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PREDICTING THE DAMAGE TOLERANCE OF NOMEX® HONEYCOMB SANDWICH STRUCTURES BASED ON DETAILED FINITE ELEMENT MODELS

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1. INTRODUCTION

The application of structural sandwich is an important design solution for load-carrying lightweight components. In aircraft structures sandwich made of graphite/epoxy face-sheets and aramid honeycomb cores is often used [1] due to features such as high strength- and stiffness-to-weight ratios as well as a good fatigue behaviour. Owing to the rather weak core material, this kind of sandwich is prone to a range of defects and damages as a result of impact loading which may accidentally occur during assembly or operation of aircraft. These damages and their effect on the load carrying capability of structures have to be considered in the damage tolerant design of airplanes and helicopters.

For the analysis of the impact damage process and the damage tolerance behaviour, numerical simulations are increasingly used and have been the focus of previous studies [2-6]. As long as only the global behaviour of sandwich components is investigated by finite element methods, it is sufficient to model the structure by using shell elements for the skins and solid elements for the core [2, 7]. Nevertheless, local failure phenomena especially of the honeycomb core structure have to be considered in the damage tolerance behaviour of the structure. Such a detailed finite element model requires not only a thorough knowledge about the basic material properties of the sandwich constituents [8, 9] but also information about the honeycomb geometry [10]. Therefore, the cell walls have to be idealised with shell elements and the resin corners with solids. Such a finite element (FE) model has to be validated following a step-by-step approach as shown in Fig. 1. Once validated, the simulation model can be applied for further investigations regarding the impact behaviour and the residual strength of honeycomb sandwich structures (Fig. 1).

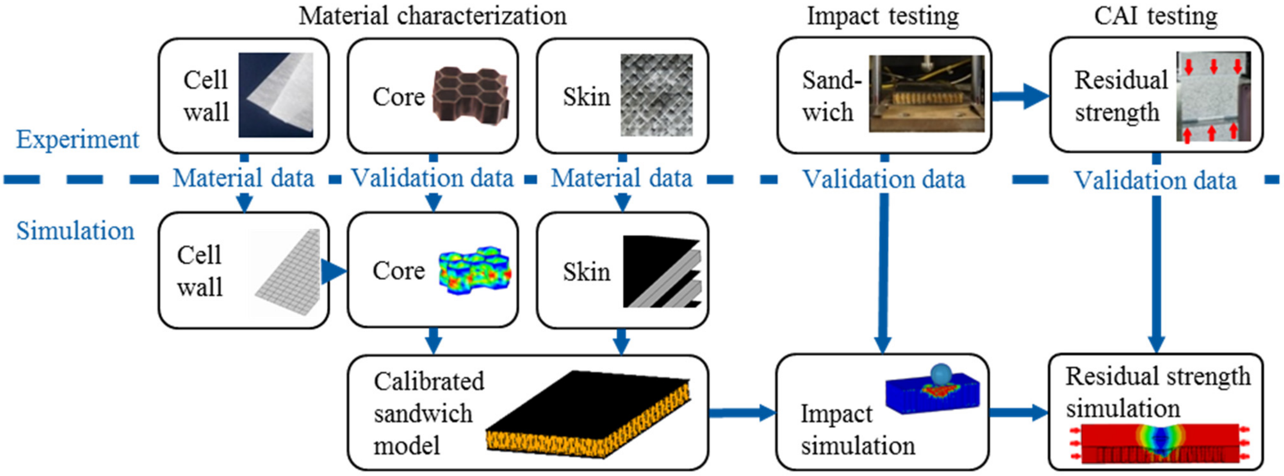

Fig. 1: Calibration process for sandwich FE models used to simulate the impact and residual strength behaviour.

In this paper a step-by-step approach is proposed to validate detailed finite element (FE) models of honeycomb sandwich structures for impact and residual strength simulations using the commercial simulation software LS-Dyna.

2. MATERIAL CHARACTERIZATION

Cell Wall

Honeycomb cores used in aerospace structures usually have cell walls consisting of three layers (resin-paper-resin) resulting from the impregnation process. In the applied simulation model this wall structure has been modelled using shell elements with 3 layers, where each layer has the material properties of the relevant constituent. Hence, the specific material properties of the pure as well as the impregnated aramid paper had to be determined by compressive, tension and shear tests (Fig. 2). Based on these experimental data the properties of the Nomex® paper as well as the phenolic resin were identified. These data are required as input parameters of the orthotropic elastic-plastic user-defined material law for paper-like materials, which has been developed at the Institute of Aerospace Engineering. Using this material model, simulations of the tests have been performed showing a very good agreement with the experimental data.

