Towards the Accurate Numerical Prediction of Impact Damage and Residual Strength of Helicopter Sandwich Structures

Sebastian Heimbs¹, Anne Fischer¹, Chris Fischer², Falk Haehnel² and Johannes Markmiller³
¹Airbus Group Innovations, 81663 Munich, Germany; sebastian.heimbs@airbus.com
²Technische Universität Dresden, Institute of Aerospace Engineering, 01062 Dresden, Germany; falk.haehnel@tu-dresden.de
³Airbus Helicopters, 86609 Donauwoerth, Germany; johannes.markmiller@airbus.com

ABSTRACT
An experimental and numerical study was conducted targeting at accurate predictions of impact damage and residual strength of honeycomb sandwich composites for damage tolerance evaluations of helicopter structures. The sandwich structure model development in Abaqus/Explicit was supported and validated step by step with material characterization tests, separate indentation tests of skin and core, sandwich impact tests and compression-after-impact tests. The applicability and accuracy of the methods and models is demonstrated by good predictions for various different helicopter sandwich structures like tail boom, side shell, and subfloor group.

INTRODUCTION
A great part of the airframe structure of helicopters is today built as sandwich constructions with honeycomb cores and thin carbon fiber-reinforced polymer (CFRP) skins. These sandwich structures have to be designed and sized such that they still have sufficient residual strength even with internal core and skin damage caused for example by transversal impact loads. New certification requirements for helicopters [1] have recently put a special focus on such damage tolerance evaluations of barely visible impact damages (BVID) (Fig. 1). In order to avoid expensive experimental test campaigns involving impact tests and compression-after-impact (CAI) tests for each new structural design, a need for accurate and efficient predictive numerical tools has risen, which can also be applied to larger helicopter structure models. Numerical methods for impact damage predictions have been the focus of numerous previous studies [2-6], but the transfer of the state of damage to subsequent residual strength simulations has been treated in much fewer investigations so far [7-12]. In fact, in most published CAI simulations, the impact damage was implemented artificiably e.g. as a simple circular delamination without a proper preceding impact simulation [13-16].

This study is intended to follow a comprehensive step-by-step approach to generate and validate finite element (FE) models of honeycomb sandwich structures for impact and CAI simulations with the commercial simulation software Abaqus aiming at capturing skin and core damage and their effect on residual strength as accurately as possible. For this purpose, extensive coupon tests have been performed to generate a reliable database of material parameters to feed the models along the simulation pyramid up to targeted applications in tail boom, side shell and subfloor group structures.

STEP 1: MATERIAL CHARACTERIZATION

A. TESTING
Skin and core material have individually been characterized in extensive test series. The relevant core materials are Nomex honeycomb structures with different cell sizes and densities. Each of those have been tested in compression, tension and shear in all three directions (L, W and T) since these data are required input parameters of 3D-honeycomb material models for homogenized solid elements. The sandwich skin material involves both unidirectional and woven fabric CFRP plies (Hexcel M18/1-G939 and M18/1-G947). Already available test data of intralaminar behavior have been completed by additional cyclic shear tests for damage propagation analysis and by delamination tests (mode I, mode II and mixed mode) in all possible ply and angle configurations in order to provide a complete material property database for all possible material lay-ups. Skin-core debonding has not been tested as this failure mode is typically prevented by an appropriate adhesive bonding with strength values exceeding the core’s strength.

B. MODELING AND VALIDATION
Homogenized 8-node solid elements in combination with the VUMAT material model Abq_Honeycomb available in Abaqus/Explicit have been the first choice for highly efficient modeling and are in the focus of this paper. Nevertheless, since this approach is not capable of representing local cell wall folding mechanisms of the core structure, detailed hexagonal cell models with accurate modeling of local unevenness have also been developed for comparison reasons and for assessment of their importance for the residual strength prediction. All compression, tension and shear tests have been simulated to validate the material model and to investigate mesh size influences (Fig. 2).

The fabric composite material has been modelled with the Abaqus/Explicit VUMAT Abq_Ply_Fabric based on the Ladeveze damage model using continuum shell elements. The cyclic shear test data have been used to calibrate the nonlinear damage model parameters. The standard Hashin failure model was used for the modeling of the unidirectional composite plies. Delamination interfaces were introduced between all plies using the efficient cohesive contact
formulation based on the conventional bilinear traction-separation approach. Double cantilever beam (DCB) and end-notched flexure (ENF) simulations were performed to validate the stiffness, strength and energy values of the delamination models.

