MODELLING THE IMPACT BEHAVIOUR OF THERMOPLASTIC COMPOSITE SANDWICH STRUCTURES

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Keywords: *thermoplastic composite, sandwich, finite element analysis, vacuum bag moulding.*

Abstract

This paper presents a modelling methodology for simulating the dynamic impact behaviour of sandwich structures with thermoplastic composite skins (60 wt% glass fibre reinforced polypropylene) and anisotropic crushable polypropylene foam cores. The sandwich beams used in this study were manufactured by vacuum bag moulding using optimised processing parameters. The numerical models were developed using the LS-DYNA explicit finite element code. The skin was modelled with an advanced composite damage progression model (MAT 162) for which an inverse calibration technique was developed. A suitable method for simulating foam core shear fracture was also investigated. An extensive experimental material characterisation program was conducted to determine the input parameters for the composite skin and foam core material models. A comparison of the experimental and finite element response of the sandwich beams under quasi-static and dynamic bending loads shows that both deformation and failure can be successfully modelled .

1 Introduction

Automotive manufacturers are now faced with increasing legislation on pedestrian protection [1]. Thermoplastic composite (TPC) sandwich structures are being considered for application in vehicle bumper and front-end crash structures so as to reduce the severity of injuries to pedestrians in the event of an accident. TPC sandwich structures offer several significant advantages including high energy absorption capability, good stiffness to weight ratio and recycling potential [2]. Furthermore, the use of an all thermoplastic sandwich with the same polymer used in the skin and core, allows for medium volume one step manufacturing of these structures [6].

Despite the advantages offered by TPC sandwiches, they have received limited application because of the lack of knowledge of their crash behaviour. In addition, today, finite element (FE) analysis codes such as LS-DYNA are used extensively in vehicle design and crashworthiness assessment [3]. Therefore, the increased application of TPC sandwich structures will also depend on the availability of accurate material constitutive models within these FE codes. Advanced foam and composite material models that can predict damage progression and fracture are emerging; however, the development of a predictive modelling methodology for sandwich structures is still in its infancy

This paper reports on an experimental and numerical investigation into the quasi-static and dynamic impact loading response and failure modes of TPC sandwich beams with varying skin thicknesses.

2 Sandwich Materials

All sandwich skins were manufactured from Twintex, which is a commingled E-glass/polypropylene, balanced twill weave woven fabric composite, with a 60% fibre weight fraction that is supplied by Saint Gobain Vetrotex [4].

For the core material, a polypropylene anisotropic crushable foam of density 64 kg/m^3 is used. The foam material is supplied by Dow Chemical Company under the tradename Strandfoam. Strandfoam is manufactured by an extrusion process that results in a highly oriented foam that has a significantly high energy absorption efficiency (80-90%) in the extrusion direction [5].

A schematic of the material configuration for the sandwich beam used in this study is shown in Fig. 1. The Strandfoam extrusion direction is orientated along the thickness of the sandwich beam for maximum crush properties in the loading direction.

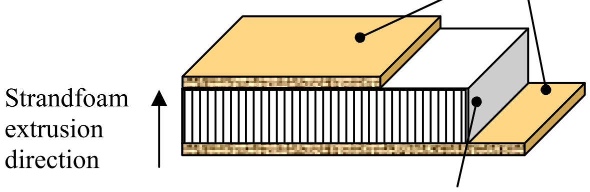


Fig. 1. Schematic of sandwich beam material configuration.

2.1 Vacuum Moulding Process Optimisation

Test specimens were cut from large sandwich beams that were manufactured in a one step vacuum moulding process. Specimen dimensions are given in section 3. Vacuum moulding is a low pressure moulding technique that offers the advantage of low capital investment and ease of installation and operation. Furthermore, it is suitable for the processing of low density foam cored sandwich beams since the low pressure minimises the core crush during the manufacturing of the beam.

A schematic of the vacuum moulding process is shown in Fig. 2. The moulding process involved stacking 0.5 mm thick preconsolidated layers of Twintex on two thin Aluminium transfer plates and preheating them above the melt temperature of the polypropylene matrix. The cold (room temperature) foam core is then placed between the preheated skins and rapidly transferred to the vacuum table. The vacuum membrane is clamped over the sandwich beam and air evacuated from under the membrane to apply a moulding pressure of 0.9 Bar for consolidating the skins and bonding to the core. Finally, the beam is removed from the mould and allowed to cool.

