A MICROMECHANICAL APPROACH TO INVESTIGATE THE INFLUENCE OF VOIDS ON THE STRUCTURAL BEHAVIOUR OF FRP UNDER COMPRESSION LOADING

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ABSTRACT

The subject of this presentation is to develop a micromechanical approach to investigate the influence of voids on the structural behaviour of FRP under compression load. Therefore, the fibre-matrix-void constellation was analysed and a reduced model composite was conducted. The idea was to imitate a real void in a fibre-reinforced polymer where they appear between fibres and in resin rich areas.

Elementary experimental and numerical studies were conducted due to the reduced model (two or more fibres and a unique void between). For the experiments a test jig was designed which fits in a light microscope with integrated photoelasticity and potential digital image correlation. While testing at different load steps the stress and strain material behaviour were analysed. Furthermore, the failure mechanisms (fibre-matrix debonding, fibre buckling and kinking) of the composite could be observed in situ. Numerical studies were compared with the test results. They included a detailed and step by step analysis of the failure mechanisms, especially of the premature fibre buckling.

1 INTRODUCTION

The formation of voids cannot be avoided during manufacturing of composite structures. The void content can be reduced by carefully chosen processing parameters, such as pressure and temperature during curing, however at the price of higher costs. In general, voids likely have an influence on mechanical properties of composite laminates. In previous works most effort has been devoted on describing the influence of voids on FRP behaviour, based on property values versus volume content, e.g. Olivier et al. [1] and Almeida and Nogueira [2] where interlaminar shear and flexural strength were investigated in consideration of the void content. Especially under compression the void content can have a significant influence as described by Suarez et al. where a 40 % reduction in compressive strength for 4 % void content could be found [3]. Similar results were found by Bazhenov et al. [4] whereas both was investigated, the link between compressive strength and void content and in addition to that the influence of the fibre diameter. That investigations demonstrated that for thinner fibre diameter the compressive strength cannot be explained only by microbuckling analysis. The compressive strength is in fact a limiting design factor because of its bad performance in comparison with the tensile strength [5-7]. Only 50-60 % of their tensile strength could be reached [6]. The sudden death behaviour, especially under compressive load, is a result of the absence of a degradation process. Only for specimens with a notch the failure propagation can be investigated however, here the failure initiation and damage progression are due to stress concentrations around the notch [8, 9] and not a result from defects like voids themselves.

To understand why composites fail or how failure mechanisms interact due to influencing factors like voids, it is necessary to reduce the complex issue into a manageable size as Ricotta et al. mentioned [10]. Especially for compression no literature could be found about failure initiation. Both Fiedler and Schulte [11] and Zhao et al. [12, 13] studied the fibre/matrix load transfer in single-fibre model composites by using photoelasticity to determine the local load and strain distribution. This testing method allows the observation of the composite during the whole testing. Compared to simulations no assumptions (except the simplifications of the model) of the mechanical material
Derived from these methods the present work reports the results of an approach to investigate the stress fields around a unique void in a fibre-reinforced model composite under compressive load using photoelasticity. In this case the composite laminates were reduced to a minimum number of constituents. Hence, a void was squeezed to form in the matrix between two glass fibres. A six image phase-stepping photoelastic technique was used to measure the stress concentrations in the vicinity of the void where also failure of the composite occurred.

2 MODEL COMPOSITE

A model composite was developed because of the complex material behaviour on microstructure level. Furthermore, a reduction is essential to achieve an understanding how the failure process will take place. Hence, studies could be focused to the vicinity of a unique void. The morphology of voids was determined from previous investigations with the common prepreg material HexPly M21/35%/134/T800S (Hexcel Corporation) from which we know, that the autoclave pressure has a dominating influence on the void formation. Therefore the autoclave pressure was varied between 7, 5, 3 and 1 bar to achieve different void volume contents [1]. Using light (LM) and scanning electron microscopy (SEM) as well as micro computer tomography the position and the morphology of the voids (highlighted by a white arrow) could be identified, as it is shown in Fig. 1. Due to their occurrence voids could be distinguished as intralaminar and interlaminar flaws. Intralaminar voids occur between fibres showing a high length/width ratio. In contrast interlaminar voids could be observed in resin rich areas squeezed between fibre layers showing an irregular shape. However, three dimensional informations about the morphology of voids and the circumstance of fibres could not be gained directly up to now. Only two dimensional informations from several cross sections out of light microscopy and SEM could be used to characterise the fibre alignment affected by the voids. Three dimensional informations about the void morphology could be collected using micro computer tomography. As specified in Fig. 1 the length of intralaminar voids is defined as its elongation in fibre direction. The width of the intralaminar voids corresponds with the dimension in plane of the lamina. The height of both types of voids is defined as the size in thickness direction of the laminate. Due to the irregular shape of the interlaminar voids the morphology is characterised by the cross section area.

