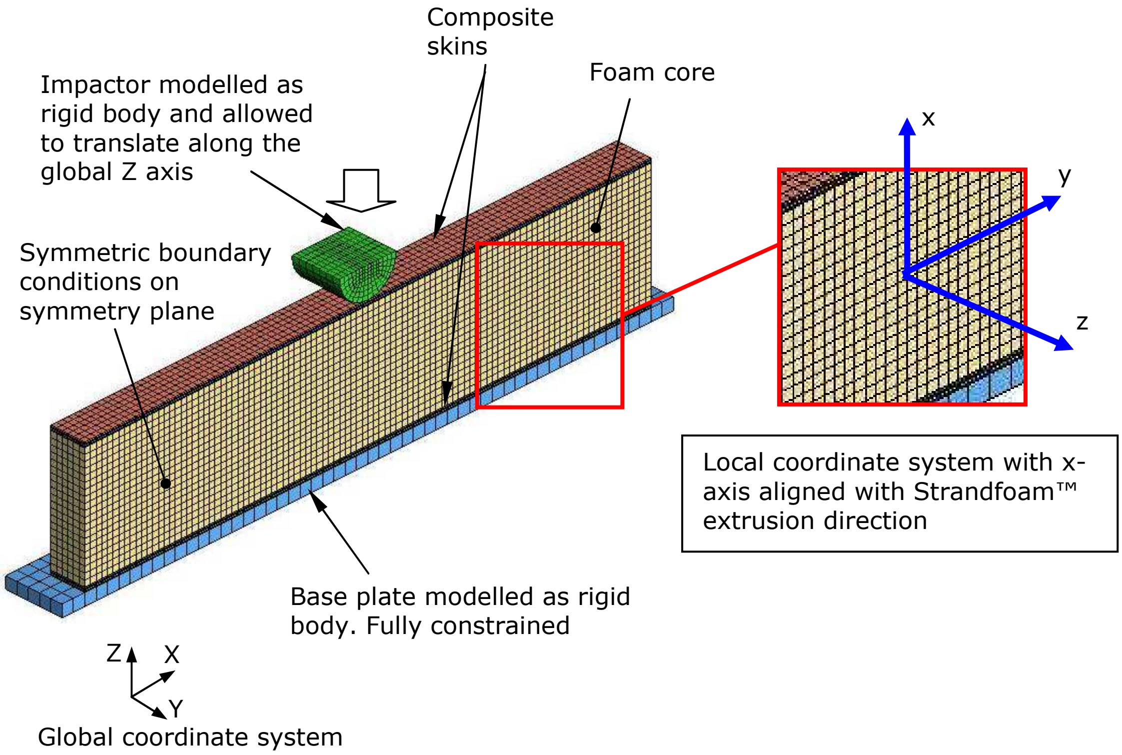


Figure 3. Finite element model and boundary conditions for sandwich beam indentation test simulations.

4.1 Composite skin model

The Twintex™ thermoplastic composite skin material was modelled with the MAT 162 composite damage progression model that has recently been implemented in the LS-DYNA explicit finite element code. This model is based on a continuum damage mechanics formulation where a set of damage history variables are used to relate the initiation and progression of damage to stiffness reductions in the material. MAT 162 is capable of simulating fibre fracture (tensile and compressive), matrix damage, fibre crush and delamination under various loading conditions. Furthermore, the model has the advantage of predicting delamination without prior definition of an interlaminar crack surface or the need to implement computationally expensive interface or cohesive models between the plies. Strain rate effects on material properties can also be accounted for in MAT 162 using logarithmic based functions. A more detailed description of MAT 162 is available in reference [7].

There are four damage parameters, m_i, in MAT 162 that are used to model the post-elastic damage in the material. These damage parameters were calibrated using an inverse modelling technique. This involved an iterative procedure where the damage parameters were determined by correlating simulations with the quasi-static and dynamic experimental stress-strain results for a series of uniaxial tests. To validate the material model and calibrated parameters, a series of benchmark coupon tests were also performed.