An investigation into the optimisation of process parameters for the vacuum moulding of TPC sandwich beams has been conducted. Various moulding parameters such as skin preheat and mould temperature, mould time and pressure have been optimised for maximising the performance and quality of the TPC beams.

The optimised moulding conditions used in this study are listed in Table 1. A detailed description of the optimisation study can be found in reference [6].

Table 1. Optimised vacuum moulding parameters for TPC sandwich beams.

Moulding Parameter	Optimised Value
Skin preheat temperature	180 - 200 °C
Vacuum table temperature	30 °C
Transfer time	25 – 35 seconds
Mould time	5 – 10 minutes
Mould pressure	0.9 Bar

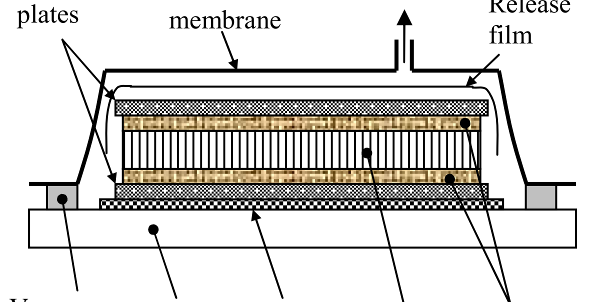


Fig. 2. Schematic of vacuum moulding process.

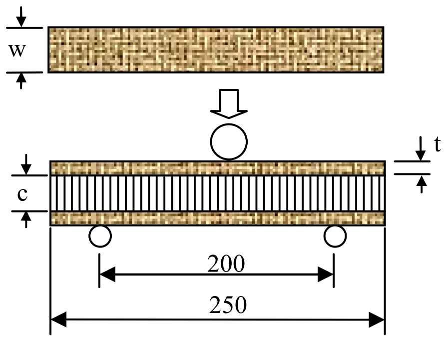
3 Experimental Methods

3.1 Quasi-Static Three-Point Bending Tests

Quasi-static three-point bending tests were conducted on the TPC sandwich beam specimens according to test standard BS EN 2746. The tests were performed on a Tinius Olsen electromechanical test machine at a crosshead speed of 10 mm/min.

The test setup and specimen dimensions are shown in Fig. 3. A 25 mm diameter cylindrical rod is used to apply a load to the centre of the beam. The specimens were simply supported over a span of 200 mm on 10 mm diameter cylindrical supports.

All sandwich specimens were 250 mm long with a width of 30 mm and nominal core thickness of 25 mm. Sandwich beams with three different skin thicknesses were investigated, respectively 1, 2 and 3 mm. All sandwich skins had a [090] fibre orientation aligned along the beam longitudinal axis.



Width, w = 30 mm
Core thickness, c = 25 mm
Skin thickness, t = 1, 2 and 3 mm

Fig. 3. Schematic of three-point bending test setup.

3.2 Dynamic Three-Point Bending Impact Tests

Dynamic impact tests on the sandwich beams were performed in a Rosand instrumented falling weight drop tower. The tests were conducted with an impact mass and velocity of 8.2 kg and 4.9 m/s, respectively, which corresponds to an incident energy of 100 J. The test setup and sandwich beam dimensions are the same as in the quasi-static test (see Fig. 3). The failure response of the beams was recorded with a high speed camera at 1000 frames/second.

4 Finite Element Modelling

Finite element (FE) modelling of the bending impact response of TPC sandwich beams was conducted using the LS-DYNA explicit FE code [7].

Fig. 4 shows the sandwich beam finite element model. In order to reduce solution time and taking account of geometric and material symmetry, only one half of the sandwich beam was modelled. All the components were modelled with single integration point eight node solid elements. Single integration point solid elements provide significant computational savings; however they are susceptible to non-physical deformation and zero strain energy modes called hourglassing. 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 supports were modelled as rigid bodies. The supports were 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 supports. An eroding single surface contact type was used to model contact between failure surfaces created by element erosion in the foam core (see Section 4.1.3).

