NUMERICAL AND EXPERIMENTAL EVALUATION OF THE FATIGUE PERFORMANCE OF BEARING LAMINATES

M. Hoffmann[1], V. Otto[2], T. Havar[3] and E. Ahci[4]

[1]Airbus Group Innovations, TX1DS, 81663 Munich, Germany
Email: marco.hoffmann@airbus.com, Web Page: http://www.airbusgroup.com
[2]Airbus Helicopters, ETMBGS, 88609 Donauwörth, Germany
Email: victoria.otto@airbus.com, Web Page: http://www.airbushelicopters.com
[3] Airbus Group Innovations, TX1DS, 81663 Munich, Germany
Email: tamas.havar@airbus.com, Web Page: http://www.airbusgroup.com
[4]Airbus Helicopters, ETMBGS, 88609 Donauwörth, Germany
Email: elif.ahci@airbus.com, Web Page: http://www.airbushelicopters.com

Keywords: Load introduction, bearing laminates, fatigue, progressive failure analysis

Abstract
A good fatigue performance is essential for composite components of highly loaded aircraft structures. In addition, reliable sizing methods are needed for reasons of certification. In this paper a combined experimental and numerical approach is presented to characterise and predict the fatigue behaviour of composite laminates. A numerical method has been developed by means of user-defined material model (UMAT) for the implicit solver Abaqus/Standard. The method takes into account fatigue stiffness and strength degradation and is able to predict failure by Puck’s 3D failure theory. It has been calibrated and validated by three point bending tests on coupon level. Finally the modelling method has been applied successfully to predict the failure mode and number of load cycles to failure of a bearing laminate.

1. Introduction

Load introductions, e.g. bearing laminates and composite lugs, are essential for further applications of composite components in aircraft structures. Beside a robust failure mode and a good performance regarding static strength, fatigue behaviour and its reliable prediction are crucial for applications in highly loaded aircraft structures. An efficient application of composite joints implies a good understanding of the complex failure behaviour. This is affected by various parameters ranging from geometrical configuration to detailed material behaviour. Nowadays the sizing of composite lugs under fatigue loading conditions is mainly based on extensive test studies. Some analytical sizing tools are available, but due to their limited ability to predict complex stress states as they are present in the vicinity of the hole, high safety factors have to be applied. More accurate and reliable sizing methods are needed to make the design process more efficient and therefore to promote the application of composite lugs in aircraft structures.

In this paper a combined experimental and numerical approach is presented. A test campaign following the building block approach is briefly described. Corresponding to fatigue testing the failure behaviour of a composite (i.e. laminated bolted joint) lug has been predicted by numerical analyses. A user-defined material model has been developed to allow for a fatigue analysis with the commercial implicit FE code Abaqus/Standard. The developed material model can be applied for fatigue evaluation of unidirectional layers of fibre-reinforced composites. The fatigue strength degradation of the material is based on experimentally derived SN curves. The evaluation of the failure indices is

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

based on the action plane based failure theory by Puck. Furthermore pre-failure and post-failure stiffness degradation is implemented to account for progressive failure.

2. Test program

The building block approach, represented by the test pyramid shown in Fig. 1, is traditionally used during the certification process of composite structural elements in aerospace industry. On the first level of the test pyramid coupon tests are carried out to build up knowledge about the basic material behaviour. Due to the low testing effort on coupon level, variations can easily be integrated into the certification process and a high number of test samples can be tested. The effect of global design requirements, like e.g. fatigue loading, environmental conditions or the sensitivity to notches on the failure behaviour can be evaluated based on standard material tests. Subsequently the test samples and set up are refined towards the full scale test of the final component.

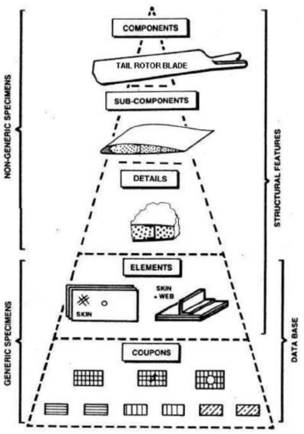

Fig. 1. Test pyramid.

