Experimental Validation of Efficient Impact Simulation Methodologies for Sandwich Structures

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Abstract

Aircraft design calls for multi-functional, weight efficient shell constructions. Composite sandwich structures satisfy this demand by the combination of two thin, stiff face sheets and an intermediate lightweight core. However, impact damage in sandwich structures can provoke a significant strength and stability reduction. The finite element based damage tolerance tool CODAC has been developed for simulating the damage resistance of sandwich structures subjected to low-velocity impacts. Since frequent design loops require a quick simulation, efficient methodologies are needed. Concerning this objective, appropriate models are proposed for analysing deformation, failure and dynamic behaviour of sandwich structures. An experimental impact test program acts as referee for the validation of the impact simulation methodologies. Force-time histories and damage sizes are examined. Comparisons between impact tests and simulations show that CODAC is capable of accurately and rapidly simulating low-velocity impact events.

Keywords:

Impact Simulation, Impact Damage, Sandwich Structures, Damage Mechanics, Finite Element Analysis.

1 Introduction

Since the economic advantage of weight reduction is immense especially for airplanes, the aircraft industry calls for multi-functional, high-performance lightweight structures. Composite sandwich structures, consisting of two thin, stiff face sheets and an intermediate lightweight core, provide a very high specific load bearing capacity. Furthermore, the sandwich core supplies thermal and acoustic insulation and the external face sheet can act as an impact detector. Thus, sandwich structures are increasingly aspired for application as fuselage and wing panels. To improve the understanding of the damage behaviour of sandwich structures, methodologies are needed, which reliably simulate impact events and accurately predict impact damage sizes.

The number of publications regarding the impact behaviour of sandwich structures has increased only in recent years. A number of experimental studies, as by Herup and Palazotto [1] or Dear et al. [2], were conducted to observe impact damage progression behaviour. It could be shown that invisible core crushing is the first damage mode which occurs during low-velocity impacts and slightly lowers the slope of the contact force-time history. At higher energies, the contact force reaches a peak value, which indicates face sheet cracking. To predict the impact response and the amount of impact damage, several simulation methodologies have been developed. Some of them are based on simple analytical approaches, which predict damage initiation but do not describe damage progression, see e.g. Petras and Sutcliffe [3]. On the other hand, finite element simulations are capable of modelling progressive damage and nonlinear material behaviour. Furthermore, they are flexible in terms of panel geometry and boundary conditions. Very fine FE models with a large number of elements also in thickness direction (e.g. by Lee et al. [4] or Nguyen et al.

[5]) require a large computational effort. Coarser models (e.g. by Palazotto et al. [6]) allow a much more efficient simulation, but usually suffer losses in accuracy. In a previous paper of the authors [7] efficient methodologies were proposed to simulate barely visible impacts, where however skin cracking was not yet regarded. By accounting for geometrical nonlinearity, a suitable description of large skin deflections and, therewith, a prediction of the onset of skin cracking is now possible. The presented paper aims at the validation of the impact simulation methodologies applied by the damage tolerance tool CODAC. The models and methods, which are used to analyse deformation, failure and dynamic behaviour of sandwich structures, are described in section 2. The impact test program, which is used for reference, is introduced in section 3. Finally, in section 4 the simulation results in the shape of force-time histories and damage sizes are presented and evaluated for different stages of material degradation.

2 Impact simulation methodologies

2.1 Dynamic analysis and contact law

The dynamic impact process is simulated by using the implicit Newmark time integration scheme [7] with the Newmark parameters $\delta = 0.7;\ \beta = 0.5$ and a time interval of $\Delta t = 5 \cdot 10^{-5} s$. Comparative studies have shown that the explicit central difference method needs extremely small time intervals to ensure stability. Overall, the explicit time integration scheme was found to be less efficient than the implicit one.

The impactor is modelled by a point mass and the contact between impactor and impacted face sheet is described by the Hertzian contact law. The contact force is applied as a parabolically distributed surface load. The number of finite elements, which are loaded during the impact event, conforms to the Hertzian contact area and increases with increasing contact load. Kärger et al. [7] investigated alternative ways of modelling the contact force and showed that distributing the contact force over the contact area is necessary to achieve mesh independent results.