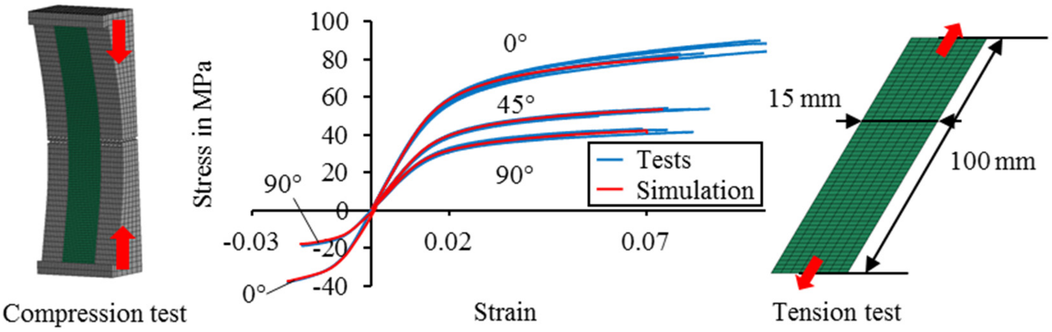

Fig. 2: Material test of Aramid paper: examples of simulation results under compression and tension.

CFRP Skin Material

The face sheets investigated were made of both unidirectional and woven CFRP fabric plies (Hexcel M18/1-G939 and M18/1-G947). Already known intra-laminar data have been complemented through additional experiments: impact tests for the failure analysis as well as mode I, mode II and mixed mode delamination tests in relevant ply and angle configurations. Finally, the properties required for the material models were determined for all relevant skin lay-ups.

The fabric composite material has been modelled using the LS-Dyna orthotropic material formulation for layered composite materials. Delamination interfaces have been considered between the fibre shell layers using solid elements in combination with the LS-Dyna cohesive mixed-mode material. Both impact behaviour and delamination propagation obtained by simulation agree very well with the experiments (Fig. 3).

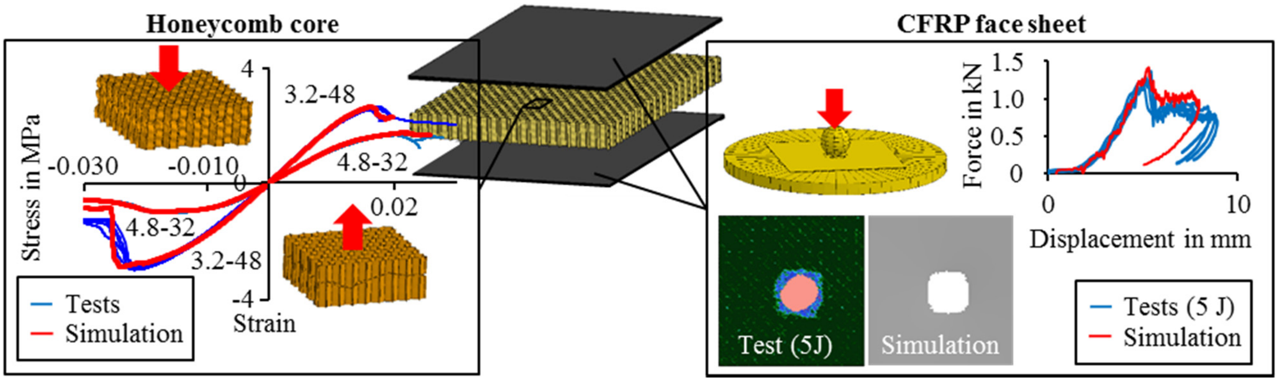

Fig. 3: Coupon test of honeycomb core and CFRP face sheet: examples of test and simulation.

Honeycomb Core Structure

These test specimens consisted of Nomex® honeycombs with cell widths of 3.2 mm and 4.8 mm and densities of 48 kg/m^3 and 32 kg/m^3, respectively. Both core types were tested under compression, tension and shear loading using 40 by 40 mm test specimens. Imperfections were analysed from the procedure described in [10] on different honeycomb configurations and were considered in the simulation models. The numerical results show a very good agreement with the nonlinear behaviour of honeycomb cores obtained from the experiments (Fig. 3).

3. IMPACT TEST ON SANDWICH SPECIMENS

Extensive low velocity impact tests were conducted at different energy levels from 2 J to 15 J in order to determine the impact behaviour of honeycomb sandwich structures. These experiments were performed according to standard CAI test procedures. A rectangular window frame support of 75 mm in width and 125 mm in length and an impactor with a semi-spherical head of 1-inch diameter has been used. A force transducer recorded the force-displacement-histories.

