STRATEGIES TO INVESTIGATE THE RESIDUAL STRENGTH OF IMPACT DAMAGED HONEYCOMB SANDWICH STRUCTURES USING DETAILED NUMERICAL MODELS

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ABSTRACT

Honeycomb cores made of phenol resin impregnated paper are widely used in sandwich structures. When employed in aircraft these structures have to be damage tolerant. This means damages, which may occur during service, have to be considered in the structural design process. For the analysis of impact damages and the damage tolerance behaviour, experiments are increasingly replaced by numerical simulation using explicit finite element codes. Regarding the residual strength of honeycomb sandwich structures two different fundamental simulation approaches are available.

The step-by-step method starts with the simulation of the impact process, subsequently followed by the compression-after-impact (CAI) analysis. In this case, the knowledge of shape, mass and velocity of the impactor is essential. When the influence of impact damage on the residual strength has to be investigated systematically, a one-step simulation approach is more suitable. This method uses simulation models, which already include the impact damage.

In order to evaluate the effect of damage modelling an experimental and numerical study was conducted. Some of the experimental findings are given in this paper. In addition, the effect of the kind of impact damage modelling on the structural behaviour under compressive loading is presented. It could be shown that the results of both simulation approaches agree very well with experimental data.

1 INTRODUCTION

Sandwich is often used as a lightweight design solution for load-carrying components of airplanes and helicopters due to their excellent mechanical properties such as high strength-to-weight and stiffness-to-weight ratios. This is particularly true for sandwich with face sheets made of carbon fibre reinforced plastics (CFRP) and non-metallic honeycomb cores [1]. Owing to the rather weak core material, this kind of structure is prone to a range of damages resulting from impact loading that may accidentally occur during assembly or operation of the aircraft. These damages and their effect on the load carrying capability of the structure have to be considered in the damage tolerant design of airframes. Therefore, it is necessary to determine damage size and severity resulting from impact events and to predict the residual strength of damaged components during the development process. Currently, this task is performed mainly by extensive testing: drop tests are carried out to simulate the impact loading, the damage size is determined by NDT methods and compression or shear after impact tests (CAI, SAI) provide the residual load carrying capability. These experimental procedures are rather costly and time consuming. Therefore, much research has been done to develop reliable simulation procedures based on finite element methods, which are able to predict the damage tolerance behaviour.

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]. Such models permit only a macro-mechanical description of the core behaviour [3]. Thus, it is not possible to account for local failure modes in case of honeycomb cores. Nevertheless, these local effects are important when the damage tolerance behaviour is of interest. For this kind of problem, more detailed numerical models [4, 5] as well as a thorough knowledge about the geometry of real honeycomb cores are required [6, 7].

There exist two fundamental approaches to simulate the damage tolerance behaviour of honeycomb sandwich structures. The first one is the step-by-step approach performing the residual strength evaluation based on simulated impact damages. This procedure requires comprehensive information about the impact history. Up to now, a limited number of investigations have been carried out transferring the state of simulated impact damage to subsequent residual strength simulations [8, 9]. Furthermore, the step-by-step approaches reported in literature use macro-mechanical models.

Another way to tackle the residual strength problem is a one-step simulation approach using artificially implemented impact damages, e.g. skin dents or elliptical delamination areas, without a preceding impact simulation [10, 11]. Type and size of the modelled damage is based on experimental data. Any knowledge about the cause of an impact damage is not necessary. So far, this kind of simulation approach has been applied only to composite laminates.

In this paper an experimental and numerical study is presented in which the two different strategies for residual strength simulation were investigated. The input data required for the simulation task such as the core failure depth as well as the damaged areas of skins and core were experimentally determined. The effect of failure modelling on the results of the one-step simulation process was evaluated through a parametric study. The numerical residual strength analysis was based on detailed finite element models of the honeycomb core, which permitted to include local failure phenomena during impact and compressive loading. Finally, the outcome of the one-step simulation was compared to tests as well as results of the step-by-step simulation approach.

2 EXPERIMENTAL ANALYSIS OF THE RESIDUAL STRENGTH

In the first phase of the research an extensive test campaign on honeycomb sandwich structures was carried out to characterize the residual load carrying capability (Figure 1).