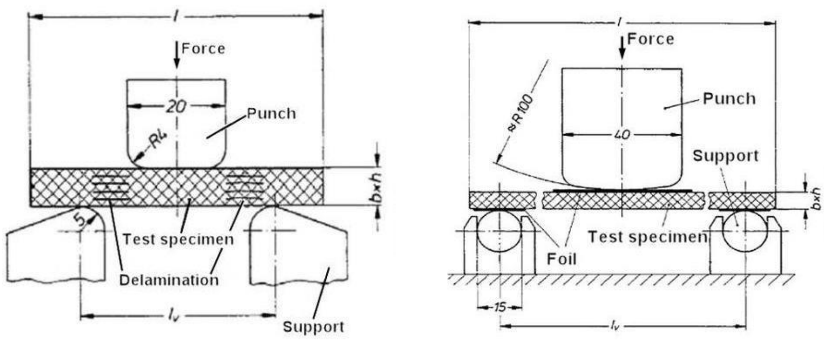

Fig. 2. Test setup and geometry of the GFC shear specimens (“three point short bending test”) on the left side and of the GFC bending specimens (“three point long bending test”) on the right side [1].

The building block approach is more and more supported by finite element analyses, especially if tests on sub-component and component level are considered. One the one hand, the numerical analyses are applied to design the test by means of the desired stress state. On the other hand, they are used to predict the results of the test regarding failure loads and failure mode.

The quality of the prediction of the failure behaviour by finite element analyses strongly depends on the quality of the material data used for the finite element simulation. In general the material parameters are directly determined by coupon tests. In the case of the numerical evaluation of the fatigue performance, a characterization of the material under fatigue loads is required. For the presented modelling approach the fatigue test results of the “three point short bending specimen” tests and of the “three point long bending specimen” tests were used. Typical test set ups are shown in Fig. 2.

The short bending specimens are used to determine the interlaminar shear strength τ_{ILS}. The test set up is well adapted to static testing, but especially for testing under fatigue loading. Fatigue tests at different load levels as well as at different mean to amplitude ratios (R-Ratio = min. load/max. load) have been carried out. Exemplarily one SN curve of the interlaminar shear strength τ_{ILS} of E-Glass Fibre Composite (GFC) at R=0.11 is shown in on the left side of Fig. 3. Following the same logic SN

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

curves for the long bending test for the stress at fibre failure could be created. One SN curve of GFC at R=0.2 is shown in on the right side of Fig. 3.

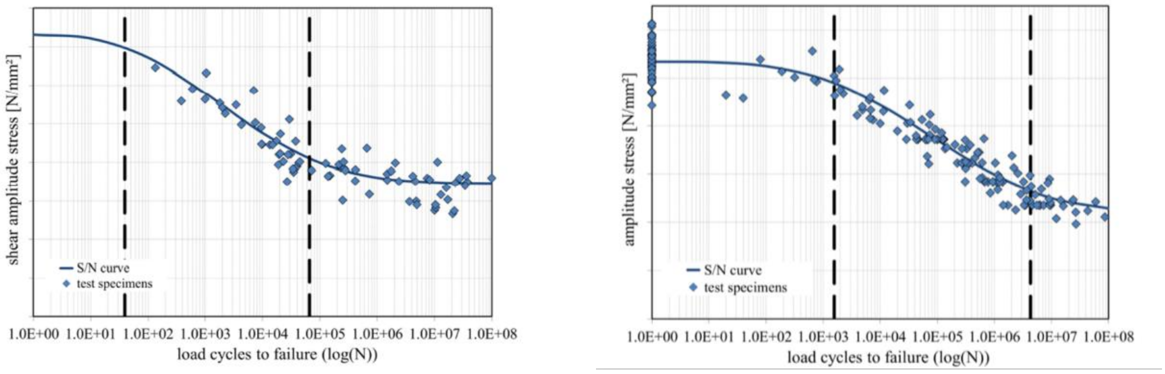

Fig. 3. SN curve of E-Glass Fibre Composite (GFC) shear specimens at stress ratio of R= 0.11 (left) and bending specimens at stress ratio R= 0.2 (right) [4].

