Multiscale modeling methods for analysis of failure modes in foldcore sandwich panels

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Abstract

The paper presents an homogenised core model suitable for use in the analysis of fuselage sandwich panels with folded composite cores under combined loading conditions. Within a multiscale numerical design process a failure criterion was derived for describing the macroscopic behaviour of folded cores under combined loading using a detailed foldcore micromodel. The multiscale modelling method was validated by simulation of combined compression/bending failure of foldcore sandwich panels.

1. Introduction

Sandwich structures consisting of thin stiff facesheets and a thick, low density core exhibit excellent stiffness-to-weight ratio and are investigated for novel light weight fuselage concepts. Currently the application of sandwich structures in transport aircraft is limited to secondary structures, since further understanding is required in the field of manufacturing, repair, vulnerability and safety before sandwich design can be applied for primary structures. Folded cores are currently investigated for future fuselage applications since the open cellular design of foldcore cells would solve the problem of humidity accumulation of closed cellular sandwich cores such as honeycombs [1-3]. Foldcore is a comparably novel core concept and can be produced out of different materials [4]. The manufacturing of foldcores is described in detail by Klett [5]. Homogenised core models and core micromodels can be used for core characterisation [6]. Different modelling techniques can be found in the literature for cellular core structures made out of Aramid paper. Impact resistance against high velocity impact loads and a corresponding micro model simulation strategy were developed [7-8] and applied to predict the impact damage [9-10]. Firstly, cellular core structures can be modelled using an homogenised model in a solid element representation [7][11]. Using a detailed shell representation of the folded core micro-geometry the instability failure can be simulated in more detail. Hereby Aramid paper can be modelled using an idealised elastic-plastic material description [8]. The detailed composition of the Aramid paper is addressed in the multi-layered material description developed in the CELPACT project [7].

For novel fuselage concepts safety regulations require an equivalent crashworthiness compared to the conventional metal fuselage design. Brittle failure mechanisms of CFRP structures make the verification of equivalent crashworthiness for CFRP fuselage concepts challenging since conventional metal fuselages absorb a significant portion of the kinetic energy by plasticization.

Current research projects addressing this topic see the highest lightweight potential in crash concepts for CFRP fuselage design by absorbing the impact energy in local crash devices which are installed in frame, cabin floor, cargo floor and sub-cargo area. In [12] a so called "frame-bend"

concept for transport aircraft made of composite material was investigated. In this concept kinetic energy is absorbed by progressive crushing of vertical struts below the stiff cargo crossbeam and with a large proportion of kinetic energy absorbed by frame bending. High energy absorption by frame bending requires installation of specific crash devices which increase the mass compared to a static sized frame. In [13] a so called "alternative tension crash" concept for transport aircraft made of composite material was investigated. In this concept kinetic energy is absorbed by tension forces in the cargo floor and cabin floor, which reduces energy absorption requirement by frame bending.

While the specific energy absorption of composite structures can exceed metal under pure compression loads, the brittle failure mode under bending loads limits their energy absorption capability during bending failure. Whilst experimental and numerical studies were already performed on monolithic CFRP frame segments [14-16], there is a limited understanding of the failure mechanisms of CFRP sandwich panels under crash relevant compression bending loads.

In this paper a multiscale failure analysis method is investigated using an homogenised core model in an implicit FE code simulation environment. The required mechanical response of the foldcore was identified by performing explicit code FE simulations on detailed core micromodels at the unit cell level.

2. The core trigger concept

Before sandwich structures can be applied in the fuselage design the certification authorities require prove of equivalent safety standards to the existing metallic reference design. For a CFRP fuselage a controlled progressive predefined crash kinematics is seen as necessary to obtain an equivalent crashworthiness. Experiments showed that failure initiation of a twin-walled fuselage panel can be controlled by a local modification of the core pattern [17]. The foldcore pattern used in the studies consists of a zick-zack pattern with additional integrated horizontal edges. Since under compression loads thin walled folded structures fail due to buckling, the foldcore compressive strength is affected if the stability properties of fold pattern are modified. Hence by modifying the length of the horizontal fold edge, the failure characteristics of the core can be adjusted according to the hinge requirements. As long as the shear stiffness remains within the required static envelope, the core trigger does not affect the structural behaviour of fuselage panels since the load carrying facesheets are not affected by the modification of the core architecture. Due to failure initiation, the core subsequently collapses and develops a rotating hinge exactly at this location. The flexibility of folded cores offers the unique possibility to implement the core trigger by a local modification of the fold pattern. Since this modification can be directly implemented in the folding process, no splicing of different core segments is required. The geometrical description for the triggered and the untriggered foldcore are provided in Figure 1.

