

Honeycomb Sandwich Material Modeling for Dynamic Simulations of Aircraft Interior Components

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Abstract

An approach for modeling sandwich structures with a Nomex[®] honeycomb core and phenolic composite faces in the commercial finite element code LS-DYNA with solid elements for the core and shell elements for the thin faces is presented, which accounts for the major sandwich failure modes. Extensive material testing was conducted to determine the parameters for the composite face material model and for the orthotropic honeycomb material model. Strain rate dependency of the material parameters as well as face-to-core debonding phenomena were also investigated and included in the model. In order to design aircraft interior components for dynamic loads, finite element models of lateral and center bins of a widebody aircraft cabin were created and simulations of different load cases were performed. A good correlation to experimental dynamic test results could be achieved.

Introduction

Overhead stowage compartments in commercial aircrafts may be subjected to high loads due to heavy baggage. Furthermore, in case of hard landing or turbulence these loads can be highly dynamic. Structural integrity has to be assured in either case. Currently these stowage bins have typically been designed for static loads. In order to investigate the dynamic behavior of such bins, numerical simulations with the commercial explicit finite element (FE) code LS-DYNA [1] were used in addition to dynamic testing. This allows a detailed analysis of the structural behavior with the objective of safety warranty and weight reduction.

Like most aircraft cabin components the stowage bins are made of lightweight sandwich structures (Fig. 1). These are a special kind of composite structure with a lightweight core separating two thin and stiff faces in order to increase the second moment of inertia and therefore the bending stiffness according to the I-beam principle (Fig. 2). The faces primarily carry the tensile and compressive loads due to bending while the core resists transverse normal and shear loads [2]. For passenger transportation applications like aircraft cabins, fiber reinforced phenolic resins are typically used as sandwich face material and aramid/phenolic (Nomex[®]) honeycomb structures are chosen for the core, because of their excellent fire safety properties. The faces are usually made of prepregs (pre-impregnated fabrics) utilizing a special phenolic resin that liquefies at high temperatures in the autoclave during the bin manufacturing process and forms a fillet joint with the honeycomb cell walls requiring no additional adhesive.

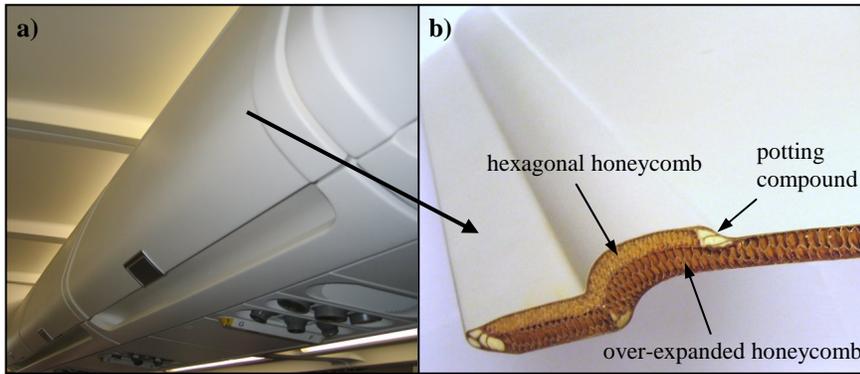


Fig. 1. a) Center bin of commercial aircraft made of honeycomb sandwich structures, b) cross section of flap

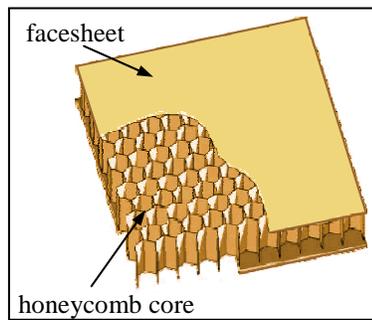


Fig. 2. Honeycomb sandwich structure

A variety of failure modes can occur in sandwich structures depending on the type of load, the constituent materials and clamping conditions (Fig. 3). Local core crushing may occur due to impacting baggage corners, often leading to a face-to-core debonding, so that no more shear forces can be carried by the sandwich structure [3]. High bending loads can lead to face fracture or core shear failure. Face wrinkling, shear crimping or global buckling failure can occur as a consequence of compressive loads in the sandwich plane [4]. Further failure modes at load introduction points (inserts) and edge joints are possible [5, 6].