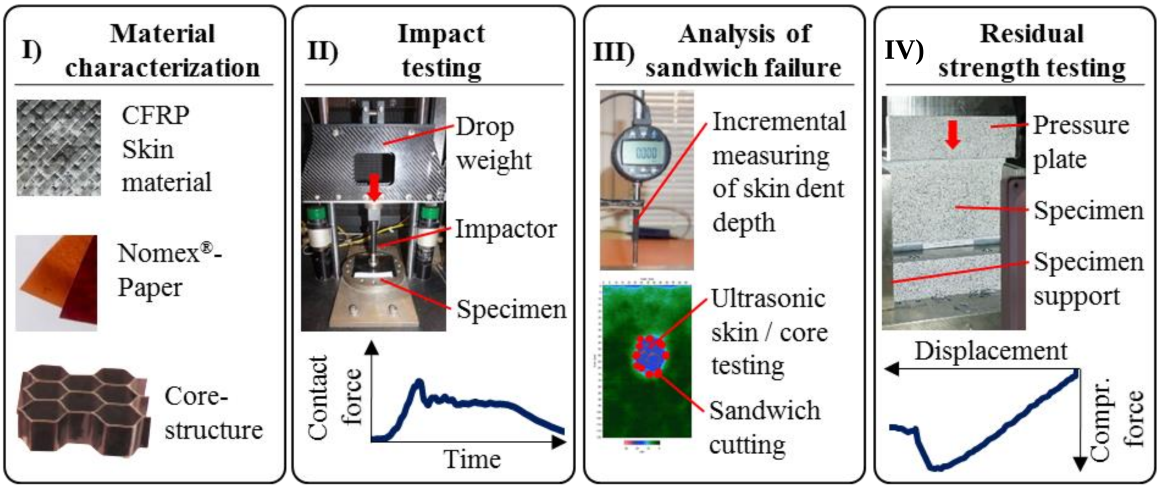

Figure 1: Residual strength test procedure for honeycomb sandwich structures

This experimental program included the determination of the cell wall material properties by tension, compression and shear tests on pure and impregnated paper material. Furthermore, the behaviour of honeycomb blocks was examined by compression, tension and shear tests. In addition, sandwich specimens with CFRP skins of thicknesses between 0.8 mm and 1.8 mm were impacted at different impact energy levels. Achieved results were the contact-force-time histories, the remaining impact dent and the in-plane and out-of-plane extension of the skin and core damage. The impact damage areas were examined using a three-dimensional measuring system, an ultrasonic method and destructive testing methods. Finally, the residual strength of the damaged sandwich specimens was determined by compression tests.

2.1 Material characterization

The material data of the relevant skin and core materials are required as input parameters for the simulation methods used. Therefore, the specific material properties of the pure and the impregnated aramid paper were determined by compressive, tension and shear tests.

The core test specimens consisted of Nomex® honeycombs with cell widths of 3.2 mm and 4.8 mm and densities of 48 kg/m³ and 32 kg/m³ respectively. Both core types were tested under compression, tension and shear loading.

The sandwich skin material included both unidirectional and woven CFRP fabric plies (Hexcel M18/1-G939 and M18/1-G947). Already known intralaminar data were completed by 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.

2.2 Impact testing

Extensive low velocity impact tests at different energy levels were conducted in order to determine the impact behaviour of honeycomb sandwich structures (Figure 2). These experiments were performed according to common 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 was used. Pneumatic rebound brakes prevented a second impact on the specimens. After crossing an electromagnetic barrier, the pneumatic brakes are activated automatically. A force transducer recorded the force-time-histories as shown in Figure 2.