Core Properties   *Core Trigger*

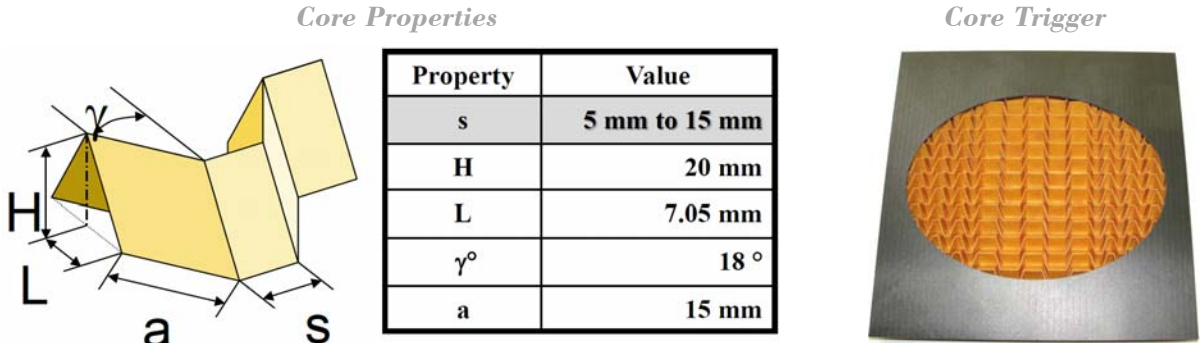| Property	Value
s	5 mm to 15 mm
H	20 mm
L	7.05 mm
$\gamma°$	18 °
a	15 mm

Fig. 1: Geometrical description of the fold pattern for the triggered and the untriggered region [17]

If a trigger mechanism needs to be investigated, it is beneficial to test the structural response under crash relevant loading condition. For a controlled crash kinematics a defined failure initiation of the fuselage segment between cargo crossbeam and vertical strut is required. Numerical studies, investigating the crashworthiness of single aisle composite fuselage concepts, indicate a combination of bending and compression during crash. To simplify the notation, the short description A [mm] is used for the ratio of bending M (kNmm) to compression load F (kN) in the fuselage segment [12].

In the literature a representative bending to compression ratio of A = 200 mm can be found for the investigated frame segment [17]. Therefore the functionality of the core trigger concepts was investigated under this representative loading condition. For the validation of the core trigger concept, quasi-static tests were conducted with the only difference of a local modification of the fold pattern for triggering. The experiments confirmed that the position of failure can be controlled by a local weakening of the core compression strength [17]. Additionally an explicit micromodel simulation approach was developed to numerically investigate the panel response under various loading condition [18]. Figure 2 shows the experimental and the explicit simulation of the panel failure.
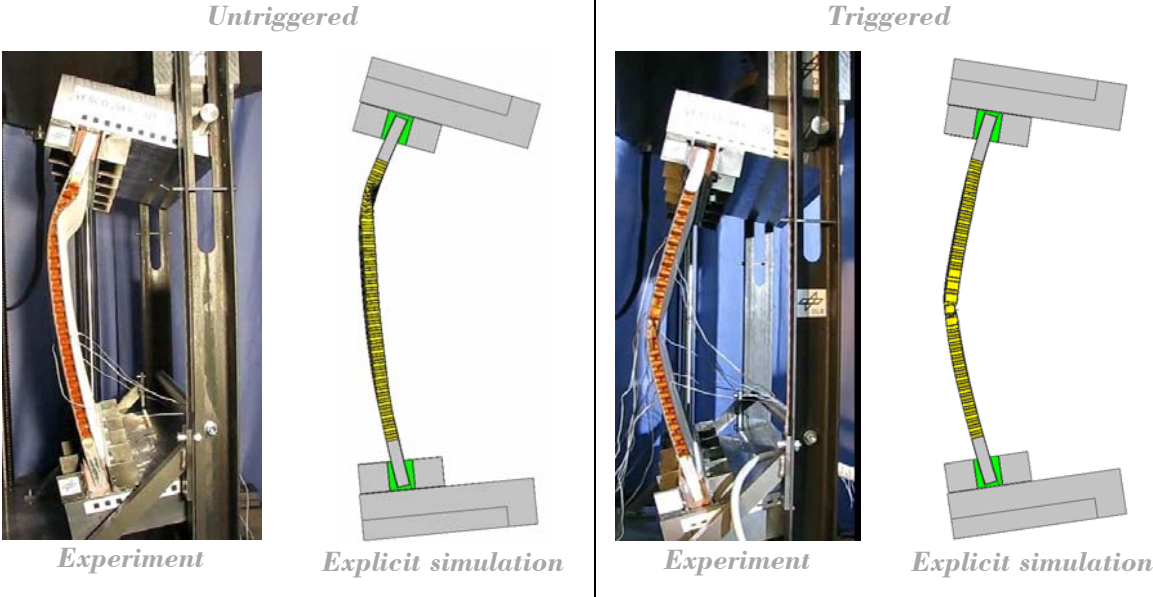

Fig. 2: Experiments and corresponding explicit simulations fuselage panels under a bending to compression ratio of A = 200 mm [17] [18]

3. Homogenization of the foldcore

3.1. Numerical representation

A detailed discretisation of the foldcore using a micromodel shell representation for the sizing process of foldcore sandwich panels on structural level is inefficient due to excessive increase of the computational costs. Therefore a homogenised description of the foldcore is used for a macroscale simulation technique predicting elastic deformation and damage initiation of foldcore sandwich panels under a given loading condition. The presented macroscale simulations were performed using the implicit solver ANSYS 12.1. The described modelling method is validated using experimental test results of foldcore sandwich panels under combined compression/bending loads [17].