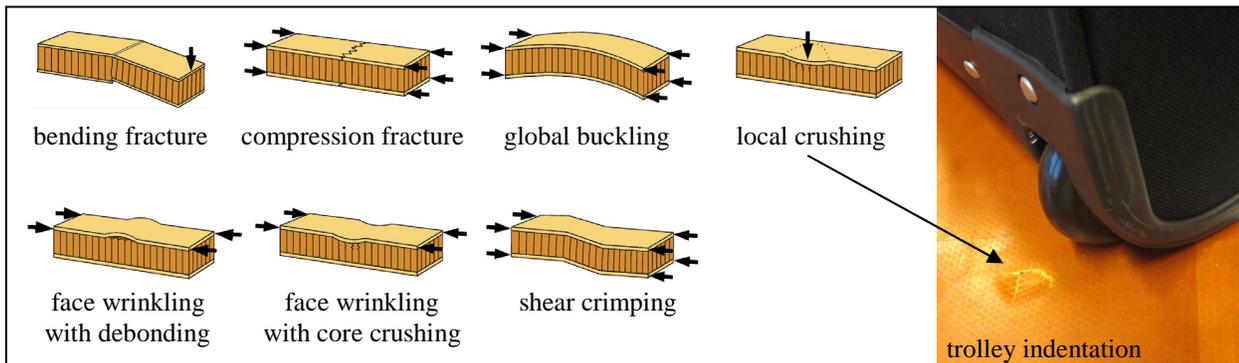


Fig. 3. Sandwich structure failure modes

The orthotropy and the inhomogeneity as well as the number of failure modes make the analysis of honeycomb sandwich structures no trivial task. Different approaches for modeling sandwich structures by the FE method exist, which differ in modeling/computational cost and accuracy of the results and their adoption depends on the specific model size and loading case.

A detailed representation of the hexagonal cells with shell elements (Fig. 4b) can predict the cell wall deformation for impact simulations reasonably well, but is unsuitable for large scale models due to the computational cost [7-11].

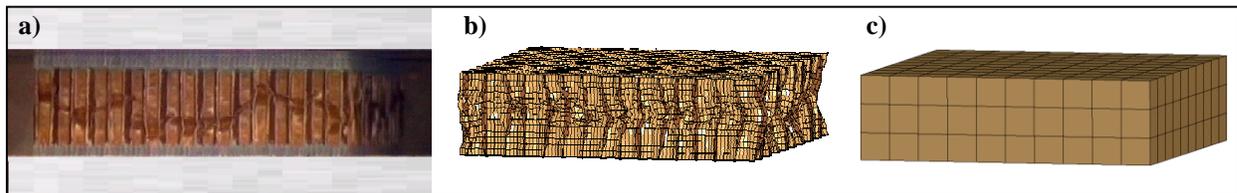


Fig. 4. Cell wall buckling in hexagonal Nomex[®] honeycomb subjected to transverse compression:
a) experiment, b) detailed cell wall modeling, c) modeling with solid elements

A simplification is to represent the cellular core as a homogeneous continuum using the honeycomb structure's effective orthotropic material parameters (Fig. 4c). Solid elements for the honeycomb core and for the sandwich faces were used in [11, 12]. In this case the small face thickness leads to a very small element edge length. In [3], [13-15] the faces were modeled with shell elements instead. A further simplification is the representation of the whole sandwich structure with shell elements, in which the faces and core are defined as separate layers [16-18]. Alternatively user-defined sandwich elements are often used [19-21]. However, most of these 2D modeling approaches are not able to account for the major sandwich failure modes.

Since the objective of the dynamic simulation of the aircraft stowage bins is the representation of most failure modes, the three-dimensional modeling approach with solid elements for the core and shell elements for the face sheets was adopted.

Material Models

Composite faces

For the GFRP faces material model #58 (*MAT_LAMINATED_COMPOSITE_FABRIC) and model #158 (*MAT_RATE_SENSITIVE_COMPOSITE_FABRIC) of the LS-DYNA material model library were used for shell elements. These constitutive models are based on the theory of continuum damage mechanics [22]. It is assumed that the deformation of the material introduces micro-cracks and cavities, which reduce the material stiffness. This is expressed through internal damage parameters, which describe the evolution of the damage state under loading and hence the stiffness degradation [23]. Five failure criteria for the woven fabric composite are used: tensile and compressive failure in warp and weft direction as well as shear failure.

Material model #158 is an enhancement of #58 and additionally incorporates simple strain rate effects [1]. A viscous stress tensor is calculated on the basis of a generalized Maxwell model, where up to six terms in the Prony series expansion can be defined through their shear relaxation modulus and shear decay constant. This viscous stress tensor is then superimposed on the rate independent stress tensor.

For comparability reasons some simulations were run using the orthotropic material model #54 (*MAT_ENHANCED_COMPOSITE_DAMAGE) [24]. However, this linear elastic-perfect plastic model based on the four failure criteria by Chang-Chang is not recommended for

modeling woven fabric composites, since different failure surfaces with different shear interaction exist in warp and weft direction that are not compatible.

Honeycomb core

For reasons of simplification, the cellular honeycomb core structure is treated as a homogeneous material using its effective orthotropic material properties. The honeycomb material directions are defined as the L-direction (ribbon direction), W-direction (direction perpendicular to the ribbon) and T-direction (thickness direction) (Fig. 5).