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 as shown in Fig. 4. The material axes for the skins and all other components are orientated along the global axes.

4.1 Material Modelling

4.1.1 Composite skin damage 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 loss 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 provided in [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, 9]. The experimental program covered a wide range of quasi-static and dynamic tests:

- 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].

The skin material properties and calibrated damage parameters for Twintex are listed in Table 2. Based on the calibration and validation results, the Young's modulus was reduced from the experimental value of 14 GPa to 10 GPa so as to improve the correlation between the simulation and bending impact test results [9].

4.1.2 Foam model

The foam core material was modelled with the MAT 142 foam model which was 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 test
- Static and dynamic shear tests

The input data used for modelling Strandfoam is listed in Table 3. The static shear properties were used in the dynamic models because Strandfoam was relatively rate insensitive under shear loading.

4.1.3 Modelling foam fracture

Ductile crushable foams, such as Strandfoam, can exhibit brittle core shear fracture under bending loads [6]. Therefore, it is important to be able to model such failure modes; however, modelling fracture in polymeric foams has received only limited attention [11]. The MAT 142 material model does not allow for fracture or element erosion. Fracture, however, was included in the analysis of the foam core by using the MAT_ADD_EROSION facility within LS-DYNA in conjunction with a fracture criterion based on maximum principal strain. Elements are eroded when the maximum principal strain reaches a specified value:

$$\varepsilon_1 \geq \varepsilon_p \;\; \rightarrow \textit{element erosion} \qquad (1)$$

where ε_1 is the maximum principal strain and ε_p is the maximum principal strain at failure.

This fracture criterion was also used to model failure at sandwich beam skin-core interface.

The maximum principal strain, ε_p, was numerically calibrated using an iterative procedure where values for ε_p were determined by correlation of simulations with experimental force-displacement and failure mode results.

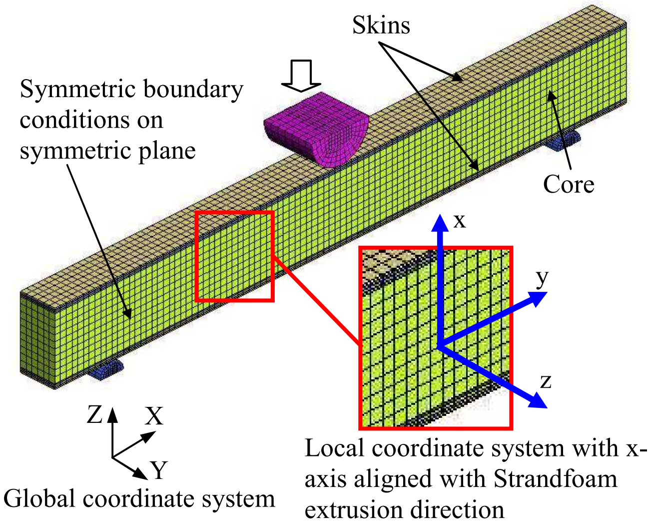


Fig. 4. Finite element half model and boundary conditions for TPC sandwich beam.

Table 2. Input data used for modelling 60 wt% Twintex [090] fabric skins

Parameter	Symbol	Value
Density	ρ	1500 kg/m³
Longitudinal Young's modulus*	E_x	10 GPa
Transverse Young's modulus*	E_y	10 GPa
Through thickness Young's modulus	E_z	5.3 GPa
	υ_{yx}	0.12
Poisson's ratio	υ_{zx}	0.14
	υ_{zy}	0.15
Shear modulus, x-y plane	G_{xy}	1.79 GPa
Shear modulus, y-z plane	G_{yz}	1.66 GPa
Shear modulus, z-x plane	G_{zx}	1.79 GPa
Longitudinal tensile strength	S_{xT}	269 MPa
Longitudinal compressive strength	S_{xC}	178 MPa
Transverse tensile strength	S_{yT}	269 MPa
Transverse compressive strength	S_{yC}	178 MPa
Through-thickness tensile strength	S_{zT}	25 MPa
Crush strength	S_{Fz}	300 MPa
Fibre shear strength	S_{FS}	110 MPa
Shear strength, x-y plane	S_{xy}	23 MPa
Shear strength, y-z plane	S_{yz}	12 MPa
Shear strength, z-x plane	S_{zx}	13.6 MPa
Coloumb friction angle	φ	20°
Tensile volume strain limit	EEXPN	2
Strength strain rate coefficient	C1	0.181
Fibre damage parameter (longitudinal)	m1	0.5
Fibre damage parameter (transverse)	m2	0.5
Fibre crush and punch shear damage	m3	2
Matrix damage parameter	m4	-0.15

