SANDWICH PANELS WITH CELLULAR CORES MADE OF FOLDED COMPOSITE MATERIAL: MECHANICAL BEHAVIOUR AND IMPACT PERFORMANCE

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SUMMARY

Innovative sandwich core structures can be produced by folding composite prepreg sheets to three-dimensional zigzag structures. The foldcores in this study are made from aramid and carbon woven fabrics with epoxy resin. This paper describes the cell walls’ mechanical behaviour under flatwise compression as well as low and high velocity impact loads. Experimental results and modelling issues for dynamic simulations are discussed.

Keywords: Sandwich, Composite folded core, Cell wall failure, Impact, Dynamic simulation

INTRODUCTION

Composite sandwich structures with cellular cores are used in numerous lightweight applications e.g. in aerospace, automotive, marine or civil engineering. In this context, honeycomb core structures made from aluminium or Nomex® aramid paper have a top ranking when it comes to weight-specific mechanical properties. However, honeycomb sandwich structures – especially in aircraft applications – suffer from drawbacks like humidity inclusion in the closed cells and an expensive discontinuous manufacturing process. In recent years, alternative sandwich core structures have been developed by folding composite prepreg sheets to three-dimensional open zigzag structures, referred to as foldcore structures. This folding can be performed in diverse discontinuous and continuous processes with several different materials and in a variety of geometries, optimised for the specific application [1, 2]. Past studies primarily cover the mechanical behaviour and numerical modelling of foldcore structures made from phenolic-impregnated Nomex® [3, 4, 5] or Kevlar® paper [6, 7, 8, 9] and aluminium [10].

The following investigation focuses on sandwich structures with composite skins and folded cores made of woven fabric composite material with carbon and aramid fibre fabrics and epoxy resin. The mechanical behaviour under flatwise compression as well as low velocity and high velocity impact loads is determined experimentally, and modelling approaches for numerical simulations of such structures with LS-DYNA are shown.
FOLDCORE MATERIALS & MANUFACTURING

This study only covers composite foldcore structures made of woven fabric material (Fig. 1), the mechanical properties and the impact performance of foldcores made of unidirectional (UD) carbon laminate is documented in [11]. Two plies of preimpregnated 2/2 twill weave carbon fabric (CF) and Kevlar® aramid fabrics (AF) with epoxy resin were used for the foldcore production (Fig. 2a). This production was performed at the Kazan State Technical University, where a process based on transformable matrices was developed [12, 13]. The flat prepreg material is placed between two of those transformable matrices, which consist of multiple rigid parallelogram-shaped plates, joined by flexible hinges. Thus, the matrices are folded in the same foldcore geometry as the prepreg sheet in-between. In contrast to deep drawing, the material is simply folded without being elongated. Afterwards, the foldcore is cured in an autoclave.

The folding pattern is a simple zigzag geometry, based on the unit cell geometry in Fig. 2b. Four configurations with different materials and geometries were investigated in this study, which are referred to as type A, B, C and D. The global densities vary from 103 to 119 kg/m³. All details are given in the overview table in Fig. 3. The aramid foldcore type A and the carbon foldcore type B are based on the same geometry initially used in the study in [11]. The carbon foldcore type C has the same global density of type B, but the cell geometry with smaller cell walls and an orientation more parallel to the transverse direction aims at higher flatwise compressive properties. Type D is a dual-core configuration with a combination of a carbon foldcore and an aramid foldcore, separated by a 1 mm thick Kevlar® composite middle layer. The global density and thickness is identical to the other types. The idea behind this dual-core configuration was to generate a two-phase impact behaviour with the ductile aramid core absorbing low impact energies, the stiff carbon core absorbing high impact energies and the Kevlar® layer acting as an additional impact protection layer.

Figure 1: Composite foldcore structures made of a) UD carbon fibre laminate [11], b) woven carbon fabric (type C) and c) woven aramid fabric (type A).