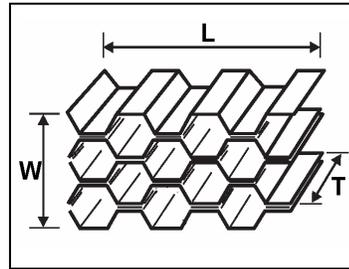


Fig. 5. Honeycomb material directions

For the honeycomb core LS-DYNA material model #126 (*MAT_MODIFIED_HONEYCOMB) was used in combination with the one point co-rotational solid element type. In this orthotropic material model nonlinear elastoplastic constitutive behavior based on experimentally determined stress-strain curves can be defined separately for all normal and shear stresses. These are considered to be fully uncoupled ($\nu = 0$). To represent strain rate sensitivity, a scale factor versus effective strain rate, which is the Euclidean norm of the deviatoric strain rate tensor, is defined that scales the stress curves [1]. For the connection between core and face elements a tiebreak contact formulation was used.

Material Testing

In order to determine the parameters for the constitutive models and to verify these models, extensive material testing was conducted on the sandwich constituents and on sandwich components.

Material Properties

The sandwich faces regarded in this study are prepregs made of glass fiber reinforced phenolic resin (GFRP) with a cured ply thickness of 0.33 mm. Tensile testing (DIN EN ISO 527-4) and compression testing (DIN EN 2850) in warp and weft direction as well as the determination of the shear properties (DIN EN 6031) were performed to obtain Young's modulus, shear modulus, tensile and compressive strength in warp and weft direction, shear strength and Poisson's ratio. Since the LS-DYNA honeycomb material model #126 requires the input of 6 uncoupled engineering stress-strain curves for normal and shear loads, compression tests in L-, W- and T-direction (DIN 53291, Fig. 6a and 6b) and shear tests in LT-, WT- (DIN 53294, Fig. 6c) and LW-plane (EFA-CFC-TP-008, Fig. 6d) were performed on Nomex[®] honeycomb specimens (C1-3.2-29, C1-3.2-48 and C1-4.8-48ox, manufacturer Schütz Cormaster). The obtained engineering stress-strain diagrams were used for the material model in tabular form (Fig. 7 - 12).

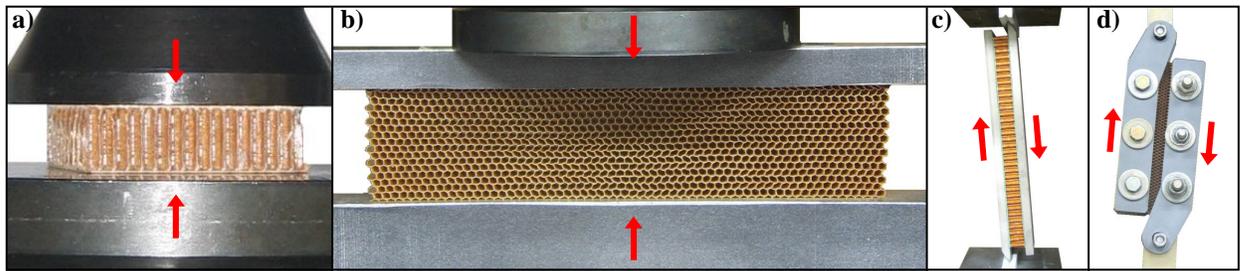


Fig. 6. Honeycomb material testing: a) compression in T-direction, b) compression in L- and W-direction, c) shear in LT- and WT-plane, d) shear in LW-plane