![Figure 1: Position and morphology of voids, highlighted by a white arrow, in CFRP (M21/T800S).](image)

For better understanding Fig. 2 illustrates the different void configurations within the FRP. In a first step the arrangement of the fibres in the vicinity of a void is simplified, so that cross sections of intra- and interlaminar voids could be analysed. In the horizontal view of the cross section could be observed that the horizontal cut of intralaminar voids could be generalised for all other cross sections. It is assumed that for load-bearing layers containing voids the longest unsupported zone of a fibre corresponds to the weakest point on FRP under compression.
In a second step a plane issue was derived from three dimensional conditions by analysing diverse cross sections, as it is shown in Fig. 3a. The overall of the horizontal cross section was split into three areas: area I is characterised by fibres without any misalignment whereat due to the void the fibres remain to be aligned in area II. For both areas many publications can be found which describe the material behaviour of composites under compression. Especially the influence of fibre misalignment was investigated in a satisfactorily manner [14-17]. However, the discrete point of view allows focusing on area III. Fig. 3b shows a cross section of a FRP including a void which supports the assumption made before.

2.1 Experimental study

2.1.1 Materials and sample preparation

For the experimental study sized E-glass fibres were used provided by P-D Glasseiden GmbH (Oschatz, Germany) with a mean diameter of $d_f=70\,\mu\text{m}$, to assure more easy handling. Silane based sizing was attached after the melt-spinning process. The fibres were specially fabricated during a changeover of the usual production by reducing the pulling rate. As matrix system a RIMR 135 epoxy resin with 30 wt. % RIMH 137 hardener provided by Momentive (Germany) was used. It was cured for 24 h at room temperature and tempered at 80 °C for 15 h as recommended by the manufacturer.

All specimens were fabricated in six steps. At first double-sided adhesive tape was applied on a glass plate prepared by a mould release agent (Loctite 770-NC Frekote) followed by positioning the glass fibres. After covering the fibres by using a second stripe of tape, resin was cast over the fibres. While a second glass plate was put on top, a single air bubble was injected into the liquid resin by using a syringe. Working carefully the air bubble could be squeezed between the fibres. Because of hydrostatic pressure, the air bubble conformed the shape of a wormhole. After curing the specimens were removed from the mould and dressed to size of 21 mm x 10 mm x 0.5 mm. Due to the handmade manufacturing procedure all samples are unique.
2.1.2 Compression test

The mechanical compression test was carried out using a test jig which fits in a transmission light microscope with integrated photoelasticity observation. In accordance to UCSB fixture [18] the test fixture was modified, as shown in Fig. 4, and clamped into the test equipment where load was transferred on the end faces of the specimens. During the tests, load (2 kN load cell) and displacement were recorded continuously by using the software DigiVision V2011.1.0 provided by Burster.

![Figure 4: a) Schematic illustration of test fixture (anti buckling guide). b) Magnified cutout of test sample.](image)

2.2 Numerical investigation

2.2.1 Model and boundary conditions

Based on the geometry and morphology of the handmade specimens, a parametric-numerical model was programmed in Ansys Classic by using its design language. Due to symmetric conditions just a quarter piece of the real existing model was represented. Additionally, the calculating time could be reduced significantly. The discrete view of fibre, matrix and fibre-matrix bonding (represented by cohesive zone elements) provides the possibility to compare the results of experimental and numerical studies. The model as well as the applied boundary conditions are shown in Fig. 5. Axial loading is modelled by a constant displacement $\Delta l$ acting on the surface in the area I. Area II is split into two parts to realise mapped meshing.

![Figure 5: Structure and boundary conditions of the parametric FE model consisting of i fibres respect to their alignment.](image)

2.2.2 FE mesh

The quarter of the volume cell (fibre as well as the matrix) was meshed by using solid45 elements (defined by eight nodes and three degrees of freedom at each node). These elements allow the feasibility of oriented material properties by an implemented element coordinate system along a
leading line. The interface between fibre and matrix is represented by conta173 and targe170 elements. Both types of elements are defined by four nodes and three degrees of freedom at each node.

