AN ENERGY-BASED METHOD FOR NUMERICAL FATIGUE ANALYSIS FOR MULTIDIRECTIONAL CARBON FIBER REINFORCED PLASTICS

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Abstract

This work describes experiments on multiaxial fibre reinforced plastic laminates, which were performed in order to create a model for the numerical fatigue analysis. To achieve this task fatigue tests of laminates with multidirectional layers submitted to constant and variable amplitude loading are analysed. The presented tests characterise the fatigue behaviour of carbon fibre reinforced plastics (CFRP) for unidirectional loading conditions and a chosen laminate. The specimens are analysed using light microscopy and computer tomography (CT).

1. Introduction

Current research and development activities in the automotive industry focus on fuel efficiency and sustainable production. Both increased customer demand regarding sustainability of products and governmental regulations have led to greater efforts to fulfil these demands. To improve structural design, it is essential to utilize new materials such as carbon fibre reinforced plastics (CFRP) which combine high specific strength, stiffness as well as energy absorption (crash) with an overall low material density (weight).

The aviation industry is already utilizing composite materials such as CFRP with great success. However, due to recent progress in manufacturing technology (high pressure resin transfer moulding - HPRTM), composites are also considered as a suitable material for light weight design in the automotive industry. While the material has been tested and simulated specifically for the aviation industry in mind, an approach has to be found to suit the needs and requirements of the automotive industry.

In this contribution the authors present an energy-based meso-scale method for the numerical fatigue analysis of CFRP structures. The model is derived from quasi-static and from constant amplitude tests on flat samples. The model is used to simulate the stiffness degradation of flat samples exposed to variable amplitude loadings. The method allows for analysis of the stiffness degradation of the tested samples and shall further be able to calculate the stiffness degradation of components.

2. Materials and Testing Procedure

The CFRP samples were produced using a high pressure resin transfer moulding process. The samples were physically and chemically analysed (density, glass transition temperature, differential scanning calorimetry, thermography and ultrasonic testing) to guaranty the uniformity of all samples. The specimens were cut into 250 x 25 x 2.5 mm^3 coupons. Specimens used for the in sito computer tomography characterization were cut into 350 x 25 x 2.5 mm^3 coupons in order to minimize interference of the metallic clamping with X-rays emitted from the CT, using a water jet cutting tool. Glass taps were applied to the ends of the specimens to achieve a better load distribution.

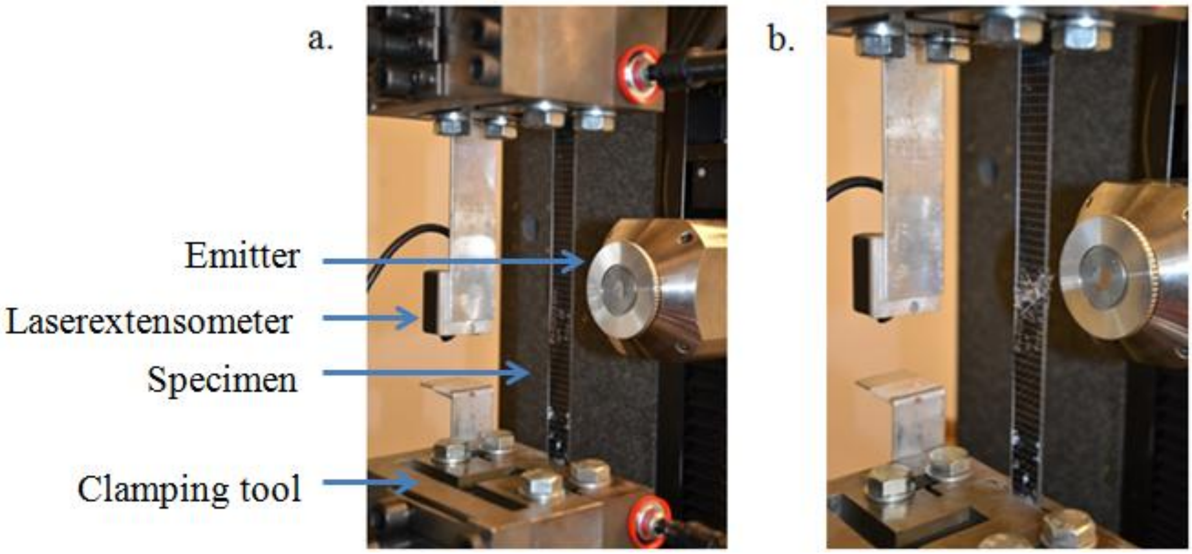

Figure 1. In situ CT testing machine with a.) a virgin sample b.) the same sample close to final failure.