The models of the sandwich structure were build up using the validated models for the honeycomb core and the CFRP skins in combination with a tied bonding interface of skin and core (Fig. 4). Investigations showed that it is important to model the meniscus resulting from the sandwich manufacturing process in order to get reliable simulation results of the core damage depth. Both impact testing and impact simulations were performed on different sandwich configurations. A good correlation has been obtained as shown in Fig. 4 using the example impacted at 5 J.

4. COMPRESSION AFTER IMPACT

After being impacted the damaged samples were prepared for residual strength testing (Fig. 4). During these experiments the compressive strain was measured on the skin surface using a three-dimensional digitisation system. As a result, the stress-strain-curves as well as the failure loads were obtained. During the compression tests, stability failure modes such as shear crimping and wrinkling have been observed. Typical test results for samples with a 0.9 mm CFRP skin are given in Fig. 4 where the compression after impact force is shown as a function of the displacement.

Residual strength simulations were conducted using LS-Dyna applying a multi-step simulation approach. Following the impact simulation, the simulation model is modified: specimen supports were added on the edges of both face sheets to prevent premature buckling. Additionally, solid elements were placed at both ends to model the load introduction. The compressive load was simulated by prescribed displacements of the load introduction surfaces longitudinal to the sandwich sample. As shown in Fig. 4 the analysis results agree very well with the experimental data achieved by the residual strength tests using the 5 J impact example.

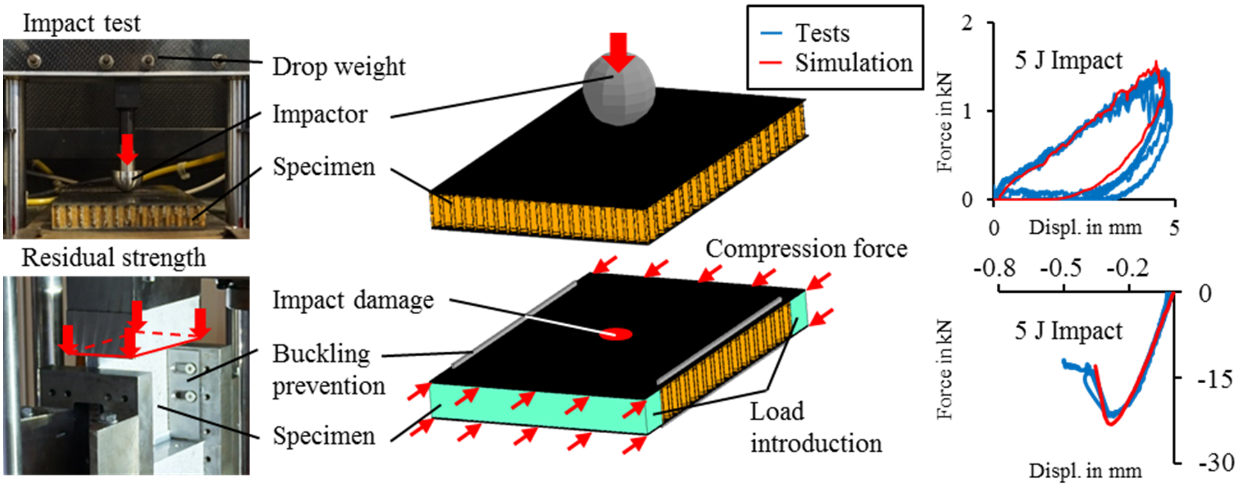

Fig. 4: Comparison of test and simulation: effect of a 5 J impact on the response and residual strength of a sandwich sample.

5. CONCLUSIONS

The experimental study performed in the presented research project provided a comprehensive database on impact-force time relations for a range of impact energies. The data were obtained for sandwich configurations typical for aircraft applications. Particularly, the knowledge gained on the quantitative magnitude is useful for the evaluation of residual strength simulations as a function of the structural damage severity.

Based on these experimental data a step-by-step simulation approach has been developed which is applicable to predict the impact behaviour as well as the residual strength of damaged sandwich structures. As numerical method, explicit finite shell elements have been used. The comparison with experimental results revealed a very good agreement.

The developed simulation approach was applied particularly to examine systematically the failure processes in honeycomb sandwich structures. The obtained knowledge on the effective mechanisms are very useful for the development of better macro-mechanical simulation methods.

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