STEP 2: CORE INDENTATION / IMPACT ON PURE SKIN

A. TESTING
Quasi-static indentation and low velocity impact tests have been performed on pure core and pure skin specimens, respectively, in order to validate the accurate modeling of each of the two sandwich constituents under localized normal loading, separately. For each type of honeycomb core five different indentation depths from 1 mm to 7.5 mm were tested and force-displacement plots and residual indentations were captured (Fig. 3). For the pure skin specimens four different laminates with thicknesses between 0.8 and 1.8 mm were selected, representing side shell, tail boom, bottom shell and sub-floor group skins. Three different energy levels from 2 J up to 10 J were tested with the acquisition of force-displacement data and delamination damage by ultrasonic C-scans (Fig. 4).

B. MODELING AND VALIDATION
The mesh dependency of the homogenized core modeling was assessed using 1 to 10 elements across the core thickness and it appeared to be significant. Very good correlation to the test data was obtained with models using element sizes in the order of magnitude of the honeycomb cell size, i.e. typically 4 or 5 elements across the thickness (Fig. 3). Also the impact simulations of the composite skin specimens showed good correlations in terms of force-displacement response and intra- and interlaminar damage using the experimentally determined material properties and validated delamination contact parameters (Fig. 4).

STEP 3: IMPACT ON SANDWICH SPECIMENS

A. TESTING
Low velocity impact tests have been performed on five different sandwich structures with different honeycomb cores and skin thicknesses, representing real tail boom, side shell and subfloor structures. The energy values varied from 2 J up to 15 J. The boundary conditions were selected according to common CAI test standards with a rectangular window frame support. Force-displacement curves were recorded and post-impact C-scans were taken to assess the extent of skin and core damage (Fig. 5). Typically, the area of internal core crushing was significantly larger than the diameter of the impactor or of the skin delamination damage, which is not visible from the outside.

B. MODELING AND VALIDATION
The sandwich structure models were built up using the validated core and skin models and tie-constraints for their connection (Fig. 5). It was found to be important to model the correct skin thickness in order to capture the bending stiffness and failure load accurately. Local skin thickness variations of the co-cured laminate (also known as telegraphing effect) cannot be captured by subtracting the nominal core thickness from the global sandwich thickness measurement. Hence, micrographs were taken to extract more accurate values of
average skin thickness (Fig. 6). The numerically predicted force-displacement curves and core and skin damage patterns were in reasonable agreement with the test data for all analyzed sandwich designs (Fig. 5).

**Fig. 6: Micrograph of sandwich skin and honeycomb cell walls demonstrating the telegraphing effect of inhomogeneous skin thickness**

**STEP 4: COMPRESSION AFTER IMPACT**

**A. TESTING**

In order to perform edgewise compression tests after impact, the core was partially removed and filled with epoxy resin on two sides of the impacted sandwich specimens. Afterwards, the edges were milled in order to be accurately parallel. A speckle pattern was added onto both surfaces for optical strain measurement and digital image correlation. Typical stability failure modes for these types of sandwich structures that were observed during the compression tests were face wrinkling and shear crimping.

**B. MODELING AND VALIDATION**

Although Abaqus offers the straight-forward capability to combine an explicit simulation step for the impact loading with an implicit simulation step for the subsequent CAI load case, this method could not be applied here due to the VUMAT material models for the skin and core that only work with Abaqus/Explicit. Hence, the slightly less efficient way of coupling an explicit impact simulation step with an explicit CAI loading step was chosen within a multi-step analysis. The accurate boundary conditions according to the tests had to be implemented for each of these steps, respectively. Simulation results show promising correlations in terms of predicted failure mode and failure load (Fig. 7).

**Fig. 7: Compression after impact: test and simulation (shear crimping failure mode)**

**CONCLUSION**

Although the anticipated target of predictive numerical tools for sandwich impact damage and residual strength assessment required strong efforts in experimental testing according to the building block approach, these nonrecurring test activities were only needed to provide material model parameters and to validate the developed models and methods. The validated models can now be used for future damage tolerance assessments of arbitrary helicopter sandwich structure lay-ups since the accuracy of the predictions has proven to be reasonable.

Lots of further parameter studies to assess the robustness of the models and the parameter sensitivity, which were performed in the framework of this study, could not be presented here in detail. A final validation on structural level is planned at the final phase of this running activity, which is the analysis of a static loading test of a complete helicopter tail boom with impact damages at different positions and the comparison to the test data.

**ACKNOWLEDGEMENTS**

This study was performed within the LuFo V-1 project SCHACH funded by the Federal Ministry for Economic Affairs and Energy of Germany. The financial aid is gratefully acknowledged. Sincere thanks are given also to Christian Reichensperger and Clement Breton from Airbus Helicopters for technical discussions and support.

**REFERENCES**


