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EXPLICIT SIMULATION OF CRACK GROWTH IN HONEYCOMB CORES OF SANDWICH STRUCTURES

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1. INTRODUCTION

High performance sandwich as used in aerospace structures typically consists of thin CFRP face sheets and Nomex honeycomb cores. Owing to the rather weak core material, this kind of structure is prone to a range of damages. While matrix cracks, fibre fracture and delamination occur in the face sheet, the cell walls of honeycomb cores are often wrinkled or crushed. Further loading of the damaged structure can initiate cracks in the core. During typical ground-air-ground cycles of airplanes, these cracks may grow further. In the worst case, this can lead finally to a complete failure of the sandwich component. Therefore, the fracture mechanical behaviour of honeycomb cores has to be considered in the damage tolerance and fatigue evaluation of aerospace sandwich structures. In this context, often the energy release rate is determined to assess the fracture behaviour of structures. This task is usually done utilizing experimental methods like the single or double cantilever beam (SCB or DCB) test [1, 2]. In order to reduce the experimental effort numerical methods are increasingly used to simulate the crack growth behaviour [3, 4]. Different fracture mechanics approaches such as the *Virtual Crack Extension* method (VCE), the *Virtual Crack Closure Technique* (VCCT) or the *Crack Surface Displacement* method (CSDE) can be applied in combination with finite element models to analyse the crack growth in honeycomb sandwich structures [4]. For the commonly used VCCT method, the structure is modelled by volumetric elements for both the core and the face sheets. Due to the large difference between the stiffness of the face sheets and the sandwich core, often large and unrealistic deformations are obtained with this approach [5]. Furthermore, previous works have shown that a homogenized model of the sandwich core cannot predict local failure behaviour correctly [6, 7].

In order to overcome these problems, this paper presents an improved approach, which is based on an explicit numerical method and a detailed sandwich core model to predict the crack growth in honeycomb sandwich structures. Layered shell elements are used to model the face sheets as well as the core cell walls. A test method has been developed and applied to characterise the crack growth of the basic core material. The investigations showed a non-negligible bridging effect of the material near the crack front. Based on this information, the material model describing the cell wall behaviour was enhanced. Finally, the structural behaviour of honeycomb sandwich specimens in SCB tests were numerically analysed.

2. MATERIAL CHARACTERIZATION

Cell Wall

The material data of the base core materials are required as input parameters for the simulation. Therefore, the mechanical material properties of the pure and the impregnated aramid paper were identified by various test methods. The in-plane tensile properties have been determined using the standardised tensile test for paper material according to DIN 1924-2. The material properties under compression and shear loading were obtained by the single curved compression test (SCCT) and the picture frame shear test [8, 9, 10].

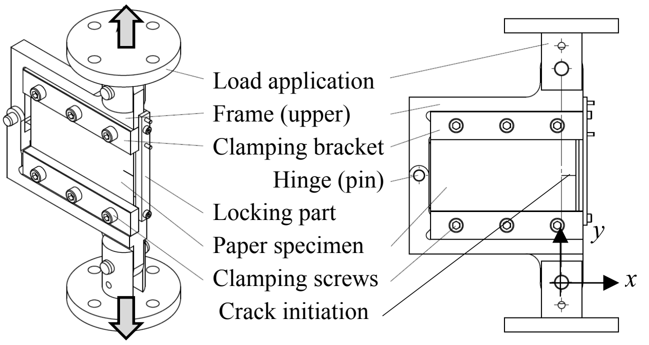
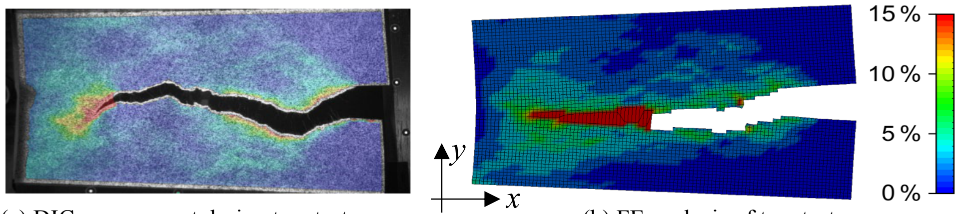


Fig. 1: Developed tear test device for paper and paper-like materials.

