MECHANICS OF COMPOSITES IN LIGHTWEIGHT STRUCTURES: EFFICIENT TESTING AND COMPUTATION ACCOUNTING FOR COMPLEX 3D BEHAVIOUR

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Abstract

Textile and thick composites show growing importance for cost efficient manufacturing and need a proper out-of-plane failure analysis for safe performance of modern aircrafts. Both important types of composites show complex 3D mechanical behaviour. The paper presents:

1. A new testing device accounting for combined out-of-plane loading.

2. An efficient computational method using finite volume-p-elements based on hierarchical shape functions and error estimators.

3. Experimental validation of 3D-failure computation.

Striving for safe and efficient industrial standards, this work provides the basis for certification issues according to experimental testing and predictive virtual testing.

1 Introduction

Anisotropic textile and thick composites are of growing importance for efficient manufacturing and safe performance of modern aircrafts. In comparison to conventional laminated composites they show even more complex nonlinear deformation and failure behaviour [1].

Three-dimensional (3D) reinforced textile composites as Non Crimp Fabric (NCF) composites provide the potential to increase the out-of-plane material performance by introducing full through thickness reinforcements. Especially the delamination resistance can be increased by stitching or tufting. To achieve their full potential, regions dominated by three-dimensional stress distributions, e. g. load introduction areas, have to be analysed properly.

Experimental tests were used to determine the parameters of the constitutive model. Besides the in-plane properties the through-thickness material properties are assumed to be primarily important for textile composites.

Appropriate standardised tests that determine the in-plane behaviour of composites are already available and commonly accepted. Furthermore over the years numerous experimental tests have been developed to characterise the out-of-plane laminate properties [6]. Most of these tests are relative simple and generate interlaminar shear failure such as the four point bending test of relative short specimens and the Iosipescu or double notched shear test. Through-thickness tension and compression material properties are mainly determined by waisted block specimens or tensile opening of curved laminates which apparently produce a poorly defined tensile stress distribution.

In order to obtain more reliable through-thickness failure data, a new test method is presented building on a test originally developed by Arcan and co-worker [7]. Taking earlier modifications [8] into account, a new test device was developed with a waisted block specimen to analyse the through-thickness failure behaviour of textile composites [9]. The test based on a simple concept in which two halves of a disc can be rotated and loaded in different directions to impose defined load conditions. Generally this test provides both, the potential to determine the pure out-of-plane material failure properties and the failure behaviour under combined load conditions.

The specimens are mounted in an inset in the centre of the test device (fig. 3), which facilitates the installation of different specimen geometries. The ability to produce three dimensional reinforcements in NCF laminates, is a challenging restriction for feasible specimen geometries that were defined.

For the purpose of proper computation, finite volume-p-elements based on hierarchical shape functions [2] were enhanced for textile composite material applications [3]. The selected three-dimensional shape functions provide an anisotropic ansatz-space aligned to layered composite materials with special respect to the thickness direction. The onset of failure is thereby predicted by a criterion that is developed to predict the strength of 3d reinforced laminates [4]. In order to control the spatial adaptivity of polynomial order of the shape functions different a posteriori error estimators [5] are evaluated and compared especially with respect to the applicability on structural models representing textile composites with orthotropic material behavior.

Finally, simulations and experimental tests of material specimens (fig. 2) and a thick double holed plate – representative for a load introduction area – validate and demonstrate the applicability of the material model and finite element implementation.

2 New Out of Plane Testing

The performance of conventional fibre reinforced composites is mainly dominated by the two dimensional in plane material properties. Therefore, most of the material and failure theories are mainly based on the in-plane material properties.

But recently rather three dimensional properties become more considered than pure two dimensional models. As a consequence it is essential to analyze the three dimensional material behaviour in order to utilise the full potential of textile composites. Especially the performance of three dimensional reinforced textiles by stitching or tufting provides high delamination strength compared with traditional unidirectional materials.

For this purpose an out-of-plane test device was developed and the material behaviour of Carbon and E-Glass Non Crimp Fabrics (NCF) composites were analysed. The performance of composites materials under combined through-the-thickness stress Szz with interlaminar shear stresses Sxz, Syz are experimentally analysed by an adequate test device. A modified version of a test device commonly known as the Arcan test was developed and different specimen geometries were tested. The experimentally investigations serve as basis for appropriate material description in numerical analysis for design purposes.

