FAILURE PREDICTION IN HONEYCOMB SANDWICH BEAMS UNDER LOW-VELOCITY IMPACT

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Keywords: *Composite sandwich beams, Honeycomb core, Low-velocity impact, Numerical modelling, Experimental tests*

Abstract

In this work, the low-velocity impact response of composite sandwich beams with carbon fibre/epoxy face-sheets and aluminium honeycomb core was studied by developing a three dimensional finite-element model, which was validated through a series of flexural tests conducted in a drop-weight tower.

The 3D finite-element model was proved to be able to predict the failure of the sandwich beams under dynamic conditions. In addition, absorption energy mechanisms were analysed.

1 Introduction

Sandwich beams with composite face-sheets and a lightweight core are commonly used in lightweight structures, due to their advantages over the conventional structural constructions such as high bending stiffness and good weight saving. There are several types of materials for face-sheets and core as well as numerous combinations of both. In aerospace applications, the most used configuration is comprised by face-sheets of carbon fibre laminates and aluminium honeycomb core. In these structures, it is important to ascertain the deformation and fracture behaviour under both static and dynamic loadings.

A significant body of literature now exists on measured and predicted properties of composite sandwich structures under static loading [1]. The sandwich structures can be subjected to low-velocity impacts during assembly and maintenance operations. Specific studies about the dynamic behaviour of sandwich structures are necessary to understand the inertia effects and the material strain rate sensitivity [2].

In the aerospace industry, the behaviour of composite sandwich structures subjected to low-velocity impact is mainly focused upon barely visible impact damage due to low-velocity impact. However, there is a need for an improved understanding of the material characteristics and impact-energy absorption modes to facilitate the design of sandwich performance. The absorbed energy during the failure of a variety of structural elements is influenced by material properties, geometry and failure mode. Failure initiation and propagation of the honeycomb sandwich under loading involves not only non-linear behaviour of the constituent materials, but also complex interactions between several failure mechanisms [3]. These mechanisms include upper face-sheet crushing, core-shear failure, lower face-sheet tensile failure, etc.

Many of the works about dynamic behaviour of composite sandwich structures are experimental studies [4]. Since experimental tests are expensive, finite-element models are usually used to perform impact events and can lead to a better understanding of the failure modes.

The most of the numerical models developed for composite sandwich structures, refer to plates and panels [5]. However, the study of sandwich beams behaviour allows simplifying the problem complexity and leading to a better understanding of the failure modes. The dynamic flexural behaviour of composite sandwich beams with foam core has been previously studied [6], however much less is known about honeycomb composite sandwich beams.

In this study failure modes of sandwich beams with carbon fibre/epoxy faces-sheets and aluminium honeycomb core under low-velocity impact, were analysed. A 3D finite-element model in Abaqus/Explicit code, validated through the comparison with experimental tests conducted in drop-weigth tower, was used to study the failure process.

2 Numerical Model

Low-velocity impact behaviour of sandwich beams with woven laminate face-sheets of carbon fibre/epoxy (2 mm in thickness) and aluminium honeycomb (foil thickness of 0.042 mm) was performed by developing a 3D finite-element model in Abaqus/Explicit code. The finite-element model reproduced a dynamic three-point bending test. The model included: impactor, sandwich beam and support device (Fig. 1). Beams of rectangular cross-section (50 mm width and 24 mm thickness) and 480 mm length were considered. The support span and Charpy-nose impactor radius, were 450 mm and 20 mm respectively. The upper and lower face-sheets were meshed with 8-node brick elements with reduced integration (C3D8R in ABAQUS). The honeycomb sandwich core was meshed with 4-node shell elements with reduced integration (S4R in ABAQUS). Geometry and dimensions of the beam model were equal to those belonging to real specimens.