An extensive experimental program of material characterisation has been conducted to support the calibration and validation of the material model [8]. The experimental program covered a wide range of quasi-static and dynamic tests, including:

- Static and dynamic uniaxial tests: shear, tensile and compression (calibration)
- In-plane and through thickness shear tests (calibration)
- Static and dynamic three-point bending tests (damage characterisation and validation)
- Dynamic plate impact tests (damage characterisation and validation)

Full details of these experiments, applied to Twintex™ are reported in [9].

4.2 Foam core model

The foam core material was modelled with the MAT 142 foam model recently implemented in LS-DYNA. MAT 142 is a transversely anisotropic elasto-plastic material model. It uses a Tsai-Wu yield surface that hardens or softens as a function of volumetric strain [10].

The input parameters for the foam model were obtained from an experimental characterisation program that included [9]:

- Static and dynamic uniaxial compression tests
- Static uniaxial tensile tests
- Static and dynamic shear tests

5. RESULTS

5.1 Force-displacement response

Figure 4 shows a comparison of the typical experimental and simulation force-displacement curves for the sandwich beam under quasi-static indentation loading. In general, there are three distinct regions of deformation. Initially the force-displacement response is linear elastic up to a yield point. After this, there is non-linear plastic deformation as the sandwich beam stiffness decreases. For the 1 and 2 mm skin beams, the post-elastic region exhibits plastic hardening as load increases with displacement. However, for the 3 mm skin beam the post-elastic response is almost perfectly plastic as the load level remains almost constant. This plastic non-linear behaviour is induced by progressive localised core crush under the cylindrical impactor along with membrane stretching and damage in the top skin. Finally, there is a sharp load increase as foam densification occurs. As the impactor moves down into the specimen, the ends of the sandwich are pulled up off the base plate due to compressive stress in the top skin (see Figure 4). It was observed that the load at the end of the linear region increases with skin thickness from ~500N for the 1 mm skin to ~1500N for the 3mm skin.

Figure 5 shows a comparison of the typical experimental and simulation force-displacement curves for the sandwich beam under dynamic indentation loading. In all cases, in its early stages, the dynamic indentation force-displacement response is similar to the quasi-static results. Initially, the load-displacement response is linear elastic followed by non-linear deformation up to a maximum load. However, in the dynamic test, the impactor rebounds at a maximum displacement point. This maximum displacement point decreases with increasing skin thickness due to the higher bending stiffness of the thick skins.

The predicted force-displacement response shows excellent correlation with the experimental results. The significant indentation and general deformation of the sandwich beam has been well predicted as shown in Figure 4 and 5.

5.2 Stress analysis

Figure 6 (a) shows the predicted distribution of the through-thickness normal stress in the Strandfoam™ core at an indentation of 35 mm for the 2 mm skin sandwich beams. There is a significant compressive zone under the impactor which extends through the whole thickness of the foam core, with a highly compressed area directly under the impactor.

The compression zone expands along the length of the beam as skin thickness increases. The thicker skins have a higher bending stiffness and are better able to transmit the indentation load to the core, along the length of the beam. In contrast, thin skins result in a small compression zone as they cause a concentration of the compression region under the impactor. This is due to the highly localised plastic deformation of the top skin as the impactor moves down into the beam.

Figure 6 (b) shows the longitudinal stress in the beam. There is a longitudinal compression stress area adjacent to either sides of the impactor that separates the two longitudinal tensile areas at the centre and near the ends of the beam.