Figure 2: a) Micrograph of cell wall of carbon foldcore type C, b) unit cell geometry.
<table>
<thead>
<tr>
<th>Type A: aramid</th>
<th>Type B: carbon</th>
<th>Type C: carbon</th>
<th>Type D: dual-core aramid + carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core geometry:</td>
<td><img src="image" alt="Type A" /></td>
<td><img src="image" alt="Type B" /></td>
<td><img src="image" alt="Type C" /></td>
</tr>
<tr>
<td>( l=29 \text{ mm}, L=10 \text{ mm}, S=20 \text{ mm} )</td>
<td>( l=18 \text{ mm}, L=7.5 \text{ mm}, S=15.5 \text{ mm} )</td>
<td>( l=29 \text{ mm}, L=10 \text{ mm}, S=20 \text{ mm} )</td>
<td></td>
</tr>
<tr>
<td>Core height ( H ):</td>
<td>28 mm</td>
<td>14 mm (AF) / 14 mm (CF)</td>
<td></td>
</tr>
<tr>
<td>Cell wall thickness ( t ):</td>
<td>0.40 mm</td>
<td>0.48 mm</td>
<td>0.50 mm</td>
</tr>
<tr>
<td>Core density ( \rho ):</td>
<td>103 kg/m³</td>
<td>113 kg/m³</td>
<td>114 kg/m³</td>
</tr>
</tbody>
</table>

Figure 3: Different foldcore configurations investigated in this study.

The skins were manufactured in an autoclave (180°C, 7 bar, 2 h) from the carbon/epoxy UD prepreg Cytec 977-2/HTS in a quasi-isotropic lay-up. For types A, B and C, 2 mm thick skins with the stacking sequence \([45°/90°/-45°/0°]_{2S}\) were used. For the dual-core type D the skins were only 1.5 mm thick with the stacking sequence \([60°/-60°/0°]_{2S}\) to obtain a comparable total thickness under consideration of the 1 mm thick middle layer made of four aramid fabric/epoxy plies. The skins were bonded onto the core in a hot press using the epoxy-based structural adhesive Scotchweed 9323 B/A (80°C, 4 bar, 4 h).

**MECHANICAL TESTING**

In order to characterise and compare the mechanical properties of the different foldcore types, experimental test series were conducted on an Instron universal testing machine. At first, the mechanical properties of the composite cell wall material were determined under normal and shear loads according to EN ISO 527-4 and DIN EN 6031 (Fig. 4a), since these data are necessary for numerical modelling of the foldcore’s cell walls. Sandwich specimens of the size 150 mm x 150 mm were tested under flatwise compression according to DIN 53291 (Fig. 4b) and transverse shear according to DIN 53294 (Fig 4c). The following explanation will focus on the compressive behaviour, since this correlates most to the impact behaviour discussed later.

![Figure 4](image)
The quasi-static compression tests gave valuable information on the cell wall deformation and failure mechanisms, shown in Fig. 5. The effective stress-strain curves are depicted in Fig. 6. The cell walls of the ductile aramid foldcore of type A buckle under compression and collapse under an average peak stress of about 3.2 MPa. Afterwards, the structure is folded in a comparable way to Nomex® foldcore and honeycomb cores up to densification [8]. In contrast, the carbon foldcores of types B and C show remarkably higher stiffness and strength properties, with values of 6.5 MPa and 8 MPa, respectively. Also in this case the cell walls buckle before fracture. After fracture, the stress drops to a very low level and the cell walls are crushed as they come into contact with the opposite skin. Despite the same density, the compressive stiffness, strength and crushing stress of type C are significantly higher than the values of type B and, in terms of weight-specific properties, even higher than those of Nomex® honeycomb cores of similar density.

<table>
<thead>
<tr>
<th>Type A:</th>
<th>Type B:</th>
<th>Type C:</th>
<th>Type D:</th>
</tr>
</thead>
</table>

Figure 5: Cell wall deformation behaviour of four foldcore types under compression.

Figure 6: Compressive stress-strain diagrams of four different foldcore types.
The dual-core type D shows a sequential behaviour. First the aramid foldcore fails with ductile deformations. When it is completely densified, the carbon foldcore fails in a brittle way. Different geometrical alignments of the two cores with respect to each other were tested with a minor effect on the result. Finally, a shifted configuration was selected, where a certain bending deformation of the middle layer is allowed under compression.

Comparing the specific absorbed energy in Fig. 7, which is the surface under the stress-strain curves divided by the core density, it can be seen that the difference is marginal for small compressive strains, but the dual-core type D and the carbon foldcore type C show the highest energy absorption potential for larger strains. Therefore, the impact test specimens were only produced with type C and type D core structures.

