Virtual Testing of Sandwich Core Structures with LS-DYNA

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Summary
Virtual testing using dynamic finite element simulations is an efficient way to investigate the mechanical behaviour of small- and large-scale structures reducing time- and cost-expensive prototype tests. Furthermore, numerical models allow for efficient parameter studies or optimisations. One example, which is the focus of this paper, is the configurational design of cellular sandwich core structures. From classical honeycomb cores to innovative folded core structures, a relatively large design space is provided allowing for tailoring of the cellular core geometry with respect to the desired properties.

The method of determining the effective mechanical properties of such cellular sandwich core structures of different geometries using dynamic compression, tensile and shear test simulations with LS-DYNA is discussed covering a number of important modelling aspects: the cell wall material modelling, the influence of mesh size and number of unit cells, the inclusion of imperfections, etc. A comparison of numerical and experimental results in terms of stress-strain data and cell wall deformation mechanisms is given for Nomex® honeycomb cores and Kevlar® or carbon fibre-reinforced plastic (CFRP) foldcore structures. Finally, the application of this virtual testing method for a geometry optimisation of a CFRP foldcore structure with respect to the compressive strength is presented.

Keywords
Sandwich structures, virtual testing, honeycomb, folded core, imperfections, LS-DYNA
1. Introduction

1.1 Motivation

In the research environment of the ground and air transportation industry constant work is conducted on developing lighter, cheaper and mechanically beneficial structures and materials. Especially in the aerospace industry, twin-skinned sandwich structures with a thick lightweight cellular core are well-known and widely used because of their excellent weight-specific stiffness and strength properties [1]. The research on new cellular sandwich core structures typically involves a large amount of specimen manufacture and testing to investigate the influence of certain core cell geometry parameters on the mechanical properties, since especially here a relatively large design space is provided from classical honeycomb cores to innovative folded core structures. This is both a time- and cost-intensive procedure. Nowadays, numerical simulations based on the finite element (FE) method have become a standard tool in the development process of the aircraft industry – from the material level over the component level up to the full aircraft (Fig. 1). Therefore, it is reasonable to use this technique also for the characterisation of cellular sandwich core structures. Instead of manufacturing expensive prototypes of innovative core structures, FE models on a parametric basis are generated and dynamic simulations of compressive and shear tests are performed in order to evaluate the cell wall deformation behaviour and the effective mechanical properties of different core geometries. This method of virtual testing, which can be combined with a core geometry optimisation for certain requirements, can be a very time- and cost-efficient approach. However, as simple as it seems, there are a number of important modelling aspects and difficulties on the way to reliable results, which are discussed in this paper.

Fig. 1: Testing/simulation pyramid in aircraft development

1.2 Sandwich Core Structures

A sandwich structure typically consists of two thin and stiff face layers separated by a thick lightweight core, which increases the second moment of inertia to achieve a high bending stiffness. The core is supposed to be as light as possible while having an adequate transverse normal and shear stiffness and strength to carry shear loads between both faces and transversal normal loads. Suitable are foam balsa wood, corrugated cores or honeycomb cores. Such honeycombs made of phenolic-impregnated Nomex® paper are the most commonly used sandwich core structure in aircraft design today. They are characterised by superior weight-specific mechanical properties. However, the closed honeycomb cells lead to draw-backs with regard to condensing water, which is trapped in these cells increasing the weight and reducing the mechanical properties. As a solution for this problem, drainable folded core structures were introduced as a new sandwich core generation (Fig. 2). Not only do they offer ventilation channels, but they can also be produced efficiently in a continuous manufacturing process from various materials and in various geometries [2]-[7]. The application of such folded core sandwich structures for the aircraft fuselage [8]-[10], aircraft engine cowlings [11] or impact protection shields [12] has been investigated in past studies. For each application, a specific core geometry has to be chosen with a suitable density and compression and shear properties, for both honeycomb and folded cores. Especially in case of new core structures like the folded cores, the experimental database of mechanical properties is very limited or not existing, making virtual tests an appropriate technique.
1.3 Literature Survey on Virtual Testing of Sandwich Core Structures