For the application of the simulation of the fatigue performance of a composite component, the sub-component test results of composite lugs have been chosen. The composite lug is already close in dimension to the real component. The different failure modes and some exemplary test results which are generated by testing composite lugs are shown in Fig. 4. The typical failure mode of composite plates is bearing failure, due to the high edge distances available. For composite lugs the edge distances are usually restricted. Therefore shear-out and net section failures are more common. The composite lug chosen for the finite element simulation failed in shear out. This is a typical failure mode which occurs at small edge distance in load direction or if the plate consists of a high percentage of unidirectional layers. Net section failure however is found when the load of the remaining cross section is too high. Often a clear distinction between different failure modes is not possible, as can be seen at the bottom right of Fig. 4.

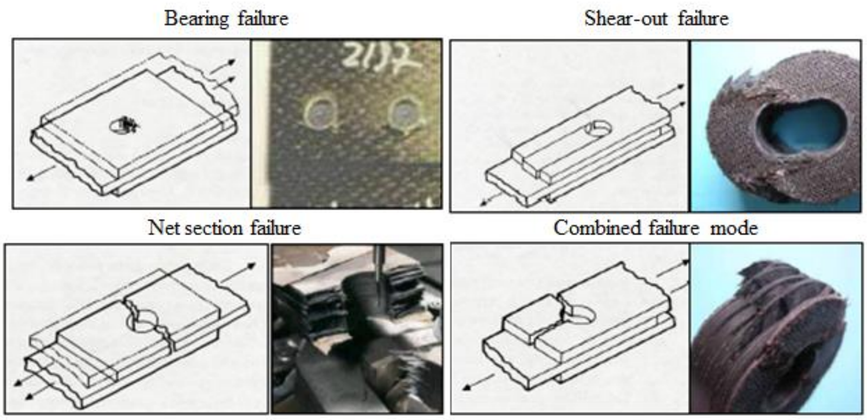

Fig. 4. Failure modes of bolted joints in composite plates [5].

3. Numerical modelling approach

The aim of this work is to provide a sizing tool for bearing laminates exposed to fatigue loading, that is compatible with a commercial FE code. It has been decided to use the implicit solver Abaqus/Standard and extend its capabilities to fatigue analyses by a user-defined material model

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

(UMAT). In this manner the local maximum stress during fatigue loading can be determined at every integration point of the material. By the application of a failure criterion the stress exposure is evaluated and a prediction of the number of load cycles to failure is made. In contrast to analytical sizing tools, an estimation of the fatigue life for all possible failure modes of bolted joints in composite plates (see Fig. 4) can be done by a single FE model. The flow chart of the UMAT used for the fatigue analyses is given in Fig. 5. The routine follows the fatigue damage model for fibre-reinforced composites developed by Kennedy [3]. It includes the determination of SN curves for arbitrary stress ratios R (R = min. load/max. load), fatigue-induced strength and stiffness degradation as well as the evaluation of Puck's 3D failure criteria. In [3] this method has already been validated for quasi-isotropic glass fibre epoxy laminates under uniaxial fatigue loading. In the present work the same approach is applied to predict the fatigue life of lugs manufactured from GFRP, which are exposed to complex three-dimensional stress states in the vicinity of the hole.