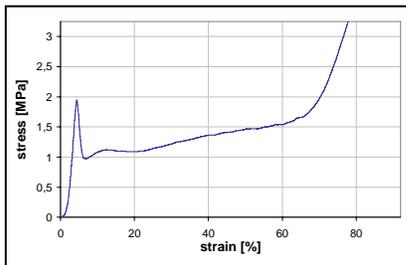


Fig. 7. Compression T

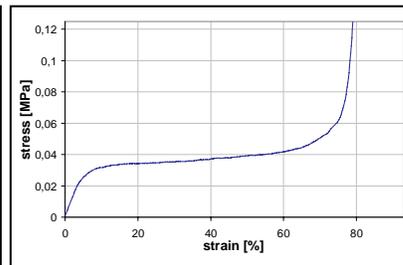


Fig. 8. Compression L

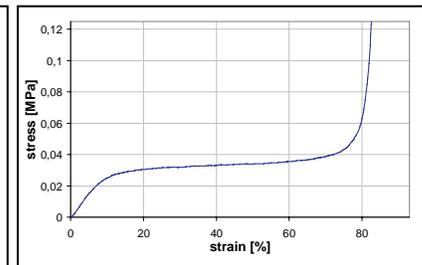


Fig. 9. Compression W

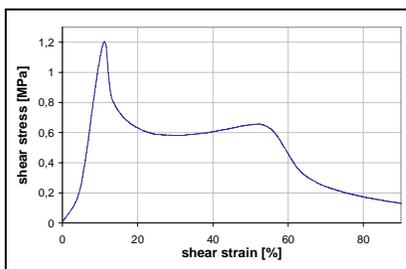


Fig. 10. Shear LT

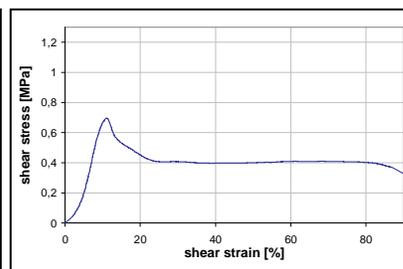


Fig. 11. Shear WT

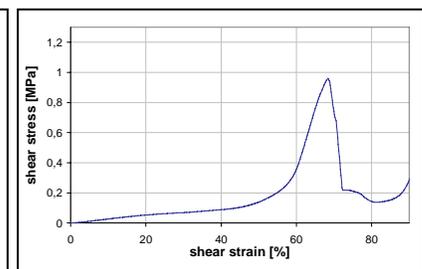


Fig. 12. Shear LW

Strain Rate Effect

High loading rates may influence material behavior, so that parameters obtained by static tests can be inadequate for dynamic simulations. Since an increase in stiffness, strength and failure strain was observed for glass fiber reinforced phenolic composites at high strain rates [25, 26], dynamic testing on a drop tower facility was conducted in addition to the static tests.

A distinctive strain rate effect was identified for the GFRP material. For both normal and shear loading marginal higher stiffness values, up to 86% higher strengths and higher failure strains were obtained at high loading rates (Fig. 13, 14). This rate dependent increase affects the strain rate domain, which occurs in the bin under dynamic loading conditions (strain rates up to 5 s^{-1}), so it has to be accounted for in the simulation (Fig. 15).

To incorporate the strain rate effect in the LS-DYNA composite material model #158, the parameters for the 6 Maxwell elements had to be determined by means of stress-strain diagrams at three different strain rates for both normal and shear loads. A stochastic optimization tool was used to identify a set of parameters, which best represents the six rate dependent experimental curves. However, this viscous stress tensor approach only works well for stress increases due to rate effects up to 15% [1] and could not be used for the 86% increase in this case.

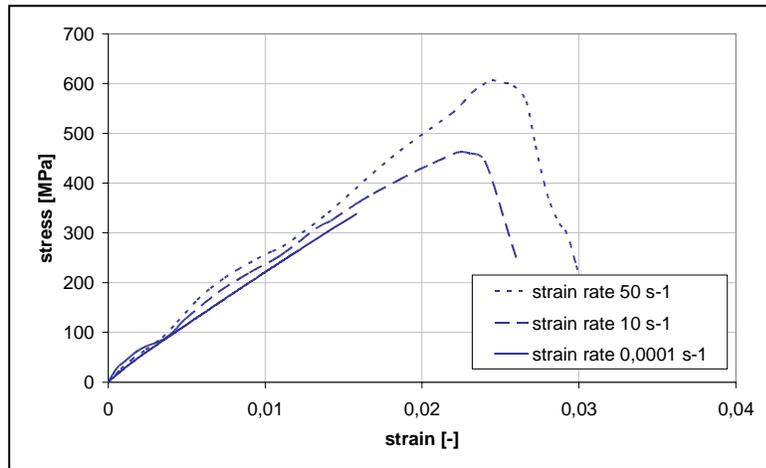


Fig. 13. Tensile stress-strain diagram of glass/phenolic composite at different strain rates

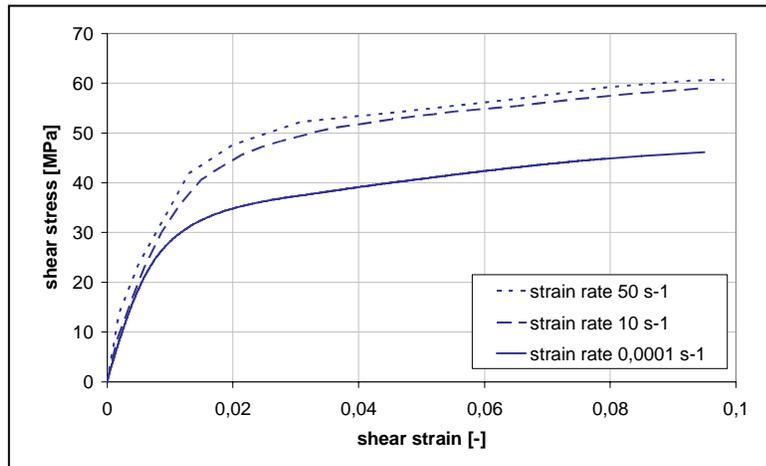


Fig. 14. Shear stress-shear strain diagram of glass/phenolic composite at different strain rates