* Young's modulus was reduced from the experimental value of 14 GPa to 10 GPa so as to improve the correlation between the simulation and bending impact test results [9].

Table 3. Input data used for modelling Strandfoam

Parameter		Static Value	Dynamic Value
Density	ρ	64 kg/m³	64 kg/m³
Axial Young's modulus	E_x	19.8 MPa	35 MPa
Transverse Young's modulus	E_y	10.4 MPa	14.8 MPa
Shear modulus in axial plane	G_{xy}	8.83 MPa	8.83 MPa
Shear modulus in transverse plane	G_{yz}	4.2 MPa	4.2 MPa

5 Results

5.1 Comparison of Quasi-Static Finite Element and Experimental Results

5.1.1 Sandwich beams with 1 mm skins

Fig. 5 shows a comparison of the simulation and experimental results for the 1 mm skin sandwich beam under quasi-static loading. The initial force-displacement response is linear elastic followed by non-linear yielding until a maximum load, after which the load gradually decreases. The simulation force-displacement curve shows good agreement with the overall shape of the experimental curve. However, the model slightly overestimates the peak load by 7% and exhibits a reduced rate of post peak damage progression.

The 1 mm skin sandwich beams fail primarily through localised core crush and top face buckling as depicted in Fig. 5. The predicted deformation and failure modes show good agreement with the experimental observations.

5.1.2 Sandwich beams with 2 mm skins

Fig. 6 shows a comparison of the simulation and experimental force-displacement results for the 2 mm skin sandwich beam under quasi-static loading. A numerically calibrated value of maximum principal strain, ε_p of 0.12 was selected for the fracture criterion. The beam response is linear elastic, followed by non-linear yielding up to a maximum load, after which an abrupt load drop occurs due to core shear fracture. The predicted response up to the point of failure agrees well with the experimental results. However, the predicted post-failure response deviates from the experimental curve as element erosion results in sharp, large load oscillations up to a displacement of 18 mm after which the load drops to zero. The model was not able to simulate the post-failure residual strength in the beam.

The asymmetric core shear fracture and skin core debonding observed in the actual test for the 2 mm skin sandwich beam has been well predicted by the simulation as shown in Fig. 6.

5.1.3 Sandwich beams with 3 mm skins

Fig. 7 shows a comparison of the simulation and experimental results for the 3 mm skin sandwich beam under quasi-static loading. The force-displacement curve is initially linear elastic, then elastic-plastic up to the maximum peak load followed by gradual load reduction. The initial elastic response is well predicted by the simulation; however, the post-elastic response of the model deviates from the experimental results, as with the 1 mm skin, marginally underestimating the rate of damage progression beyond the peak load.

The beam exhibits asymmetric failure with minor core shear fracture and skin-core debonding occurring on only one side of the beam close to the supports (see Fig. 7). The failure mode has been well described by the simulation without the inclusion of the maximum principal strain fracture criterion and corresponding element erosion. The level of observed shear fracture and damage in the core is too low to be described by the element erosion approach.