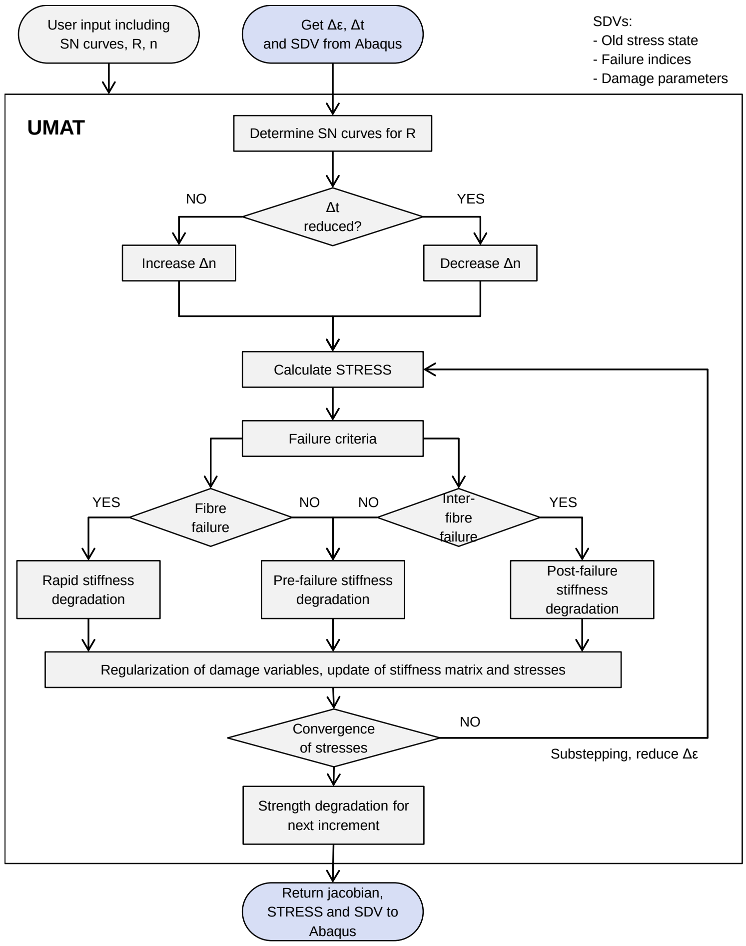

Fig. 5. Flow chart of UMAT for fatigue analyses.

Since coupon test data is typically only available for a limited number of stress ratios, an automated generation of SN curves of arbitrary stress ratio by the use of a Constant Life Diagram (CLD) has been integrated into the material routine. Due to its efficiency, especially when SN curves are available for more than three different stress ratios [4], a piecewise linear CLD following the approach given in [5] is applied (see Fig. 6).

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

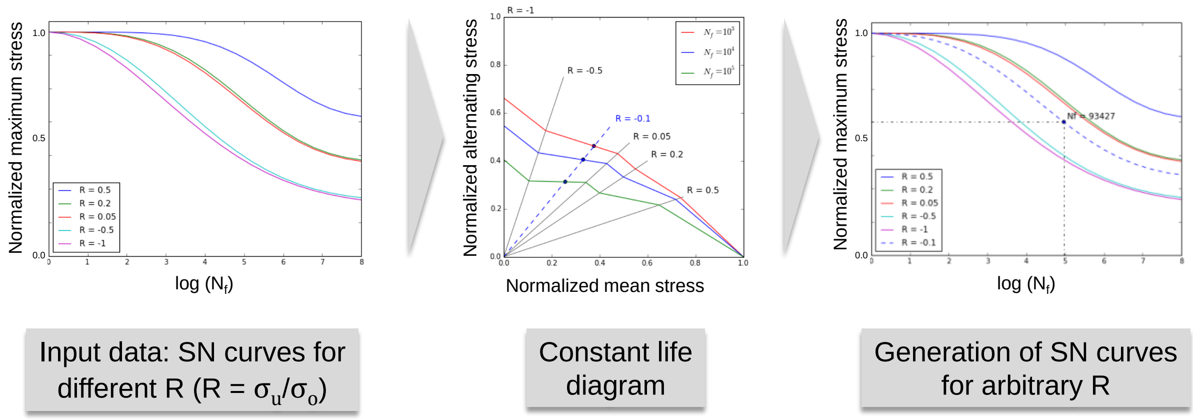

Fig. 6. Determination of SN curve of arbitrary stress ratio by a piecewise CLD approach.

