Description of the multi-axial stiffness degradation in fatigue loaded NCFs by means of a finite-element RVE-based degradation model

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INTRODUCTION

NCFs are complex materials compared to unstitched laminates. Their laminate lay-up always includes different sub-plies with different orientation. Therefore the need for NCFs only arises, when materials with complex fibre orientations and therefore complex loading conditions are used. Under fatigue load each sub-ply will be loaded by transverse and shear loads, which will cause cracking in the matrix of this ply. Cracking leads to a local stiffness reduction of the ply, which again will lead to load redistributions. The work presented in this paper consists of experimental tests with bi-axially fatigue loaded tube specimens made out of glass-fibre reinforced plastics. Additionally a modelling approach based on a representative volume element is shown, which is capable to model the stiffness reduction due to cracks in arbitrary NCFs for given damage states.

BODY OF THE ABSTRACT

Especially for NCFs the need for models that are capable of predicting material properties and their degradation under multi-axial loads arises. As already mentioned in the introduction these materials are needed only when complex loads occur, because otherwise plies with orientations different from the loading direction would only increase the parts weights and costs.

Experimental testing

Tube specimens (Figure 1, left) out of a quadraxial NCF were manufactured using RTM and loaded with constant amplitude fatigue loads in a tension-torsion machine. Four different loading directions were applied by either turning the upper end of the specimen against the lower end (shear), by moving the upper end axial against the lower end (axial tension) or by combination of both.

![Fig. 1: Tube specimen (left) and bi-axial fatigue testing (right)](image-url)
The fatigue tests were divided into characterization steps, in which static tests were performed in order to calculate the material stiffness and fatigue damage steps in order to introduce the damages. After a number of cycles each specimen was observed under a light-microscope in order to monitor the damage state on different specimen locations. The cracks seen in these locations were counted and crack densities were calculated. Fatigue tests using constant amplitude block loading with different loading amplitudes and loading directions were performed as well.

Modelling approach

For the modelling approach a finite element representative volume element (using MSC.Patran and Abaqus) was created. This RVE consists of a cracked ply, which is supplied by two uncracked layers, whose fibres are orientated perpendicular to the cracked ply. In this work fibre-direction of the uncracked ply will be the 0° direction. Each RVE includes two cracks (for the sake of boundary conditions) and the desired crack density is adjusted by changing the RVE-length. Figure 2 shows a RVE.

![Fig. 2: schematic view of the modelling approach (left) and RVE (right)](image)

The influence of parameters like the fibre-volume ratio, the absolute stiffness of the cracked ply, the relative stiffness of all plies and the material were varied. The degradation of the different mechanical properties was described using master-damage curves and a damage parameter D, which is calculated by multiplying the crack density with the thickness of the cracked ply.

Summary

The applicability of the model is shown by using the experimental results. For each specimen the crack densities were taken, the stiffness degradation was modelled and the total stiffness of the specimen was calculated by using classical laminate theory. These results were compared to the stiffness degradation in axial direction (Young’s-Modulus) and in torsional direction (shear modulus). The overall prediction of the model was very good. The model allows calculating ply-stresses for a given damage state, which will help to establish damage accumulation criteria for bi-axially loaded NCFs.