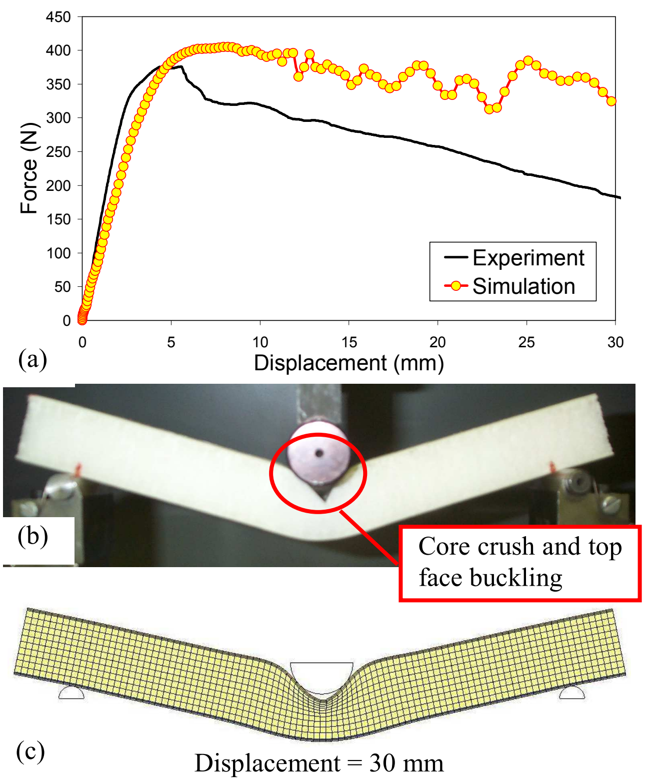


Fig. 5. 1 mm skin sandwich beam quasi-static results (a) force-displacement curves (b) experimental deformation (c) predicted deformation.

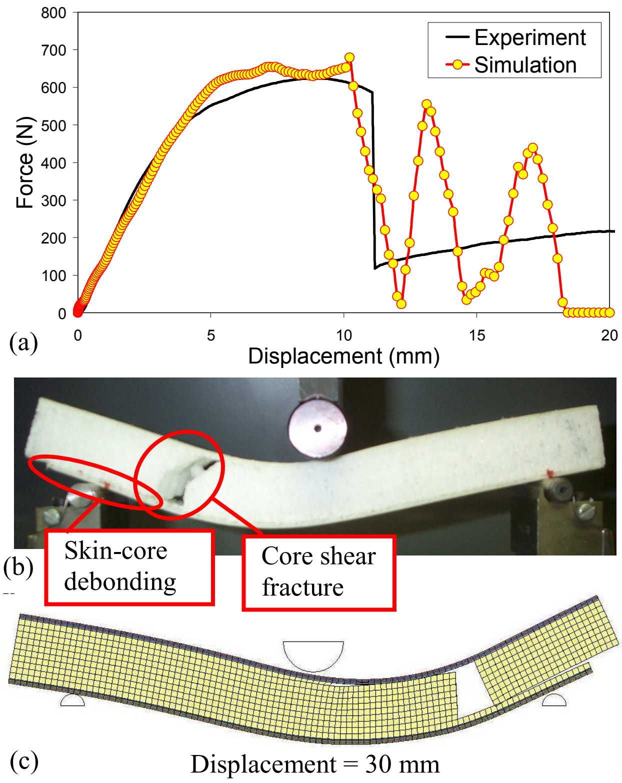


Fig. 6. 2 mm skin sandwich beam quasi-static results (a) force-displacement curves (b) experimental deformation (c) predicted deformation.

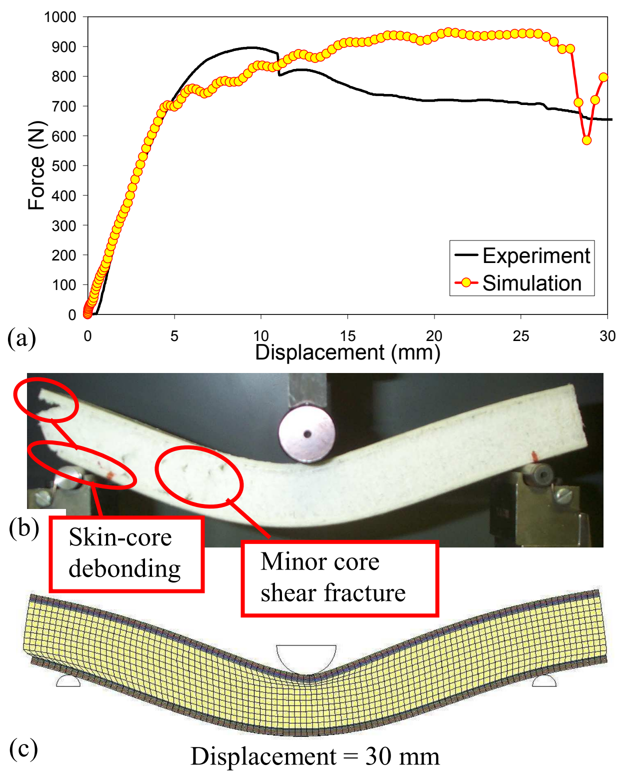


Fig. 7. 3 mm skin sandwich beam quasi-static results (a) force-displacement curves (b) experimental deformation (c) predicted deformation.