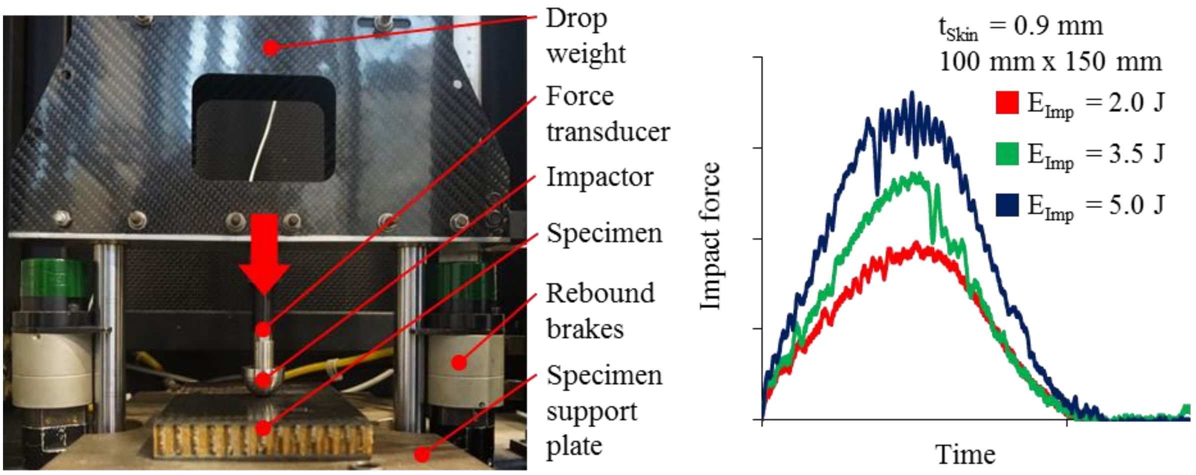

Figure 2: Impact test set-up and results

2.3 Analysis of honeycomb sandwich failure

The impact damage sizes as shown in Figure 3 are required input parameters of the simulation approach that uses modelled skin and core damages. Therefore, the indentation depth of the skin layer was measured incrementally using a dial gauge DIGI-Met system. In order to consider the relaxation of the sandwich this measuring method was applied only 48 hours after the impact test. In addition, the skin delamination and core damage areas were determined by ultrasonic testing using the impulse-reflection-method. A typical ultrasonic image used for this purpose is shown in Figure 3. Additionally, sandwich specimens damaged at different impact energy levels were sliced through the impact centre to verify the in-plane and out-of-plane core failure. Typical results for the skin and core damages related to the impact energy for a sandwich configuration with 0.9 mm thick skins and 4.8 mm wide honeycomb cells are given in Figure 3.

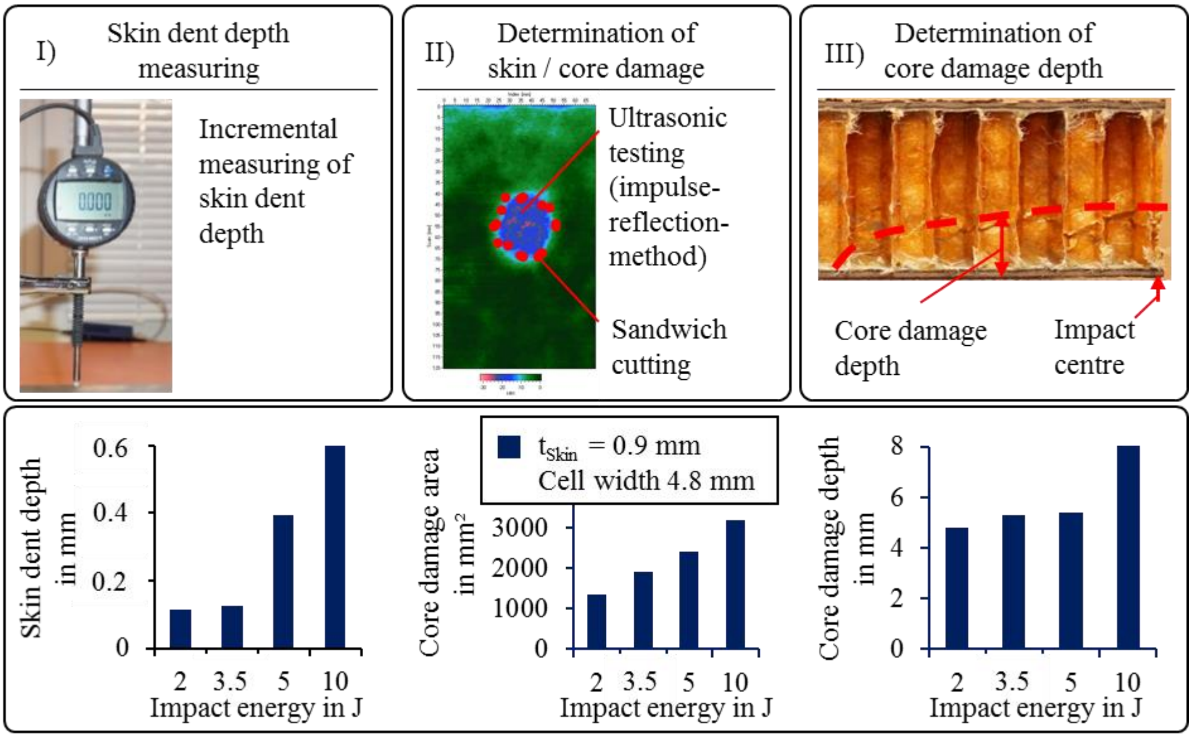

Figure 3: Impact damage analysis procedure

2.4 Residual strength testing

The impact damaged sandwich samples were subsequently prepared for residual strength testing (Figure 4). In a first step, the core of the test specimens was partially removed in the area of the load introduction and filled with epoxy resin. Afterwards, the edges were machined in order to achieve accurately parallel load introduction areas.