The idea of performing virtual tests on honeycomb core structures with detailed FE simulation models is not new and first came up in the end of the 1980s. The reason was to obtain the in-plane elastic properties of aluminium honeycomb, which are not provided in honeycomb data sheets, since those values are very low compared to the out-of-plane properties and often they are neglected. Chamis et al. [13], Karlsson and Wetteskog [14], Martinez [15] and Elspass [16], [17] used NASTRAN and ADINA models to calculate all nine independent effective elastic properties. Similar studies have been conducted later by Mistou et al. [18] on aluminium honeycomb, by Foo et al. [19] on Nomex® honeycomb and by Allegri et al. [20] on carbon honeycomb. With improving computational power, not only the elastic behaviour prior to cell wall buckling but also the cell wall folding mechanisms in the post-damage region could be analysed in virtual tests. For this purpose, dynamic simulations with an explicit time integration scheme were used. Aminanda et al. [21] used the commercial FE code RADIOSS, Lamb [22] as well as Aktay et al. [23] used PAM-CRASH, and Gotoh et al. [24] as well as Tryland [25] used LS-DYNA to simulate the out-of-plane compressive behaviour and cell wall folding of aluminium and Nomex® honeycomb cores.

All the above-mentioned studies were based on ideal, uniform hexagonal honeycomb models without any imperfections. However, this is far from reality, since all cellular structures show imperfections and irregularities resulting from the manufacturing process, which strongly influence the core’s stiffness and strength. An ideal model without imperfections will therefore always overestimate the mechanical properties and lead to questionable results [26]. This topic is addressed by Hohe and Becker [27], who list the following possible cell wall imperfections: cell wall intersections with round rather than perfect angular corners, non-constant wall thicknesses, cell wall curvature and missing cell walls. The influence of those imperfections on the mechanical in-plane properties was analysed by Li et al. [28] (irregular cell wall thicknesses, irregular cell geometries), Yang et al. [29] (irregular cell wall thicknesses, uneven cell walls), Yang and Huang [30] (different thicknesses of cell wall junctions), Simone and Gibson [31] (different thicknesses of cell wall junctions), Simone and Gibson [32] (cell wall curvature) as well as Guo and Gibson [33] (missing cell walls), all using ABAQUS models of honeycomb cores.

As a consequence, different researchers applied different methods to implement imperfections into meso-scale honeycomb FE models for virtual testing simulations. Aaron Jeyasingh [34] and Mohr [35] performed out-of-plane compression test simulations of aluminium honeycomb models with LS-DYNA using special nodal boundary conditions or a superposition of the first eigenmode onto the nodal coordinates to initiate cell wall buckling. This latter technique was also applied by Xue and Hutchinson [36] in ABAQUS/explicit having a strong influence on the resulting stress-strain curve. Fan [37] investigated a tilting of the cell walls about 0.2° in flatwise honeycomb compression test simulations, but found this to be an insufficient measure for imperfection compensation.

Besides those studies on honeycomb sandwich cores, some researchers also performed virtual testing simulations on folded core structures accounting for imperfections. Hachenberg et al. [38] performed virtual tests with LS-DYNA to characterise the out-of-plane compression and shear properties of Nomex® foldcores with different geometries. Round instead of angular folding corners were investigated as imperfections, having a significant influence on the global stiffness properties. Those models were generated on a parametric basis using the tool SANDMESH [39], which also allows for a distortion of the node’s coordinates (node-shaking) as imperfection compensation. Heimbs et al. [40] used LS-DYNA simulations to characterise the complete in-plane and out-of-plane compression and shear properties of Kevlar® foldcore, not only the elastic behaviour but the complete stress-strain curves up to large deformations. Imperfections were compensated by reducing the cell wall material
properties. Kilchert et al. [41] performed a compression test analysis on similar Kevlar® foldcore structures using the FE code PAM-CRASH and a node-shaking technique to cover imperfections. This literature survey shows that some work has already been done in the field of virtual testing of sandwich core structures. However, most studies are limited to special core geometries (mostly hexagonal honeycomb), special cell wall materials (mostly aluminium), to few load cases (mostly out-of-plane compression tests), to the elastic pre-damage behaviour or they do not account for imperfections, which is essential for such cellular structures. Therefore, the current paper tries to address this topic from a more versatile perspective. The model development and virtual testing of different honeycomb cores (hexagonal and over-expanded) as well as folded cores made of Nomex®, Kevlar®, or carbon fibre composites is presented. Virtual tests with LS-DYNA are performed in all material directions (in-plane and out-of-plane) under various loading conditions (compression, tension, and shear). The topic of imperfections is discussed extensively, imperfections are categorised and different methods for the compensation of imperfections are investigated. Parameter studies are conducted to investigate the influence of model size, mesh size, loading rate etc. Finally, the application of this virtual testing method for the optimisation of a carbon foldcore’s geometry is addressed.