The main design features of the experimental setting and their virtual representations are shown in figure 3. In the experiment the facesheets of the sandwich panel with a radius of 2000 mm consisted

of two identical Cytec HTS/977-2 prepreg laminates with a laminate setup of [90°/0°/90°/0°/0°/+45°/-45°/0°]$_s$, where the 0° direction corresponds to the flight direction. The facesheets are modelled with the eight nodes structural *SOLID185*, in which the smeared orthotropic laminate properties were directly included from material characterisation tests. The stiff leverage devices were modelled simplified using multipoint constraint *MPC184* rigid beams between load introduction and sandwich panel. The loading was applied on *MASS21* point elements representing the mass of the leverage devices. The degrees of freedom of these point elements were constrained according to the experimental setup. For the reduction of computational cost a half model was used applying symmetric boundary conditions on the vertical centreline of the sandwich.

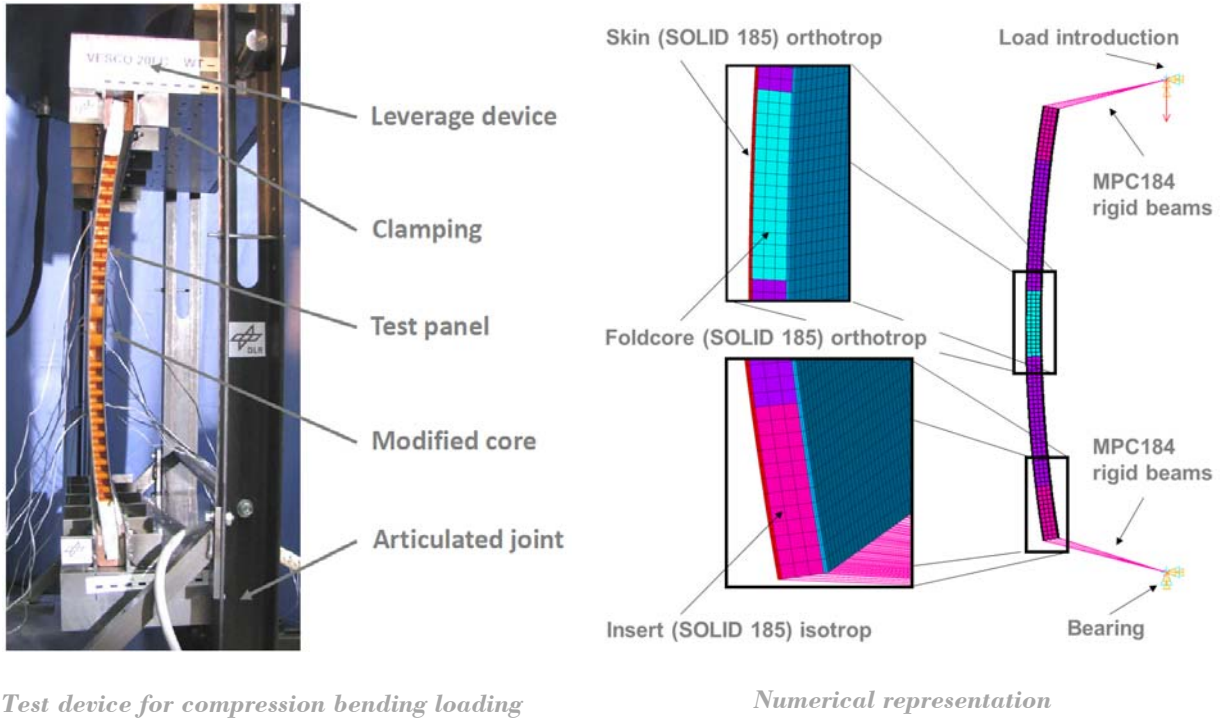*Test device for compression bending loading*   *Numerical representation*

Fig. 3: Discretization of the experimental test device

3.2. Development of a failure criterion

A direct shell micromodel of the foldcore, as conducted in the explicit simulation approach [18], is difficult to apply on macroscale due to the enormous increase of computational cost. For these simulations a homogenised foldcore representation and macroscopic failure description using solid elements is more suitable. The application of a simplified unidirectional strain- or stress based failure criterion for the folded core is not appropriate. This becomes obvious if considering the remaining compression strength of a folded core after the walls are deflected by shear. In the literature the macroscopic failure envelope of core materials is often described by the normalized failure criterion

$$\left(\frac{\sigma_C}{\sigma_{C,max}}\right)^n + \left(\frac{\tau}{\tau_{max}}\right)^n = 1 \tag{1}$$

where σ_c is the transverse compression, τ the shear stress, $\sigma_{c,max}$ the uniaxial compression strength and τ_{max} the shear strength. In the literature experimental studies can be found, investigating the core failure under combined loading condition to identify the exponent *n* for different core materials.