### 2.2.3 Material properties

The elastic material properties of glass fibre and epoxy are summarised in Tab. 1. For small deformations the mechanical behaviour of both materials is assumed to be linear-elastic. However, the characterisation of the non-linear material behaviour of the matrix was implemented by entering strain and stress data points of compression tests carried out in our previous work [19]. The interval of the data points was chosen by strain steps of 0.5 % whereas linearity is assumed between every two sets of data points.

<table>
<thead>
<tr>
<th></th>
<th>( E ) / GPa</th>
<th>( v )</th>
<th>( G ) / GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fibre</td>
<td>72.00</td>
<td>0.20</td>
<td>30.00</td>
</tr>
<tr>
<td>Epoxy</td>
<td>3.13</td>
<td>0.35</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 1: Elastic material properties of glass fibre and epoxy, respectively solid45 elements.

The interface is modelled using the cohesive elements which are implemented in the software Ansys. The mechanical behaviour of the elements is defined by bilinear maximum traction (\( \sigma_{\text{max}} \), \( \tau_{\text{max}} \)) and critical fracture energies (\( G_{I_c} \), \( G_{II_c} \)). Tab. 2 shows the material properties of the cohesive elements. The values of the strength and fracture energies are taken from literature [20-22].

<table>
<thead>
<tr>
<th></th>
<th>( \sigma_{\text{max}} ) / MPa</th>
<th>( G_{I_c} ) / N/mm</th>
<th>( \tau_{\text{max}} ) / MPa</th>
<th>( G_{II_c} ) / N/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface</td>
<td>37</td>
<td>0.002</td>
<td>72</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Table 2: Elastic material properties of interface, respectively cohesive zone elements (conta173, targe170).

### 3 RESULTS

#### 3.1 Mechanical behaviour of the model composite

##### 3.1.1 Experimental study

In general, the failure mode of composites under compression is due to the loss of stability of the fibres leading to microbuckling. In former work it could be shown that photoelasticity is proved to visual stress concentrations and the shape of buckling modes [14, 19]. However, several types of specimens with different aspect ratios (\( l/b_v=1, 2.3 \) and 3.8) of voids were manufactured, tested and analysed. Fig. 6a, 6b and 6c shows a cutout of an isochromatic fringe order pattern of these model composites consisting in each case of eight embedded E-glass fibres (hid by grey stripes) with a diameter of \( d_f=80 \mu m \) at the applied compressive load of \( N=260 \) N. In all three cases the highest isochromatic fringe order appears close to the end cape of the void as well as along the void. It is an indication of the existence of higher stress. The X-shape of the stress concentration close to the end cape of the voids could be attributed to stress rearrangement and is similarly based on open holes without any reinforcement. In contrast to that the wave form of the stress concentrations in the matrix along the fibre parallel to the void inclusion could be attributed to the loss of stability of the fibres under compression [14, 19]. It leads to varying lateral loads depending on the length of the fibre. Finally, the buckling patterns could be obtained due to the different buckling modes of the fibres. In addition fibre buckling based on the informations from the isocromatic fringe order pattern is highlighted (white dashed line) in Fig. 6b and 6c. To get more informations about the mechanical behaviour of the matrix some further work was performed by using the digital photoelasticity.
Therefore the Matlab routines COPA and RICO (provided by Siegmann) were used to determine the values and the direction of the principal stresses in the matrix along the fibre [23].

![Schematic illustration:](image)

Figure 6: Photoelastic study of model composite (eight fibres) depending on aspect ratio of the void. a) $l_v/b_v=1$ (N=260N); b) $l_v/b_v=2.3$ (N=250N); c) $l_v/b_v=3.8$ (N=276N).

Due to the symmetry Fig. 7 shows one quarter of the model composites and the determined principal stress. Fig. 7a, 7b and 7c represent a contour plot of the equivalent stress of model composites with several aspect ratios of the void. The drawn direction of the principal stresses in Fig. 7b could be transferred to all contour plots. By the means of the direction of the principal stresses it could be concluded that the X-shape of stress concentrations close to the end cape of the void resulted from shear stresses due to stress rearrangements. Furthermore, the longer the void becomes ($l_v/b_v>2$), the smaller the stress distribution appears in area III as shown in Fig. 7b in comparison to Fig. 7c. Because of the just one-sided support the fibres attempt to buckle towards the free space and induce a transverse tensile load in the matrix leading to the stress concentrations.

![Contour plots](image)

As mentioned before COPA-/ RICO-Software allows to determine the equivalent stress in the matrix along the fibre. Fig. 8a shows the stress concentration in the matrix along the fibre at the far side of the void. The equivalent stress is normalised to the applied load. Because of the assumption of linear-elastic material behaviour the stress concentration is overestimated. Especially for short voids, the highest stress concentration could be attributed to the shear stress. Whereas for elongated voids the stress concentration is located at the passage where the void exposes the fibre.