The surface-based tie constrain was adopted to define the adhesive bonding between both face-sheets and core, thus a perfect bonding between them was considered. As the damage in the face-sheets is located at the region in contact with the impactor, the upper ply of the carbon/epoxy face is usually damaged, and therefore it was necessary to define the contact between the impactor surface and a node region in the face-sheets that included all the plies. To further simplify the problem, frictional response during contact between the impactor and the structure was neglected.

The impactor and support device were made up of steel. Since no plastic deformation was detected after the dynamic tests, a linear elastic behaviour was used for the steel (E=210 GPa, ν=0.3). The impactor was modelled using 4-node tetrahedral elements (C3D4 in ABAQUS). It was meshed in great detail to reproduce the cilindrical shape of the experimental device. The impactor density was modified to reproduce the mass used in the experimental tests, 3.96 kg. Except for the vertical movement, all impactor motions were disabled in the simulations, in order to ensure normal impact over the upper face-sheet.

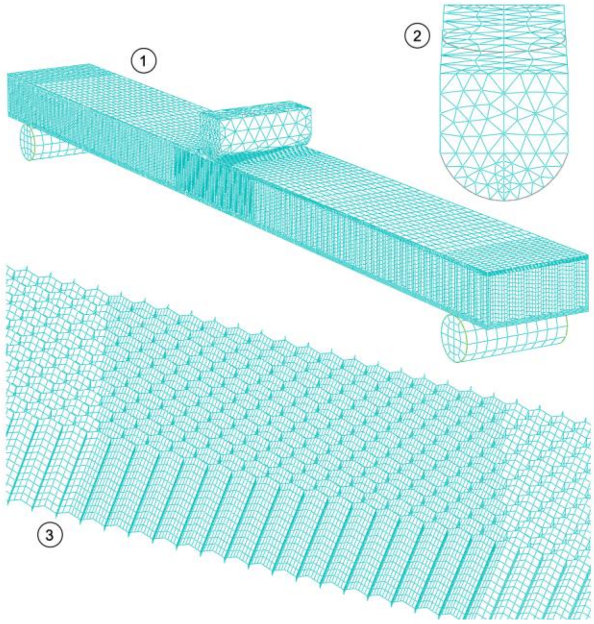

Fig.1. Numerical model mesh: 1) Entire assembly, 2) impactor, and 3) honeycomb mesh detail.

The sensitivity of the mesh was evaluated by carrying out successive space discretizations; the selected mesh consisted of 123,634 elements: 1,650 elements were used to mesh the impactor, and 121,584 elements to mesh the sandwich beam. In this case, 17,664 elements were needed to define both face-sheets and 103,920 elements to define the core. The mesh was especially dense towards the impact area.

The face-sheets behaviour was modelled through a user subroutine (VUMAT) which includes the Hou failure criteria [7] and a procedure to degrade material properties. Face-sheets properties are presented in Table 1.

Density [kg/m^3]	$\rho = 1600$
Young's modulus [GPa]	$E_1 = E_2 = 68.5$
Poisson ratio	$\nu_{12} = 0.22$
In-plane shear modulus [GPa]	$G_{12} = 5$
Interlaminar shear modulus [GPa]	$G_{13} = G_{23} = 4.5$
Tensile strength [MPa]	$X_T = Y_T = 555$
Compressive strength [MPa]	$X_C = Y_C = 795$
In-plane shear strength [MPa]	$S_{12} = 98$
Interlaminar shear strength [MPa]	$S_{23} = 64$

Table 1. Carbon/epoxy woven laminate mechanical properties.

The aluminium honeycomb core was defined as an isotropic elastic-perfectly plastic material which properties are presented in Table 2.

Density [kg/m^3]	$\rho = 2700$
Young's modulus [GPa]	E = 68.9
Poisson ratio	$\nu_{12} = 0.33$
Yield stress [MPa]	$\sigma_y = 280$

Table 2. Mechanical properties of 3003 aluminium.