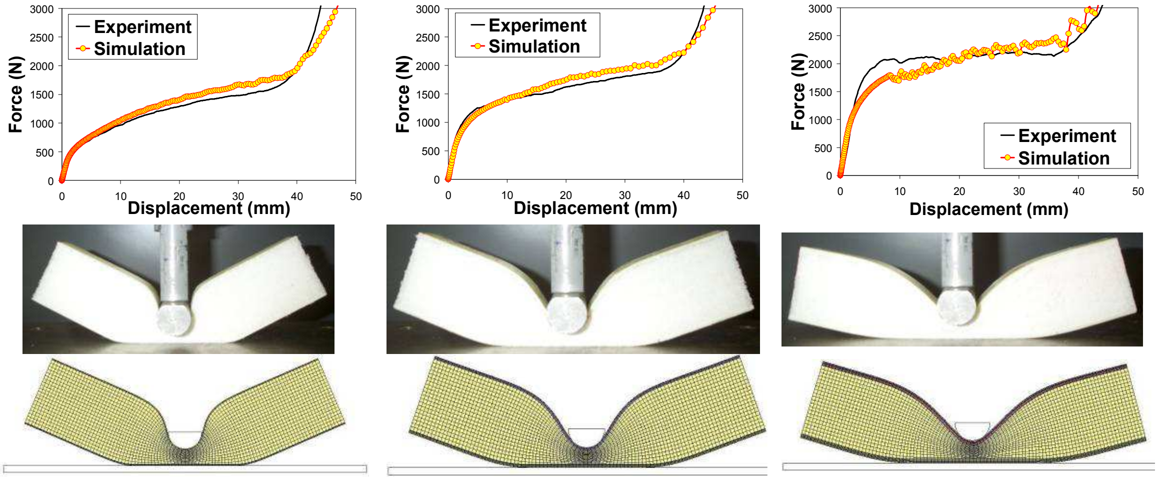
Figure 6 (c) shows the distribution of through-thickness shear stress and two shear zones adjacent to the impacted region.

Figure 7 shows the longitudinal tensile stress in the skins induced as the impactor moves down into the sandwich specimens. These longitudinal tensile stresses, particularly in the top skin, cause the ends of the sandwich beam to lift up off the base plate.

5.3 Damage modes

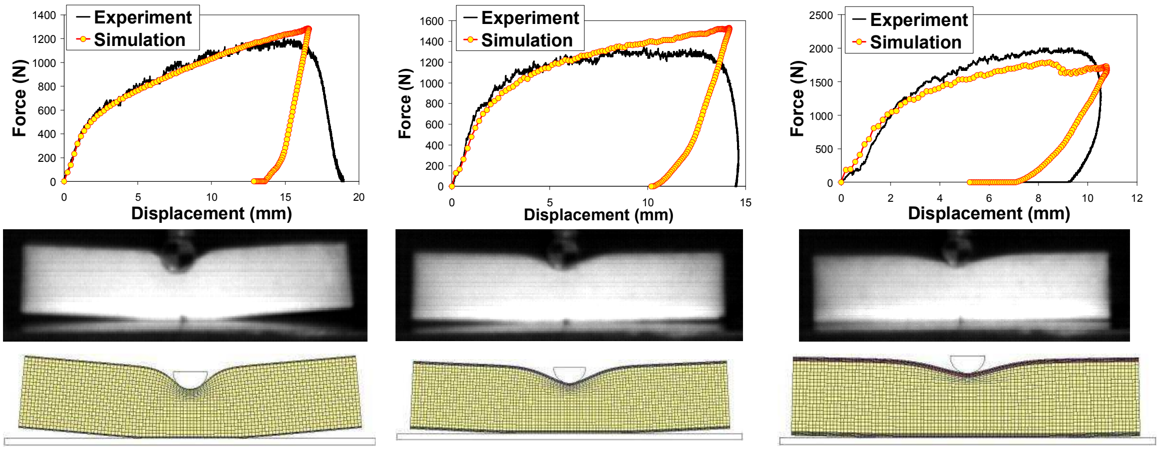
The primary failure modes in the top skin occurred locally, under the impactor. Figure 8 shows a comparison of the experimental and predicted damage in the 2 mm top skin laminate. The predicted macroscopic damage modes and sequence show reasonable agreement with the experimental observations where damage occurs in a localised region directly under the impactor as expected. The simulation shows that the initial damage is by matrix and compression fibre failure occurring due to compression and shear stresses. Interlaminar stresses also cause the development of delamination in the top skin laminate.

Under dynamic indentation loading, only minor matrix damage is observed in the skins.



(a) (b) (c)

Figure 4: Comparison of the experimental and simulation force-displacement curves and deformation modes for the quasi-static indentation tests: (a) 1 mm skin (b) 2 mm skin (c) 3 mm skin.



(a) (b) (c)

Figure 5: Comparison of the experimental and simulation force-displacement curves and deformation modes for dynamic indentation tests: (a) 1 mm skin (b) 2 mm skin (c) 3 mm skin.