2.2 Deformation model

To achieve a rapid and accurate deformation and stress analysis, a three-layered finite shell element S815 is used, which has been proposed by Wetzel et al. [9]. Element S815 is an isoparametric quadrilateral eight-node shell element. By means of 15 degrees of freedom per node (three translations, two rotations for each of the three layers and two further degrees of freedom per layer to describe the displacements in thickness direction) it accounts for shear deformation and transverse compressibility.

Since an accurate approximation of the transverse stresses is an important requirement for detecting impact damage, transverse stresses are improved by the so-called Extended 2D-Method. The method is based on an equilibrium approach and was originally proposed by Rolfes and Rohwer [10] for monolithic laminates and single-layered shell elements with first order shear deformation theory. To analyse sandwich structures, the method has been extended for a three-layered shell theory by Kärger et al. [11].

In a former paper of the authors [7] the impact simulation had been performed without taking geometrically nonlinearity into account, which did not give satisfactory results for large deflections and visible damages of the impacted skin. Therefore, the strain-displacement relation of the upper skin is now extended by nonlinear strain terms, which consider the membrane effect of large deflections and allow predicting the onset of face sheet cracking.

2.3 Failure model

To predict damage growth during the impact event, a progressive damage mechanics approach is applied. Stress-based failure criteria are used to detect damage initiation. Subsequently, the material resistance of the damaged regions is reduced by macroscopic degradation models. Since strain-rate dependency is very low at low-velocity impacts [12], it can be neglected for the studied cases.

The core is loaded by a combination of transverse compression and transverse shear. Therefore, a failure criterion is used, which includes both, transverse normal as well as transverse shear stresses to detect core failure [13]. If a new core failure is identified, the material behaviour of the damaged core is modelled according to experimental results of quasi-static tests. Such tests provide not only the material properties of the undamaged core, but also the core crushing stiffness and the core crushing strength. These values are essential for correctly measuring the amount of energy, which is absorbed by the crushing core. Figure 1 exemplarily shows a few force-displacement-curves from transverse compression tests, which were conducted at ILR Dresden [14] with NOMEX honeycomb cores. The experimental curves are approximated by the stepwise linear function of the core failure model. More details on the degradation model, including stiffness reduction factors and core crushing strength can be found in [7].

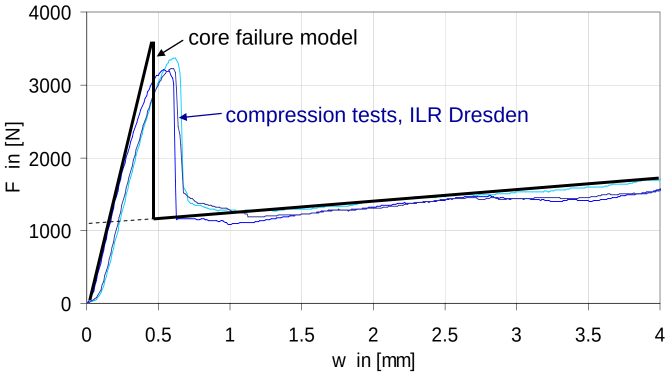


Figure 1: Force-displacement curves of core compression tests; experimental results by [14].

For modelling skin damage during an impact on a sandwich structure, fibre breakage is the most relevant failure mode and needs to be taken into account. On the other hand, matrix cracking and delamination were found to have insignificant effects on the impact force-time history as well as on the damage propagation. These failure modes may occur, but they do not provoke considerable stiffness reduction under impact loading. On the contrary, degradation due to fibre failure is essential for accurately simulating the onset of visible skin damage. Fibre breakage is predicted by the maximum stress criterion. To describe the damage behaviour of the skin, force-displacement curves of three point bending tests are used, see Figure 2. These curves can be subdivided into three phases: In phase 1 all skin laminas are still intact and behave linear elastically. When the criterion for fibre breakage is exceeded for the first time, phase 2 starts and, henceforth, a few laminas are damaged and behave according to a degraded, linear-elastic material model. Phase 3 does not start before all laminas have failed. At this point, the complete skin starts to tear and the force-displacement curve drops down to a very small value.