2. Core Materials in this Study

2.1 Nomex® Honeycomb Cores

The first sandwich core structures investigated in this study are classical Nomex® honeycomb cores in a hexagonal and an over-expanded configuration by the manufacturer Schütz Cormaster (Fig. 3). While the hexagonal cells are used for flat sandwich panels, over-expanded cells are typically used for curved structures because they can be bent along one axis without any anti-clastic saddle-shaped curvature. Both cores have a global density of 48 kg/m³, which is a typical value for aircraft cabin applications (overhead stowage bins, ceiling or sidewall panels etc.) and a cell size of 3.2 mm (hexagonal) or 4.8 mm (over-expanded). The cell walls are made of a 0.05 mm thick Nomex® T412 aramid paper with an additional phenolic resin coating, resulting in a total average wall thickness of 0.0613 mm.

2.2 Folded Cores

In addition to the classical honeycomb cores, two different folded core structures are investigated. One is made of phenolic resin-impregnated Kevlar® paper (random fibre distribution) with a global density of 48 kg/m³, produced by IFB Stuttgart, Germany. Just like the Nomex® paper (meta-aramid), Kevlar® is an aramid fibre (para-aramid) but with a different chemical configuration, resulting in higher mechanical properties. The other foldcore is made of a carbon fibre-reinforced epoxy laminate (CFRP) produced from prepreg material by Kazan State Technical University, Russia. The laminate consists of three unidirectional layers with a [0°/90°/0°] lay-up and a total wall thickness of 0.35 mm. The core density has a value of 102 kg/m³. While the carbon fibre foldcore shows a simple zigzag geometry, the Kevlar® core has additional folding edges in the width direction (Fig. 4).

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**Fig. 3:** Hexagonal (a) and over-expanded (b) Nomex® honeycomb core structures

**Fig. 4:** Kevlar® paper (a) and carbon fibre (b) folded core structures
2.3 Imperfections

According to the categorisation of imperfections by Heimbis [42] (Fig. 5), both global imperfections (e.g. irregular cell geometry, uneven cell walls) and local imperfections (e.g. rough surfaces, resin accumulation in cell wall corners) are present in Nomex® honeycomb cores resulting from the manufacturing process, i.e. the expansion of the hexagonal cells and the dipping into phenolic resin. The same is true for folded cores, with global and local imperfections resulting from the folding toolings.

![Imperfections](image.png)

**Fig. 5:** Categorisation of imperfections in cellular honeycomb and folded core structures [42]

3. Model Development

The model development for virtual testing simulations of cellular core structures includes the generation of the structure’s finite element mesh, the assignment of material laws, the implementation of imperfections and the definition of boundary and loading conditions. Keeping in mind the geometrical variety of such core structures, it would not be very efficient to build up or modify the finite element model each time by hand. Therefore, an automatic model generation tool on a parametric basis was developed, reducing the pre-processing work to a minimum.