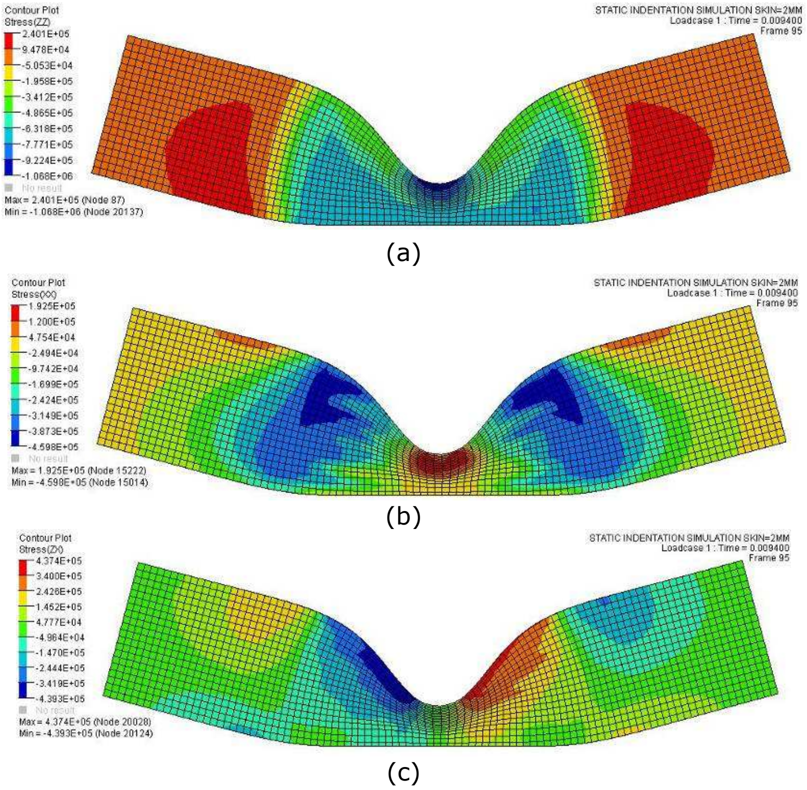


Figure 6. Predicted stress distribution in the 2 mm skin sandwich foam core at an indentation of 35 mm for the quasi-static simulation: (a) through-thickness stress (b) longitudinal stress (c) through-thickness shear stress.

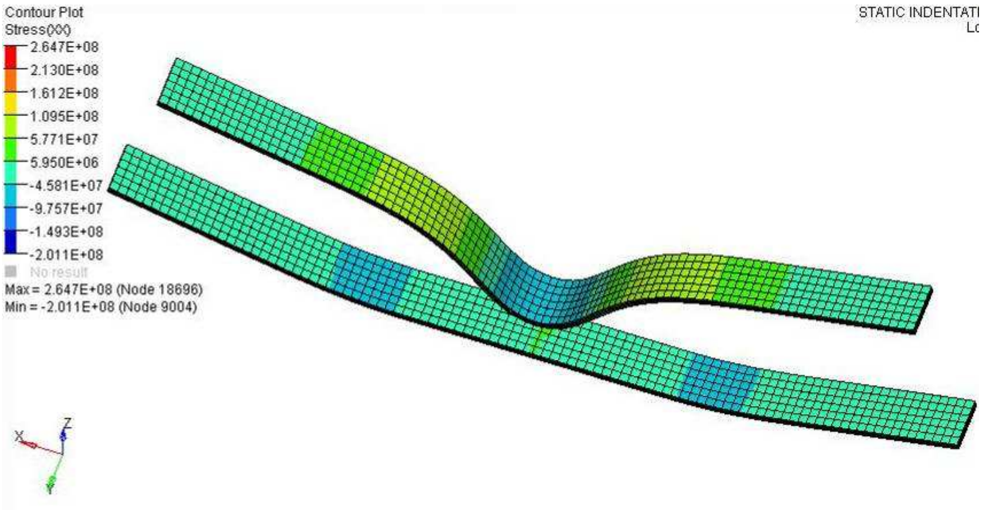


Figure 7. Predicted stress distribution in the 2 mm skins at an indentation of 35 mm for the quasi-static simulation.