3 Model validation

Low-velocity impact tests were conducted in an instrumented drop-weight tower, CEAST Fractovist 6785, to validate the numerical model. A three-point bending device was used to ensure the flexural behaviour of the sandwich beams. The experimental impact energy ranged from 8 to 37 J. The tests were recorded by a high-speed video camera to measure the impact and the post-ricochet velocity of the impactor. Absorbed energy was calculated as the difference between impact and residual energies.

The variables used to validate the numerical model were contact-force history and absorbed energy. Fig. 2 shows the comparison between numerical and experimental contact-force histories for three impact energies. Contact-force history curves show good agreement with experimental results in terms of peak-force and contact time. Peak-force remains almost constant for different impact energies, thus impact energy has no significant influence in peak-force value. On the contrary, significant differences can be found in contact-force history shape. For impact energy of 13 J and 20 J force history curves presented a smooth shape, while impact energy of 29 J leaded to a sudden drop of the force value after failure.

Absorbed energy was calculated as a function of the impact energy. Absorbed energy during impact test can be directly related to damage generated on the beam and residual mechanical properties [8]. Good agreement between numerical predictions and experimental results can be seen in Fig. 3 showing two different trends for low and high-impact energies.

For impact energies lower than 22 J, absorbed energy is low compared to impact energy. Composite face-sheets do not experience any failure and a small amount of energy is absorbed by the honeycomb core. For impact energies higher than 25 J the honeycomb core fails, thus upper composite face-sheet is damaged leading to an increment in the absorbed energy. The initiation of the upper face-sheet failure is predicted by the numerical model for impact energies higher than 27 J. However, experimental results are scattered about a transition region between low and high-impact energy tests. It is difficult to obtain an accurate upper face-sheet failure threshold through experimental testing; numerical models allow for more accurate predictions.

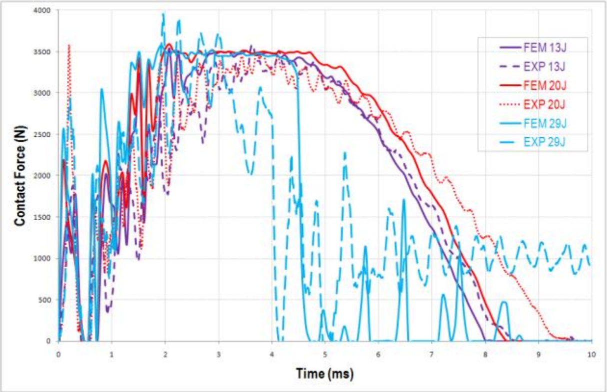

Fig.2. Contact-force history: comparison between experimental results and numerical prediction.

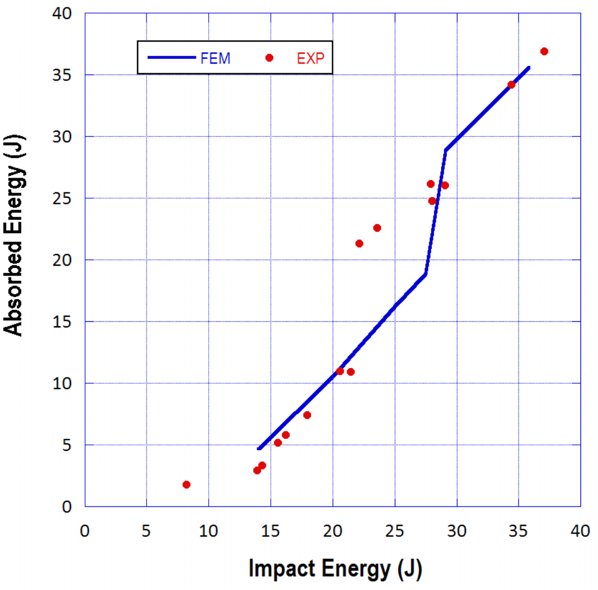

Fig.3. Absorbed energy vs. impact energy: comparison between experimental results and numerical prediction.