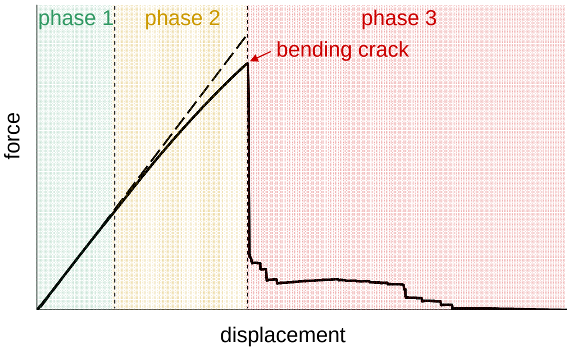


Figure 2: Force displacement curves of skin three-point bending tests; experimental results by [14].

While in phase 1 the initial material properties can be applied for all laminas, in phase 2 the damaged laminas need to be degraded. Material degradation is carried out by reducing the in-plane normal stiffness components according to the results of experimental bending tests. All other stiffness components do not considerably influence the impact progression and can be set to a value close to zero. When finally fibre failure occurs in all laminas, phase 3 begins. However, the skin tearing in phase 3 cannot be properly described by the simple linear material models, which are desired for an efficient impact simulation. In fact, energy-based damage or fracture mechanical models are needed for this stage. In favour of computational efficiency, such expensive models are not included in the fast FE tool CODAC. Consequently, the simulation stops at the beginning of phase 3, i.e. as soon as the skin starts to tear. The objective of the simulation is to properly describe the first two phases (inclusive core damage and minor skin damage) and to predict the onset of crack growth.

2.4 Finite element meshing

In the finite element mesh the impacted area is a lot finer than the outer parts of the panel, so incremental damage growth can be well predicted at the location of high stress concentration, while the computational effort is kept small. The FE simulation can be further accelerated by applying the symmetry boundary conditions of the sandwich plate and by modelling only that region, which is actually affected by the impact event. Therewith, the rather coarse mesh shown in Figure 3 can provide satisfactory results, as will be seen in chapter 4.

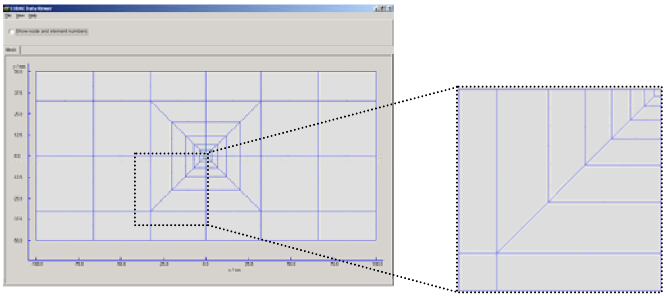


Figure 3: FE Mesh.

3 Experimental investigations

The impact test programme, which is used to validate the impact simulation methodologies, was conducted at the department of Aerospace Technology at Dresden University (ILR Dresden, [14]). Experimental results in the form of force-time and displacement-time histories, damage photographs and ultrasonic scans were provided by courtesy of ILR Dresden.

3.1 Test setup and materials

The impact facility of ILR Dresden is illustrated in Figure 4. In the impact test program sandwich panels of 400mm x 400mm size were completely supported and laterally fixed against bouncing. The plates were divided into eight parts of 100mm x 200mm, of which seven parts were impacted by energies between 1J and 15J. The impactor had a hemispherical steel tub with a diameter of 25.4mm and a mass of 1.10kg.

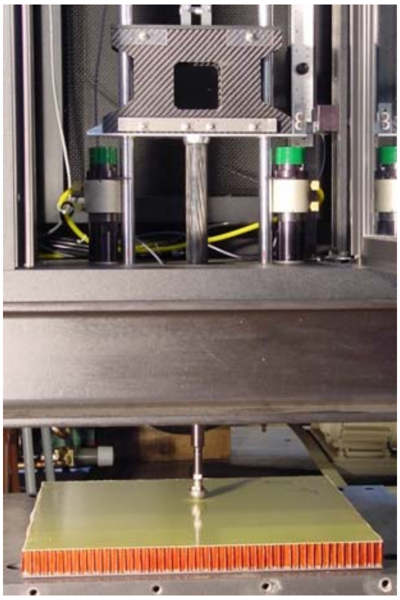


Figure 4: Impact facility at ILR Dresden [14].