During testing the compressive strain was measured on the skin surface using a three-dimensional digitisation system. As a result, the stress-strain-curves and the failure load could be obtained. During the compression tests, stability failure modes such as shear crimping and wrinkling were observed. Typical test results for samples with a 0.9 mm CFRP skin and two core configurations are given in Figure 4 were the residual strength is shown as a function of the impact energy.

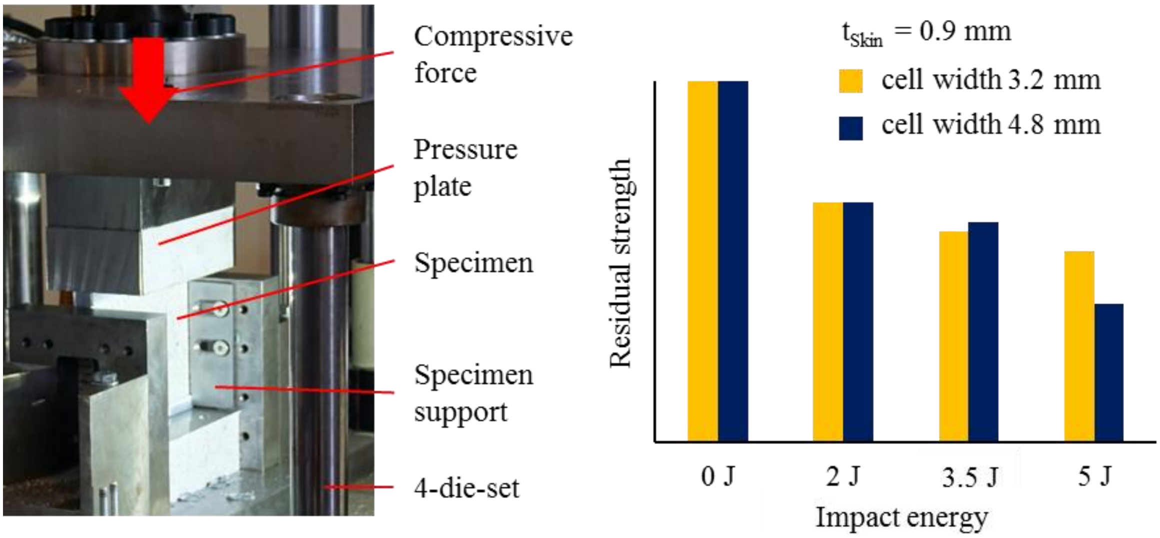

Figure 4: Residual strength test set-up and test results

3 RESIDUAL STRENGTH SIMULATION APPROACHES

In the second phase of the research, models based on the two different approaches to analyse the residual strength of damaged sandwich were developed (Figure 5).