However, the experimental results are inconsistent describing partly different coefficients for the same core material [19-22]. Depending on core material and the experimental setup the coefficient differs between a linear and quadratic interpolation. In [23] the failure was investigated experimentally for foldcores with a zick-zack fold pattern. A linear correlation was identified to fit the best the experimental results.

However, if considering the architecture of foldcores in detail, it can be assumed, that equation (1) seems to be a very simplified approximation, since the foldcore has already a direction dependent shear behaviour due to its fold pattern. Under this consideration it seems beneficial to distinguish the failure enveloped additionally into the two main shear direction τ_L and τ_w. If furthermore a load component dependent damage initiation is assumed, the complexity of the description increases to

$$\left(\frac{\sigma_c}{\sigma_{c,\max}}\right)^{n_C} + \left(\frac{\tau_L}{\tau_{L,\max}}\right)^{n_L} + \left(\frac{\tau_W}{\tau_{W,\max}}\right)^{n_W} = 1 \qquad (2)$$

A significant number of experiments would be required for each fold pattern to identify the describing parameters. For the aramid paper an explicit numerical methodology was developed in the European funded project CELPACT, which can be used for numerical material characterisation tests. Since core failure can be investigated numerically under combined stress states with a foldcore micromodel, the required parameters can be identified efficiently by simulation.

Virtual material characterisation tests were performed on a representative number of unite cells (3 times 5) using the explicit solver PAM CRASH V. 2009 [7][17]. For the investigation of the core behaviour under bi-axial loading, a defined load was applied on the core in a first load step. Hereafter a second load component was additionally introduced by displacement control up to failure. Using this approach the core behaviour can be investigated numerically under each combined loading condition. Hereafter the description of the 2D fracture envelopes was derived by fitting the corresponding exponents according to the obtained failure stresses. The fracture envelope and the corresponding exponents are shown for the triggered foldcore in Figure 4. The results indicate, that applying a linear fit according equation 1 would inaccurately predict the failure characteristics of the used fold pattern.
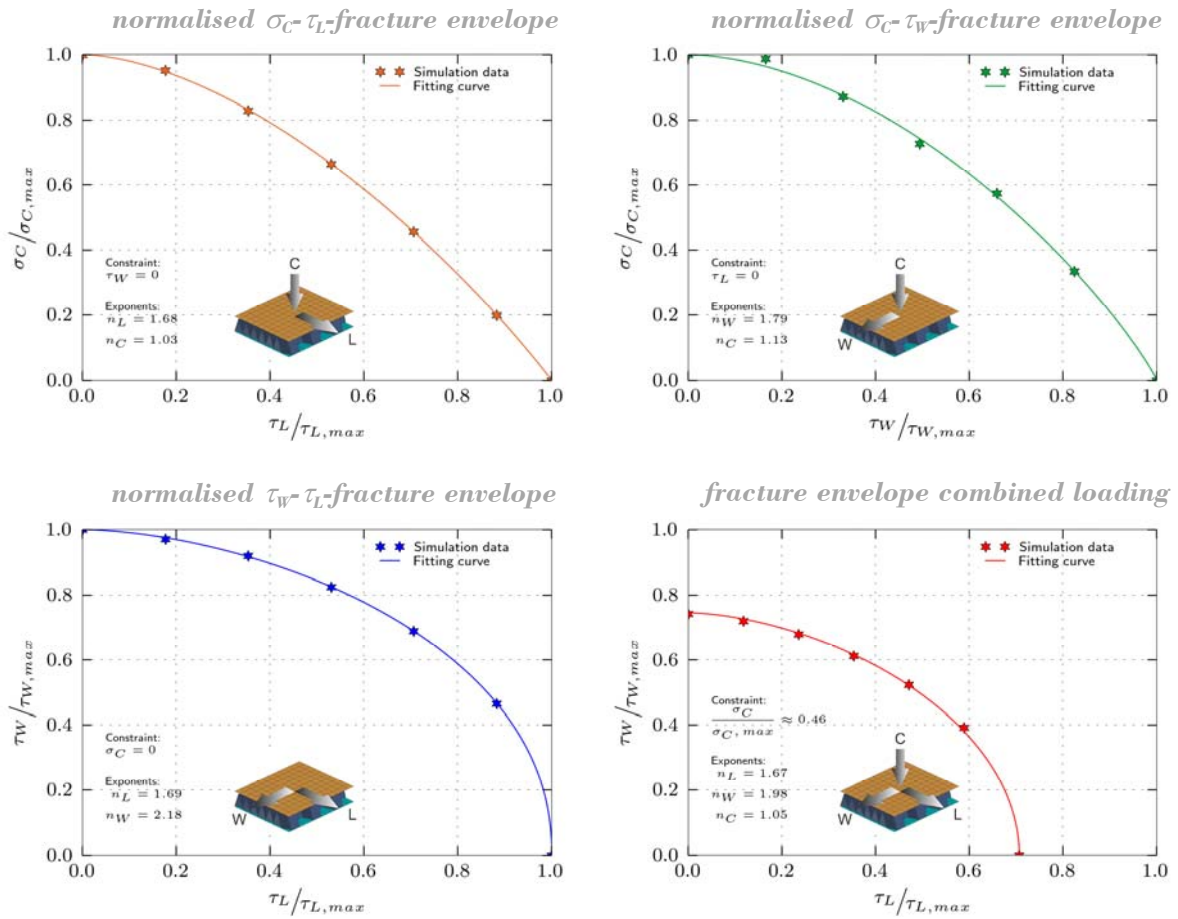
Fig. 4: Fracture envelope for the triggered foldcore