The studied sandwich plates consist of CFRP face sheets and 28mm thick honeycomb cores of NOMEX 4.8-48. Since the outer skin shall act as an impact detector and the inner skin needs to carry the main loads, the sandwich is asymmetric: The thin top skin consists of only three fabric plies of Material CYTEC 977-2/HTA and has a nominal thickness of 0.63mm. The bottom skin is composed of one lowermost fabric ply and twenty UD tapes with lay-up $[(0_2/45/90/-45)_s]_s$; the total thickness is 2.7mm. The fabric plies are used to improve the impact resistance, while the tape plies provide high membrane and shear stiffness and strength values to achieve a high load bearing capacity.

3.2 Experimental results

Figure 5 exemplarily shows the force-time-histories for impact energies of 1J, 4J and 15J. To illustrate the scatter of the experiments, two curves per impact energy are shown. From the force-time histories two types are distinguishable: The 1J curve is almost sine-like, whereas the 4J and the 15J impacts lead to a sharp bend at about 1kN. This sharp bend is caused by the abrupt failure of the face sheet, which starts to tear at this point. Another much slighter bend is found in all force-time curves at a much lower energy level, when the core starts to fail.

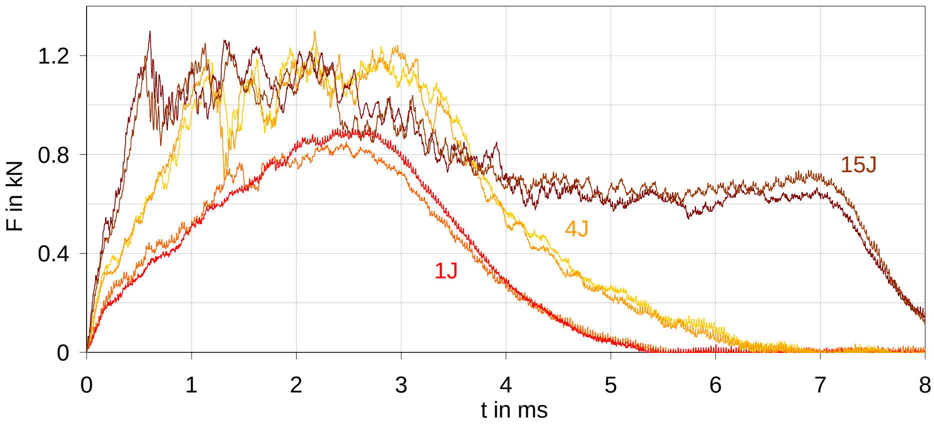


Figure 5: Force-time histories from impact tests at ILR Dresden [14].

Further important experimental results are damage images. Figure 6 shows the damage of the top skin (left and middle figure) and of the core (right) for a 4J impact: At the impact location the skin is indented and torn. The honeycomb core is crushed at an area, which is considerably larger than the skin damage.

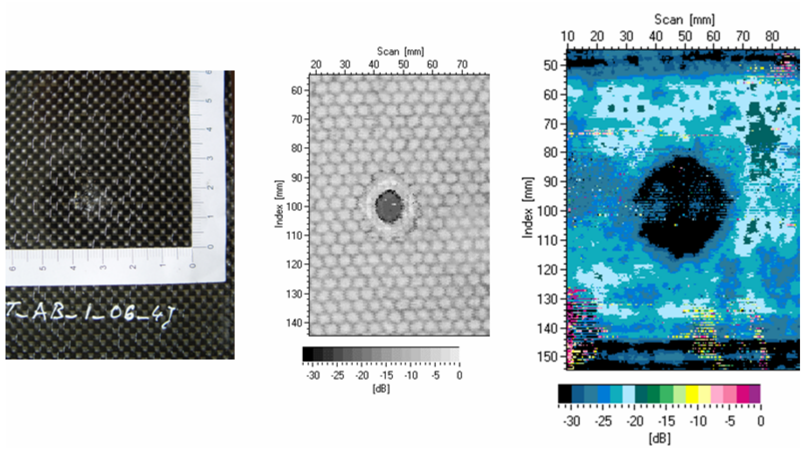


Figure 6: Damage images from ILR Dresden [14]: top skin photo and ultra sonic scans of back side echoes from top skin (showing damage in impacted skin) and bottom skin (showing core damage area) of a 4J impact.