3.1 Parametric Model

The parametric model generation tool was developed in PATRAN’s command language PCL. It is based on the input of the geometric parameters of a honeycomb’s or folded core’s unit cell (Fig. 6), the model size (length, width, height or number of unit cells), the element size and type as well as the boundary conditions. Inside the code a unit cell is generated from the geometry input and duplicated in both in-plane directions as determined by the model size. Overlapping cell walls are trimmed. In case of the honeycomb core, single and double cell walls are modelled just like in the real structure. Two rigid sandwich faces are generated on the upper and lower side of the core, where the loads are applied. The whole model is meshed with 4-node shell elements according to the defined element size and the core and the faces are connected by a contact formulation. Then the boundary conditions are applied to the face sheets. The user decides if half symmetry of the specimen is used to reduce computational cost. In that case the necessary boundary conditions are included at the symmetry surface. At the end a keyfile for LS-DYNA is written, which can be used to perform compression, tensile or shear test simulations (Fig. 7).
3.2 Cell Wall Material Modelling

Cell wall material modelling is a crucial factor in the sandwich core models, because it strongly influences the structure’s elastic and failure behaviour. At the same time, however, it is very difficult to obtain the mechanical properties of the shell element’s cell wall material.

In case of Nomex® honeycomb cores, the cell walls are made of phenolic resin-impregnated aramid fibre paper. Resulting from the manufacturing process, there are single and double cell walls inside the core structure (Fig. 8a). Tsuji et al. [43] as well as Foo et al. [19] experimentally characterised this cell wall material in tensile tests, providing stress-strain curves as well as stiffness and strength values. The material behaviour is very ductile and can be estimated by a bilinear elastic-perfect plastic material law. Furthermore, there is a difference in the properties of the machine direction and cross direction of the Nomex® paper. Therefore, the orthotropic elastic-perfect plastic composite material model MAT54 in LS-DYNA was chosen for material modelling, representing the stress-strain curves of the references above with acceptable accuracy.

The difference between machine direction and cross direction is much lower for the phenolic resin-impregnated Kevlar® fibre paper (Fig. 8b). Such paper samples were tested in tension and compression in [44]. Therefore, instead of an orthotropic model, the isotropic bilinear material model MAT24 in LS-DYNA was adopted for cell wall material modelling of the Kevlar® foldcore. A detailed discussion on the constitutive modelling of this material is given by Kilchert et al. [41].

In contrast to these resin-impregnated aramid fibre papers, the CFRP foldcore is made of a composite laminate with three unidirectional plies in a [0°/90°/0°] lay-up (Fig. 8c). Mechanical properties taken from data-sheets of this material were validated with tensile tests of such specimens. The composite material model MAT54 in LS-DYNA was used for the modelling of each lamina. Each single layer is represented by one integration point through the shell thickness with the respective fibre orientation angle. The crush-front algorithm of MAT54 was also used, which reduces the strength of elements neighbouring eroded elements to facilitate the representation of a pre-damage and a progressing crushing of the brittle CFRP material [45].
3.3 Imperfection Modelling

So far the cellular core models have a uniformly perfect geometry. As discussed before, in reality cellular structures are neither uniform in geometry nor free of imperfections and irregularities. This affects the buckling load of the single cell walls and the whole structure’s strength. Therefore, a mesoscale model without imperfections will always lead to an overestimation of stiffness and strength values. Neglect of imperfections can also cause discrepancies due to uniform unit cell behaviour. In this work, several different approaches to account for imperfections in the FE models were investigated.

One way is to include the actual imperfections in the mesh. Global geometric imperfections can be modelled by randomly distorting the core’s geometry prior to meshing (Fig. 9a). Local imperfections like uneven cell walls can be represented by randomly modifying all nodes’ coordinates (‘node-shaking’, Fig. 9b). Both features were included in the parametric models based on random numbers. The effect of this approach was investigated in preliminary flatwise compression test simulations. In general, both the honeycomb and foldcore structures first exhibit cell wall buckling as a stability failure under compressive loads followed by a cell wall fracture in case of the brittle CFRP foldcore or a continuous folding pattern in case of the ductile aramid paper cores. The random geometry distortion approach reduces the buckling load but not in a sufficient way for the simulation results of virtual compression tests to agree with experimental data. The influence of the node-shaking approach is slightly higher with a considerable decrease of the global compressive strength. However, compared to experimental stress-strain curves, which are still lower, not all imperfections can be covered by these approaches.