The most important requirement for the experimentally determination of out-of-plane properties was the applicability in a standard hydraulic test machine. Therefore a test device for tubular specimens was not useable. Only uniaxial movement of the test equipment should be necessary even though combined load conditions should also be feasible. For all experiments an Instron 100 kN hydraulic test machine was used.

A promising concept to test composites under combined shear and tensile load conditions was originally published 1977 by ARCAN et al. [7]. The original idea was to test a circular specimen plate with two facing asymmetric cut outs manufactured of an entire composite plate as shown by figure 1 a). The tensile forces are applied in the vertical direction and introduce a significant shear stress state within the cross sectional area A–B. By rotating the disk from the vertical to the horizontal position combined tensile and shear through to pure tensile load conditions can be realised.

Later the original test was modified by other researchers. HAJJAR et al. [8] developed 2004 a similar test fixture, which requires smaller specimens by mounting a butterfly shaped specimen geometry on two halves of metallic disks depicted in figure 1 b).

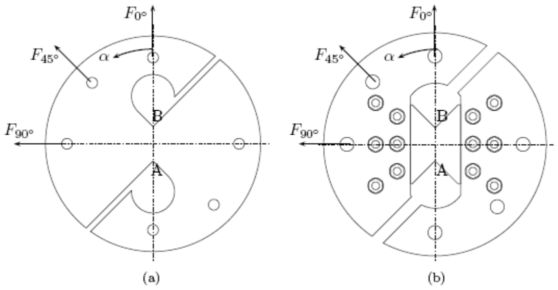

Fig. 1. a) Original Arcan disk [7] and b) modified test by Hajjar [8]

The applicability of the out-of-plane test is aimed at investigating three dimensional reinforced specimens by tufting or stitching the preform. Due to the tufting stitch length the specimen geometry is restricted to plate thicknesses of approximately 30 mm. Therefore the butterfly shaped specimen geometry appears to be impractical for out-of-plane tests of relevant textile specimen.

2.1 Specimen Design

By finite element analysis waisted specimen geometries were found to be adequate for tensile through-the-thickness load conditions, figure 2. The specimen length of 30 mm is small enough to be cut out from the thickness direction of a tufted plate. Furthermore, two different demands restrict the cross sectional area of the specimen.

First, at least a representative cross sectional area of the material should be tested. The Carbon NCF material is stitched by a tricot binding with a stitch length of 2.6 mm.

Second, the cross sectional area should be small enough to provide a homogeneous uniaxial tensile stress state in the middle of the specimen.

A cross sectional area of 10 mm x 10 mm provides an adequate compromise between both restrictions. The specimen geometry provides representative stress Szz along the specimen direction for tensile load cases. The load is introduced without any clamping by a wedge shaped specimen inset at the top and bottom of the specimen.

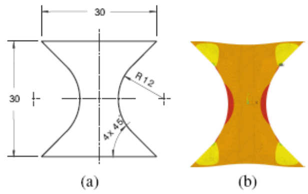

Fig. 2. a) Specimen geometry, b) FEA results for tension in thickness direction

2.2 Test Device Design

The specimen is installed in a modified Arcan test rig displayed in figure 3 (a). The waisted specimen (pos. 9) is installed in the centre of the disk with a specimen inset (pos. 4). That allows quick installations of different specimens by changing complete insets with already installed specimens. The specimen inset is mounted by adjustable clamping devices (pos. 2).

The position of the disks can be changed in seven steps from pure tensile trough to pure shear and combined tensile shear load conditions. Fits are used to adjust the precise orientation thereby each halve of disk is clamped with 4 screws. Two identical halves of disks are used on the front and back side.

The main advantages of this test device design are:

- Simple specimens can be used. In contrast to the original test device by ARCAN the specimen dimensions are smaller. The specimens are relative simple to produce by water jet cutting. Due to small specimen geometries only a minimal material amount is needed. Furthermore plates with moderate thicknesses are sufficient.
- The test results are comparable to each other because same specimen geometries are used for different load cases and combined out-of-plane load conditions. Otherwise only tubular specimens provide the flexibility to test different load cases with the same specimen geometry. A standard uniaxial test machine can be used. The machine displacement provides the test load and the material deformations are

measured by strain gauges. Therefore, this test is flexible and relatively inexpensive.

- Especially for determination of the accuracy of failure criteria, the behavior under well defined combined load cases can be measured. This allows validation of three dimensional failure criteria as well as determination of the elementary material properties.