Constant amplitude fatigue tests on coupon specimens were performed under load control at six load levels and a load ratio of R = 0 with a constant frequency of f = 10 s^{-1}. All specimens were tested until rupture occurred or until n = 2 x 10^6 cycles were reached.

Variable amplitude tests on coupon level were performed under load control for four load levels and a constant load ratio of R = 0.1. Furthermore tests with a tensile mean load were performed with load conditions of R = 0.1, R = 0.5 and R = 0.9 and a constant frequency of f = 4 s^{-1}. All samples were tested until n = 500.000 cycles were reached.

The specimens analysed in the in situ CT were tested under constant amplitude loading with constant load ratio of R = 0.1 until rupture occurred.

3. Proposed model for fatigue simulation of carbon fibre reinforced plastics

The fatigue behaviour of CFRPs depends on the stacking sequence of the layers, the production process (HPRTM, pre-preg) used, applied load, the direction of the applied load, the load ratio R as well as the environmental conditions. Due to this various influences and due to the complex damage behaviour of the material [1, 2] a multitude of fatigue models have been developed [3]. They can be classified as classic fatigue models, phenomenological residual strength, stiffness models and progressive damage models.

A quasi-static damage model [4] was used to characterize the fatigue behaviour of the material [5]. However, testing revealed that a more detailed modelling is necessary to take into account the fatigue damage phenomena. This model is going to be explained in this section.

3.1. Model description

The simulation method is based on the total strain energy and therefore possesses the possibility to calculate the damage propagation similar to the crack propagation described by the Paris Law. Additionally, it is possible to include damage caused by impact or mis-use in the simulation. Therefore it is necessary to have the ability to characterise quasi-static and fatigue damage.

For the calculation the total strain energy of a plate (E_D) is used. Various damage variables corresponding to the load direction are further included (d_{11}, d_{22}, d_{12}) in order to describe the degradation behaviour of the material. The total strain energy for a cycle (E_{DLW}) follows as:

$$E_{DLW} = \frac{1}{2}\cdot\left[\begin{array}{l} \dfrac{\sigma_{11}^2}{S_{11}^{i-\Delta t}\cdot(1-\Delta d_{11}^i)} + \dfrac{\sigma_{-11}^2}{S_{11}^{i-\Delta t}\cdot\alpha\cdot(1-\Delta d_{11}^i)} - \dfrac{\nu_{12}}{S_{11}^{i-\Delta t}\cdot(1-\Delta d_{11}^i)}\sigma_{11}\sigma_{22} \\ + \dfrac{\sigma_{22}^2}{S_{22}^{i-\Delta t}\cdot(1-\Delta d_{22}^i)} + \dfrac{\sigma_{-22}^2}{S_{22}^{i-\Delta t}\cdot\beta\cdot(1-\Delta d_{22}^i)} - \dfrac{\nu_{21}}{S_{22}^{i-\Delta t}\cdot(1-\Delta d_{22}^i)}\sigma_{11}\sigma_{22} + \dfrac{\sigma_{12}^2}{2G_{12}^{i-\Delta t}(1-\Delta d_{12}^i)} \end{array}\right] \quad (1)$$

S_{11}^{i-1}	Stiffness in fibre direction at the point in time i.
S_{22}^{i-1}	Stiffness normal to fibre direction at the point in time i.
G_{12}^{i-1}	Shear modulus at the point in time i.
d_{xy}^{i}	Damage for the direction xy at the point in time i
α	Damage coefficient for compressive loading in fibre direction – the variable has yet to be defined.
β	Damage coefficient for compressive loading normal to fibre direction at the point in time i – the variable has yet to be defined.

The time and direction dependent energy rate is calculated using the derivative of E_{DLW} in d_{xy} and allows to describes the time and direction dependent damage of the lamina.

$$\Delta Y_d^G = \frac{\partial E_{DLW}^G}{\partial d_{xy}^G} \quad (2)$$

ΔY_d^G	Damage - energy - release rate for the point in time G.

In order to describe the damage evolution based on the number of applied cycles n an equation, which describes the experimental data, is used. Using the theory proposed by Van Paepegem [6] it is possible to derive a function which describes the evolution of the damage variable depending on number of cycles n and normalised upper stress level σ_O.

