EFFICIENT MICRO-MECHANICAL MULTIAXIAL FATIGUE TESTING AND MODELLING FOR GFRP LAMINATES

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Keywords: Multiaxial Fatigue, Intralaminar damage, Fatigue Testing

Abstract

Recent progress in the development of a physical based micro-mechanical multiaxial fatigue model for glass fibre reinforced composite materials is presented. The model relies on data rich information on off-axis crack initiation and propagation obtained using an automated crack counting method and is based on the GLOB-LOC constitutive micro-mechanical framework. Off-axis crack initiation and propagation due to multiaxial fatigue loading are modelled using damage based criteria from literature for the initiation phase and Paris' law like relationship for crack growth. It is demonstrated how fatigue failure parameters needed for these criteria can be derived from an experimental campaign using only two different laminate layups. Results obtained using a preliminary damage evolution model are discussed, and plans for future research are outlined.

1. Introduction

Glass fibre reinforced polymer (GFRP) laminates are used extensively in wind turbine blades as well as for many other weight critical applications. Weight critical composite structures are often subjected to severe fatigue loading conditions over their service life. The fatigue loading experienced by GFRP laminates is typically non-proportional and multiaxial resulting in a large number of factors which cause strength and stiffness degradation. The most widely applied design method accounting for fatigue makes use of rainflow counting for converting bending moment time-series into Markov matrices. To take the effect of mean stress into account, fatigue strength data based on phenomenological methods such as Palmgren-Miner's linear damage accumulation rule combined with uniaxial S-N curves at one or several R-values are used. The phenomenological methods require extensive testing from down-scaled laminate coupons to full scale component tests, and, at best, can only be considered valid for the specific tested laminates. To reduce the amount of fatigue testing required and to propose safer and more reliable multiaxial fatigue criteria it is necessary to obtain a deeper understanding of the damage mechanisms involved in the fatigue degradation and incorporate these phenomena in predictive models.

An extension of the micro-mechanical GLOB-LOC model [1] with a multiaxial crack density fatigue evolution law along with a test campaign strategy to inform the model is presented in the present paper. Material failure parameters are defined in terms of stochastic initiation fatigue strengths and crack growth rates derived from the recently developed Automatic Crack Counting (ACC) methodology [2]. This enables quick, accurate and data rich assessment of the damage state to provide material properties from a limited number of fatigue tests. The micro-mechanical multiaxial fatigue

Excerpt from ISBN 978-3-00-053387-7

model presented here predicts the layerwise crack density evolution based on measured crack initiation strengths and crack growth rates.

2. Multiaxial Material Characterisation:

The multiaxial fatigue model uses the two damage based initiation criteria presented in [3]. The two criteria predict crack initiation due to either a high local hydrostatic stress (LHS) or a high local maximum principal stress (LMPS). To use these criteria, two different multiaxial loading conditions must be tested to derive the off-axis crack initiation S-N curves. The characterisation was carried out by studying the damage evolution in two different layups. Specimens with a $[0/90]_s$ and a $[0/-40/0/40]_s$ layup were tested. The laminates were produced using manual material placement with non-crimp E-glass UD fibre fabrics and impregnated with epoxy using vacuum assisted resin transfer moulding. All specimens were tested in uniaxial tension at a stress ratio equal to R = 0.1 using a 100 kN Instron servo hydraulic test machine. Information on the tests and the test specimen material is given in Table 1.

Table 1. Specimen material properties and test parameters

Laminate	Thickness [mm]	E_1 [GPa]	V_f [%]	No. fatigue tests	No. Stress levels	$\lambda_{12} = \frac{\tau_{12}}{\sigma_{22}}$
$[0/90]_s$	2.08	26.2	47	8	4	0.0
$[0/40/0/-40]_s$	4.16	29.4	51	6	3	2.3

