Numerical Determination of the Nonlinear Effective Mechanical Properties of Folded Core Structures for Aircraft Sandwich Panels

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ABSTRACT:

Folded core structures are the focus of numerous research projects with regard to advanced aircraft sandwich panels. Impact or crash simulations with such types of cellular structures require knowledge of the homogenized mechanical properties, since a detailed cell wall modeling approach is impracticable for large sandwich structures. One way to determine these nonlinear effective mechanical properties is extensive experimental testing under compressive, tensile and shear loading. Another way is to use detailed finite element models of the cellular core in combination with virtual material testing. In this case, a variation of geometric or constitutive parameters can easily be performed in order to optimize the structure's mechanical properties. This paper describes the development of such detailed folded core models in LS-DYNA. The parameter identification of the cell wall material and the validation of the models were performed by means of an optimization with LS-OPT with regard to basic experimental data of the core manufacturer. Merits and limits of this approach are discussed. The application of the folded core material model for drop test simulations of a sandwich fuselage barrel is briefly addressed.

Keywords:
Folded core, sandwich structures, material modeling, effective mechanical properties, virtual material testing, aircraft fuselage, drop test

INTRODUCTION

Composite sandwich structures made of fibre-reinforced plastic (FRP) faces and a honeycomb core have a successful history as lightweight materials in commercial aircraft design due to their outstanding weight-specific stiffness and strength properties. They are not only used for aircraft interior components (e.g. overhead bins, floor panels, etc. [1]) but also for numerous exterior parts (e.g. radome, rudder, aileron, aerodynamic fairings, etc. [2]). The application of this design concept to primary structures, i.e. the aircraft fuselage, offers a high potential for weight saving and function integration and has so far only been utilized for small business jets [3]. However, this concept poses a number of challenges to the designer, like condensing and accumulating water in the honeycomb cells resulting from the temperature difference between ground and air. Therefore, the commercial aircraft manufacturer Airbus has developed a promising concept for a sandwich fuselage named VeSCo (Ventable Shear Core) [4]. As the name suggests, a ventable core with open cells is one of the principles of this concept, allowing for handling of the condensate, which is not possible with closed honeycomb cells [5-7]. This advanced core structure is a folded core, which can be produced from almost any sheet material in a number of different geometries in a continuous process [8-13]. The current study focuses on folded cores made of phenolic resin-impregnated Kevlar® paper (Figure 1).