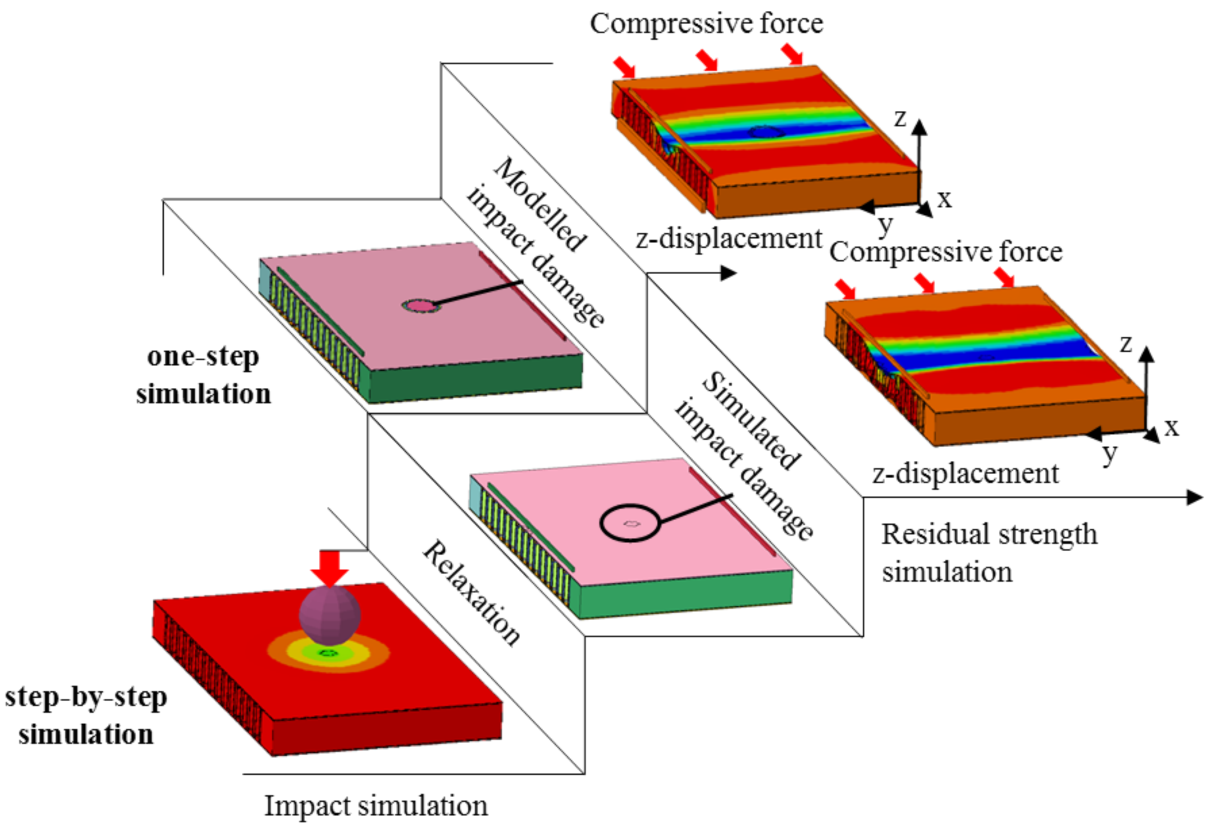

Figure 5: Approaches for the residual strength simulation of impact damaged sandwich structures

The step-by-step approach is based on impact damages determined by numerical simulation. The method starts with the impact simulation at different impact energy levels. After a relaxation time, which is required to reduce the impact-induced vibrations, a compressive force is applied on the damaged sandwich structure. The obtained results are stress-strain-curves and failure loads. The validation of this approach by experimental data requires a comprehensive knowledge about the shape and the mass of the impactor.

In contrast to the step-by-step procedure the one-step approach is based on experimentally measured structural damages. Any knowledge about the impactor shape and the previous impact history is not required.

Both simulation approaches were investigated in this study using a detailed finite element model for the honeycomb core as well as the skin layers and an explicit solver.

4 FINITE ELEMENT MODELLING

In order to provide detailed finite element models of arbitrary sandwich configurations a parametric tool called *SandMesh* has been developed at the Institute of Aerospace Engineering. This program permits to generate very fast finite element models of sandwich structures with honeycomb, foam and folded cores. The main advantage of *SandMesh* is the capability to model detailed honeycomb structures including imperfections such as cell wall waviness, angular deviation of the glued cell walls, resin concentrations and random material distributions [6].

The basic finite element model used for both simulation approaches is shown in Figure 6. The local honeycomb cell geometry is based on data reported in [6]. The material properties for the aramid paper as well as for the resin were taken from [4]. The compressive load was simulated by prescribed deformations of the load introduction surfaces longitudinal to the sandwich sample. To prevent a premature buckling of the sandwich 1 mm wide specimen supports were added on both sides of the sandwich (Figure 6). The boundary conditions as well as the used material formulations of the employed nonlinear dynamic solver LS-Dyna are also given in Figure 6.