For calculation purposes it is useful to normalize n, σ_O and d to receive a normalised damage D. The normalised damage value D = 1 denotes the rupture of the sample.

$$D = a \cdot (\tilde{\sigma} \cdot \tilde{n}) \cdot e^{\left((-1) \cdot b \cdot \sqrt{\tilde{\sigma} \cdot \tilde{n}}\right)} + c \cdot (\tilde{\sigma} \cdot \tilde{n})^{f} \cdot \left(1 + e^{(g \cdot ((\tilde{\sigma} \cdot \tilde{n}) - h))}\right) \tag{3}$$

The variables a, b, c, g, h are material constants which have to be calculated using the experimentally received data. $\tilde{\sigma}$ denotes the normalised stress level while $\tilde{n}$ denotes the normalised number of cycles for each load level. Figure 2 displays which part of the damage propagation is defined by formula (3).

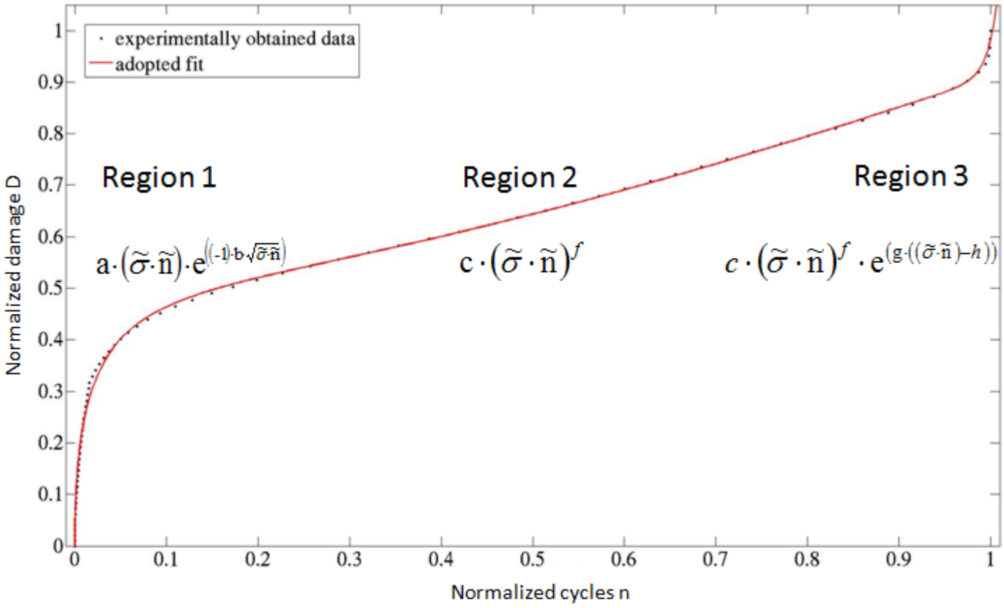

Figure 2. Damage propagation for a selected multidirectional laminate. Displayed are experimentally obtained data and the proposed fit.

Using these formulations, it is possible to calculate the damage energy release rate for each integration point in the FE -simulation and adjust the material constants in order to describe the overall stiffness loss of the material. The stiffness degradation can further lead to a change in loading path in a structural components [7], which needs to be taken into consideration for further iterations.

To end the simulation following abortion criteria were defined:

I. D reaches the value defined for rupture.
II. The maximum level of the damage energy release rate for the applied load is reached.
III. The difference of the damage energy release rate between two cycles is higher than the allowed energy density release rate for quasi-static loading.

4. Results and Discussion

The simulation results shown below for variable amplitude loading with a constant stress ratio R = 0.1 and for constant amplitude loading with a various stress ratio R were solely calculated using the experimental data obtained by experiments with constant amplitude loading and a stress ratio R = 0.

Figure 3 displays the results of tests and variable amplitude loading with a constant load ratio R = 0.1. The experiment was designed to apply a fictions damage sum of D = 0.8 (according to Miners Rule) after the fourth repetition of the chosen loading block. The purpose of this choice was to collect data for current and future studies and for a direct comparison between a conventional fatigue model and the developed approach. In the experimentally obtained stiffness-time data “steps” can be observed, which are related to the used measurement system and the change of block with CA loading applied by the testing system.