5.2 Comparison of Dynamic Finite Element and Experimental Results

5.2.1 Sandwich beams with 1 mm skin

Fig. 8 shows a comparison of the simulation and experimental results for the 1 mm skin sandwich beam under dynamic loading. By contrast with quasi-static loading, in this case, core shear fracture does occur. . A numerically calibrated value of ε_p of 0.06 was selected for the fracture criterion. The experimental force-time history is fairly oscillatory which is due in part to inertial effects and vibration of the beam. The initial response is very stiff and is linear elastic up to the initial peak load, after which there is a gradual load drop, followed by an increase in load again to the second peak load followed by a noisy plateau which ends with an abrupt load drop as the specimen fails by core shear fracture and skin-core debonding. The simulation captures the general description of the force-displacement response. However, the initial peak load is under estimated by 26% while the second peak load is over estimated by 24%. In addition, the second peak load occurs much later in the simulation than in the actual test.

The near symmetric failure through core shear fracture and skin-core debonding observed in the test has been predicted by the model. However, in the test, core shear fracture occurs very close to the impactor, while in contrast, the predicted shear fracture occurs nearer the supports.

5.2.2 Sandwich beams with 2 mm skin

Fig. 9 shows a comparison of the simulation and experimental results for the 2 mm skin sandwich beam under dynamic loading. A numerically calibrated value of ε_p of 0.04 was selected for the fracture criterion. The predicted force-time history shows good agreement with the general shape of the experimental response. The predicted initial peak load shows excellent agreement with the experimental results. However, the second peak load is over estimated by 20% and leads the experimental second peak load by 0.42 ms.

The symmetric core shear fracture and skin-core debonding have been well predicted.

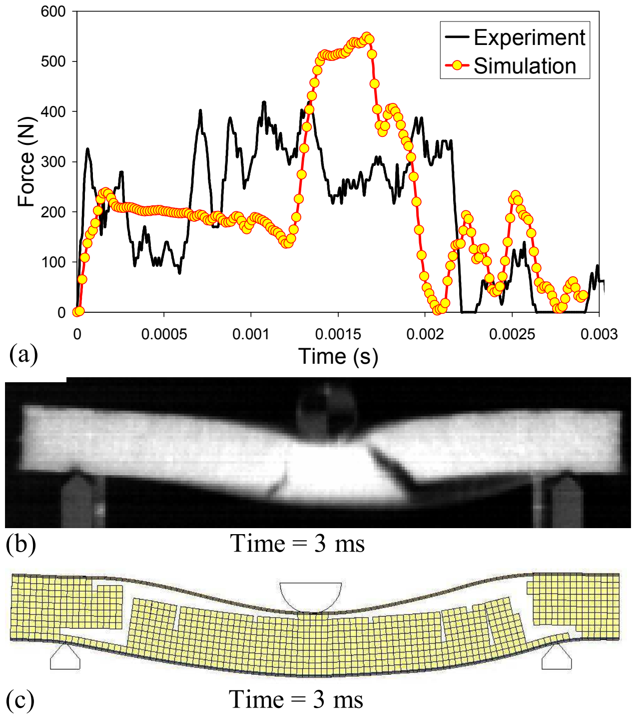
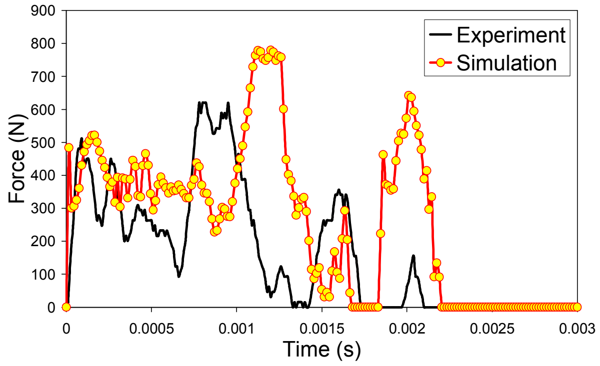


Fig. 8. 1 mm skin sandwich beam dynamic results (a) force-time histories (b) experimental deformation (c) predicted deformation.