To enable quicker installation of different specimens a modular specimen inset was developed, figure 4. Specimens (pos. 4) are installed in a centre plate (pos. 1) which is clamped by screws (pos. 3) on two outer plates (pos. 2). Therefore only the specimen within the centre plate has to be changed. The specimen is bonded to the centre plate with an adhesive (X60). The metallic parts are pre-treated with releasing agent. The two component adhesive bonding is low viscous and the experience has shown that the manufacturing tolerances between the specimen and the cut out of the centre plate are best filled with a fast curing adhesive. For that purpose an aligned bonding fixture is used to guarantee a precise specimen orientation. Therefore, a widely unproblematic specimen installation is feasible.

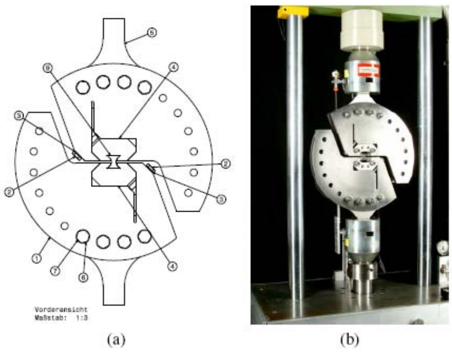

Fig. 3. a) Modified Arcan Device b) Installation in uniaxial Instron test machine

2.3 Test Results

A choice of Carbon and E-Glass fibre composites are tested. Both materials are untufted Non Crimp Fabrics (NCF). All specimens fail within the waisted cross section like shown by figure 4. The material deformations are typically measured by a double strain gauge for the vertical and horizontal direction on the specimen front and if required with a single strain gauge for the transversal contraction on one side of the specimens. For future tests a strain gauge rosette will be used to measure the full deformation of the specimen.

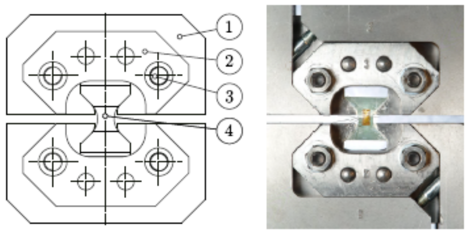

Figure 5: Inset and E-Glass specimen

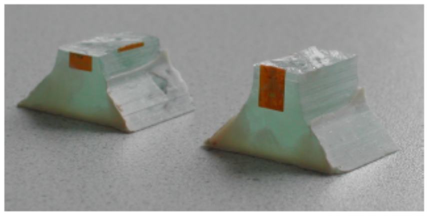

Fig.4. Insert and E-Glass specimen; Failed NCF E-Glass tensile specimen

Unfortunately not enough specimens were tested yet according to statistical demands. On all tensile specimens the failure propagated across multiple plies (figure 4). Also for most combined out-of-plane load conditions a failure within one layer was extreme rare. It is assumed that the failure propagates due to numerous initial micro cracks on the specimen edges. These micro cracks are generally located on different plies and propagate independently through the specimen thickness. Therefore the final failure surface contains the propagated failure behaviour through different plies.

A direct connection of the polyester stitching yarn of the NCF preform to the failure behaviour of the E-Glass as well as Carbon materials could not be determined. The failure surface and failure behaviour under through-the-thickness load conditions seems to be independent to the influence of the Polyester stitching yarn.

The material behaviour of E-Glass fibre composites is mostly ductile compared with

Carbon fibre composites. This results in higher material compliances and cause problems by testing the out-of-plane behaviour. The test results in figure 5 of quasi-isotropic E-Glass NCF composites under through-the-thickness tensile loading is accompanied by a type of stuck and sliding process. This phenomenon was not measurable with Carbon composites and seems to be the consequence of higher material compliances of E-Glass composites. In consequence that the specimens are not rigidly clamped they can slip locally by partially reducing local stresses. This behavior appears in the stress strain curve as a horizontal jump backwards. Therefore, these effects are probably the consequence of the load transfer through the inset wedges and correspond with the material compliances within a local region of the specimen.