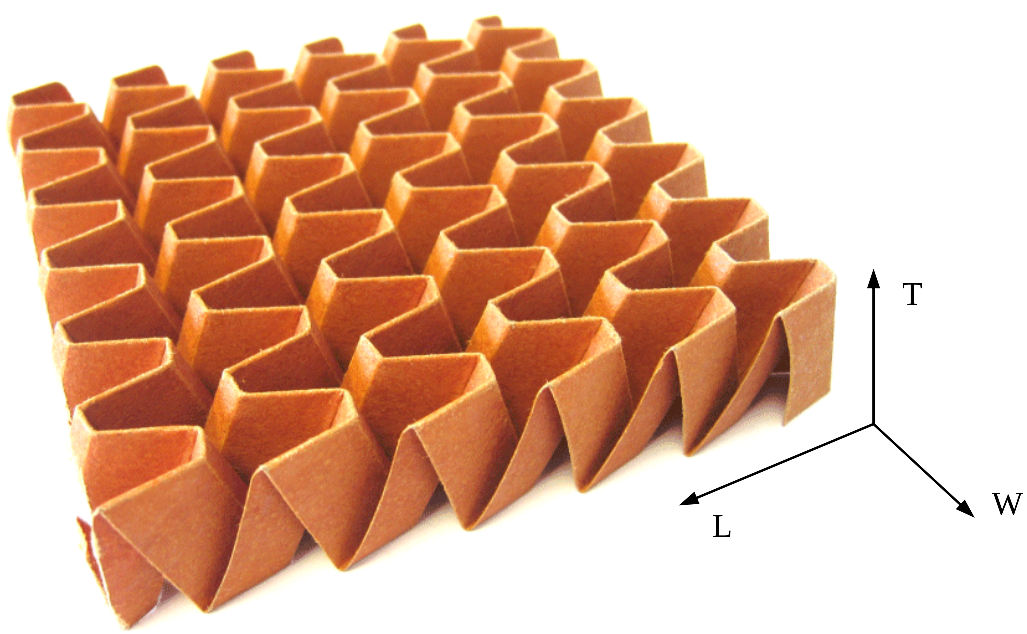

Figure 1: Folded core structure made of Kevlar® paper and its material axes

When it comes to the development of an aircraft fuselage concept, finite element (FE) simulations can be a useful tool in the design process. Not only quasi-static inflight loads have to be accounted for, but also highly dynamic load cases like a survivable crash landing scenario. The crashworthiness of a fuselage is typically evaluated by a vertical drop test [14-16]. Dynamic simulations of a drop test in addition to an experiment for validation reasons can drastically reduce time and cost of development and easily allow for parameter variations. The correct constitutive modeling regarding stiffness, strength and post-damage behavior of the sandwich structure, which is primarily loaded in compression and shear during the crash load, is of great importance. A shell-solid-shell modeling approach with 2D-elements for the FRP faces and 3D-elements for the core has shown to be the best compromise between computational cost and the ability to represent most sandwich failure modes. In this context, the commercial FE-software LS-DYNA [17] offers a homogenized, nonlinear orthotropic material model for honeycomb core structures (MAT 126: MAT_MODIFIED_ HONEYCOMB), which is based on the input of the structure’s effective stress-strain curves for normal and shear loading in all three material directions. This data is typically determined by experimental testing [18, 19]. But since such test series are associated with a large amount of time and cost with regard to specimen preparation and testing devices, an alternative way of determining these nonlinear effective mechanical properties was investigated and is presented in this paper: virtual material testing. The development of micro-scale FE-models of folded core structures and the performance of compression and shear test simulations allow for the efficient determination of the stress-strain data, which is the input for MAT 126 (Figure 2). Furthermore, alternative folded core geometries can easily be considered and even a shape optimization of the cell geometry is possible. A minimum of experimental data is solely necessary for the validation of the micro-scale models, but in this context the stiffness and strength data of the manufacturer initially are sufficient and a test series is not essential.

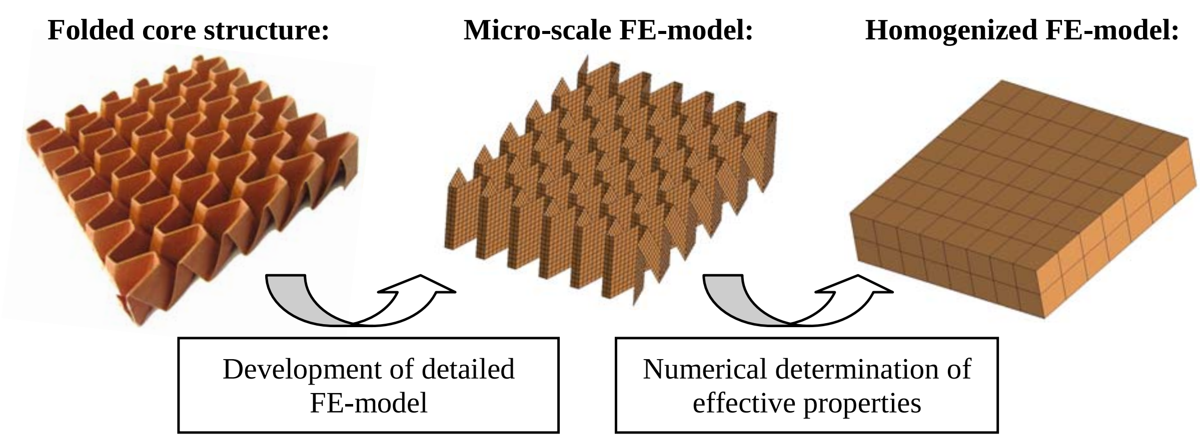

Figure 2: Approach for the numerical determination of the effective properties of folded core structures

Although folded core structures are monoclinic, for simplification reasons they are modelled with the orthotropic material model MAT 126 in this study, neglecting the coupling of in-plane compression and transverse shear.

MICRO-SCALE MODEL OF FOLDED CORE

Micro-scale models of the folded core structure were generated with shell elements of the Belytschko-Tsay type [17] according to the specified geometric data. The influence of mesh size and specimen size on the structure's effective properties was investigated in compression test simulations (Figures 3 and 4). The mesh size influences the ability of representing cell wall buckling in an accurate manner. Therefore, a coarse mesh was impracticable. Very fine meshes led to huge computational cost and instabilities, for which reason the mesh size in the middle of Figure 3 was finally chosen, whose stress level differed only marginally from the finer mesh. The specimen size only had a minor influence on the compressive stress level with slightly higher stresses for large specimens, where the effect of the unsupported free edges is less significant. With respect to computational time, the smallest specimen size was chosen in this study.