The simulation results for the description of the 2D fracture envelope requires the compressive exponent n_c to be between 1.0 and 1.13, the shear exponents n_L to be between 1.68 and 1.69, and the shear exponent n_W to be between 1.79 and 2.18. The slightly different values for the same exponent indicate that even the complex description is not able to completely describe the failure characteristic of the foldcore. Since the exponents directly correlates to the importance of the corresponding load component, especially the compressive loading seem to have a strong impact on the failure initiation. The averaged exponents for the two investigated fold patterns and a visualisation of the 3D-fracture envelope of the triggered foldcore are shown in figure 5.

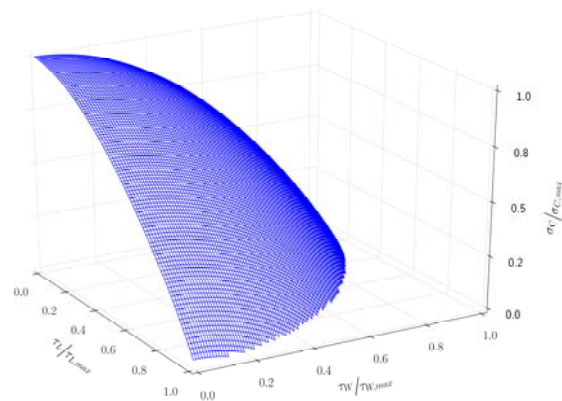|	Index	triggered	untriggered
σ_C compression damage coefficient	$\overline{n_C}$	1.08	1.09
τ_W shear damage coefficient	$\overline{n_W}$	1.99	1.77
τ_L- shear damage coefficient	$\overline{n_L}$	1.69	1.43

Fig 5: Averaged coefficient for the description of the failure criterion and 3D-fracture envelope

4. Results and Discussions

The simulation method was validated with the experiments investigating a triggered and untriggered foldcore sandwich panel under a compression to bending ratio of A = 200 mm. The stress state of each core element was extracted from the simulation and the corresponding core damage was calculated using the fracture envelope according equation (2) and the exponents from figure 5. For the experiment of the untriggered fuselage panel the obtained core damages are plotted in figure 6. The crosshead loading of 29 kN corresponds to the point of failure obtained in the conducted experiment of the untriggered sandwich panel.
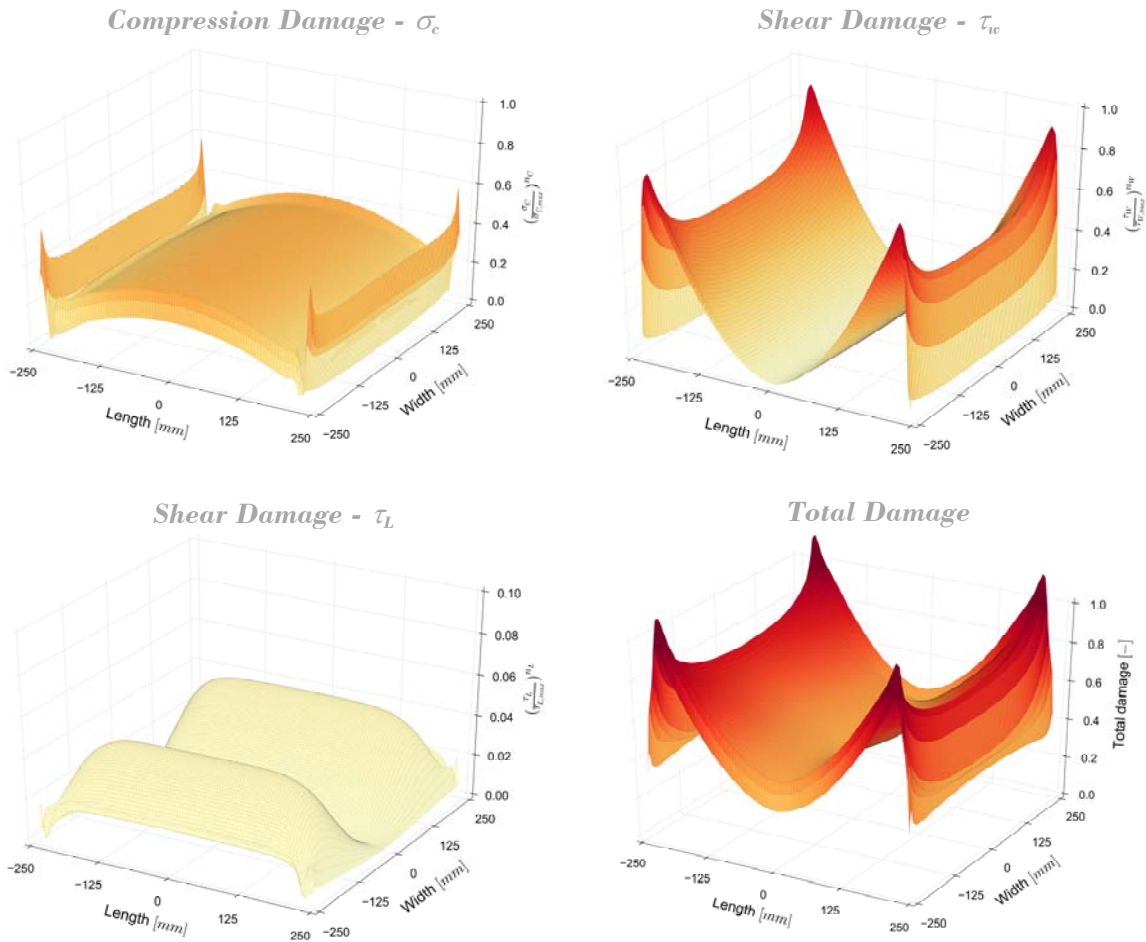