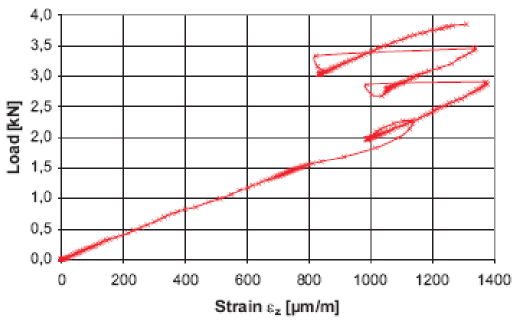

Fig. 5. Tensile load strain curve of E-Glass specimen

Nevertheless, nearly the same elasticity modulus is measured between each sliding effect. Therefore, a continuous stress strain curve as shown in figure 6 is approached if the measured values after each sliding effect are added with a strain offset. These offsets correspond to the sliding distance during the test. By continuously loading the material, failure is reached within the waisted cross section of the specimen and the conditions due to the wedge introduced test load are not characteristic for the final material failure behavior.

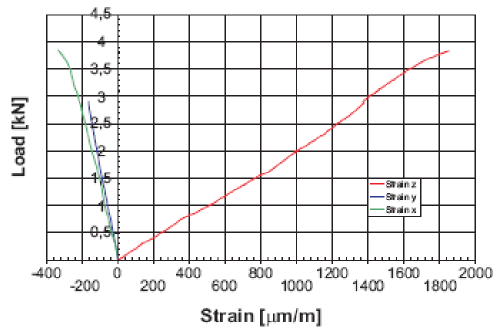

Fig. 6. Modified load strain curve for E-Glass

3 Simulation Methods

The experimentally determined through-the-thickness material properties and parameters serve as basis for appropriate material descriptions in numerical analysis of structural parts made of laminate composites exhibiting pronounced three dimensional stress states. Failure is thereby predicted by a criterion that was primarily developed to predict the strength of 3d reinforced laminates [4].

In such areas or thick structures proper computation of three-dimensional stress distributions requires the use of volume elements because shell theories come to their limits of validity. Especially for the purposes of analyzing thick composite structures a volume element based on hierarchical shape functions is being developed, [2,3]. Additionally, in our work the element is used within the p-version of the finite element method to achieve superior convergence properties during the computation process.

Thereby, different a posteriori error estimators are applied to control the spatial adaptivity of polynomial order of the shape functions. In case of the selected anisotropic ansatz space for the displacements even a simple error indicator is able to distinguish between the error contribution of in- and out-of-plane stresses.

In applications used material parameters, which describe the deformation and failure behaviour of textile laminates, are based on experimental investigations. With focus on the out-of-plane properties the new test device was used. The material behavior of Carbon and E-Glass Non Crimp Fabrics (NCF) composites were experimentally explored. The performance of composites materials under combined through-the-thickness stress Szz with interlaminar shear stresses Sxz, Syz are experimentally analysed.

The numerical model and the determined parameters are validated by finite element simulations of the conducted tests.

Applicability of the developed finite p-element implementation is demonstrated by analysis of a mounting plate with two holes. Thereby the mounting plate is modeled as a substructure coupled to the global model by prescribed displacements. The model shows a pronounced three-dimensional stress state for that failure is predicted caused by the out-of-plane stresses.

3.1 Volume P-Element Formulation

Finite element formulations can be associated to the h- or p-method due to how convergence of the numerical solution is achieved. H-method achieves convergence by mesh refinements while the polynomial degree of the ansatz functions remains constant. In contrast in p-method the mesh remains unchanged and convergence is assured by increasing the polynomial degree of the shape functions. Investigations during the past 20 years have shown that hierarchical shape functions have superior characteristics compared to standard shape functions based on Lagrange polynomials.

The developed element interpolates the displacements by sets of higher order hierarchical shape functions derived from Legendre polynomials. This shape functions are orthogonal. Thus round-off errors usually associated with polynomials of high degree are avoided. Coupling between hierarchical degrees of freedom is minimized and a more dominant diagonal form of the stiffness matrix is obtained. This ensures an improved condition of the stiffness matrix.

It was followed the latter concept to implement the element formulation into the open finite element environment B2000++ provided by the swiss Company SMR. Advantage thereby is a geometrical description of the elements that is independent of the polynomial oders p, q so that pre- and postprocessing are equivalent to cubic standard elements. Generally, this concept requires a FE-program-kernel allowing for an at runtime adjustable (dynamical) element formulation.

Figure 7 displays as an example the distribution of dof for the ansatz space S2,3_3D. To all nodes of out-of-plane edges six dof are assigned, all other nodes are allocated by three dof's.