The first damage mode observed was initiation of off-axis cracks, mainly at the specimen edges, which grew across the specimen until they were arrested by meeting another crack or the opposite specimen edge. The off-axis crack damage evolution was continuously monitored during the fatigue tests using the ACC method presented in [2]. ACC quantifies the crack state for each ply in terms of the length and location for each individual crack for every processed image. Using a suitable data mining approach it is then possible to derive statistically representative failure parameters for crack initiation and crack propagation from the crack field data as shown in [4]. A prerequisite for deriving this data is information on when cracks start to interact. If cracks are distanced sufficiently far apart they will not feel the presence of other cracks and can therefore be regarded as isolated. Each isolated crack therefore represents an independent sample point of the random variable, which for fatigue is number of cycles to failure. A unit-cell fracture mechanics analysis as presented in [5] is used to determine when a crack can be regarded as isolated. For the tested laminates it was found that a distance $d = 3t_k$, where t_k is the thickness of the damaged ply, was sufficient to ensure that there is no interaction between cracks.
The crack field was data mined for initiation of independent off-axis cracks. The results are shown in an S-N diagram in Figure 1. As shown in [4], the initiation of off-axis cracks has a stochastic nature which is accurately modelled by a Weibull distribution with the cumulative distribution function given as

$$F(x) = 1 - exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right]; x > 0 \quad (1)$$

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where x is the random variable with number of cycles as unit, η is the scale parameter expressed in number of cycles to initiate 63% of isolated cracks, and β is called the shape parameter. β and η can be determined for each stress level using a maximum likelihood estimator (MLE). The average value of β for each laminate is given in Table 2 and η is plotted in Figure 2 with 95% confidence bound for each tested stress level. It is assumed that the influence of stress level can be described by a power law of the form $S = c\ N_f{}^k$, where S is the stress level in terms of either *LHS* or *LMPS*, N_f is the number of cycles to initiate an off-axis crack and k and c are fitting constants. Figure 2 shows the power law fitted to the obtained scale parameters and it is seen that the fitted power laws model the influence of stress level on cycles required to initiate a crack well.
A model for the S-N Weibull field can be derived by inserting the power law $S = c\ N_f{}^k$ in (1) and is given as

$$F(x) = 1 - exp\left[-\left(\frac{x}{(S/c)^{1/k}}\right)^{\beta}\right]; x > 0 \qquad (2)$$

The 3rd and 97th percentile curves are plotted in Figure 1, and it is seen that the vast majority of data points are encapsulated by the S-N Weibull field.

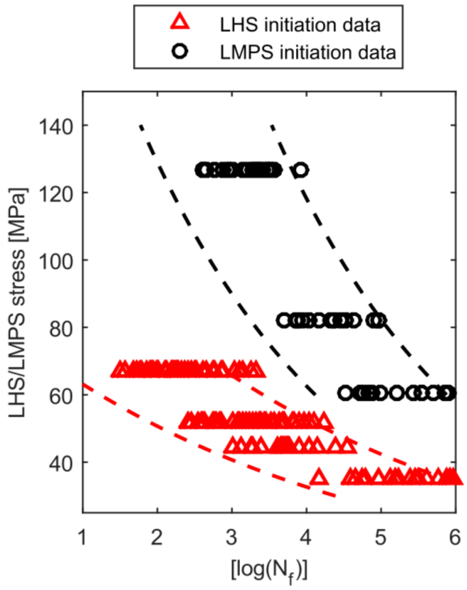

Figure 1. S-N data for isolated crack initiation for (red) [0/90]$_s$ layup and (black) [0/-40/0/40]$_s$ layup.

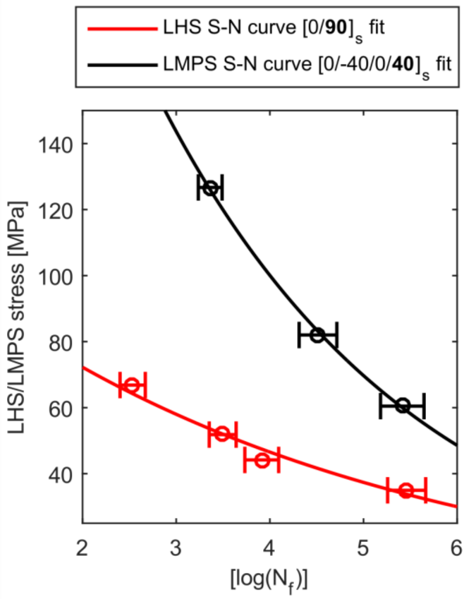

Figure 2. LHS and LMPS S-N curve derived using a [0/90]$_s$ layup for the LHS curve and a [0/-40/0/40]$_s$ layup for the LMPS curve.