Fig. 6: Core damage for the untriggered foldcore sandwich panel with *A* = 200 mm and crosshead force *F* = 29 kN

The simulation predicts a panel failure near the load introduction which is in agreement with the observed failure in the experiment as shown in figure 7. Thus despite the homogenisation of the foldcore the developed multiscale modelling method is suitable for failure identification of the core. The application of the failure envelope additionally offers the unique possibility to analyse the complex stress state of the foldcore by splitting the loading into the different load components. As shown in figure 6 the shear component τ_w can be identified to be the main load component which initiated the panel failure in the experiment. The corresponding shear damage increases from 0 % damage in the center (pure bending) up to 80 % damage at the position of failure. These shear loads can be explained by the panel curvature during failure.
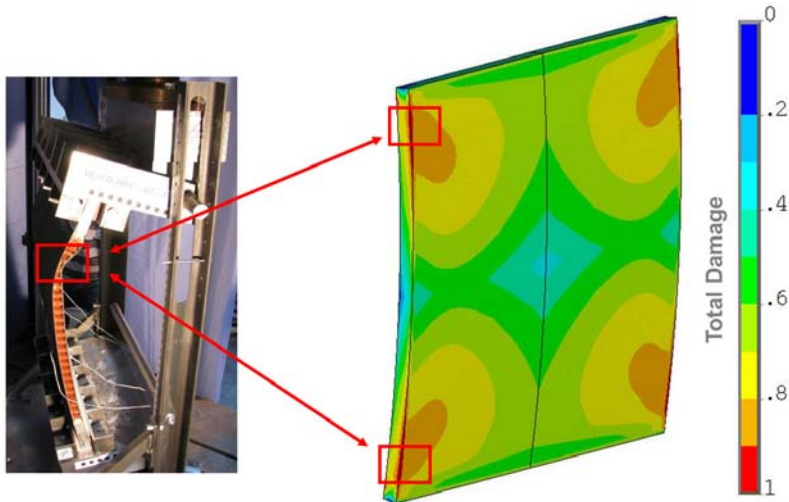
Fig. 7: Comparison of the experimental and the numerical results [crosshead force *F* = 29 kN]

The shear component τ_L, which is caused by the lateral contraction of the inner and outer skin, has with a fraction of 4 % only a small impact on the core load. The compression damage increases from 20 % (near the load introduction) up to 35 % (at the panel centre). Hence the results indicate that a combination of shear τ_w and through thickness compression σ_C led to the failure at the corner of the panel.