4 Comparison of simulation and experiment

In this section the impact energy of 4J is taken as an example to compare computational and experimental results in the shape of force-time histories and damage sizes. In this regard, different stages of modelling the material degradation (no degradation, core degradation, skin degradation) will be discussed.

4.1 Force-time history

In Figure 7 three computed force-time histories are compared to experimental curves of two 4J impacts. The top curve illustrates a simulation result, where no degradation is taken into account. This approach clearly overestimates the stiffness of the sandwich plate and computes too large contact forces. By applying the proposed core degradation model, the contact force in Figure 7 decreases as soon as core damage is detected (dashed curve). Now there is a good agreement with the experimental results up to a contact force of about 1kN. To simulate the force drop at that point, the skin degradation model needs to be applied. Up to 1kN the skin degradation model causes almost no changes in the force-time curve, since only the two outermost laminas are slightly affected and since the skin is still capable of bearing loads. Face sheet tearing and therewith the substantial force drop does not take place until all laminas have failed. In the simulation this occurs a little earlier than in the test. However, the difference between 1.09kN in simulation and 1.17kN in experiment is very small. As mentioned in section 2.3, the simulation stops here at the point of first skin cracking.

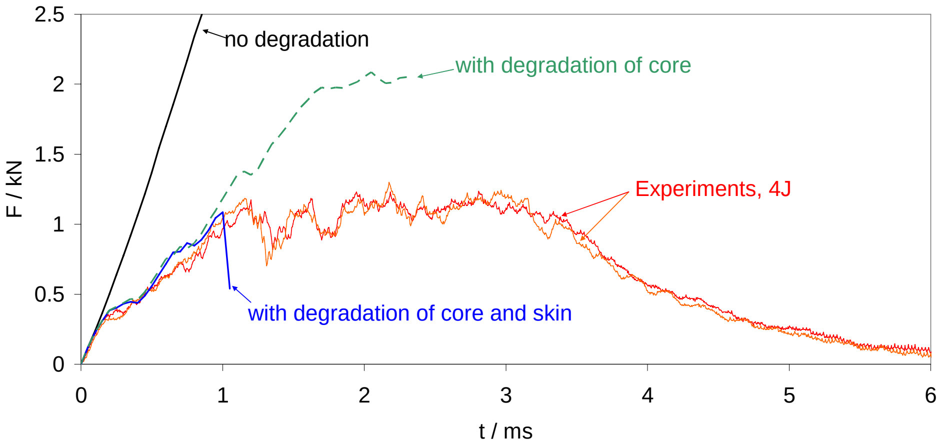


Figure 7: Force-time histories of a 4J impact for different stages of degradation.

4.2 Core damage

Figure 8 shows the computed core damage areas for the different stages of degradation (areas with blue crosses) in comparison with the measured core damage area (red quarter circle). If no degradation is taken into account, the core damage is predicted too small (middle image in Figure 8), since the stiffness of the sandwich plate is overestimated. In the case of skin degradation the core damage is also too small (bottom right image in Figure 8), since the simulation stops when the skin starts to tear. Of course, in reality the impact process continues at this point, the skin deflects further and the area of core damage increases. Consequently, the computed core damage at the moment of skin tearing is a reliable lower bound of the damage area. A reliable upper bound can be found by a simulation without skin degradation (top right image in Figure 8). In this case, the deflection of the intact face sheet is shallower, but affects a larger area causing core failure in a larger area.