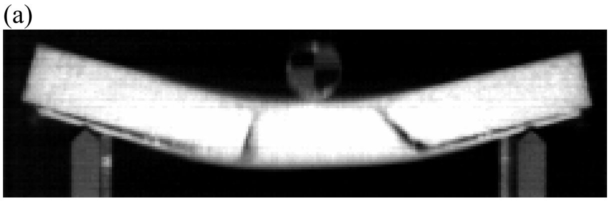
5.2.2 Sandwich beams with 3 mm skin

Fig. 10 shows a comparison of the simulation and experimental results for the 3 mm skin sandwich beam under dynamic bending loading. Like the 1 mm skin, a numerically calibrated value of ε_p of 0.06 was selected for the fracture criterion. Again the predicted force-time history shows good agreement with the general shape of the experimental curve. The predicted initial peak load shows excellent correlation with that observed experimentally. However, the second and third load peaks are significantly under and over predicted, respectively.

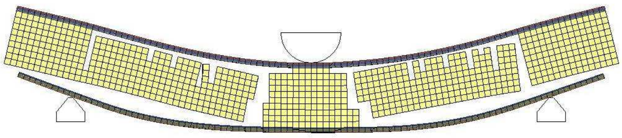
The predicted core shear fracture and skin-core debonding correlates reasonably well with the experimental observations, although exact fracture locations are difficult to predict.



(a)

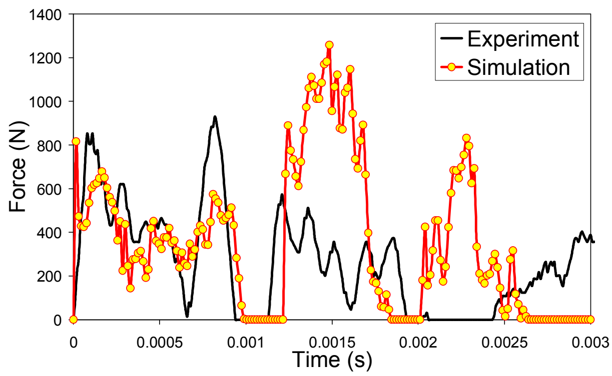


(b) Time = 3 ms

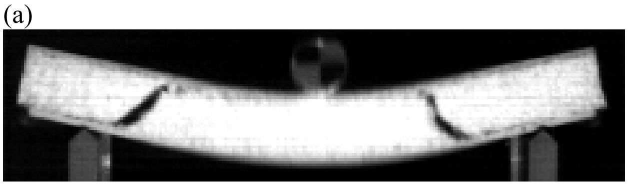


(c) Time = 3 ms

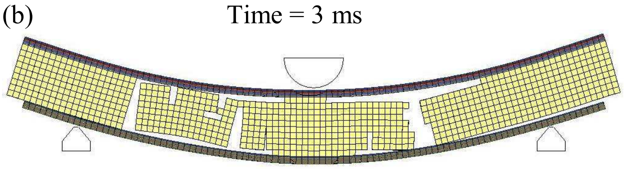
Fig. 9. 2 mm skin sandwich beam dynamic results (a) force-time histories (b) experimental deformation (c) predicted deformation.



(a)



(b) Time = 3 ms



(c) Time = 3 ms

Fig. 10. 3 mm skin sandwich beam dynamic results (a) force-time histories (b) experimental deformation (c) predicted deformation.