When an off-axis crack reaches a certain length it will grow in a steady state manner [5]. The required length for steady state crack growth can be determined from a unit-cell analysis as shown in [5]. For the tested laminates it was found that a length $L_c = 3t_k$ results in steady state crack growth. Isolated cracks in the crack field data were tracked and crack growth rates at different stress levels were computed. Figure 3 shows the measured crack growth rates in the [0/90]$_s$ and [0/-40/0/40]$_s$ laminates plotted against G_{tot}. A substantial variation in the measured crack growth rates at a constant stress level is observed, but a Paris' law like trend in the data sets is clearly seen. Paris' law like relationships of the $CGR = D \cdot G_{tot}^n$ type were fitted to the data with an MLE and the fitting constants are given in Table 2.

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Table 2. Derived fatigue failure parameters for each failure mode for the tested material where the units for each variable is, N_f [cycle], S [MPA], CGR [mm/cycle] and G_{tot} [kJ/m²].

Failure mode	β	$S = c\,{N_f}^k$		$CGR = D \cdot G_{tot}^n$	
		c	k	D	n
LHS	0.99	112	-0.095	29	4.5
LMPS	1.23	425	-0.16	0.018	2.7

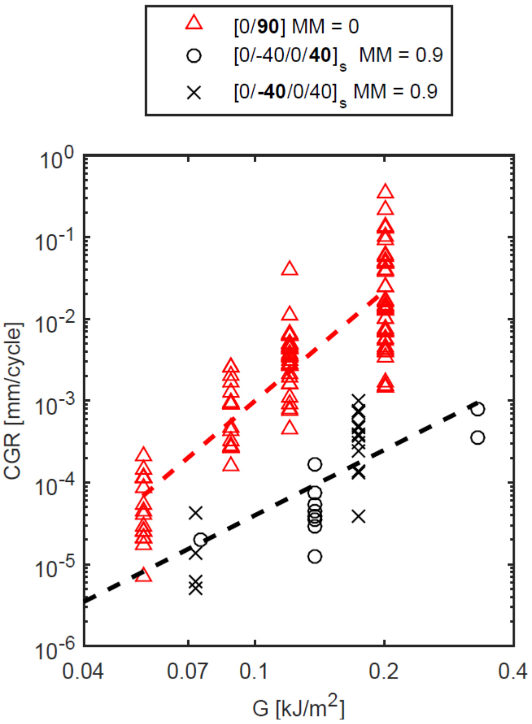

Figure 3. Paris' law master curves for mode I dominated crack growth (red) and mode II dominated crack growth (black).

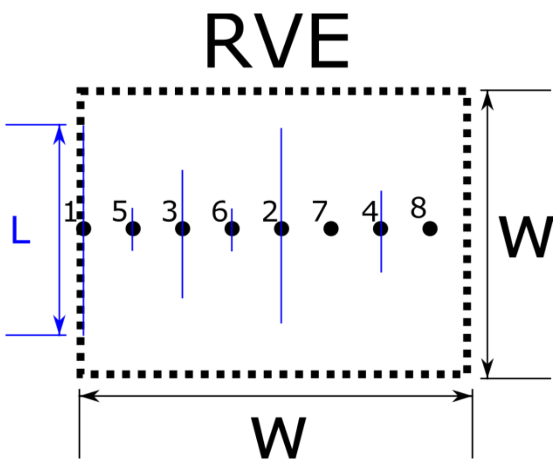

Figure 4. Parametrisation of off-axis crack evolution used in preliminary model. The numbers indicate the sequence in which cracks initiate.