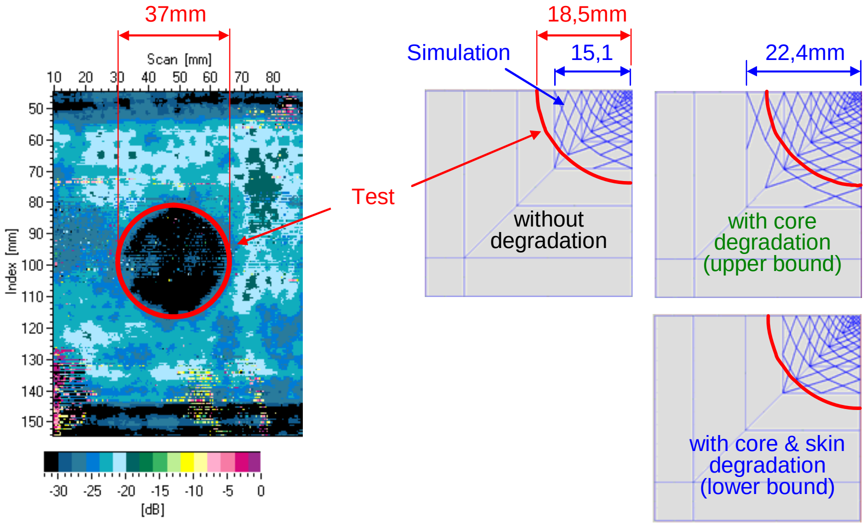


Figure 8: Sizes of core damage for a 4J impact and different stages of degradation.

4.3 Skin damage

Since the simulation stops at the moment of first skin cracking, the final skin damage size cannot be computed. The area of fibre failure at this moment is actually very small, as can be seen by the simulation results in Figure 9. Summarizing, the pure presence of a through-thickness skin crack, which firstly and substantially lowers the load capacity of the sandwich plate, is correctly predicted, whereas the final size of the skin crack cannot be predicted.

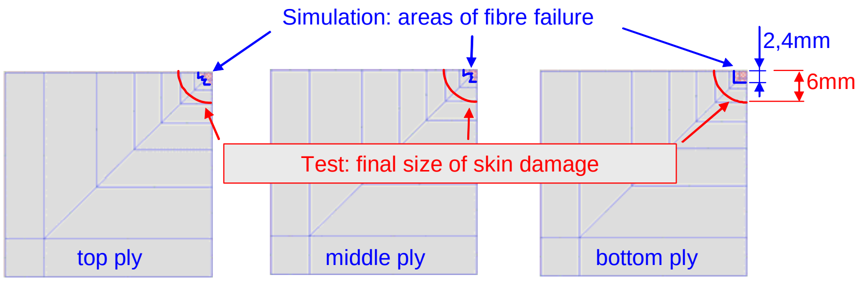


Figure 9: Areas of fibre failure at the moment of first skin cracking in comparison with the final skin damage size at a 4J impact.

5 Summary and conclusions

Figure 10 summarizes force-time histories and core damage sizes for all studied impact energies between 1J and 15J. For each of the energies the simulation results (blue) are compared to the experimental results (red). In simulations the core damages are approximated by means of an upper and a lower bound. In experiments the core damage diameters are determined by ultra sonic scans from the back side echoes of the bottom skin, cf. rightmost image in Figure 6. From simulation results the following conclusions can be drawn:

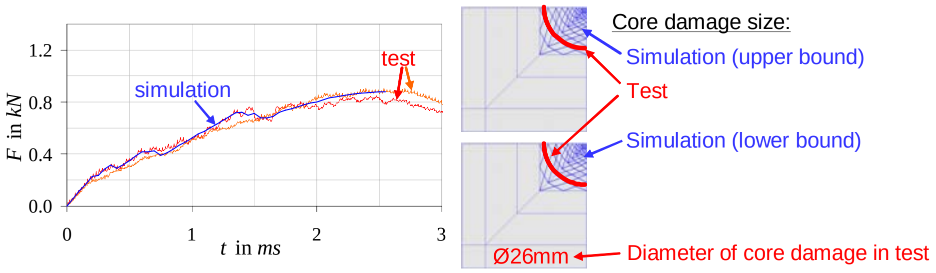
- For each energy the initial slope of the force-time curve is very well described, i.e. the impact behaviour of the undamaged sandwich plate is suitably modelled by the three-layered finite shell elements S815, by the Hertzian contact law and by the implicit Newmark time stepping scheme.

- First core damage occurs already at a very low energy level. Subsequently, the slope of the force-time curve decreases. This shallower slope is correctly predicted by simulation, i.e. the impact behaviour of a sandwich plate with core damage is suitably modelled by the core failure model including core failure criterion as well as core degradation.