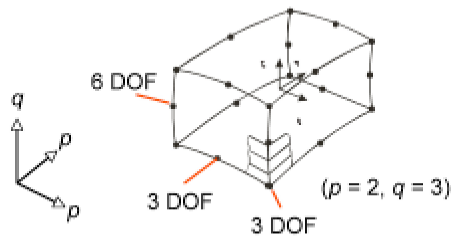

Fig. 7. p-element, number of dof's at nodes e. g. p = 2, q = 3

3.2 Adaptive Modelling and Error Estimation

Goal of adaptive modelling strategies in FEA is to achieve a more efficient and accurate solution of the given mechanical problem. Normally, adaption of the discretization (the ansatz space) and steering of the solution algorithm respectively are successful methods. Basis of steering h- or p-adaptivity in FEA is error estimation. In literature it is differentiated between error indication and estimation whether qualitative predictions or quantitative bounds of the error are given. Further information and explanations are given in detail by [5].

Reference solutions used for the error estimation play a very important role. But even for practical relevant problems exact solutions are in general unknown. Therefore, mostly the error is extrapolated by the difference of two computed solutions. If the error is predicted only in dependency of mesh data and further input data one speaks of "*a priori*" estimation. Estimation utilising the already computed solution is called "*a posteriori*" estimation. At the moment, a posteriori estimators of the following two general groups are implemented within the volume p-element code:

- *Indication based on gradient recovery*

Basic idea is the introduction of averaged continous stresses $\sigma_{average}$. The L^2-norm of the difference between $\sigma_{average}$ and the approximated discontinous stress σ_h

$$\| \sigma_h - \sigma_{average} \| \rightarrow \min$$

is an indicator of the dominating error. Great advantage of these indicators is the low computational effort. The most important disadvantage is that no real bounds of the error are given.

- *Element residual methods*

Starting point is the main equation of error analysis. These estimators take the element residuum

$$R := div\, \sigma_h + \mathrm{f}$$

and the stress discontinuities on the element boundaries

$$J := \begin{cases} \frac{1}{2}(\sigma_h^+ n^+ + n^- \sigma_h^-) & on\ \partial K_i \\ t - \sigma_h n & on\ \partial K_N \\ 0 & on\ \partial K_D \end{cases}$$

as a measure for the element error into account. The error e = $u - u_h$ could be estimated in the energy norm with help of the CHAUCHY-SCHWARZ-inequality to

$$\| \mathrm{e} \|^2 \leq C \bigcup_{(K)} \left\{ h_K^2 \, \| \mathrm{R} \|^2_{L2(K)} + h_K \, \| J \|^2_{L2\partial K} \right\}$$

with

$$\| \ldots \|^2_{L2(K)} = \left(\int_\Omega | \ldots |^2 \, dV \right)^{\frac{1}{2}}$$

thereby the constant C couldn't be determined in general. For example Babuška and Rheinboldt proposed such an estimator.

An error indicator of the gradient recovery type was selected because of its simplicity and the low computational costs. The indicator is enhanced and modified in form of different weightings of stress components and normalisation to global maximum stress values before evaluating the equation. This indicator is then able to deliver nodal information about spatial directions in which deficiencies of the ansatz space lead to high contributions to the error of the stress-field.

Thus this indicator gives reasonable results to adopt the polynomial orders p and q. To get a measure of the overall error, and to get information about the element-wise error contributions, a residual error estimator is evaluated too. As an example figure 8 visualizes the residual error measures as vectors on element faces and in the element volume in order to give an idea about the spatial distribution.

3.3 Simulation of Tests in the New 3D-Testing Device

For verification purposes of the applied 3D-failure criterion, finite element simulations of the modified Arcan test were conducted. The parameter set of the failure criterion is determined by multi scale analysis as proposed in [1] because some of the parameters don't admit a direct experimental determination. Figure 8 depicts the displacement field, strongly amplified due to the prescribed displacement of the lower fixtures. For the selected finite element mesh the discretization error was evaluated by the a posteriori estimation of residual errors.

On the right, figure 8 shows the error measure as vectors on element surfaces and in the element volume. The visualisation makes clear that a considerable error only occurs in the region of the transition from the fixtures to the waisted cross section. This error decays very rapidly so that there is no influence on the stress state within the mainly tested cross section, which is a strong positive quality criterion for the new testing procedure.