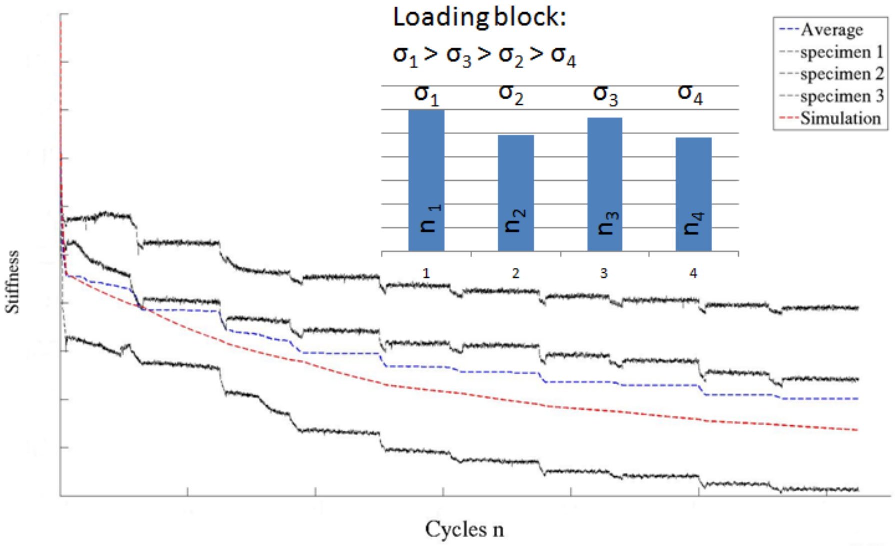

Figure 3. Comparison of data received by experiments and simulation for various amplitude block loading with a constant stress ratio of R = 0.1.

Figure 4 displays experimentally obtained results for constant amplitude loading with various load ratios R. To collect data for a wide range the load ratios were chosen as follow $R_1 = 0.1$, $R_2 = 0.5$ and $R_3 = 0.9$.

Although the simulation displays a more conservative result the general tendency of the material behaviour, as well as the steps at each change of the load ratio can clearly be seen and identified. The achieved stiffness result after the fifth loading block derivates less than 6 percent compared to the average value obtained in the experiment.

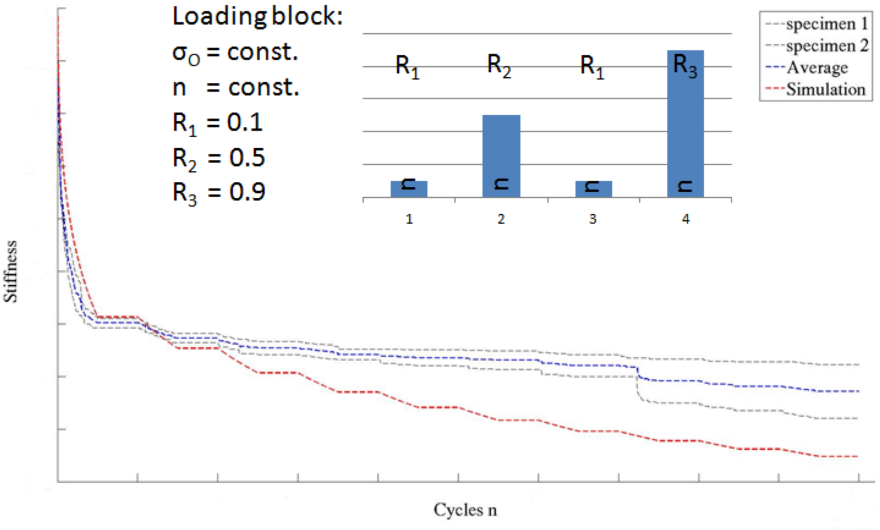

Figure 4. Comparison of experimentally received data to the numeric simulation for constant amplitude loading with various stress ratios R after the fifth iteration of the loading block displayed above.

To further obtain a better knowledge of the material behaviour in situ computer tomography was used. This new experimental characterisation enables an “online monitoring“ of the material. It is possible to follow the stiffness reduction (c/c_0) of the specimen and to conduct CT characterizations on random and predefined points in time (Figure 5). Although it is necessary to stop the applied cyclic loading to conduct the characterisation, it is not necessary to dismount the specimen and therefore render the specimen useless for additional testing. While the obtained results are promising further experiments have to be conducted to achieve the maximum of accuracy of the used characterisation method (Figure 6).