6 Conclusions

Finite element simulations of the quasi-static and dynamic impact response of foam cored thermoplastic composite sandwich structures has been presented and compared with experimental results. The sandwich beams were manufactured using an optimised single-step vacuum moulding process. The various failure modes in the skin and foam core have been investigated. It has been shown that the dominant failure modes in the sandwich beam under quasi-static loading are face compression (buckling), core shear fracture, skin-core debonding and local core crush. For dynamic loading, the sandwich beams fail primarily by core shear fracture and skin-core debonding. Furthermore, the location of the core shear fracture along the beam moved further away from the impactor as skin thickness increased. This is due to thick skins providing better load distribution along the length of the beam

The application of the LS-DYNA MAT 162 damage model to skin behaviour in combination with a novel approach to modelling core shear fracture using a principal strain failure criterion has resulted in useful predictions. For quasi-static loading of the beams, reasonable agreement for both load-displacement and failure was achieved between simulations and experimental results. For dynamic loading, elastic response, initial peak loads and the occurrence of core shear fracture and skin-core debonding were also simulated well. However, under the dynamic loading rates, the more complex post initial failure response involving beam vibration and multiple load peaks was more difficult to simulate. This is likely to be due to the inability of the skin damage model to allow for plastic response [9]. Also, predicting the exact location of the core shear fracture and damage progression requires further work. In addition, the application of element erosion may result in a mesh sensitive solution [11]. Mesh sensitivity may be resolved by using a non-local approach that has been implemented in LS-DYNA to regularise the solution [7]. The non-local approach was not applied in this study. In the future, further refinement of the foam material model, in particular, is needed for better qualitative and quantitative correlations.

Acknowledgements

The authors would like to acknowledge financial support from the UK Engineering and Physical Sciences Research Council (EPSRC) through the Nottingham Innovative Manufacturing Research Centre (NIMRC). Thanks are due to Saint Gobain Vetrotex for supplying the Twintex material and to Dow Automotive for providing the Strandfoam core material.

References

1. *Directive 2003/102/EC of the European Parliament and Council relating to the protection of pedestrians and other vulnerable road users*. http://europa.eu.int/comm/enterprise/automotive/pagesbackground/pedestrianprotection/index.htm
2. Skawinski, O., C. Binetruy, P. Krawczak, J. Grando, E. Bonneau, J.-M. Scanzi, and B. Hilaire. *Modelling of Bending Behaviour of Glass/PP - PP Foam Core Sandwich Panels Manufactured by Isothermal Compression*. in *ECCM-10*. 2002. Brugge, Belgium.
3. Haug, E. and A. De Rouvray, *Crash Response of Composite Structures*, in *Structural Crashworthiness and Failure*, N. Jones and T. Wierzbicki, Editors. 1993, Elsevier: Essex. p. 237-294.
4. *Saint Gobain Vetrotex International www.twintex.com*. [cited 2003; Available from: www.twintex.com/tw-docu.html.
5. Burr, S.T. and G.D. Vogel, *Material Model Development for Impact Analysis of Oriented Polypropylene Foam Structures.* SAE Paper No. 2001-01-0310, 2001.
6. Kulandaivel, P., *Manufacturing and Performance of Thermoplastic Composite Sandwich Structures*, in *PhD Thesis*. 2006, The University of Nottingham: Nottingham.
7. Hallquist, J.O., *LS-DYNA Keyword User's Manual Version 970*. 2003, Livermore: Livermore Software Technology Corporation.
8. Brown, K., R. Brooks, and N. Warrior. *Numerical Simulation of Damage in Thermoplastic Composite Materials*. in *Proceedings of the 5th European LS-DYNA Users' Conference*. 2005. Birmingham, UK.
9. Brown, K., *Finite Element Modelling of the Dynamic Impact Behaviour of Thermoplastic Composite Sandwich Structures*, in *PhD Thesis*. (To be published), The University of Nottingham: Nottingham.
10. Hirth, A., P. Du Bois, and K. Weimar. *A Material Model for Transversely Anistropic Crushable Foam in LS-DYNA*. in *7th International LS-DYNA Users Conference*. 2002. Dearborn, Michigan.
11. Mines, R.A.W., *On the Numerical Simulation of the Progressive Collapse of Polymer Composite Sandwich Beams Under Impact Loading*, in *Advances in Dynamics and Impact Mechanics*, C.A. Brebbia and G.N. Nurick, Editors. 2003, WIT Press: Boston.