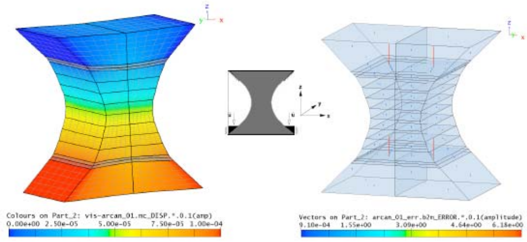

Fig. 8. Displacement field and residual error of the volume and the faces

In case of the numerical failure analysis of the E-Glass NCF, first a displacement of 0,001 mm at the lower fixtures was preset. For each sublayer of the E-Glass NCF the failure criterion of JUHASZ [4] was evaluated for a set of selected points. Elements in the region of the waisted cross section incorporate 8 sublayers of the E-Glass laminate. Figure 9 displays on the left the predicted margin of safety at each point of all sublayers.

As expected, the minimal margins appear at the flanks where the cross section has its minimal area, plotted in dark blue. For the lowest value of 112.21 the maximum stress component Szz causing fracture in x-y-plane follows to 49.4 MPa. This value is in good accordance with experimental results, where strength values in thickness direction between 42.0 and 51.8 MPa were measured.

Figure 9 presents on the right for each sublayer the stress distribution of the z-component. Except for the border areas, the stress distribution is homogeneous within the waisted cross section as required during the specimen design process. Stress peaks occur only localised at specific points near the free edges at the waisted flanks. Due to the load introduction the upper and lower fixtures cause a small area of compression in z-direction near the edges.

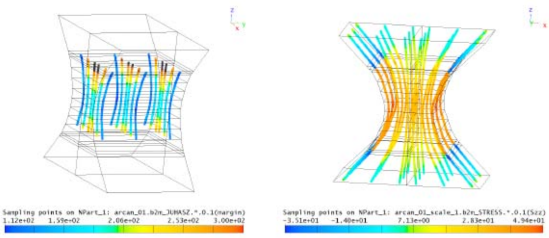

Fig.9. Margin of safety for sublayers of E-Glass NCF and stress component Szz at failure

3.4 Prediction of Thick Composite Load Introduction

At a load introduction area, like displayed in figure 10, the structural thickness is large against the other dimensions so that for numerical analysis a discretization using volume elements is required.

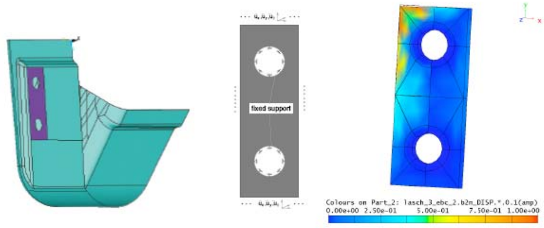

Fig.10: Load introduction area, mechanical system of the substructure, displacement amplitude

In the presented simulations the mounting plate is analysed as a substructure of the global shell model coupled through prescribed boundary conditions of the nodal displacements. Figure 10 shows a sketch of the mechanical system, the holes are totally fixed. In the submodel one p-element incorporates about 40 sublayers of the E-Glass laminate. On the right of figure 10 the displacement field caused by the prescribed boundary conditions is visualised.

Evaluation of the residual errors has shown that satisfactory approximations of the displacements and stresses with the quite coarse mesh need polynomial orders of the shape functions above five. The global displacement field is in total relative smooth.

For the given load case of prescribed boundary conditions, the failure criterion of JUHASZ [4] considering the validated parameters was applied to selected points in x-y-plane for each sublayer.

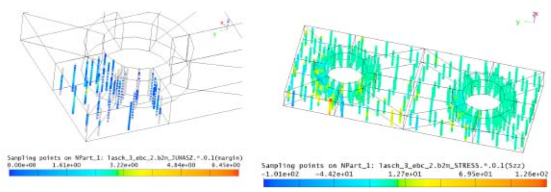

Fig. 11: Margin of safety and stress Szz for each sublayer of the E-Glass NCF

Figure 11 displays the margin of safety for each sublayer with a zoom of the upper left corner of the mounting plate. According to the applied failure criterion, material strength is manifoldly exceeded plotted as grey points especially near the hole. Regarding the stress distribution of the component in thickness direction in figure 11, it becomes apparent that the experimentally determined through thickness strength will be exceeded due to the occurring three dimensional stress states. Destructive experiments of the load introduction prototype weren't conducted yet so that validation on structural level will be future work.

4 Summary

The paper focused on new methods for testing and computation of anisotropic textile and thick composites for the aircraft industry.

Proper foundations are laid for standard testing procedures and accurate virtual testing methods up to certification issues.

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