After the macroscale simulation could predict the failure initiation for the untriggered foldcore sandwich panel, the same methodology was applied on the conducted experiment of the modified foldcore sandwich panel (figure 2). In figure 8 the obtained results are shown for the different damage components according to equation 2. The integration of the different fold pattern gets directly obvious in the shape of the compressive damage. In the area of unmodified foldcore geometry similar pattern of compression and shear damage are obtained. In the area of modified foldcore geometry the compression damage is considerably increased compared to the untriggered foldcore sandwich panel. This local increase in compression damage directly shows the functionality of the core trigger concept, in which the failure of a sandwich panel is initiated by a defined local modification of the core properties. Whilst the modification of the fold pattern has strong impact on the compression failure characteristics, the simulation indicates only a small influence on its shear behaviour.
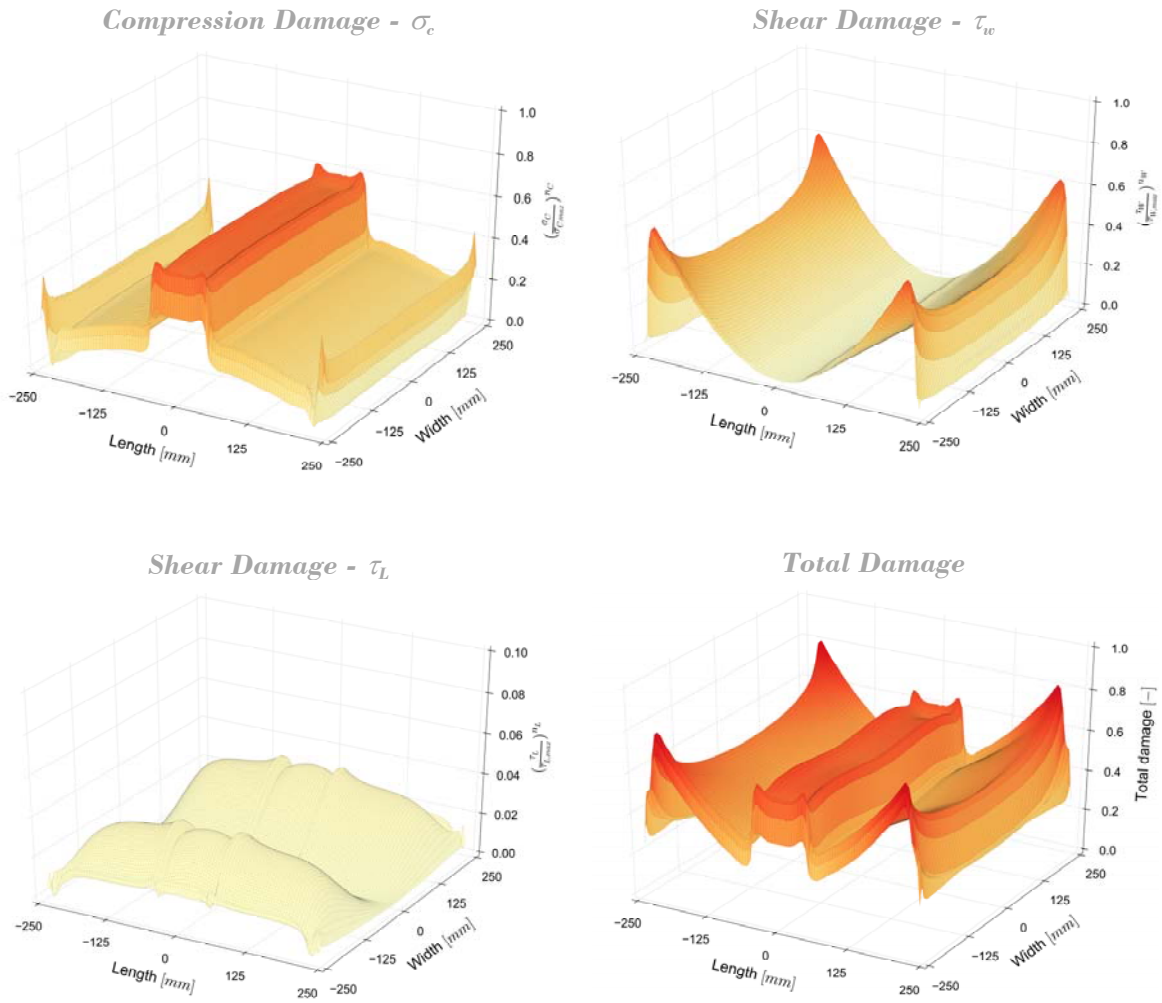
Fig. 8: Core damage for the triggered foldcore sandwich panel with *A* = 200 mm and crosshead force
F = 25.8 kN

However, the total damage indicates unsufficient through thickness compressive loads for having initiated the panel failure. The simulation predicts a 35 % safety margin in the trigger region during failure. Existing deviation due to the idealised numerical representation of the foldcore and the insufficient modelling of geometric- and material nonlinearity are not able to explain the obtained difference between the numerical results and the experimental outcome. A failure mode, which is not considered by the failure hypothesis, had to have initiated the failure. The fracture enveloped describes failure and core damage characteristics under various combined loading conditions. Since the detailed architecture of the foldcore is lost after the homogenisation, the fracture envelope cannot predict failure modes which depend on the detailed architecture of the core. The experiment showed a fracture of the compressed facesheet with a locally crushed core in the trigger region. Since a failure due to insufficient core strength can be excluded, the failure had to be initiated by insufficient support of the facesheets. By increasing the horizontal foldedges for triggering the support of the facesheet and therefore the local buckling stress is affected by the modification of the fold pattern. Studies investigating the buckling behaviour of cellular core show a strong influence of the detailed core architecture on the critical failure stress [24-26]. For the identification of the failure mode additional simulations using a foldcore mircomodel on a representative number of unite cells were performed investigating the panel behaviour under combined core and facesheet load. The foldcore was numerically compressed by usage of a rigid wall pressing against the upper facesheet