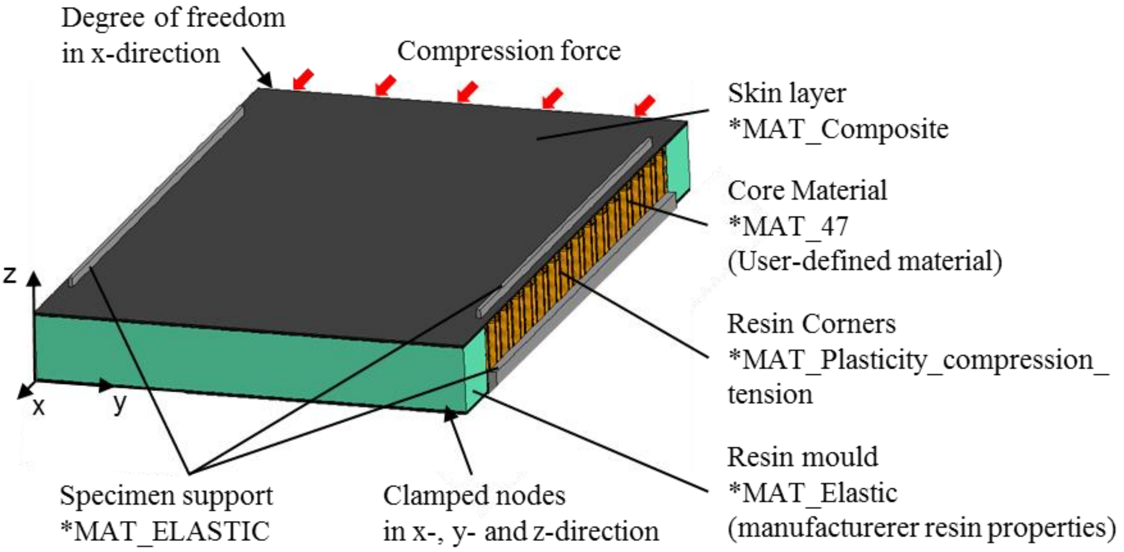

Figure 6: Finite element model for residual strength simulation

In this study the honeycomb cores were modelled by using 4-node shells for the cell walls and volume elements for the resin corners. The shell elements had three material layers in order to account for the distribution of paper and resin material in the cell walls. The nonlinear behaviour of the paper material was considered by a user-defined material model, which was developed at the Institute of Aerospace Engineering and implemented in LS-Dyna. This material model was used for all layers of the core elements including the paper and resin material. The face sheets made of carbon fabric were modelled by using 4-node-shell elements and the material MAT_Laminated_Composite_fabric. Delamination interfaces were inserted between all plies using the efficient volume cohesive formulation based on the LS-Dyna material MAT_Cohesive_General.

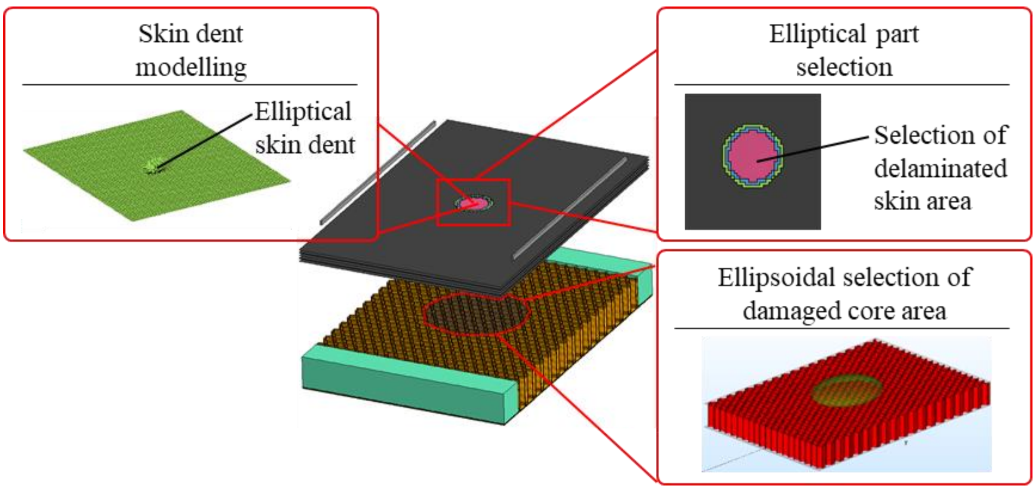

Figure 7: Skin and core damage modelling for one-step simulation

The one-step approach starts with modelling the core and skin damage as shown in Figure 5. Details of the finite element model used in this research is presented in Figure 7. The damaged skin and core areas are based on data determined in the experimental study. Firstly, the skin dent is considered in the finite element model by prescribed node displacements in the thickness direction of the sandwich. The delaminated part of the skin is modelled by an elliptical area where the material properties of the skin, e.g. the stiffness moduli, were reduced to represent the damaged material. Finally, the damaged core volume is defined by a semi-ellipsoid (Figure 7). For all finite elements being located in this volume both, the material properties of the paper and the resin are decreased to model the core damage.