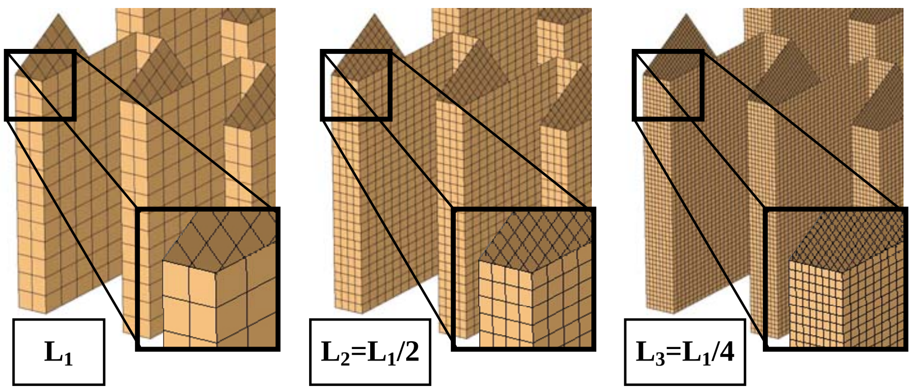

Figure 3: Investigation of the influence of mesh size

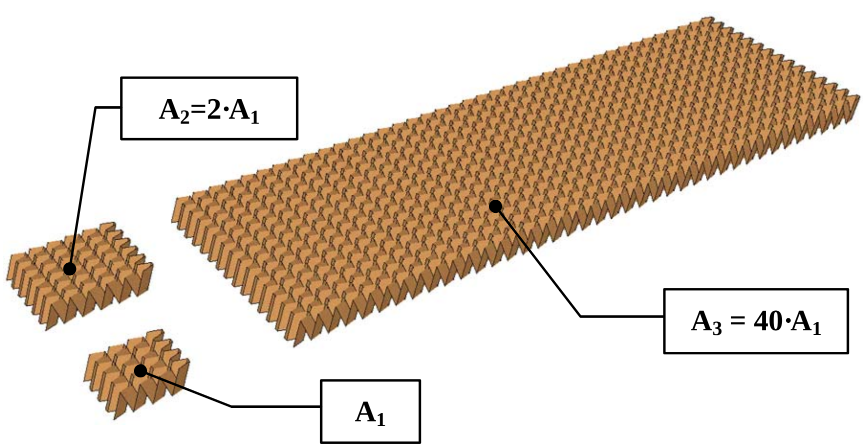

Figure 4: Investigation of the influence of specimen size

PARAMETER IDENTIFICATION OF CELL WALL MATERIAL

Besides the geometry and mesh size of the micro-scale model, the cell wall thickness and material properties have the major influence on the structural behavior of the folded core. Since no reliable data of the phenolic resin-impregnated Kevlar® paper existed, an inverse approach was chosen to specify this data. The three values 1. thickness, 2. Young's modulus, and 3. yield strength of the paper were defined as parameters in the LS-DYNA model. Within an optimization procedure the best set of parameters was to be identified, which leads to effective properties of the folded core that correspond to the manufacturer's data. In this context, the target was to minimize the difference to given flatwise compressive and transverse shear data with regard to stiffness and strength. These are typically the only data specified by core manufacturers, since they most significantly characterize the sandwich core. For this parameter identification the software LS-OPT was used with a quadratic metamodel, three parameters and two simulation models (Figure 5). Although the Kevlar® paper is not isotropic due to the distinctive machine direction orientation of the fibers, the material model used for the cell wall material in this investigation was the bilinear isotropic model MAT 24 in order to limit the complexity of this study. The starting values were adopted from unimpregnated Kevlar® paper and led to an overestimation of the folded core properties. The reason for this behavior will be discussed later. After 12 iterations, an optimum parameter set with a good consistence to the target values was determined. Furthermore, it was assured that the cell wall buckling and folding pattern agreed with experimental observations.