Puck's 3D failure theory, as it was applied during World-Wide Failure Exercise II [6], is used to determine the stress exposures for fibre failure $f_{E,FF}$ and inter-fibre failure $f_{E,IFF}$. Failure is predicted if $f_{E,FF} = 1$ or $f_{E,IFF} = 1$, respectively. Fibre failure is predicted by the maximum stress criterion (Eq. 1) where the static strength parameters $R_{||,s}$ in fibre direction are replaced by the residual strengths $R_{||}(n)$ after n load cycles, which are incrementally degraded by (Eq. 2) from [7]. By this approach an accumulation of strength degradations from m blocks of fatigue loading under different stress ratios and maximum stresses is considered; where σ^i_{max} is the maximum stress and Δn the number of load cycles during loading block i. The number of load cycles to failure $N_f\,(\sigma^i_{max})$ is directly derived from the corresponding SN curve.

$$f_{E,FF} = \frac{|\sigma_{11}|}{R_{||}\,(n)} \tag{1}$$

$$R_{||}(n) = R_{||,s} - \sum_{i=1}^{m} (R_{||,s} - \sigma^i_{max}) \frac{\Delta n_i}{N_f\,(\sigma^i_{max})} \tag{2}$$

For the prediction of inter-fibre failure the action plane related failure criteria by Puck are applied (Eq. 3 and Eq. 4). The evaluation of these failure criteria requires an iterative procedure to determine the action plane A of an angle θ_{fp} where inter-fibre failure is most likely to occur. The three-dimensional stress tensor of the unidirectional lamina is translated into the fracture plane coordinate system (1,n,t) using tensor transformation. The stress exposure is determined based on the degraded fatigue resistances to shear stresses ($R^A_{\perp||}$ and $R^A_{\perp\perp}$) and to the tensile normal stress ($R^{(+)}_{\perp}$) transverse to the fracture plane, following equation (Eq. 5). $p^{(+,-)}_{ij}$ are so-called inclination parameters which describe the shape of the failure envelope. Values between 0.2 and 0.3 are recommended for these parameters [3].

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

$$for \quad \sigma_n \geq 0:$$

$$f_{E,IFF}(\theta_{fp}) = \sqrt{\left(\frac{\tau_{nt}}{R^A_{\perp\perp}(n)}\right)^2 + \left(\frac{\tau_{nl}}{R^A_{\perp||}(n)}\right)^2 + \left[\sigma_n\left(\frac{1}{R^{(+)}_{\perp}(n)} - \frac{p^{(+)}_{\perp\psi}}{R^A_{\perp\psi}(n)}\right)\right]^2} + \frac{p^{(+)}_{\perp\psi}}{R^A_{\perp\psi}(n)}\sigma_n \tag{3}$$

$$for \quad \sigma_n < 0:$$

$$f_{E,IFF}(\theta_{fp}) = \sqrt{\left(\frac{\tau_{nt}}{R^A_{\perp\perp}(n)}\right)^2 + \left(\frac{\tau_{nl}}{R^A_{\perp||}(n)}\right)^2 + \left(\sigma_n \frac{p^{(-)}_{\perp\psi}}{R^A_{\perp\psi}(n)}\right)^2} + \frac{p^{(-)}_{\perp\psi}}{R^A_{\perp\psi}(n)}\sigma_n \tag{4}$$

$$R(n) = R_s\left(1 - \sum_{i=1}^{m} \frac{\Delta n_i}{N_f(\sigma^i_{\max})}\right) \tag{5}$$