Up to now, there is only a limited knowledge about the effect of reduced material properties and the influence of the in-plane damage modelling of the core and the skin layers on the residual strength of honeycomb sandwich structures. Therefore, a comprehensive parametric analysis was performed to investigate the effect of the approximated damage modelling on the results obtained by the one-step residual strength analysis.

5 PARAMETRIC ANALYSIS OF DAMAGE MODELLING

The parametric study was carried out employing the nonlinear dynamic solver LS-Dyna. The aim was to evaluate how the parameters of the core and skin defects effect the residual strength behaviour. Some of the results obtained on a compressively loaded sandwich plate with 0.9 mm thick skins and a honeycomb core with 4.8 mm cell width are presented in Figure 8.

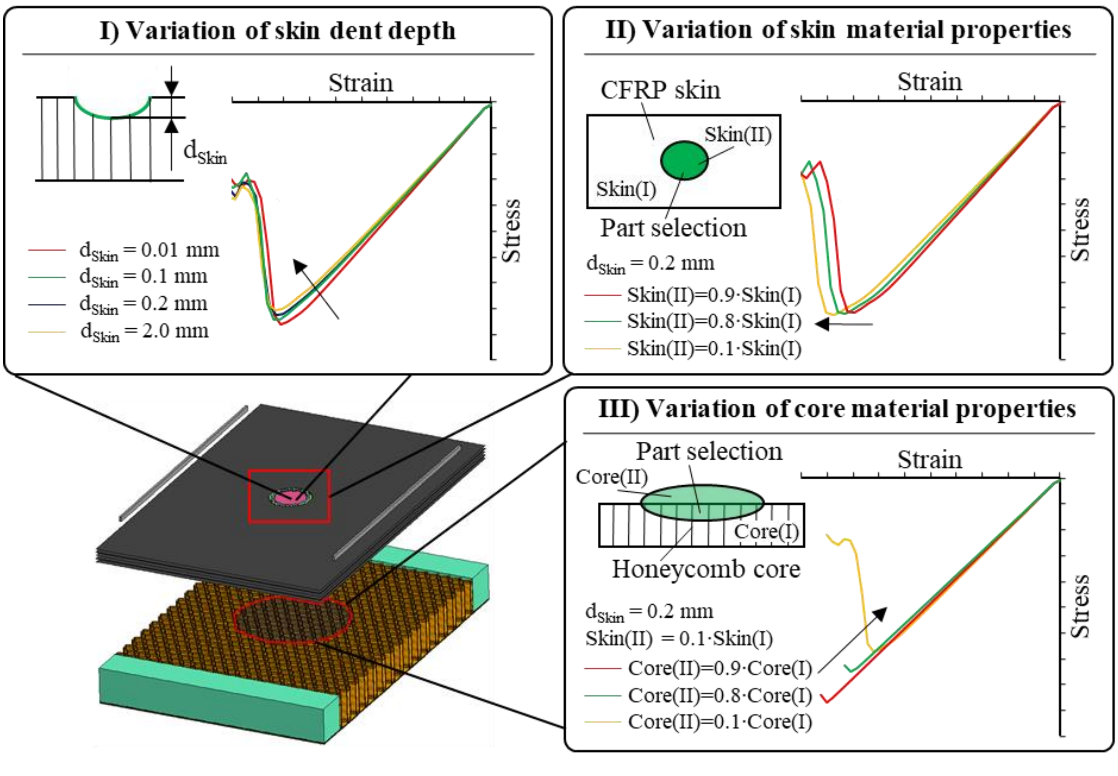

Figure 8: Compression-after-impact simulation results of a honeycomb sandwich

The compressive strains are presented in Figure 8 as function of the stress for three different types of modelled impact damages. The effect of the skin dent was investigated by varying the dent depth of d_{Skin} (Figure 8 I). The sandwich with undamaged skins shows a typical linear deformation behaviour up to the failure load. With an increasing dent depth the stress-strain-curve becomes more nonlinear, because structural buckling occurs from the beginning. In accordance with the experimentally measured dent depth, the following investigations were performed with a d_{Skin} of 0.2 mm. In the second step the effect of the skin material properties in the impact damage area was analysed (Figure 8 II) by varying the stiffness moduli. The stress-strain curves obtained clearly show a minor effect on the sandwich stiffness as well as on the compressive failure strain. In contrast, the variation of the cell wall stiffness reveals a significant influence on the structural behaviour (Figure 8 III). Both the failure stresses and strains decline with decreasing material properties in the damaged core area.