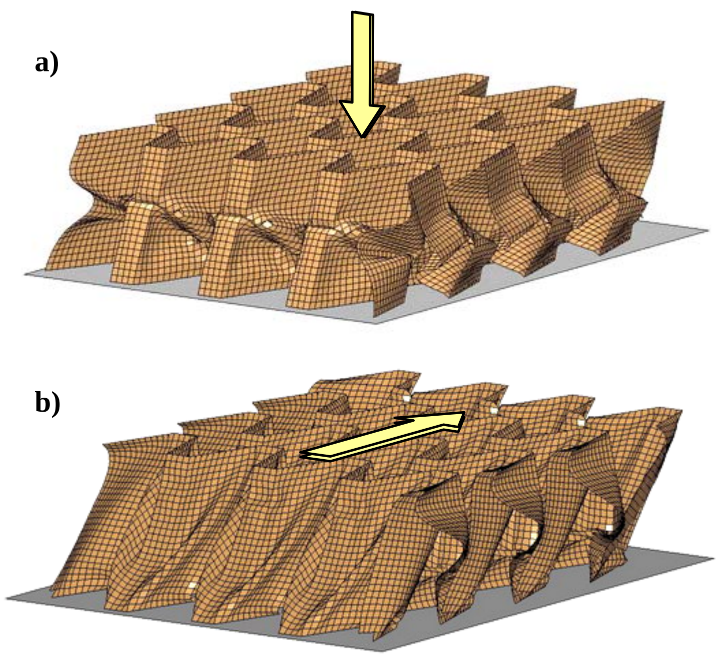

Figure 5: Folded core under a) flatwise compression and b) transverse shear load

VIRTUAL MATERIAL TESTING

After the parameters of the cell wall paper were determined and at the same time validated against experimental compression and transverse shear data of the core manufacturer, complete quasi-static material testing simulations were performed for compression, tension and shear in all material directions. Although not all of these properties seem to be of greatest importance within a sandwich structure, they all have to be defined in material model MAT 126. Leaving these properties blank can lead to instabilities, making arbitrary assumptions should be avoided. The effective stress-strain curves for compression and shear are illustrated qualitatively in Figure 6. It is noticeable that the curve shapes not only show the typical characteristics of cellular structures, e.g. plateau stresses and compaction regions for compression, but also are very similar to the experimental stress-strain curves of hexagonal honeyombs reported in [18].