Another way to reduce the buckling load is to consider a pre-buckling of the cell walls. To achieve this, the first buckling modes – calculated within an implicit analysis – have to be superposed onto the unit cell’s mesh, scaled to about 1-5% of the shell thickness (Fig. 9c). A further method for including imperfections in the FE mesh is to scan the real cellular core specimen in a micro-CT apparatus (Fig. 9d) and translate the three-dimensional X-ray data into a finite element mesh with special software tools. The result is a mesh of the actual specimen that covers all real geometrical imperfections. Another way of imperfection modelling is to keep the ideal mesh and reduce the cell wall properties (material data and wall thickness), which can either be done uniformly for the whole model or stochastically distributed for individual elements (Fig. 10). This latter approach can also be implemented in the parametric model generation tool by defining a certain number of different parts with randomly reduced material properties and wall thicknesses and assigning these parts randomly to the elements.

In case of a uniform reduction, a parameter identification procedure with LS-OPT with respect to existing experimental data of the core structures is suitable, which was documented for the Kevlar® foldcore in [40]. The experimental data from the foldcore manufacturer IFB Stuttgart were the target values, while the cell wall’s thickness as well as stiffness and strength were defined as parameters. Within the parameter identification loop with LS-OPT, compression and shear test simulations were performed in order to determine the set of parameters with the best correlation to the target values. Hereby, the lack
of imperfections in the FE model is compensated by the use of cell wall properties that are on purpose lower than in reality. This approach led to a very good correlation to the experimental stress-strain curves, while still maintaining a realistic buckling pattern in the simulation.

Fig. 9: Imperfection modelling through geometry distortion (a), node-shaking (b) and pre-buckling (c). (d) shows a sectional view through the CFRP foldcore using three-dimensional micro-CT data.

Fig. 10: Imperfection modelling by randomly assigning different part properties to individual elements.

Reality is a combination of the approaches presented here: There are geometrical imperfections in the cellular structure and there are variations in the material properties and the paper thickness, especially in case of impregnated aramid paper. The weakest or thinnest areas of a cell wall determine the global properties, since damage will start from these areas, which justifies the approach of reducing the properties in the model.

3.4 Boundary and Loading Conditions

On the upper and lower surface of the core structure a rigid skin plate was generated for transverse tests, where the boundary and loading conditions were applied. The connection of the core structure and the skins was achieved by a Tied_Nodes_to_Surface Contact in LS-DYNA. For the lower skin all rotational and translational degrees of freedom were fixed and for the upper surface a time-dependent linear displacement function was defined. The direction of this displacement was chosen with respect to the desired compression, tensile or shear loading scenario. The reason for the utilisation of these additional rigid skin plates instead of ascribing the boundary conditions directly to the upper and lower nodes of the core model was to have a contact surface to prevent the cell walls from unrealistic out-of-plane deformations during the folding or crushing process. In case of in-plane testing, the skin plates were placed at the respective sides of the core model in the same manner as for the transverse tests described before.
4. Virtual Testing

4.1 Quasi-Static Simulations

Typical material tests are performed at a quasi-static loading rate. To perform the virtual tests in the simulation also quasi-statically would be very expensive, since the explicit integration scheme of dynamic simulation codes usually leads to very small time steps resulting in an immense computational time. Increasing the loading rate in the simulation has to be done with care, because the material behaviour of ductile cellular structures is typically rate-dependent due to micro-inertial effects [46] and the results of a dynamic test may not be directly comparable to static test results. Since the time step of the simulation depends, amongst others, on the material density, a common technique to reduce the computational time for quasi-static explicit simulations is to increase the density of the materials in the model. This technique, known as mass-scaling, has also to be done very carefully, because an increased mass normally leads to a different structural behaviour due to inertial effects and an increased kinetic energy. Although the velocities in a quasi-static simulation are so small that a slight increase of the mass does not lead to a significant change in the system response, the engineer always has to check if the kinetic energy of the system is negligibly small after increasing the density. With this mass-scaling technique very low loading rates can be achieved in an acceptable computational time.