6 RESULTS OF THE RESIDUAL STRENGTH SIMULATION

Based on the parametric investigation an additional numerical study was performed to show the applicability of both simulation approaches. For this purpose different sandwich configurations were analysed that are typical for aircraft applications.

The sandwich example shown in Figure 9 is made of a 15 mm thick honeycomb core with 4.8 mm cell width and a density of 32 kg/m³. The skins consist of 0.9 mm thick CFRP laminates. Both types of residual strength simulations were performed on sandwich damaged by a 3.5 Joule impact.

In case of the step-by-step procedure the impact was simulated with a semi-spherical impactor head of 1 inch diameter and a weight of 1.02 kg. Subsequently, the plate was subjected to a compressive load in the longitudinal direction. The one-step approach was based on an impact damage modelled according to the corresponding experimental results. Derived from the experience gained by the parametric investigation, the stiffness moduli of the skin and core materials in the damage zone were reduced to 10% of their pristine values.

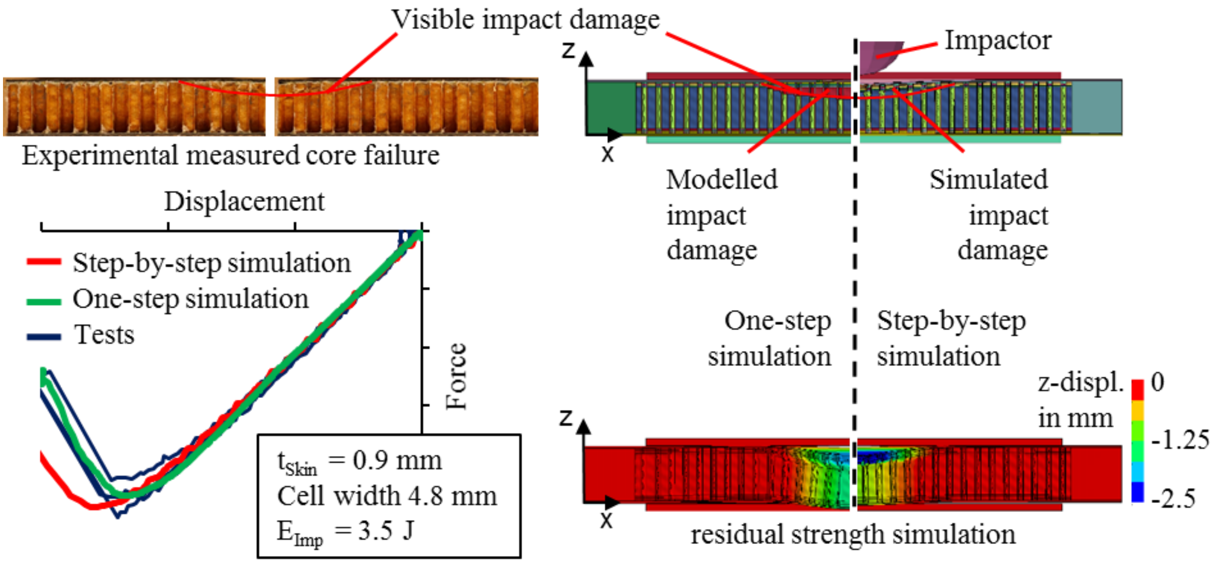

Figure 9: Compression-after-impact: comparison of test and simulation

As shown in Figure 9 the analysis results of both simulation approaches agree very well with the experimental data achieved by the residual strength tests.

7 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. These data contribute to a further improvement of the accuracy of simulation methods used in the design process of aircraft structures.

For the numerical studies, a parametric mesh generator was developed. This program permits to create finite element models of honeycomb cores including the relevant structural damage. Within the scope of a parametric simulation study, the effect of modelled skin and core damages on the residual strength behaviour was evaluated using a one-step simulation procedure. The analysis revealed that particularly the core damage simulated by a reduction of the cell wall stiffness has a considerable effect on the residual strength of honeycomb sandwich. It could be shown that the results obtained by both the step-by-step as well as the one-step simulation approach agree very well with experiments. Therefore, it can be concluded that both methods are applicable to predict the residual strength of damaged sandwich structures with good accuracy.

ACKNOWLEDGEMENTS

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