In addition to the SN curve based strength degradation a stiffness degradation procedure is applied to account for progressive failure of the laminate during the fatigue analyses by means of stress redistribution. Prior to failure the stiffness degradation is following the nonlinear approach taken from [8] as shown in equation (Eq. 6); where $C_i(n)$ is the residual stiffness and $C_{i,0}$ is the initial value of the stiffness. α and β are empirical parameters (see Table 1), which were fitted to stiffness measurements coming from fatigue tests of unidirectional glass fibre/epoxy laminates in [8]. After inter-fibre failure (IFF) has been predicted by Puck's IFF criteria, the matrix-governed stiffness parameters are further degraded by the post-IFF stiffness degradation approach from [3] given in equation (Eq. 7). In this equation $C_i(IFF)$ is the value of the specific stiffness at inter-fibre failure, while η_{ri}, c_{ri} and ξ_{ri} are empirical parameters which control the shape of the degradation curve and are taken from [9]. If the criterion for fibre failure is met, all stiffness parameters are abruptly reduced to a minimum value of 5% of their initial level. In any case, the evolution of the stiffness parameters is controlled by the viscous regularisation approach by Duvaut-Lions [10] to promote convergence of the implicit stress analyses.

$$C_i(n) = C_{i,0}\left(1 - (1-\alpha_i)\left(\frac{n}{N}\right)^{\beta_i}\right) \tag{6}$$

$$C_i = C_i(IFF)\left(\frac{1-\eta_{ri}}{1 + c_i(f_{E,IFF} - 1)^{\xi_i}} + \eta_{ri}\right) \tag{7}$$

Table 1. Stiffness degradation parameters.

C_i	Pre-failure [8]		Post-IFF [9]		
	α_i (1)	β_i (1)	η_{ri} (1)	c_{ri} (1)	ξ_{ri} (1)
E_{11}	0,852	0,419	-	-	-
E_{22}, E_{33}, G_{23}	0,755	3,167	0,03	5,30	1,30
G_{12}, G_{13}	0,684	1,654	0,25	0,70	1,50

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

4. Numerical analysis results

As a first step to validate the developed numerical modelling approach, FE models of the two coupon tests presented in chapter 2 have been generated. The composite specimen has been modelled by 8-noded continuum elements (element type C3D8). The section properties have been defined by the *Composite Layup* option in Abaqus with two layers per element row. Supports and punches of the bending test rigs have been modelled as deformable bodies with the linear elastic materials properties of steel (E = 210 GPa, ν = 0,3). Contact with a coefficient of friction of 0,2 has been defined between the specimen and the supports. Force controlled loading has been applied to load the specimen up to the desired maximum stresses. A stress ratio of 0,14 and a maximum number of 10^8 load cycles, which should ensure the presence of failure, have been defined as manual user inputs. A comparison between SN curves derived from coupon tests and numerical failure predictions for specific maximum stresses is given in Fig. 7 for the three point short bending test. The numerical failure predictions perfectly match the SN curve derived from the test data. The location of failure in the symmetry plane of the laminate due to interlaminar shear stress is also predicted very well. Therefore the numerical modelling approach could be validated on coupon level.