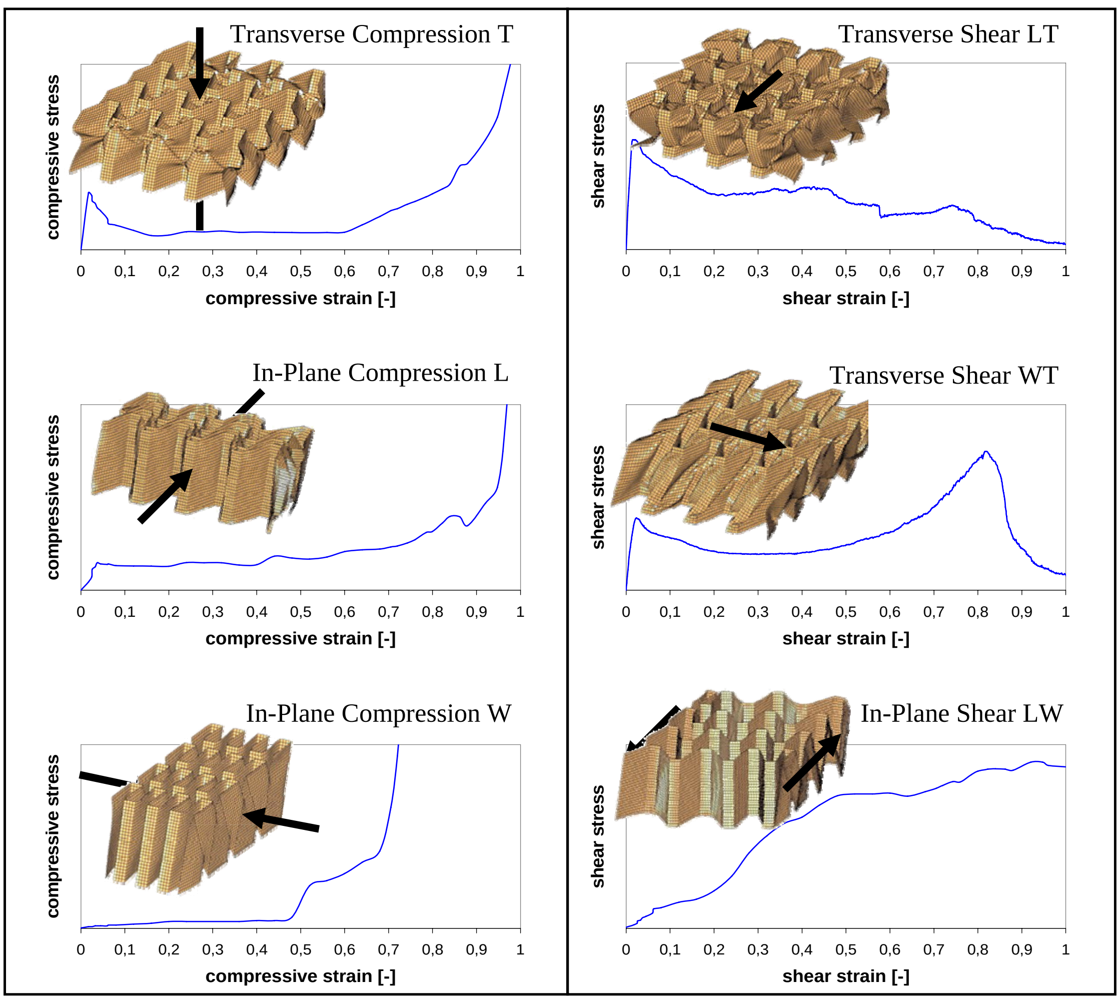

Figure 6: Qualitative stress-strain diagrams of folded core for compression and shear loads in all three material directions

DISCUSSION

The approach of virtual material testing as a promising alternative to extensive experimental testing was presented, in the first instance, on a simplified level. These simplifications are e.g. the utilization of an isotropic material model for the Kevlar® paper. In reality this paper is not isotropic and clearly distinguishes a machine direction and cross-direction. In addition, only the compliance in initial stiffness and strength values was the target of the optimization/parameter identification procedure. The compliance with the post-damage region of the stress-strain curves was not included in the present study. Therefore, the material model parameters affecting the structure's post-damage behavior, i.e. the tangent modulus and plastic failure strain in MAT 24, were kept constant. Figure 7 shows the influence of these two parameters on the stress-strain curves exemplarily for shear load in the LT-plane. The correct representation of the post-damage behavior has a great influence on the energy absorption capability of the core material under crash loads.

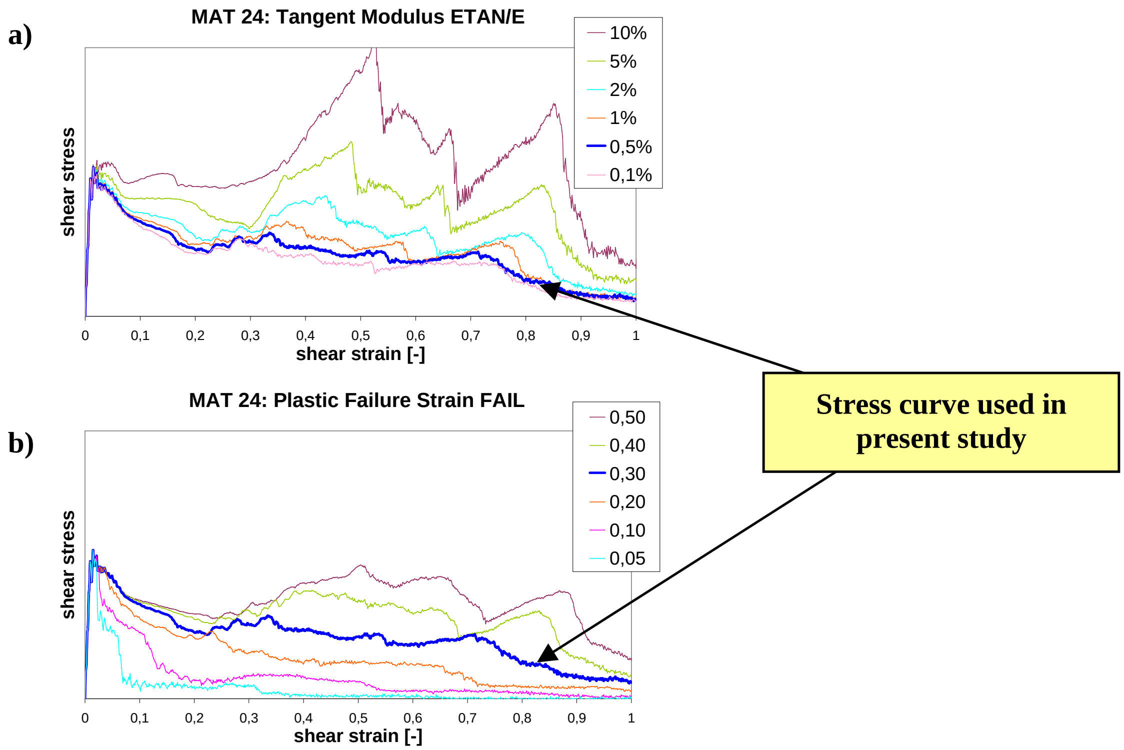

Figure 7: Influence of the parameters a) ETAN and b) FAIL in MAT 24 on the LT shear stress curve