4.2 Influence of Modelling Parameters (Mesh Size, Model Size…)

Besides the loading rate and simulation time a number of other parameters have a strong influence on the simulation results, first of all the mesh size. Although coarser meshes reduce the computational cost, they are not able to accurately represent cell wall folding phenomena. A convergence study of different element sizes from 0.8 mm to 0.15 mm was performed for a honeycomb model in flatwise compression. The resultant stress-strain curves show an equal behaviour in the elastic beginning but large differences in the post-buckling regime (Fig. 11). The reason is the inability of coarse meshes to represent the folding phenomena correctly. The results converged for element sizes below 0.2 mm. Also the model size, i.e. the number of unit cells, has an influence on the resulting stress-strain curve. This is especially true for free specimen edges without boundary conditions, but also for models with symmetric or periodic boundary conditions at the specimen edges. Even in an ideal model and in particular in a model with imperfections not all cells fail at the same time, which results in a smoother effective stress curve in case of a larger number of cells. For a comparison with experimental data, the model size should ideally be of the same dimension as the test specimen. Further parameters having an influence on the simulation results are the material model, element type, and mass scaling.

![Fig. 11: Influence of element size on compressive stress-strain curve for honeycomb model](image)

4.3 Comparison with Experimental Data

The final simulation results of virtual tests on honeycomb and foldcore models after calibrating the simulation parameters and material model values are discussed as follows. Two different criteria have to be met for a satisfying correlation with experimental test results. Firstly, the effective stress-strain curves should be comparable, especially with respect to the elastic stiffness, the strength value and the post-damage stress level. Secondly, the structural cell wall deformation pattern with buckling, folding or crushing mechanisms has to be consistent with experimental observations. This is mandatory for comparability and typically facilitates the compliance of the stress curves as well.
• Hexagonal Nomex® honeycomb (cell size 3.2 mm, density 48 kg/m³, height 15 mm):

Flatwise compression tests in thickness direction of Nomex® honeycomb specimens showed the following cell wall deformation mechanisms. After an elastic compression the cell walls buckle and the stress-strain curve becomes nonlinear. The load can still be increased until the cell walls collapse and the first fold develops with the stress level dropping to about 50% of the peak value. Starting from here, a continuous folding of the cells can be observed under an almost constant plateau stress level, with a total of 21 folds for a 15 mm thick specimen. Once the structure is compacted, the stress level rises again steeply in the densification regime.

This behaviour could exactly be covered by the LS-DYNA model with MAT54 for the cell walls, Belytschko-Tsay shell elements with a length of 0.2 mm, node-shaking and reduced properties for imperfection compensation and a loading rate of 15 mm/s combined with mass-scaling. The cell wall deformation with its buckling and folding pattern and the stress-strain curve of one unit cell are shown in Fig. 12. The simulation curve shows many oscillations, each representing one fold of the unit cell. The comparable experimental curve is much smoother resulting from a larger number of cells. A larger simulation model also leading to a smoother curve is shown in Fig. 13a. However, besides higher discrepancies for large strains the simulation curve correlates satisfactorily to the test data. Similar virtual tests for the identification of the transverse shear (Fig. 13b) or in-plane compression behaviour (Fig. 13c) were also conducted with a good correlation to experimental results.

![Fig. 12: Hexagonal honeycomb unit cell deformation and stress-strain curve for flatwise compression](image1.png)

![Fig. 13: Nomex® honeycomb cell wall deformation in simulation and experiment for flatwise compression (a), transverse shear (b) and in-plane compression (c)](image2.png)
• Over-expanded Nomex® honeycomb (cell size 4.8 mm, density 48 kg/m³, height 15 mm):

For the model of the over-expanded honeycomb only the cell geometry was changed in the parametric model generation tool. Everything else like the material model and properties or the element type and size (0.2 mm) were identical as in the hexagonal model before. The resulting stress-strain diagram for flatwise compression, shown in Fig. 14, again corresponds satisfactorily to the experimental curve with a slight underestimation of the compressive strength. Again, the stress level in the simulation before compaction is significantly lower than in the experiment, indicating that some friction or contact mechanism during the folding process might not be covered sufficiently by the simulation model.