Experimental and numerical results exhibit good agreement, so that the model was used to gather more information about the failure process of a composite sandwich beam with aluminium honeycomb core.

4 Results

Failure mechanisms for impact energy of 13 J and 35 J are analysed in this section. These impact energies were selected to characterise the two trends observed in Fig. 3.

Numerical results obtained for impact energy of 13 J can be seen in Figs. 4 and 5. Fig. 4 shows contact-force history, while Fig. 5 shows the evolution of core plastic strain during the impact event. Three different tendencies can be observed in contact-force history. Until 2 ms, contact-force increased and plastic strain in honeycomb core can be neglected, see Fig. 5.1, thus sandwich behaviour can be considered linear-elastic. When contact-force reached a value around 3.5 kN, force history presented a flat tendency from 2 ms until 4 ms and honeycomb-core crushed due to the extension of plastic strain region, Fig. 5.2. Finally, force history decreases from 4 ms until 8 ms when the contact between impactor and sandwich beam ends. Impactor returned with a post-ricochet velocity lower than impact velocity due to energy absorption mechanisms, and permanent strains can be found in honeycomb core. The energy was absorbed mainly by core plastic strain while no damage was detected in composite face-sheets.

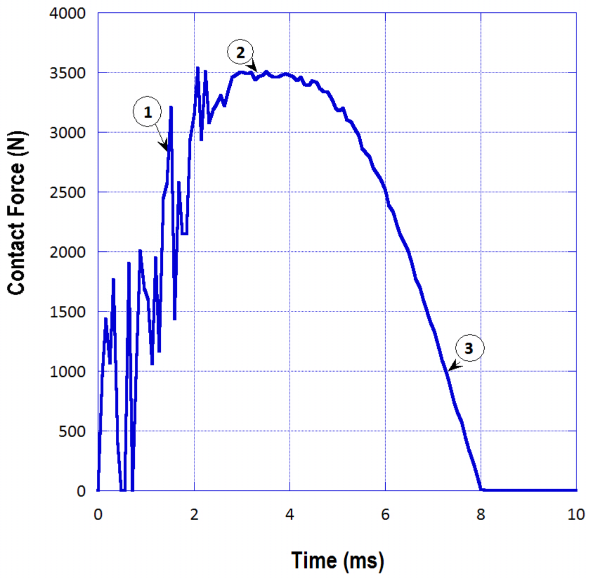

Fig.4. Contact-force history predicted for an impact energy of 13 J.