![Figure 7: Comparison of specific energy absorption of four different foldcore types.](image)

**IMPACT PERFORMANCE**

Sandwich structures can be exposed to various impact scenarios from low velocity impacts (v < 10 m/s, e.g. tool drop on surface) over high velocity impacts (v < 1000 m/s, e.g. runway debris, hail or bird strike on aircraft structures) to hyper velocity impacts (v > 1000 m/s, e.g. space debris on satellite structures). The impact performance of a sandwich structure, i.e. damage mechanisms and energy absorption capability, is strongly dependent on the skin material and thickness. However, the core – supporting the skins – also significantly influences the impact behaviour. Further influence factors are the sandwich thickness, boundary conditions, impactor geometry and stiffness, etc. To evaluate the impact behaviour of foldcore sandwich structures, both low velocity and high velocity impact tests were performed on type C and type D foldcore sandwich panels (Fig. 8).

![Figure 8: Illustration of test setup for a) low velocity and b) high velocity impact testing.](image)
Low Velocity Impact

The low velocity impact (LVI) tests were conducted on a drop tower with a hemi-spherical steel impactor, having a diameter of 25.4 mm and a total weight of 1.56 kg. The sandwich plate with composite skin material as described before and a size of 300 mm x 300 mm x 32 mm was fully supported on a rigid foundation in order to limit the complexity for modelling purposes. The impact location was the middle of a foldcore cell wall, although further experiments proved that the influence of the impact location is negligible. Impact energies of 5 J (2.5 m/s) to 60 J (9 m/s) were tested. Additional tests with 2 J showed no significant skin or core damage and hence are not shown here. The damage assessment of the upper skin was conducted in a nondestructive way with ultrasonic C-scans. The core damage was evaluated by the destructive technique of cutting cross-sections (Fig. 9).

The corresponding impact force plots are shown in Fig. 10. A comparison of the curves for both types shows higher slopes and higher peak values for type C, which is primarily the result of the higher stiffness of the carbon foldcore and the 2 mm thick skin compared to the aramid foldcore and the 1.5 mm thick skins in the dual-core sandwich of type D. The oscillations in the curves both arise from vibrations in the system excited by the transient loading as well as damage in the sandwich structure. The carbon foldcore crushes very locally under the impact point with first damage already at 5 J, while the aramid foldcore of type D is compressed in a more ductile way. Skin damage is primarily based on delaminations as interlaminar failure with additional fibre and matrix breakage starting from 20 J as intralaminar failure modes. The highest low velocity impact energy of 60 J was just not high enough to evaluate the full potential of the dual-core configuration, since the impactor was stuck in the upper half of the sandwich structure with a slight loading of the lower carbon foldcore (see the second increase in the 60 J force curve of type D in Fig. 10). All in all, the low velocity impact testing showed that the damaged region is very localised for both types and the amount of absorbed energy is comparable.

<table>
<thead>
<tr>
<th>5 J</th>
<th>10 J</th>
<th>20 J</th>
<th>30 J</th>
<th>40 J</th>
<th>60 J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type C:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Type D:</td>
<td></td>
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</table>

Figure 9: LVI damage assessment of skin (ultrasonic C-scans) and core (cross-sections).
High Velocity Impact

A gas gun was used for the high velocity impact (HVI) tests. In this case, the sandwich plates with an identical configuration as in the LVI tests had a size of 400 mm x 400 mm x 32 mm, including a Rohacell® foam core at all four edges for load introduction purposes (Fig. 8b). The plates were simply supported at the edges to allow for a bending deformation under the impact load. Two different impactors were used, on the one hand a 13.5 g steel cube with an edge length of 12 mm, representing e.g. a piece of runway debris propelled by the tires of an aircraft, and on the other hand a 100 g steel bar with the dimensions 109 mm x 30 mm x 4 mm, which reflects e.g. the load case of a released part of a turbine blade. The impact angle of the steel cube was 90°, i.e. perpendicular to the surface. For the steel bar an angle of 60° was chosen. Since some of the steel cubes were stuck in the sandwich core, the nondestructive X-ray-based technique of micro-computed tomography (3D micro-CT) was applied that allows for a three-dimensional look into the damaged core (Fig. 11).