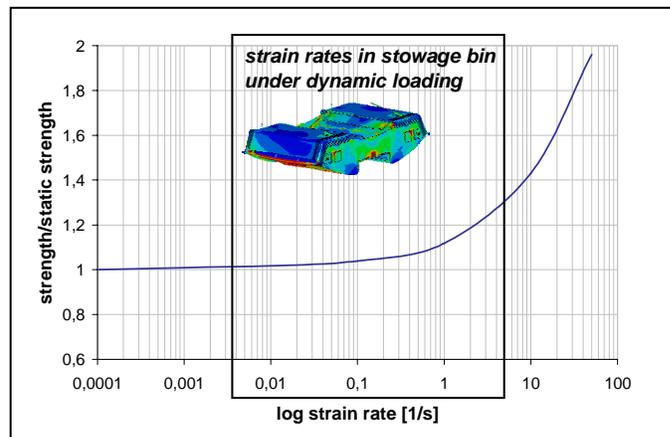


Fig. 15. Strain rate dependent tensile strength increase for glass/phenolic composite

Since a strain rate effect is also known for Nomex[®] honeycomb structures [27], dynamic testing was also conducted on this material on a drop tower facility. The results of six different strain rates (0.002 s^{-1} to 300 s^{-1}) showed an increase of the stress curves up to 30% compared to the previously determined static curves. The scale factor versus effective strain rate for the LS-DYNA material model #126 was identified by means of the experimental results of these dynamic compression and shear tests (Fig. 16).

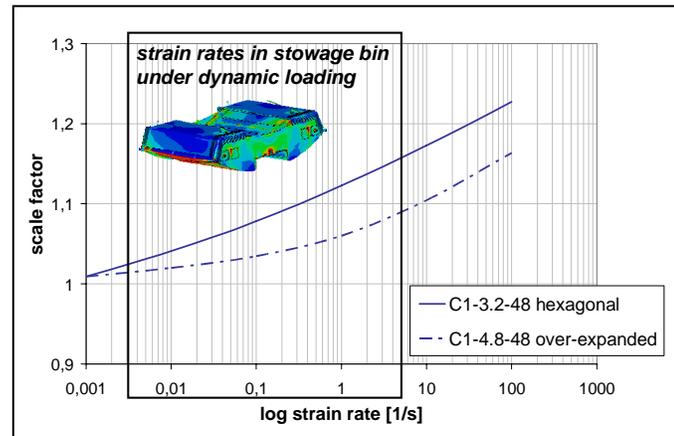


Fig. 16. Strain rate dependent scale factor for honeycomb stress-strain curves

Face-to-core adhesive bond

Because face and core elements in the FE model are connected using a tiebreak contact definition, failure limits for normal and shear interface stresses can be specified in order to represent the failure mode of face-to-core debonding. To determine these values, tensile tests (DIN EN 2243-4), shear tests (DIN 53294) and climbing drum peel tests (DIN EN 2243-3) were conducted on sandwich specimens (Fig. 17).

Since in most specimens the honeycomb core failed under normal or shear loads prior to the adhesive bond, the determination of failure limits is difficult. They are slightly higher than the honeycomb strengths and were specified heuristically.

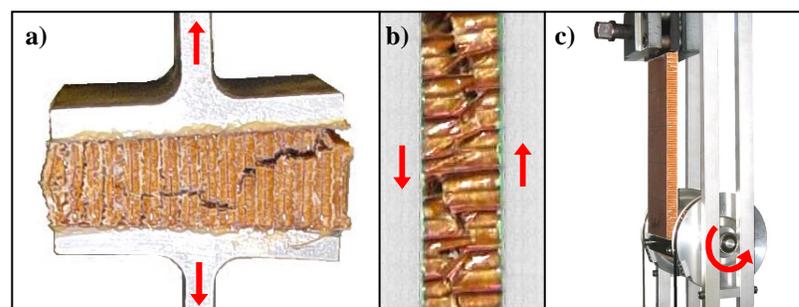


Fig. 17. Testing of face-to-core adhesive bond: a) tensile test (core tensile failure), b) shear test (core shear failure), c) climbing drum peel test

Influence of resin fillets on core properties

So far the material data for the honeycomb material model were obtained using specimens from the honeycomb manufacturer. But during the manufacturing process of the stowage bin in an autoclave, resin of the face prepregs flows through the cell wall corners resulting in resin fillets which increase the core density up to 50% (Fig. 18). The question arises if these resin fillets lead to a reinforcement, which should be accounted for in the material model. Therefore the same compression and shear tests as described before were performed on honeycomb specimens taken out of a bin structure after peeling off the faces. These tests showed that the resin fillets have a negligible influence on the transverse core properties, i.e. compressive behavior in T-direction and shear in LT-/WT-plane. However, the stress curves under in-plane loading increased by a factor of 10 due to the resin fillets on the upper and lower surface. Therefore the stress curves of these sandwich core specimens were used for the honeycomb material model.