![Fig. 14: Over-expanded honeycomb unit cell deformation and stress-strain curve for flatwise compr.](image)

• Kevlar® folded core (density 48 kg/m³, height 30 mm):

The mechanical behaviour of the Kevlar® foldcore’s cell walls under flatwise compression is comparable to the Nomex® honeycomb. After a linear elastic compression the cell walls buckle and subsequently are folded under a nearly constant plateau stress level until compaction. The LS-DYNA model is based on the isotropic material model MAT24 with the parameters defined in a parameter identification procedure with LS-OPT, as described before. The element length in this case, based on a convergence study, was chosen as 1.25 mm, because the cells are significantly larger as for the honeycomb model. Since hourglass effects occurred in this model, fully integrated elements (type 16) had to be used. A relatively high loading rate of 200 mm/s was chosen in order to complete the parameter identification procedure in an acceptable time, which involves a large number of calculations. No mass scaling was used and it was demonstrated that this loading rate does not change the structural response. The comparison between experiment and simulation for flatwise compression is shown in Fig. 15. The cell wall deformations as well as the stress-strain curves match with a high degree of accuracy. A greater difference can be seen in case of transverse shear tests. While the curves in WT-plane match consistently, a discrepancy in the TL-plane is visible. After reaching the shear strength, the experimental curve drops to a very low level, while the stress level in the simulation remains higher.

![Fig. 15: Kevlar® foldcore cell wall deformation and stress-strain curve for flatwise compression](image)
The reason for this behaviour is a debonding of the cell walls and the skin during the experiment (see Fig. 16), resulting in a drop of the stress values. Such a failure is not possible in the simulation, since no debonding failure was implemented in the contact formulation. Therefore, the simulation curve shows the core shear behaviour as it would be with a better bonding performance. Based on this good correlation, the validated Kevlar® foldcore model was also used to characterise the complete compressive, tensile and shear behaviour in all in-plane and out-of-plane material directions using virtual tests. These results could be used for a homogenised modelling of the core in a sandwich structure, see [40] for the complete stress-strain curves.

![Fig. 16: Kevlar® foldcore cell wall deformation and stress-strain curve for transverse shear](image)

- CFRP folded core (density 102 kg/m³, height 28 mm):

The mechanical behaviour of the CFRP foldcore cells is different to the aforementioned aramid paper core structures. After cell wall buckling under flatwise compression the cells do not fold but fracture due to the brittle nature of the composite laminate. This leads to a drop of the compressive stress to a very low level. The simulation model, built with MAT54 in LS-DYNA and Belytschko-Tsay shell elements with a side length of 2 mm, is only able to cover this behaviour to a limited extent. The cell wall buckling and fracture initiation with the steep drop of the stress level are represented correctly (Fig. 17), but once a complete row of elements is deleted, the compression force drops to zero. Due to the angular geometry of the folded core cells, the elements do not come into contact again. The force does not increase until the upper and lower halves of the failed foldcore have contact with the compression plates. For this reason, the post-damage behaviour cannot be represented correctly with this approach. Different simulations were performed introducing a row of trigger elements with lower strength values at the top of the unit cell intending a continuous crushing by means of the crush-front algorithm in the LS-DYNA material model MAT54. But still the model failed row by row leading to respective compression force drops to zero. Such FE-simulations of in-plane crushing of composite materials have been pointed out as problematic tasks before [47], [48]. Additionally, in the experiment a certain residual connection of the two fractured cell wall halves remained through single intact fibres (Fig. 18), so that a complete disconnection as in the model did not occur, influencing the post-damage behaviour. However, the behaviour prior to failure could be modelled with an acceptable degree of accuracy.

![Fig. 17: CFRP foldcore unit cell deformation and stress-strain curve for flatwise compression](image)
Despite these limitations, the model was used to identify the stress-strain response under compression, tensile and shear loads in all three material directions through virtual testing as in case of the Kevlar® foldcore before. These complete mechanical property data were again used for homogenised core modelling and could not be obtained as easily by experimental test series.

Fig. 18: CFRP foldcore cell wall fracture in simulation and experiment for flatwise compression

5. Optimisation of Sandwich Core Geometry

The LS-DYNA models described so far showed the potential to predict the mechanical response of cellular core structures in virtual test series with a high degree of accuracy. Therefore, the next step obviously is the utilisation of this method in the development process of new core geometries, tailored for specific applications. Based on the parametric model generation tool and the virtual testing simulations, this technique is much more efficient than producing core prototypes (and the respective toolings as well) and testing them in a lab.