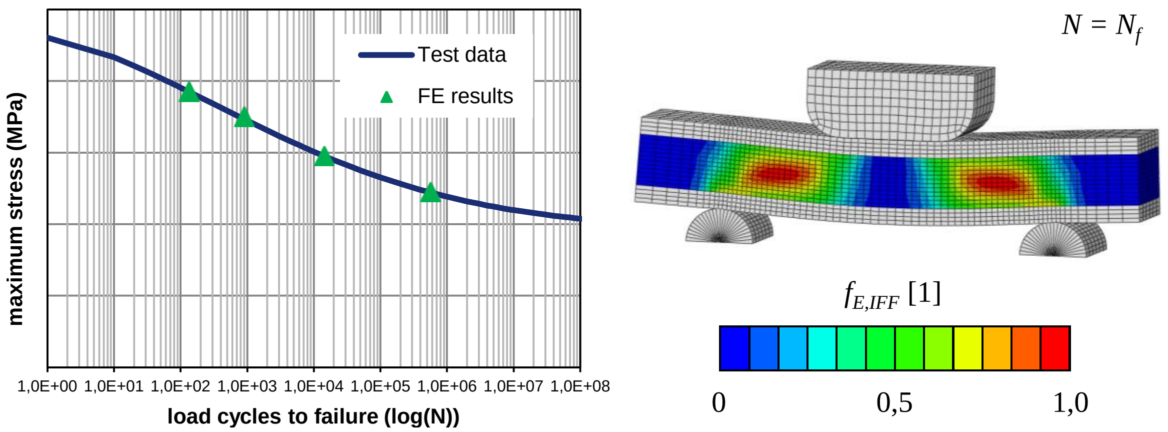

Fig. 7. Numerical failure predictions of the three-point short bending tests.

Finally, the presented modelling approach has been applied to predict the failure of a GFRP lug exposed to uniaxial fatigue loading in direction x (see Fig. 8). The model size has been reduced by making use of symmetry conditions. All element types, material models and contact properties have been adapted from the FE models of the coupon tests. The detailed layup of the GFRP lug, which is composed of unidirectional layers oriented in 0°, 90°, -45° and 45°, has again been defined by the *Composite Layup* option. A fine mesh with a number of 40 elements along the edge of the half hole in peripheral direction as well as in radial direction between the hole and the free edges of the lug has been chosen, to give an accurate representation of the stress state in the vicinity of the hole, where failure is supposed to occur. The force-controlled loading has been applied at the end surface of the bolt, which corresponds to the load application during the test. The progressive failure analysis has carried out for a stress ratio of 0,14 and up to a number of 10^8 load cycles.

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

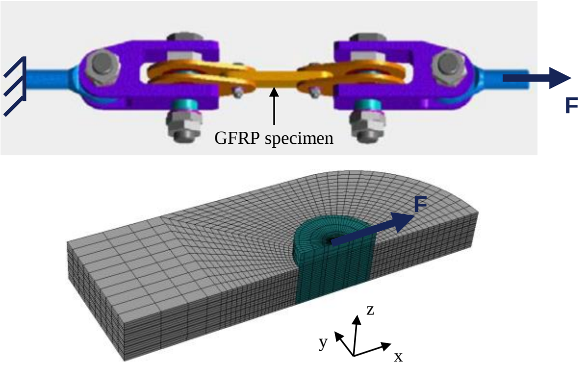

Fig. 8. Test setup [2] and FE model of GFRP lug.

In the test the GFRP failed at approximately 484.000 load cycles. The observed failure mode was shear-out failure (see Fig. 9). The main resistance to this type of failure is given by the -45°- and +45° layers within the shear stressed section of the lug. The numerical failure analyses predict the same failure mode. Due to the considered bending deformation of the bolt the first fibre failure is predicted in the outer -45° and +45° layers at a number of 406.000 load cycles. Due to the brittle nature of fibre failure, it is already considered as total failure of the lug. At this number of load cycles inter-fibre failure has already spread widely throughout all layers of the laminate. The numerical fatigue analysis has been able to predict the correct failure mode of the GFRP lug. If the scatter of the number of load cycles to failure at a constant stress level in the coupon tests (see Fig. 3) is considered, the conservative prediction of the fatigue life is also in good agreement with the lug test.