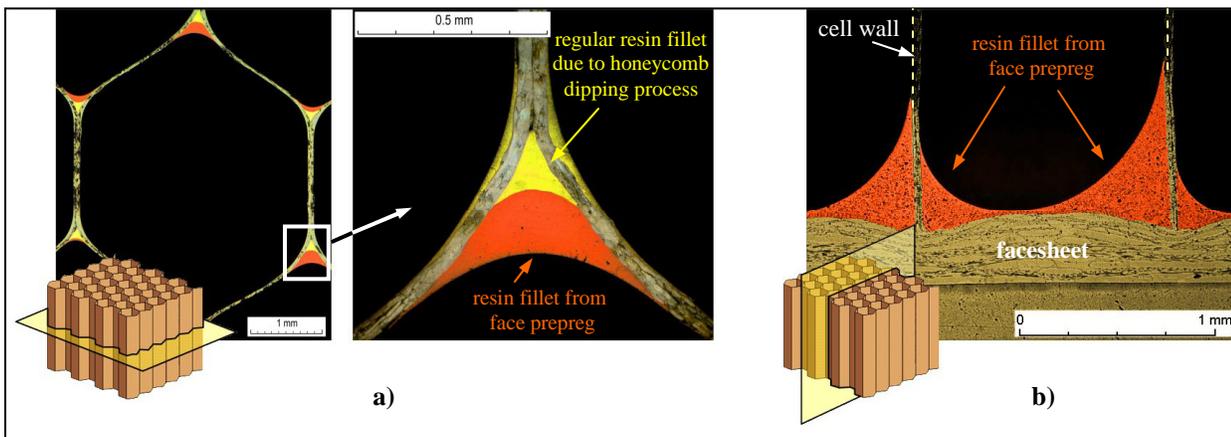


Fig. 18. Microscopic views of a) horizontal cross-section and b) vertical cross-section of Nomex[®] honeycomb sandwich: fillets due to prepreg’s resin are highlighted

This sandwich manufacturing process also leads to uneven faces with a non-uniform face thickness (telegraphing effect, Fig. 18b) and a variation of the fiber volume fraction (Fig. 19). This should be kept in mind when modeling the faces as a homogeneous material with a constant thickness.

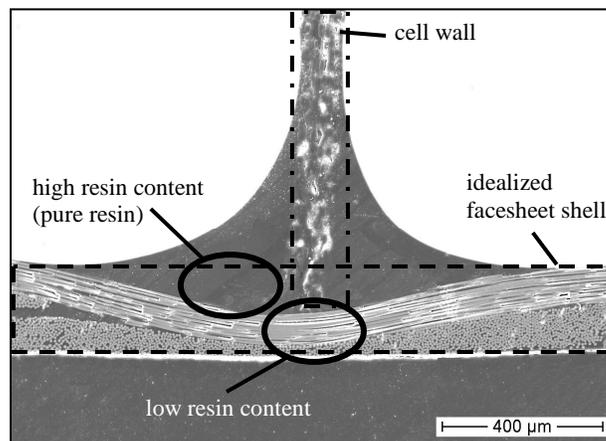


Fig. 19. Scanning electron microscopy (SEM) of bond between Nomex[®] cell wall and woven fabric/phenolic faces: large variation of fiber volume fraction

Sandwich component testing

After developing the material models for sandwich faces and core using respective material tests, experiments on sandwich structures and components were performed in order to verify the material models. The facesheet strength values had to be decreased in order to obtain consistent results. This is explained by the aforementioned unevenness and variation of thickness and fiber volume fraction of the faces in the sandwich structure.

Flexure tests (DIN 53293) were conducted on 15 mm thick GFRP/Nomex[®] sandwich specimens. The LS-DYNA simulation led to a corresponding representation of the core failure (Fig. 20).

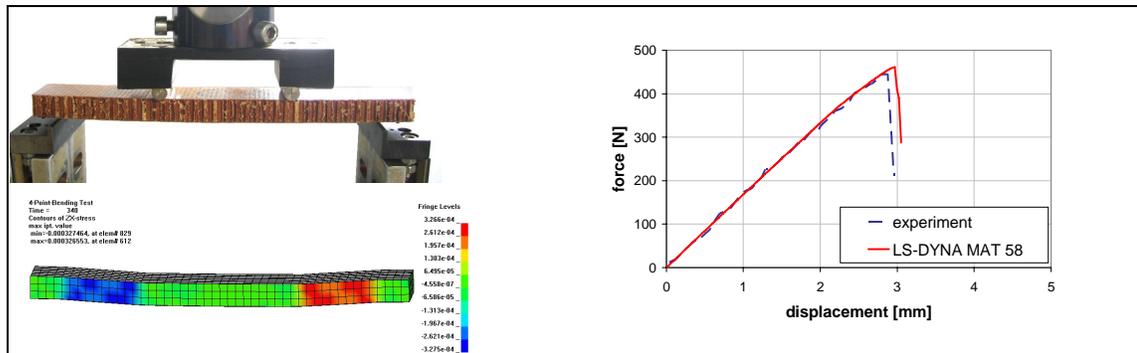


Fig. 20. Flexure test on sandwich specimen: experiment and FE simulation (transverse shear fringe plot)

Edgewise compression tests (ASTM C364) are used for the evaluation of sandwich failure modes under in-plane compression. Such tests were conducted on specimens with different geometries (height, thickness) and materials (GFRP, CFRP, different core densities) for comparability reasons. The GFRP sandwich panels failed in a shear crimping mode, while the major failure mode for CFRP sandwich panels was face wrinkling (Fig. 21). Both failure modes could be represented in the corresponding LS-DYNA simulations.