Another aspect of great importance are imperfections in the core structure. The micro-scale model in this investigation literally has a uniformly perfect geometry. Additionally, the folding edges of the core were idealized without consideration of the curvature. In reality no cellular structure is neither uniform in geometry nor free of imperfections. This affects the buckling load of the single cell walls and the whole structure's strength. Therefore, a micro-scale model without imperfections will always lead to an overestimation of strength values. This is the reason why the first iteration with the starting values of Kevlar® paper in the parameter identification with LS-OPT resulted in too high strength levels of the folded core. In this study, the lack of imperfections in the FE-model was compensated by the use of reduced cell wall properties as a result of the parameter identification. However, advanced micro-scale models of cellular structures for virtual material testing should incorporate imperfections by means of a stochastic approach. In this study, only quasi-static simulations were performed. Another challenge is an investigation, if the micro-scale models allow for the determination of rate-dependent properties, since strain-rate effects are known to exist for similar cellular core structures as a result of inertial effects during cell wall bending [20].

APPLICATION TO DROP TEST MODEL

The effective stress-strain curves were transformed in tabular format and implemented in material model MAT 126. This material model was used for the core (solid elements) of the fuselage skin's sandwich structure in a FE-model of a VeSCo fuselage barrel developed in cooperation with Airbus Deutschland GmbH. Figure 8 shows a drop test simulation of the aircraft section representing one of numerous investigated design configurations. Core deformation and damage, especially under shear loads in WT-plane, could be evaluated as a result of such simulations.

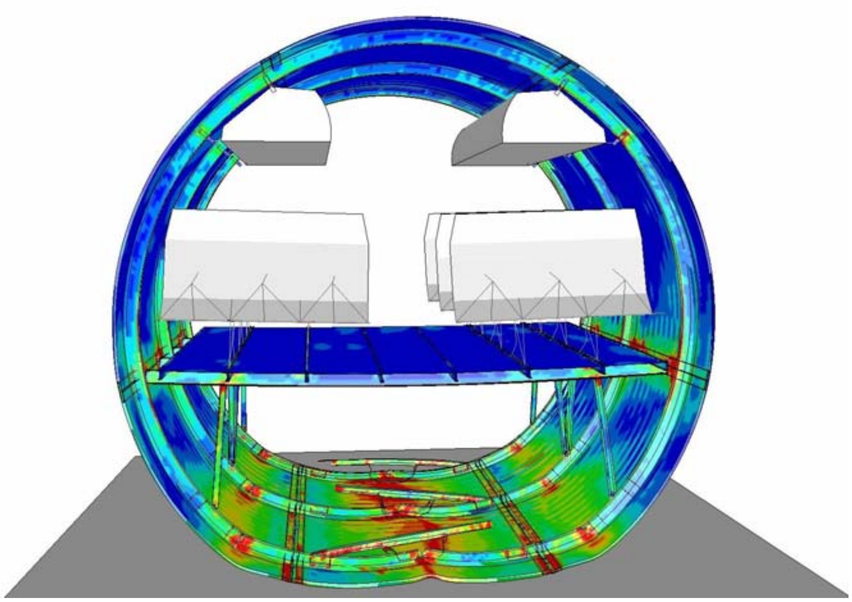

Figure 8: Drop test simulation of sandwich fuselage barrel

SUMMARY AND CONCLUSIONS

Material modeling of sandwich structures with a shell-solid-shell approach incorporating the orthotropic honeycomb material model MAT 126 in LS-DYNA requires knowledge of the nonlinear effective stress-strain curves of the core for normal and shear loads in all three material directions. In this paper a virtual material testing technique of folded core structures was presented as a time- and cost-efficient alternative to extensive experimental testing, which also allows for a shape optimization of the core geometry. A micro-scale model of the folded core was developed and the cell wall parameters were identified in accordance to basic experimental data using LS-OPT. It was shown that simplifications in the micro-scale model of the cellular structure may lead to inaccuracies in the results, so that e.g. imperfections should be incorporated in the model. Altogether, the numerical determination of the effective properties of sandwich core structures by virtual testing turned out to be a promising method, which could be adopted for drop test simulations of an advanced sandwich fuselage barrel.

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