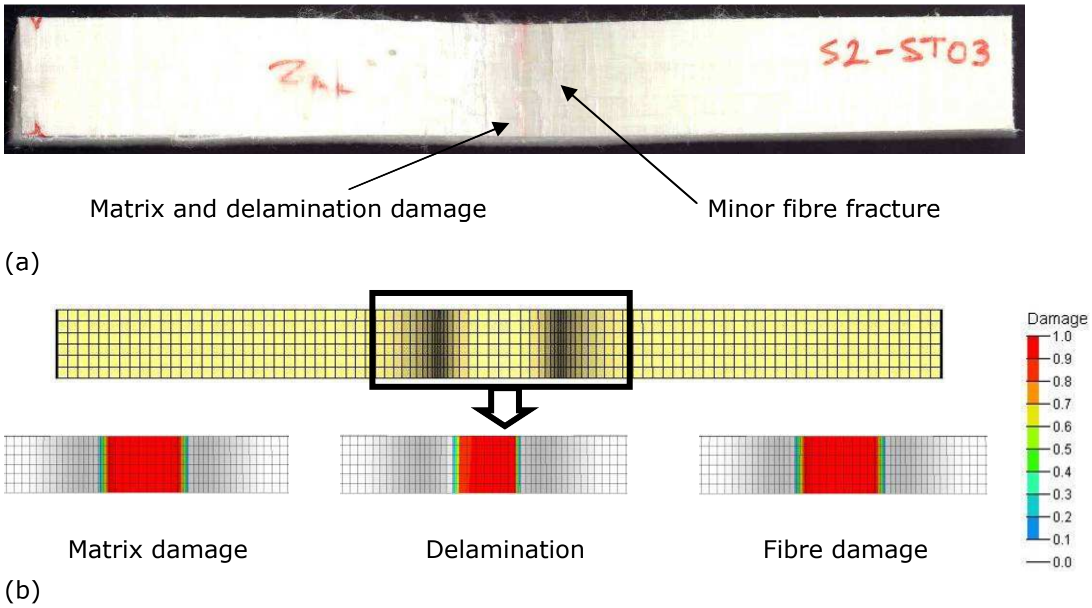


Figure 8. Comparison of (a) experimental and (b) simulation results for damage in the top skins for the 2 mm skin sandwich beam under quasi-static loading.

6. DISCUSSION AND CONCLUSION

This work has developed a validated finite element methodology for simulating the elastic and failure response of thermoplastic composite sandwich structures under localised indentation loading. The modelling that has been presented permits the investigation of the damage modes induced in the foam core, in the TPC skins and at the skin-core interface.

First, quasi-static and dynamic indentation tests were conducted which showed the force-displacement response of the sandwich beam is highly non-linear under localised loading. This non-linearity is induced by localised core crush under the impactor as the foam strands buckle and inter-strand shear occurs. High membrane stresses develop in the top skins which results in the ends of the beam being lifted off the supporting rigid plate as the impactor moved down into the specimen. The top skin was also seen to exhibit multiple failure modes such as matrix damage, fibre fracture and delamination under or near the impactor. These failure modes were induced by the high membrane and contact stresses in the impact area. For the three different skin thicknesses assessed in this study, it was shown that the amount of localised core crush under the impactor decreases as the compression zone increased with increasing skin thickness. This is a result of the thicker skin being better able to distribute the indentation load along the length of the beam.

The results deduced from the finite element model for the indentation tests show good agreement with the experimental results. The model was able to accurately simulate the large deformations caused by the localised loading in the sandwich structures. In all cases, good agreement for load-displacement, energy absorbed and damage was achieved between simulations and experimental results. The LS-DYNA MAT 162 composite model provided good predictions of the various damage modes in the skin and this study further validates its capabilities.

The sandwich modelling methodology presented in this study improves the confidence in using finite element techniques for simulating the non-linear response of composite sandwich structures under static and dynamic localised indentation loading. However, significant skin and core materials characterisation tests are required to obtain accurate simulations.

ACKNOWLEDGEMENTS

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