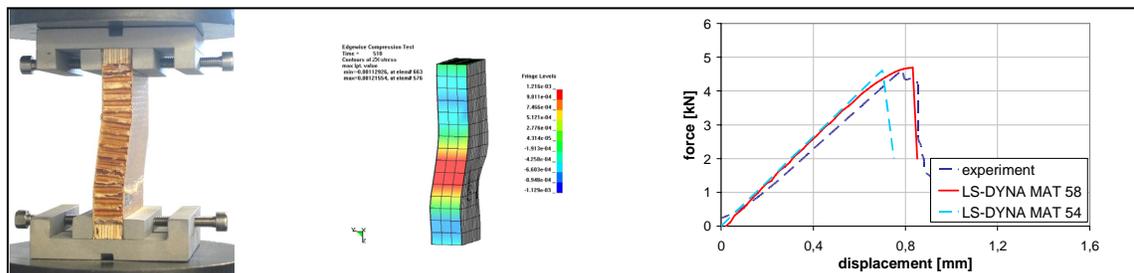


Fig. 21. Edgewise compression test of GFRP sandwich: shear crimping failure

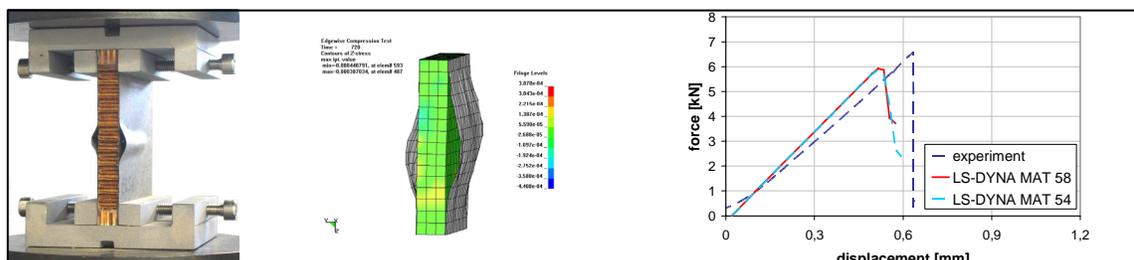


Fig. 22. Edgewise compression test of CFRP sandwich: face wrinkling failure

Since the load introduction points are a potential location for damage of the stowage bin's sandwich structure, pull-out tests of an attached bracket were performed on 15 mm thick GFRP/Nomex[®] sandwich panels. Potting compound was used as core reinforcement at the load introduction points. The experiment resulted in face cracks transverse to the loading direction on both the compression and tensile side of the bracket attachment. The longitudinal cracks led to the catastrophic failure of the sandwich structure. With the LS-DYNA simulation of this test a good representation of the experiment concerning failure progress and failure load could be achieved (Fig. 23).