Given that a non-linear material behaviour of the matrix could not be included within the Matlab routines as well as the fact of suppressed misalignment of the fibres. Further investigations by numerical studies follow in the next section.
3.1.2 Numerical investigation

In contrast to the experiment the numerical investigation allows to fulfill all assumptions made before. This leads to less stress concentrations in the matrix, as shown in Fig. 8b. In general, the characteristics of the stress distribution along the fibre at the far side of the void are in accordance with the experimental results. Due to the included non-linear material behaviour of the matrix the level of the stress concentration is reduced. In addition to that it demonstrates, that the stress concentration due to stress rearrangement close to the end cap of the voids is just relevant for short voids. It leads to the result that the longer the void, the more negligible becomes the stress concentration in this area.

However, the failure of the composites under compression is not a result of just one unique influencing factor. As Bazhenov et al. [4] and Liebig et al. [19] demonstrated the fibre diameter as well as the fibre-matrix bonding are relevant, too. This leads to the numerical investigation of the influence of the aspect ratio of the void and the fibre misalignment on the first fibre-matrix debonding. The aspect ratio shows just a slight influence on the fibre-matrix debonding. With increasing fibre misalignment ($\Phi_0 = 0^\circ$, $1^\circ$ and $2^\circ$) the initiation of the fibre-matrix debonding ($\epsilon_c = 3.38\%$, $2.50\%$ and $2.00\%$) is influenced significantly.

3.2 Failure mode in FRP in the presence of voids

In any case the illustrated failure mechanisms of a model composite could be observed, as shown in Fig. 9. A specimen was loaded until first visual damages appeared. After that, the loading was stopped and a series of photos were taken. First a fibre-matrix debonding occurs leading to loss of stability of the fibre which fails because of Euler buckling (Fig. 9b). Second, due to stress rearrangements shear deformation can be observed and an additional fibre failure occurs (Fig. 9c + d). While a continuous load decreases further fibres fail until a superimposed global buckling of the specimen (Fig. 9e + f). However, the successive failure of the fibres are formed under a very small damage angle $\zeta$, which gives a hint on an elastic material behaviour of the interface [24].

4 DISCUSSION

Due to the observations on the reduced model composite it could be demonstrated how the failure initiation and its propagation proceeds, as illustrated in Fig. 10. Based on the findings made by a model composite with two embedded fibres (Liebig et al. [19]) the first visible failure occurs between the fibre and the end cap of the void, resulting in fibre-matrix debonding (Fig. 10b). i.e. the first failure mechanism depends on the adhesive strength between fibre and matrix as well as on the foundation of the fibre itself. While the fibre-matrix debonding propagates along the fibre its failure is driven by the loss of stability leading to Euler buckling (Fig. 10c). This induces stress rearrangements and is conducted to an overloading of the nearest fibre, which will fail when its compressive strength is reached (Fig. 10d). In consequence of the ongoing failure of the fibres a damage angle $\zeta$ is formed which draws conclusions from the interface [24, 25].
The model composite has in contrast to advanced composites a big distance between the fibres. Consequently, the matrix sustained high shear stresses leading to opacity of the matrix in light microscopy image, as shown in Fig. 10e.

Figure 9: Failure initiation and propagation in a model composite with a void inclusion. a) Unloaded model composite (eight embedded fibres). b) Fibre-matrix debonding at the end cap of the void and additional fibre buckling. c) Further fibre-matrix debonding. d) Second fibre failure. e) Third fibre failure and high shear deformation. f) Fourth fibre failure (here not shown) and superimposed global buckling of the specimen.

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5 CONCLUSIONS

The presented work shows the specific influence of voids on their vicinity within a fibre-reinforced polymer. Because of the local effect of voids on the compressive strength a spatial viewing is insufficient. Particularly in the case of load-bearing layer a better understanding of the failure modes due to voids is essential. Therefore a micromechanical approach was taken to analyse the degradation. As a result of experimental investigations the failure initiation and propagation could be observed. The failure initiation in the composite is significantly influenced by the stiffness of matrix and fibres, the fibre foundation and the fibre misalignment. In addition, the aspect ratio of the voids leads to stress concentrations in the matrix, leading to premature fibre-matrix debonding and to an ongoing loss in stability of the fibre, depending on its foundation, which finally causes fibre kinking.

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