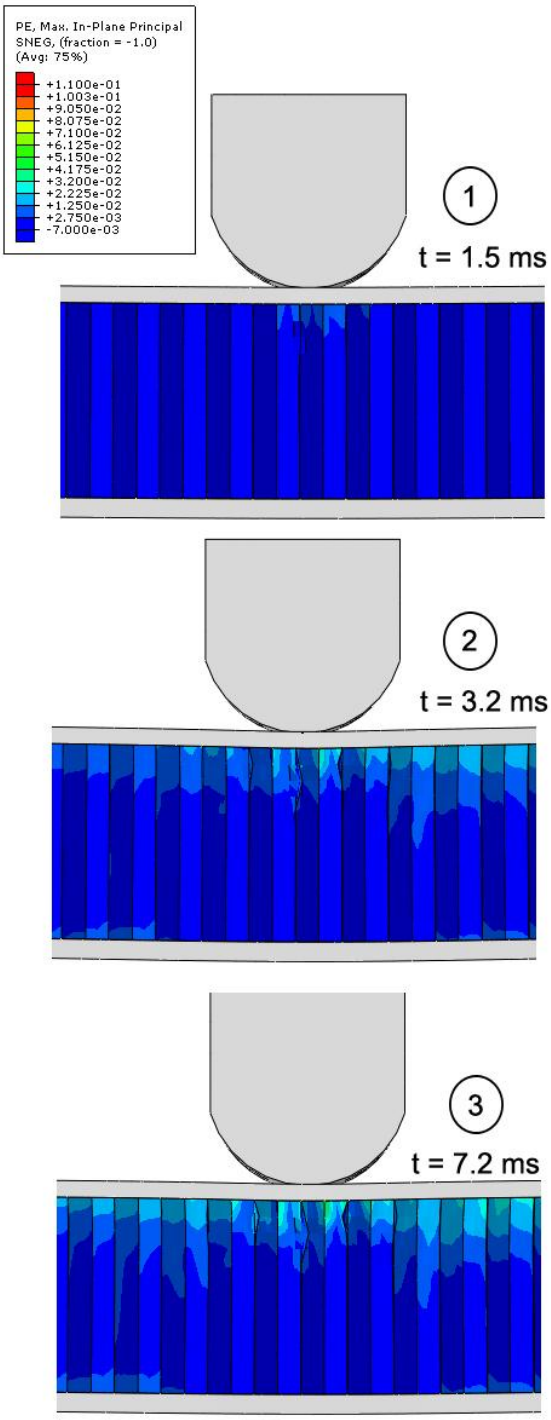

Fig.5. Evolution of core plastic strain for impact energy of 13 J.

Likewise, numerical results obtained for impact energy of 35 J can be observed in Figs. 6 and 7. Fig. 6 shows contact-force history, while Fig. 7 shows the evolution of core plastic strain during the impact event. Contact-force history presented several differences with respect to the 13 J impact energy results. During the first tendency, until 1.5 ms, contact-force increased, but noise level is greater than in the previous case and plastic strains can be found in honeycomb-core, Fig. 7.1. Therefore, sandwich behaviour cannot be considered linear-elastic. When contact-force reached a maximum value, around 3.5 kN, similar to that obtained with impact energy of 13 J, force history presented a flat tendency from 1.5 ms until 4.5 ms. Honeycomb core crushed, reducing its stiffness and leading to a failure in upper face-sheet, Fig. 7.2. Finally, a sudden drop can be seen in force history after 4.5 ms. Sandwich beam absorbed the entire impact energy, and impactor stopped over the upper face-sheet.

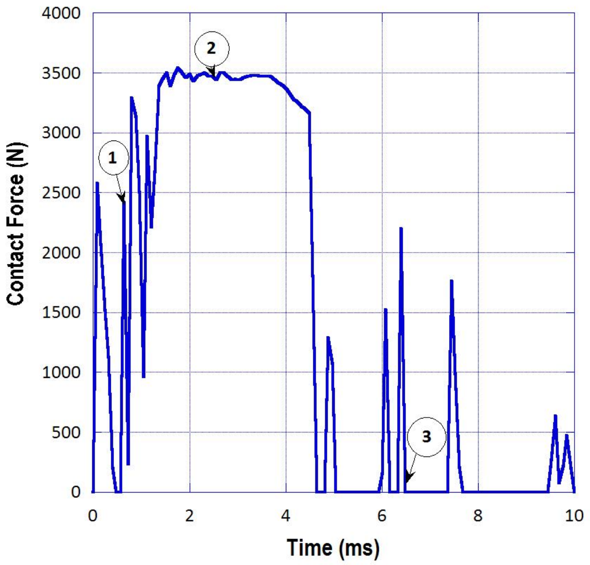

Fig.6. Contact-force history predicted for an impact energy of 35 J.

The energy was absorbed mainly by upper face-sheet failure but honeycomb core played an important role in energy absorption mechanisms. The onset of upper face-sheet failure was due to the previous crushing of honeycomb core. For lower impact energies, the reduction of core thickness was negligible, see Fig. 5, thus upper face-sheet was subjected to lower bending stresses. However, for higher impact energies, the extension of the plastic strain region in the honeycomb core produced a significant reduction in core thickness leading to the failure of upper face-sheet. Moreover, after the failure of the upper face-sheet, honeycomb core presented a remaining stiffness that constrained the upper face-sheet displacement and contributed to the energy absorption.