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according to the implicit outcome. In a second load step the upper faceheet was compressed displacement controlled. The numerical output is shown in figure 8. Despite small buckling modes are already obtained in the foldcore after the first load step, the core loading is unsufficient for initiating a core failure. After having introduced the additional facesheet compressive loading a local instability failure is obtained. The result supports the assumption that the failure in the triggered foldcore region was due to a combination of through thickness compression core loading and wrinkling failure of the compressed facesheet. Since the developed failure hypothesis only considers the stress state of the core, failure modes, which directly depend on the detailed core architecture in combination of facesheet loads, cannot be identified by the developed fracture envelope.
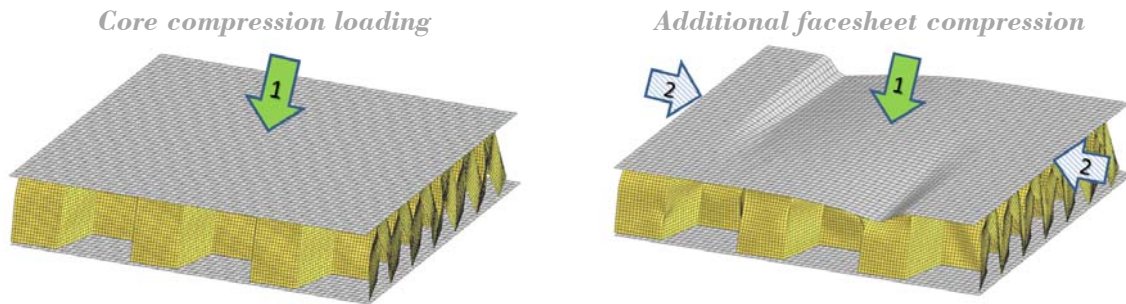

Fig. 8: Influence of facesheet compression on failure initiation

Comparing the presented multiscale modelling method with a foldcore micromodel simulation of the experiment, especially the requirement of developing a 3-D failure envelope for each fold pattern is challenging. If explicit simulations are used for the identification of the failure characteristics, the inaccuracies existing in the material description cannot be excluded by the application of a macro-scale modelling method. Additionally the homogenized representation of the foldcore is not able to capture all failure modes as intercellular buckling modes which depend on the detailed architecture of the cellular core. Since an intercellular buckling failure of the facesheet cannot be identified by the modelling method due to the homogenisation of foldcore, this failure mode has to be investigated separately. Therefore a micromodel simulation approach with detailed representation of the foldcore seems to be favourable, if the influence of a fold pattern modification on the panel failure has to be studied. On the other hand with the presented multiscale modelling method large structures made out of foldcore sandwich panels can be analysed efficiently by obtaining the safety margin against core failure for each homogenised core element.

5. Conclusions

A multiscale simulation approach for efficient stress analysis and failure identification of foldcore sandwich panels under combined loading is presented. Since a detailed modelling of the cellular architecture is inefficient on structural level, a homogenized representation of the foldcore is applied. The complex failure characteristics of the foldcore is described by a proposed failure envelope which considers compression loads as well as direction dependent shear loads. The failure envelope was derived by virtual material characterisation tests, performed on a representative number of unite cells using foldcore micromodel simulations.
The multiscale modelling methodology was validated by experiments investigating a trigger concept for foldcore sandwich panels. The trigger concept utilises the manufacturing process of the foldcore technology to locally adjust the mechanical properties of the foldcore. By varying the fold parameters in the manufacturing process a region with reduced mechanical strength properties can be fabricated. This allows controlling the location of failure in a sandwich structure during a crash event.

Whilst the simulation results show that failure modes and sensitivities of the cellular core can be analysed very efficiently, limitations were found by failure modes which strongly depend on the detailed architecture of the core.

Comparing the presented multiscale modelling method with the application of a direct micromodel simulation of the experiment, especially the requirement of developing a macroscopic description of the failure envelope for each fold pattern is challenging. Therefore a micromodel simulation seems to be favourable, if the influence of a modified fold pattern on its failure behaviour has to be studied. On the other hand the homogenised core representation has the unique advantage, that the complex stress state of the cellular core can be analysed efficiently on macroscale. This can legitimate the effort of developing the required failure envelope, especially if the fold pattern is fixed.

Acknowledgements

Conflict of Interest

The authors declare that they have no conflict of interest.

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