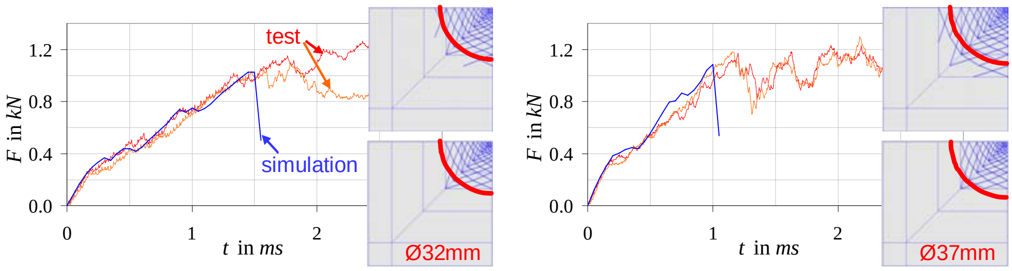
- If the impact energy is big enough to reach a threshold contact force (in our case about 1kN), the skin starts to tear and the contact force drops substantially. This is not the case at a 1J impact, as shown by experiment and simulation in Figure 10(a). The 2J impact is a borderline case: In one of the experiments the force drops down; in another experiment the skin does not crack. The simulation is conservative in this case and computes skin cracking. For all higher energies the skin fails in both, experiments (at a contact force between 1.05kN and 1.30kN) and simulations (at a contact force between 1.03kN and 1.12kN). Consequently, the skin failure model is suitable to predict the onset of skin cracking.

- The computed upper and lower bounds of core damage cover the experimental core damage sizes very well. Since the simulation does not include crack growth, a final size of skin damage cannot be predicted. However, the prediction of the presence of skin cracks is possible and is correct. This information is already important in order to estimate the residual load bearing capacity of an impacted sandwich structure.

- Depending on the impact energy and on the extent of degradation, the simulations took between 30sec and 100sec on a personal computer with 2.3GHz. Therewith, the high efficiency of the presented models and methodologies is confirmed.

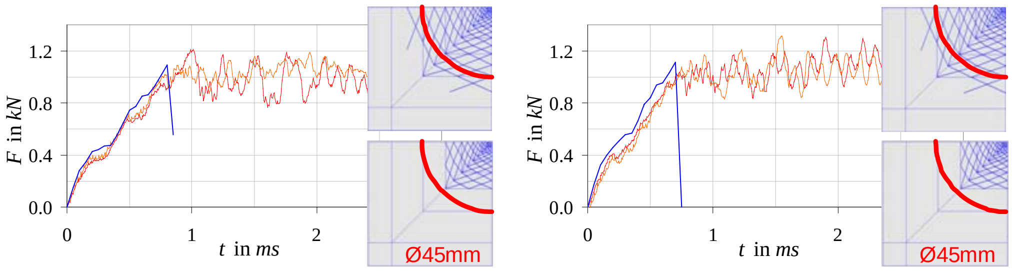


(a) 1J impact



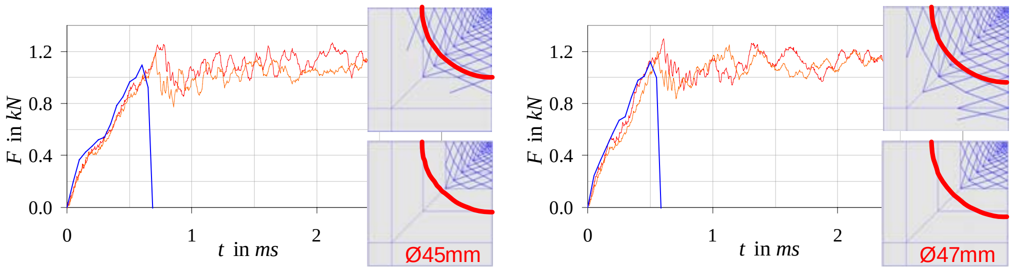
(b) 2J impact

(c) 4J impact



(d) 6J impact

(e) 8J impact



(f) 10J impact

(g) 15J impact

Figure 10: Force-time histories and core damages for all studied impact energies.

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