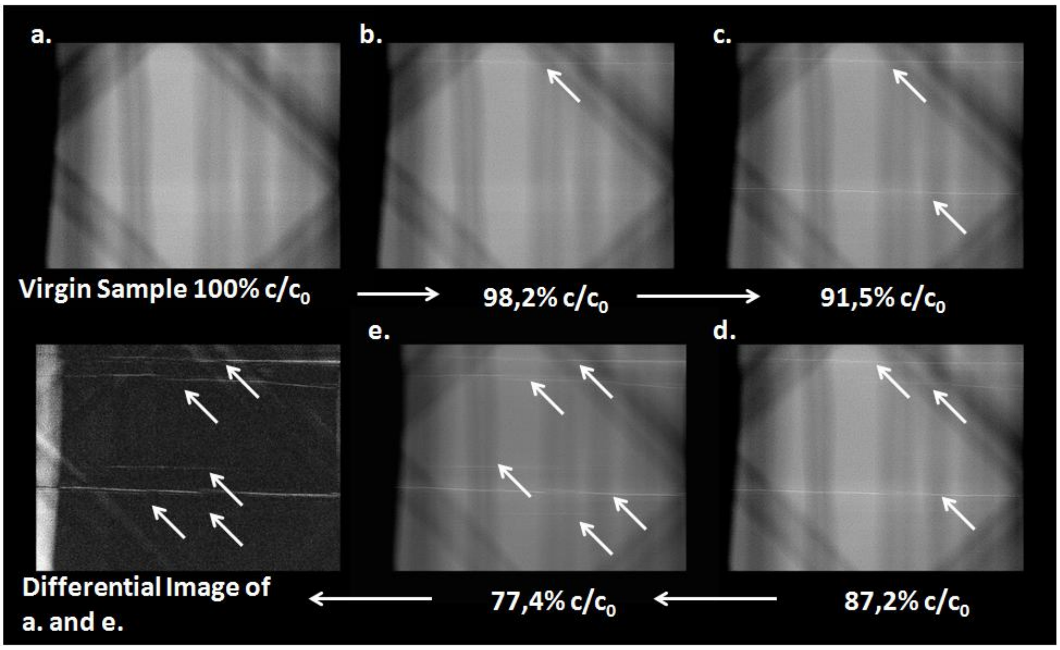

Figure 5. CT images during constant amplitude loading of a specimen for a chosen layer. Image a. denotes the virgin sample without any stiffness loss (c/c_0) whereas images b. to e. show the damage evolution. The differential image highlights the change of the material from step a. to e. The arrows mark damaged areas in the specimen. A resolution of 8 µm was used and each measurement scans a layer with a thickness of 15 µm.

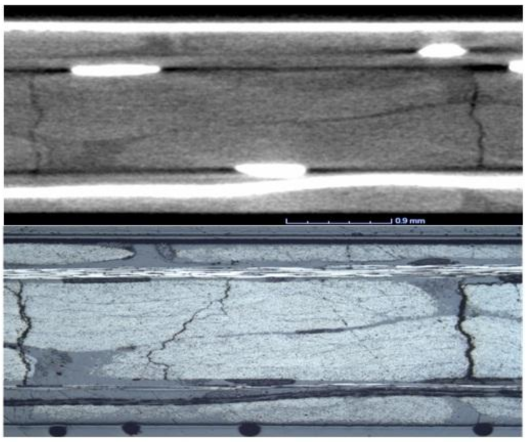

Figure 6. Comparison of x-ray computed tomography (top) to micrograph (bottom).

The images obtained using computer tomography show the local failures within the material such as the stacking sequence of the laminate but much more detailed images are delivered using the classical micrograph. Form the images obtained so far it is possible to conclude that the crack density in the vicinity of glass fibres is higher than other locations. Additionally it is possible to observe the transition of inter-fibre failure in a single ply into a local delamination in the neighbouring area.

5. Conclusion and Outlook

This contribution displays experimentally and numerically obtained fatigue data of tests under variable amplitude loading with constant load ratio R and under constant amplitude loading with various load ratios R for carbon fibre reinforced multidirectional laminates, produced with high pressure resin transfer moulding. The material parameters for the numerical simulation were obtained using quasi-static and constant amplitude loading ($R = 0$) on test coupons. The data were further used to calculate the damage energy release rate. Using the formulas (2) and (3) it was possible to simulate the material behaviour under variable amplitude loading. The correlation between simulation and experiment proofed to be good. Computer tomography and micrograph supplied further information on the damage behaviour for the tested multidirectional laminate.

Further experiments are planned to gather additional information of the damage evolution under tension – tension, tension – compression and compression – compression mode.

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