The scope of the high velocity impact testing covered the three characteristic load cases: 1. the impactor rebounds from the outer skin, 2. the impactor penetrates the outer skin and gets stuck in the core and 3. the impactor penetrates the whole sandwich structure. Some examples of these load cases are shown in Fig. 12.
<table>
<thead>
<tr>
<th>13.5 g steel cube:</th>
<th>100 g steel bar:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type C:</strong></td>
<td></td>
</tr>
<tr>
<td>137 m/s, 125 J</td>
<td>53 m/s, 142 J</td>
</tr>
</tbody>
</table>

**Type D:**

| 132 m/s, 116 J   | 52 m/s, 138 J   |

![Figure 12: Examples of HVI post-test images: steel cube penetrated and steel bar stuck.](image)

At velocities of around 130 m/s or energies of around 115 J the steel cube penetrated the sandwich plate of **type C**, while it was still stuck in the dual-core sandwich **type D** with a significant damage of the backside skin (Fig. 12 left). For energies of approx. 140 J the steel bar was stuck in both **types C** and **D** specimens, although the backside skin was almost penetrated, which means that all kinetic energy was absorbed by the sandwich structure. The micro-CT scanning results showed large areas of skin/core debonding of the backside skin, which did not occur in the LVI tests due to the fully supported boundary conditions. Overall, a direct comparison of the high velocity impact performance of **types C** and **D** is difficult, since the carbon skin thickness has a major influence and it was lower for **type D** with only 1.5 mm compared to 2 mm for **type C**. However, a penetration still occurred at lower velocities for **type C**, highlighting that the dual-core configuration **type D** shows good energy absorbing potential with a further optimisation of the choice of middle layer and core types being worthwhile.

**MODELLING & SIMULATION**

Since experimental testing of innovative materials and structures like foldcores can be time-consuming and expensive when it comes to the manufacturing of toolings, prototypes and test specimens as well as the testing and damage assessment, numerical simulations are an established efficient tool in the development process of engineering structures. Therefore, finite element (FE) models of the composite foldcore sandwich structures were developed in the commercial explicit FE software LS-DYNA.

The shell element models were generated step by step, starting with one element and coupon test simulations in order to validate the composite material models for the cell walls and skin laminates, followed by foldcore compression test simulations (Fig. 13a) and finally impact simulations (Fig. 13b). For the cell walls made of woven fabric composites, the continuum damage mechanics-based material model Mat_Laminated_Composite_Fabric (MAT58) was used, while the UD laminate of the skins was modelled
with Mat_Enhanced_Composite_Damage (MAT54). A tiebreak contact definition with failure option was used for the connection of skin and core in order to cover skin/core debonding. Interlaminar failure inside the upper skin was implemented by the utilisation of a delamination contact algorithm between single layers of shell elements (‘stacked shell’ modelling approach). Since the composite foldcore geometry suffers from global as well as local imperfections and irregularities due to the manufacturing process, the implementation of those imperfections in the numerical model was one of the major modelling issues, which is discussed in further detail in [14, 15].

The models were validated against experimental data and could be used for a detailed evaluation of failure mechanisms inside the sandwich structure and geometrical parameter studies. For example, the specification of foldcore geometry type C with improved compression properties as compared to the reference geometry of type B was also a result of a pure numerical geometry optimisation study with LS-DYNA [14].

![Figure 13: LS-DYNA models for a) compression test simulation, b) low velocity impact simulation, c) high velocity impact simulation.](image)

**CONCLUSIONS**

The mechanical behaviour of sandwich structures with composite folded cores and carbon fibre-reinforced composite skins under flatwise compression and impact loads was evaluated both experimentally and numerically. While foldcores made of woven aramid fabric show a rather ductile behaviour, carbon foldcores with their brittle nature absorb energy by crushing. Their weight-specific compression properties are even higher than those of Nomex® honeycomb cores of similar density. The dual-core configuration with two layers of foldcore and an aramid composite middle layer showed the potential of a two-phase energy absorption behaviour, which can be tailored by the choice of the constituents and the variation of the geometrical configuration. Dynamic finite element simulations have shown to be an efficient tool in the development of such innovative structures that exhibit a large design flexibility in terms of possible core geometries and materials.
ACKNOWLEDGEMENTS

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