In the following study, such an optimisation of the core geometry for a specific target was performed for the CFRP foldcore. The target in this case was to maximise the compressive strength of the core structure while maintaining the global density of 102 kg/m³ and the height of 28 mm from the reference geometry. Additional requirements regarding the producibility of the structure with respect to a minimum cell wall size were also taken into account. The shear properties were allowed to be slightly lower.

In a first step, the aim was to investigate the influence of changing single geometric parameters (three different edge lengths \( l_1, l_2 \) and \( S_1 \), see Fig. 6) on the compressive properties. Therefore, the parameters were changed individually and the resulting stress-strain curves, obtained in compression test simulations in LS-DYNA, were divided by the resulting density. This is necessary, since the parameter change affected the overall density, and the results had to be comparable. In a second step, two parameters were changed at the same time, while the third one was kept constant. The other two were changed in such a way that the overall density always was constant. This was done using the following equations for the density of the CFRP foldcore according to Fig. 6.

\[
\rho_{\text{CFRP foldcore}} = \frac{t \cdot \rho_{\text{CFRP}} \cdot (2 \cdot A_1 + A_2)}{S_1 \cdot l_2 \cdot h}
\]

with

\[
A_1 = \sqrt{q(q-a)(q-b)(q-c)}; \quad A_2 = S_1 \cdot S_2 \quad q = \frac{a+b+c}{2}; \quad a = l_1; \quad b = \sqrt{h^2 + (l_2 - S_2)^2}; \quad c = \sqrt{(l_2 - S_2) + V}^2 + S_1^2 + h^2.
\]

With the help of this information an improved geometry could be defined, which is shown in Fig. 19a. Compared to the original geometry the cell walls are smaller, which corresponds to higher buckling loads, and the vertical angle is lower, which leads to a cell wall orientation more parallel to the transversal load direction.

As can be seen in Fig. 19b the buckling load could be increased by 66%, the compressive strength by 29% and the compressive stiffness by 2% while maintaining the same density and core height. The optimisation was only performed with respect to the compressive behaviour. However, the effect on the shear behaviour was analysed in subsequent shear test simulations. In the TW-plane the transverse shear strength increased by 44% and the shear stiffness by 59%. In the TL-plane the transverse shear strength decreased by 33% and the shear stiffness by 37%.
Conclusions

The method of virtual testing of cellular sandwich core structures using dynamic FE simulations as an efficient alternative to experimental test series was presented in this paper. This study included different core structures – hexagonal and over-expanded honeycomb cores as well as folded cores of different geometries and materials – all showing a different mechanical behaviour under compression and shear loads. The respective material modelling in LS-DYNA, the methods to include imperfections in the model and the influence of simulation parameters like the mesh size were addressed. The results of virtual testing simulations showed a good correlation to experimental results with respect to cell wall deformation mechanisms and stress-strain data. Therefore, these models can not only be used for the complete characterisation of the mechanical behaviour under compression, tension and shear loading in all in-plane and out-of-plane directions, which is usually not done experimentally. They also allow for a detailed investigation of cell wall deformation patterns and failure modes to get a better understanding of the structural behaviour, which can be difficult using solely experimental observations. To show that this efficient virtual testing method is suitable for the development of cellular core geometries for specific requirements, an optimisation study of a CFRP foldcore geometry with respect to its compressive behaviour was performed. However, the limitations of this approach always have to be kept in mind. Not only do a large number of parameters affect the simulation results and have to be adjusted with care, but also a detailed knowledge of the cell wall material properties and imperfections is essential for an adequate modelling. In an experimental test series a certain number of specimens are typically tested to account for statistical deviations or scatter of the properties, also caused by imperfections and irregularities. The virtual testing simulation on the other hand leads to just one single solution. To be able to make a statement on theoretical scatter and to quantify the influence of the modelling parameters, stochastic simulation methods are a possible valuable extension to this study.

References