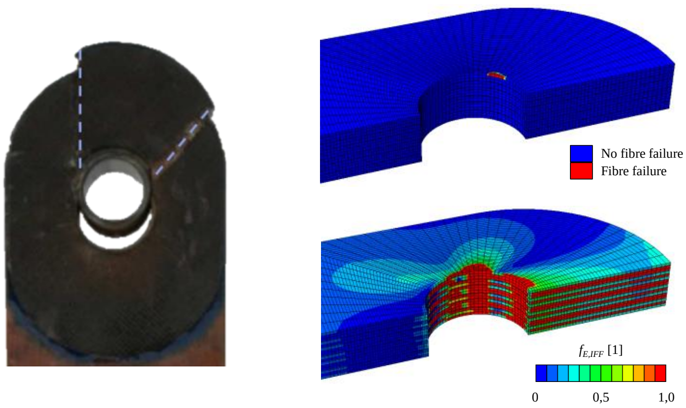

Fig. 9. Failed GFRP lug after test (left) and predicted failure from FE analyses at N = 406.000.

5. Conclusions

In this paper a numerical modelling approach to predict the progressive failure in composite laminates under fatigue loading has been presented. Based on the damage model published by Kennedy [3] the modelling approach includes a failure prediction by Puck's 3D failure theory in combination with fatigue-degraded strength parameters. In addition, the model accounts for pre- and post-failure degradation of all three-dimensional stiffness parameters. The modelling approach was validated by three point bending tests on short (interlaminar shear failure) and long beams (fibre failure) on coupon level. Finally the modelling approach has been applied to predict the failure of a GFRP lug on sub-component level. The predictions of the failure mode as well as of the number of load cycles are in good agreement with the test results. In ongoing research activities the modelling approach is being

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

applied to composite lugs with different layups and geometries to check the robustness of the modelling approach and its capability to predict different failure modes.

Acknowledgments

This study was performed within the LuFo V-1 project SCHACH funded by the Federal Ministry for Economic Affairs and Energy of Germany. The financial aid is gratefully acknowledged. The authors also wish to thank Max Wedekind and Rupert Pfaller for technical discussions and support as well as Jean-Michel Rameau for his contribution to the development of the numerical modelling method during his Master's thesis.

References

[1] R. Pfaller and A. Weinert. Statistical investigation of composite and metallic coupon and component tests, *Proceedings of 27th ICAG Symposium, Jerusalem, Israel*, June 5-7 2013.

[2] R. Pfaller and E. Ahci Ezgi. Einfluss von Geometrie und Materialparametern auf die Festigkeit von Verbindungen in Hubschrauberstrukturen, *Proceedings of DGLR Congress, Darmstadt, Germany*, September 23-25 2008.

[3] C. Kennedy, C. Bradaigh and S. Leen. A multiaxial fatigue damage model for fibre reinforced polymer composites. *Composite Structures*, 106:201-210, 2013.

[4] A. Vassilopoulos, B. Manshadi and T. Keller. Influence of the constant life diagram formulation on the fatigue life prediction of composite materials, *International Journal of Fatigue*, 32:659-669, 2009.

[5] T. Park, M. Kim, B. Jang, J. Lee and J. Park. A nonlinear constant life model for the fatigue life prediction of composite structures, *Advanced Composite Materials*, 23:337-350, 2014.

[6] H. Deuschle and B.-H. Kröplin. Finite element implementation of Puck's failure theory for fibre-reinforced composites under three-dimensional stress, *Journal of Composite Materials*, 46:2485-2513, 2012.

[7] L. Broutman and S. Sahu. A new theory to predict cumulative fatigue damage in fiberglass reinforced plastics. *Proceedings of 2nd Conference on Composite Materials: Testing and Design, Anaheim, USA*, April 20-22 1971.

[8] V Passipoularidis, T. Philippidis and P. Brondsted. Fatigue life prediction in composites using progressive damage modelling under block and spectrum loading. *International Journal of Fatigue*. 33:132-144, 2011.

[9] M. Knops and C. Bögle. Gradual failure in fibre/polymer laminates. Composites Science and Technology, 66:616–25, 2006.

[10] G. Duvaut and J. Lions. *Les inequations en mecanique et en physique*. Dunod, Paris, 1972.

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