Investigations have shown that fibre bridging is important when failure mechanisms are considered (see Fig. 2(a)). The bridging occurs after a region reaches its maximum stress. Since the effective stiffness decreases and becomes negative, this behaviour cannot be observed using standard tensile tests. Hence, fracture toughness tests are necessary. Unfortunately, there are no suitable experimental methods for paper. Standards like the *Elmdorfer Tear* test according to ASTM D1424 and the *Brecht Imset* test according to DIN 53115 ensure only a mode III failure. Only the *Van den Akker* tear test applies a mode I loading to paper [11]. However, due to the nature of this test the repeatability is low and the procedure is hard to simulate by finite element analysis. Therefore, a new tear test method has been developed (Fig. 1).

To ensure a pure in-plane loading, a planar test configuration has been chosen. The specimen is clamped on two frame members. An asymmetric hinge connects these parts and ensures that the clamped paper is loaded with a tensile stress distribution. Due to the hard clamping and the tensile stress distribution, it is not possible to measure the fracture toughness directly. However, the test setup can easily be simulated using finite element analysis, Fig. 2(b).



(a) DIC measurment during tear test (b) FE analysis of tear test

Fig. 2: y-strain distribution of test and simulation results for the developed tear test (y-strain).

Honeycomb Geometry

For the investigation a Nomex® honeycomb core Cormaster C1-4.8-32 provided by *Schütz GmbH* was used. The core has a cell size of 4.8 mm, a density of 32 kg/m³ and a height of 40 mm. To determine the geometrical parameters for the FE model, micro sections and pictures were made. As it turned out, the measured cross section geometry deviated considerably from an actual hexagon [6]. The investigated cores were slightly over-expanded and the single and double cell walls differed in length. In addition, local resin reservoirs existed in the transition zone from single to double walls.

CFRP Face Sheets Material

The face sheets consist of four layers of a CFRP fabric prepreg (Hexcel fabric 926 and epoxy resin 913) with an overall thickness of 1.4 mm. An AF163 adhesive film connects the face sheets with the core. The adhesive film forms a meniscus layer. Since the cracks normally grow in the honeycomb core, it can be assumed that the adhesive film does not influence the fracture mechanical behaviour.

The fabric composite material of the face sheets has been modelled using the LS-Dyna orthotropic material law for layered composites. The required mechanical properties were determined by standard test methods. Delamination interfaces between the layers were not considered, since no delamination has been observed in the experiments.

3. SCB TEST ON SANDWICH SPECIMENS

The *Fraunhofer Institute IMWS* (Halle) carried out the SCB tests [5]. The used test setup is shown in Fig. 3(a): the lower face sheet of the specimen is clamped onto a test fixture and a hinge is glued onto the upper face sheet. A rod and a loading cell connect the hinge with the upper part of a universal test machine. During the test a force F is applied to the hinge. At a critical load level, the crack starts to grow from the initiation point in positive W-direction. Once a crack length of 40 mm is reached, the upper frame part is moved back to its original position and the first loading cycle is completed. Subsequently, a second loading cycle starts until a total crack length of 80 mm. An example for the resulting force-displacement relationship is given in Fig. 3(b).

4. EXPLICIT SIMULATION

Material Model

A regressive failure model has been developed to enhance the applied user defined material model to describe the cell wall behaviour. The regressive failure process begins at the maximum stress, which is determined by a previously defined failure criterion (e.g. *Tsai-Wu* criterion). For this stress state the equivalent strain at failure $\hat{\varepsilon}_e$ is given by the effective strain

$$\varepsilon_e = \sqrt{\frac{2}{3}\varepsilon_{ij}\varepsilon_{ij}}\,. \tag{1}$$