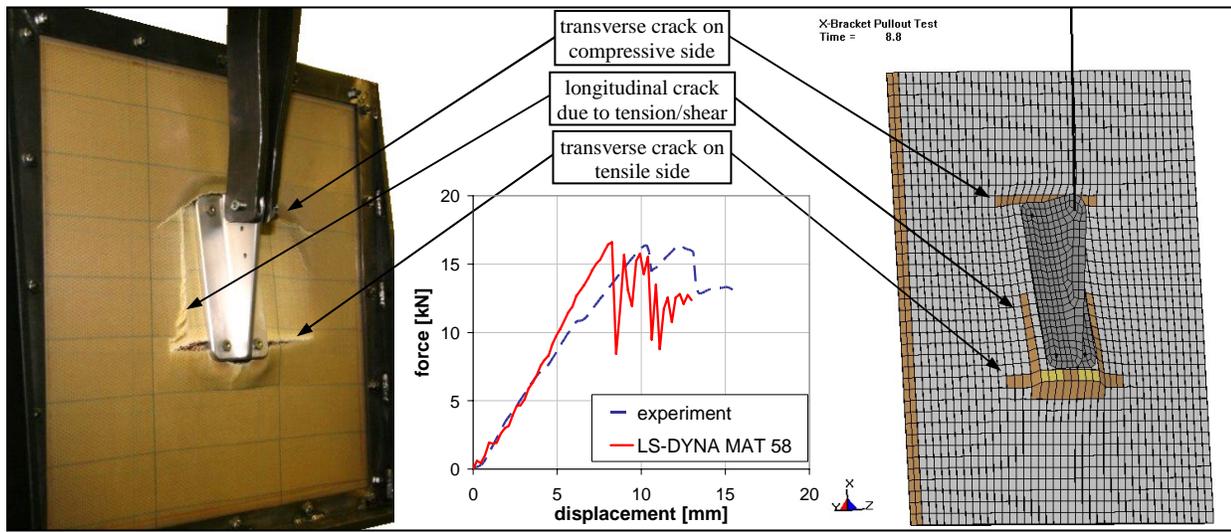


Fig. 23. Bracket pull-out test on GFRP sandwich panel: experiment and simulation

Dynamic Simulations of Aircraft Interior Components

The material models verified by sandwich component tests were incorporated into FE models of functional demonstrators, which represent interior components of a widebody commercial aircraft. Those demonstrators are a lateral (fixed) bin and a center (movable) bin made out of GFRP/Nomex[®] sandwich structures (Fig. 24) with hexagonal honeycomb cores used for plane surfaces and over-expanded honeycombs used for curved surfaces. Areas subject to high stresses were reinforced with additional face layers.

The simulation is based on dynamic tests conducted on a test sled, on which these stowage bins were mounted horizontally and vertically. In the dynamic tests the sled was exposed to a defined deceleration from a constant initial velocity. The bins were equipped with trolleys up to their maximum load capacity.

The FE models of the stowage bins were created with the previously described material models for the sandwich structure. For the faces shell elements with a reduced integration scheme of the Belytschko-Tsay type [1] were used, the core was modeled with one point co-rotational solid elements. During the dynamic tests the accelerations, displacements and forces in the connecting rods were recorded. The LS-DYNA simulations showed a very good accordance with these data in both loading cases. Just like in the tests, the simulated bins kept their structural integrity under the applied load.

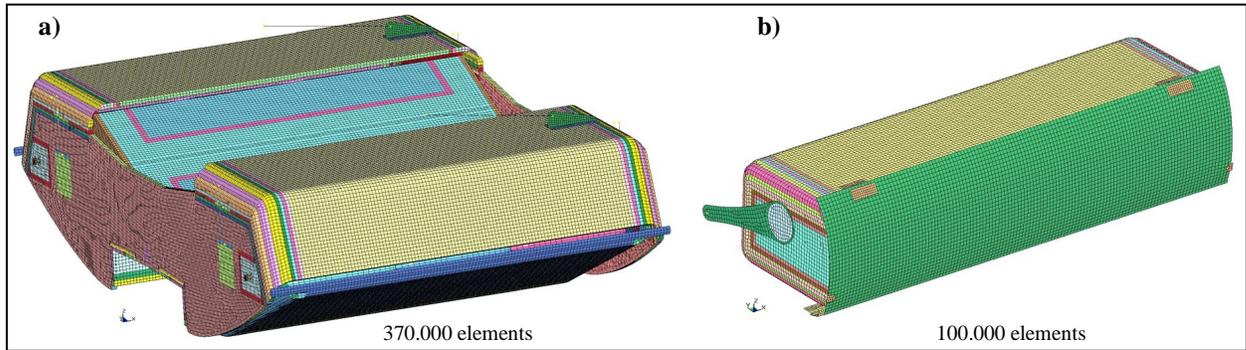


Fig. 24. FE models of overhead stowage bin demonstrators: a) center hatrack, b) lateral hatrack

Even if in this specific case no catastrophic failure of the sandwich structure occurred, the benefit of the verified model is the ability to correctly represent the failure modes. This can be utilized when changing the design of the stowage bins in order to reduce weight or when investigating different attachment points for the connecting brackets. Prototype manufacturing and testing of each configuration would be too expensive in cost and time. Corresponding FE models are generated with a minor effort and are capable of predicting the structural behavior under dynamic loads.

Conclusions

A modeling approach with 3D core elements and 2D facesheet elements was applied to honeycomb sandwich structures, which is capable of representing major sandwich failure modes such as local core crushing, core shear failure, face fracture, shear crimping, face wrinkling and face-to-core debonding. A strain rate effect exists for both face and core materials, which can be incorporated in the respective LS-DYNA material models. The material properties obtained by coupon tests of the respective materials led to consistent results in simulations of sandwich component tests and dynamic tests of aircraft cabin components. However, some uncertainties remain, like the resin flow from the face prepregs that results in a reinforcement of the honeycomb core and change of the face properties. The face thickness varies 1. at the cell walls and in-between, 2. at the inner mould side and the outer vacuum bag side of the sandwich and 3. at surfaces with a different physical configuration in the autoclave. The same is valid for the fiber volume fraction and therefore the composite mechanical properties. This effect has a significant influence on the sandwich structure's mechanical properties but is difficult to quantify for sandwich modeling.

Acknowledgement

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