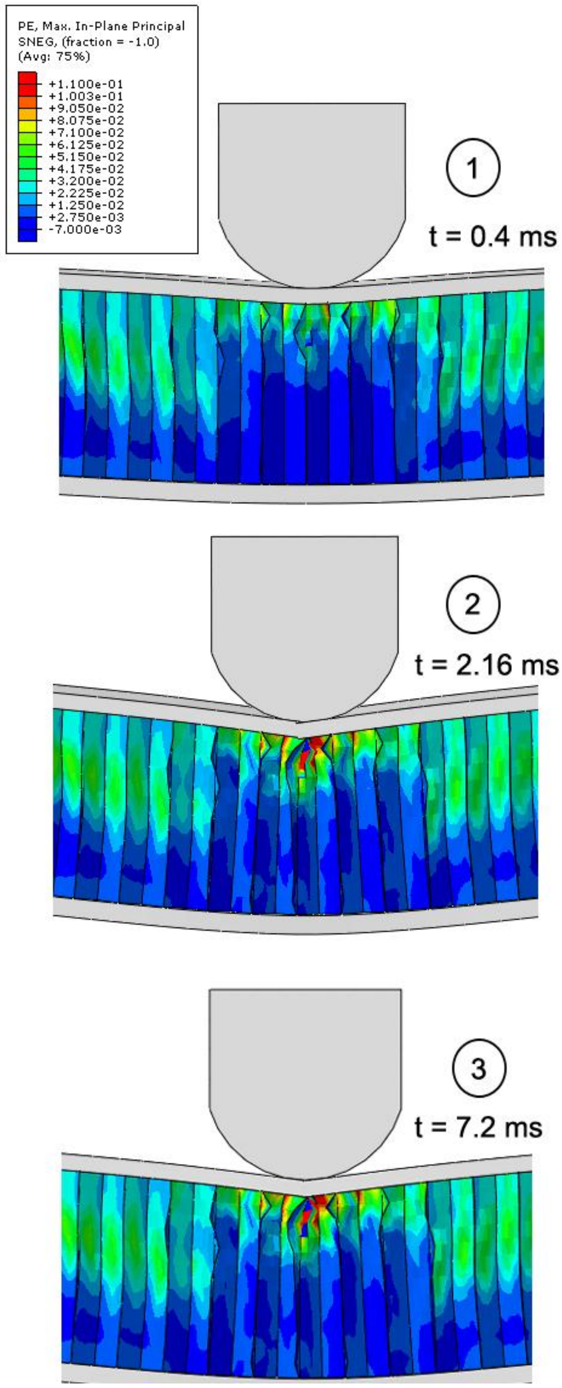

Fig.7. Evolution of core plastic strain for impact energy of 35 J.

5 Conclusions

A finite-element numerical model was developed to predict the failure of aluminium honeycomb-cored sandwich composite beams under low-velocity impact tests. The numerical model was validated by comparison with experimental results obtained in low-velocity impact tests conducted on a drop-weight tower. Contact-force history and absorbed energy predicted by finite-element model were in agreement with experimental results.

Numerical model results were analysed to predict failure modes and energy absorption mechanisms. Two different trends were observed for lower and higher impact energies.

For lower impact energies, the impactor returned after impact with a post-ricochet velocity lower than impact velocity. Energy is mainly absorbed by plastic strains found in the honeycomb core. However, the reduction of core thickness can be neglected and no damage was detected in composite face-sheets. Thus absorbed energy is much lower than impact energy, and small permanent strains can be found in honeycomb core.

For higher impact energies, the entire impact energy is absorbed by the sandwich beam and the impactor stopped on the upper face-sheet. The great extension of the plastic strain region in the aluminium honeycomb core, produced a significant reduction of the core thickness leading to the failure of the upper face-sheet. The energy is absorbed mainly by the failure of upper face-sheet.

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