3. Preliminary Model

A preliminary fatigue crack density evolution model has been developed. The crack evolution process has been parametrised as shown in Figure 4, where it is assumed that a new crack initiates between two existing cracks. The cracks are allowed to grow a certain length, which has been chosen as the maximum length the cracks can grow in the test specimens. The GLOB-LOC model [1] has been used as damage model. The GLOB-LOC model provides a method to compute the stress redistribution and the reduction in energy release rate for the off-axis cracks when the crack density increases. An example of crack density evolution predictions for the $[0/90]_s$ is shown in Figure 5. It is seen that the model predictions show a similar trend as the measured crack density with decreasing crack density evolution rate and saturation at approximately the same value as the measured crack density. The mismatch between the model predictions and the measured crack density may be attributed to the parametrisation of the off-axis crack evolution. The chosen parametrisation is a simplification of the actual evolution process where cracks initiate on the edges and grow towards the other side of the laminate. This means that the real crack initiation problem is not a 1D problem as assumed in the current (preliminary) parametrisation (Figure 4), and instead should be parameterised as a 2D problem. Therefore the current and future research focus is to devise a new and more physically based parametrisation of the crack evolution process.

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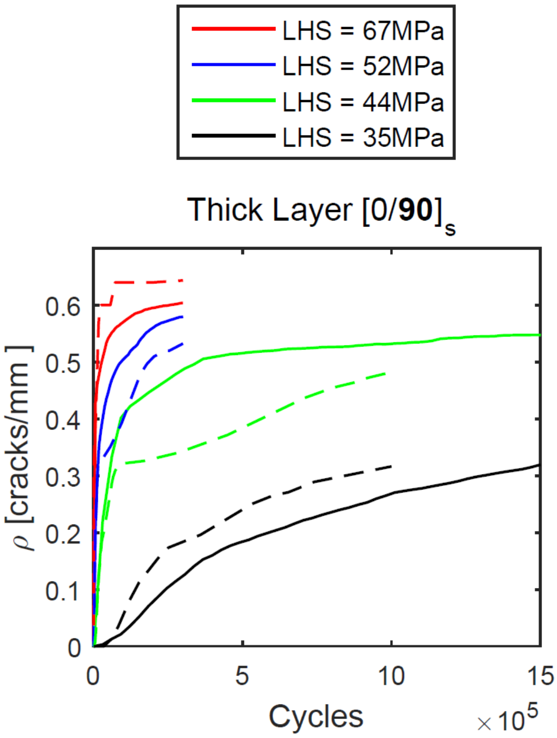

Figure 5. Measured crack density as function of number of cycles (solid lines) in comparison with preliminary model results (dashed lines).

4. Conclusions and future research

A physical based micro-mechanical multiaxial fatigue model for crack density evolution prediction has been proposed along with the key building blocks of the model. Fatigue failure parameters needed for the chosen initiation and propagation criteria have been derived for a GFRP material using a data rich experimental measurement method. The derived data shows that fatigue strengths and crack propagation rates display a large degree of scatter. This scatter is an inherent property of the material, which should be accounted for in the modelling using a proper stochastic treatment of derived data. A simple preliminary model has been developed, and predictive results from this model have been presented. The crack density predictions obtained using the model show similar trends as the experimentally measured crack density evolution, but the discrepancies between model predictions and experimental observations indicate that model improvements are needed. The current and future research effort is therefore to improve the model predictions by developing a more realistic parametrisation of the crack evolution process.

5. Acknowledgments

The work presented was conducted as a part of a Ph.D. project at the Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark. A part of the research was carried out during a visit of the corresponding author at the University of Southampton, Faculty of Engineering and the Environment, Southampton, UK. The project has received sponsorship from Innovation Fund Denmark through the "Danish Centre for Composite Structures and Materials for Wind Turbines (DCCSM)". The support received is gratefully acknowledged.

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Excerpt from ISBN 978-3-00-053387-7