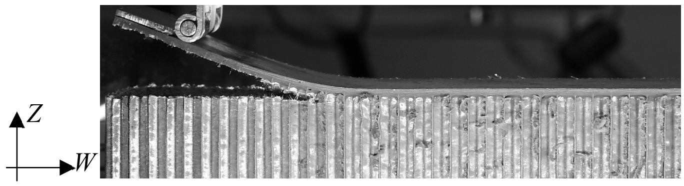
The effective residual strain $\mathrm{d}\varepsilon_e$ defines a region for which the material retains a residual stiffness throughout fibre bridging. In this region the stress state is attenuated. For this, a regressive attenuation factor is defined as follows:

$$f_\mathrm{R}(\varepsilon_e) = \begin{cases} 1 & \varepsilon_e \leq \hat{\varepsilon}_e \\ \left(1-\left(\frac{\varepsilon_e-\hat{\varepsilon}_e}{\mathrm{d}\varepsilon_e}\right)^{n_\mathrm{R}}\right)^{1/n_\mathrm{R}} & \hat{\varepsilon}_e \leq \varepsilon_e \leq \hat{\varepsilon}_e + \mathrm{d}\varepsilon_e \\ 0 & \varepsilon_e \geq \hat{\varepsilon}_e + \mathrm{d}\varepsilon_e \end{cases} \tag{2}$$

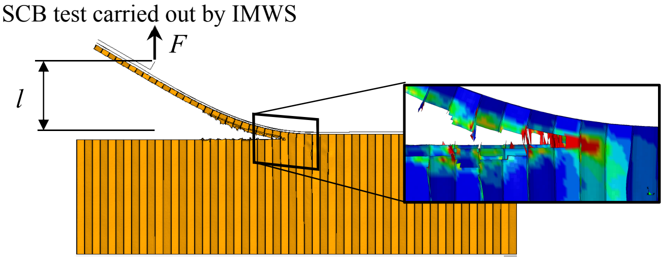
It becomes clear, that the regression exponent n_R defines the decreasing stress-strain behaviour for values greater than $\hat{\varepsilon}_e$ and smaller than $\hat{\varepsilon}_e + \mathrm{d}\varepsilon_e$. Exponents greater than 1 lead to a progressive decay and values less than 1 to a digressive decay. By simulating the developed tear test, the parameters $\mathrm{d}\varepsilon_e = 17{,}6\%$ and $n_\mathrm{R} = 0{,}55$ could be determined, Fig. 2(b).

SCB Simulation

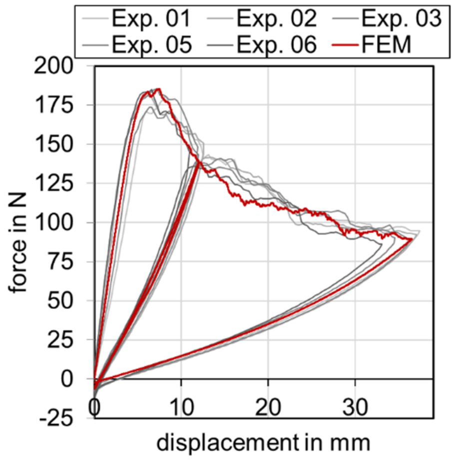
Simulations of the single cantilever beam test were conducted using the developed user-defined material model [8] in the explicit finite element tool LS-Dyna, see Fig. 3(c). The mesh was created with the help of the SandMesh 2.0 software which has been developed at the Institute of Aerospace Engineering of the TU Dresden. This tool allows to create finite element models including imperfections and irregularities, like those detected on the honeycomb specimens. The cell wall material has been modelled as a three-layer material with the stacking sequence phenolic resin / aramid paper / phenolic resin. Material parameters not determined in section 2 were taken from [7]. As shown in Fig. 3(b) the analysis results agree very well with the experimental data determined by *IMWS*.



(a) SCB test carried out by IMWS



(c) FE simulation of the SCB test



(b) FEA (red) and test (grey) results

Fig. 3: Single-cantilever-beam (SCB) test, simulation and comparison of the results.

5. CONCLUSIONS

The numerical study performed in the presented research project provides an alternative to commonly used fracture mechanical analyses. The explicit simulation approach yields conclusive results and is in good agreement with experimental data. An advantage of the method is that no SCB testing is necessary to determine the energy release rate. In theory, it is possible to carry out such simulations based merely on the data of the constituent materials (i.e. aramid paper and phenolic resin) as well as on the core geometry. However, in practice it is necessary to calibrate the sandwich simulation by tensile or compressive tests of the sandwich core.

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