DAMAGE EVOLUTION IN GLASS FIBRE REINFORCED COMPOSITES

Steffen Stelzer[1], René Rieser[2] and Gerald Pinter[3]

[1]Institute of Material Science and Testing of Plastics, Department Polymer Engineering, Montanuniversität Leoben, Franz Josef Straße 18, 8700 Leoben, Austria
Email: steffen.stelzer@unileoben.ac.at, Web Page: http://www.kunststofftechnik.at
[2] Institute of Material Science and Testing of Plastics, Department Polymer Engineering, Montanuniversität Leoben, Franz Josef Straße 18, 8700 Leoben, Austria
Email: rene.rieser@stud.unileoben.ac.at, Web Page: http://www.kunststofftechnik.at
[3] Institute of Material Science and Testing of Plastics, Department Polymer Engineering, Montanuniversität Leoben, Franz Josef Straße 18, 8700 Leoben, Austria
Email: gerald.pinter@unileoben.ac.at, Web Page: http://www.kunststofftechnik.at

Keywords: Composite, Fatigue, damage evolution, damage mechanisms, non destructive testing

Abstract

Endless fibre reinforced polymer (FRP) composites nowadays are being used for structural components in applications, where weight reduction is essential for reducing operational costs and emissions. Many of these components are subjected to fatigue loading during their service life. Yet, information on damage mechanisms and their evolution under cyclic loading are missing.
In this work, glass fibre reinforced epoxy composites with various stacking sequences are subjected to fatigue loading. The stiffness degradation of the samples is recorded via cyclic tensile tests and correlated to damage initiation and propagation.

1. Introduction

In spite of many challenges like manufacturing and material costs, modelling and design complexity or material anisotropy, endless fiber reinforced polymer materials (composites) are increasingly used in applications, where weight savings can help to reduce fuel costs or increase efficiency. When applied in structural applications, they are most often exposed to fatigue loading. Thus their fatigue life and endurance limits need to be assessed. The fatigue behavior of endless fibre reinforced composite materials has been investigated by many research groups over the last 30 or 40 years. The most prominent authors in the field of fatigue of composites are namely Reifsnider [1], Talreja [2] and Haris [3]. But there are many more research groups that focussed on the fatigue characterization of carbon fiber reinforced (CFRP) and glass fiber reinforced polymer (GFRP) composites.

In the recent past, various authors [4–6] focussed on the creation of constant life diagrams for composite materials. Others [7–11] investigated the effect on delaminations on the fatigue life of composite materials. Some [12–15] investigated the change of Young's modulus during fatigue testing. And more recent developments included the evaluation of cycle-dependent classical laminate theory of a multiaxial laminate [16]. Other authors investigated hysteresis effects on the fatigue life of composite materials [12,17,18]. Pinter et al. [19] investigated the fatigue behaviour of composites by iso-cyclic stress-strain diagrams. And several authors applied the classical S-N approach to composite materials [15,20–22].

Yet, although there is an increasing interest in evaluating the fatigue performance of composite laminates, there is still no clear connection between structural changes in the material due to crack initiation, growth, coalescence and saturation and the mechanical performance of the composite

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

material. More recently, a group including Talreja increased the efforts towards understanding fatigue damage mechanisms in composite materials. Various authors formed a multiaxial fatigue team with the aim to assess the fatigue behaviour of composite materials and to describe the fatigue life with physically based prediction models that are suitable to account for the actual damage mechanics [23–25].

In this work, GFRP composites will be investigated with a combined online damage monitoring and mechanical evaluation strategy in order to build up know-how in the correlation of damage evolution and mechanical properties. Together with the assessment of various non destructive testing methods, this knowledge will be tranfered to CFRP composites in following studies.

2. Experimental

2.1. Materials and specimens

In benefit of the visibility of crack initiation and propagation during fatigue testing, glass fibers were used as reinforcement material. The unidirectional glass fiber fabrics had a grammage of 220 g/m². The fabrics were cut to the required dimensions and fiber angles on a digital cutter (G3 by Zünd Systemtechnik AG, CH) The final specimen plate had a stacking sequence of $[0/45/90/-45/0]_{2s}$. Specimen plates were infiltrated with Epikote Resin MGS LR160 and Epikure MGS LH160 curing agend and pressed to final dimensions using vacuum assisted pressing on a Wickert 3500S press (Wickert Maschinenbau GmbH, D).

Specimens according to Figure 1 were cut from the plates by water-lubricated precision sawing and aluminium tabs were attached to the ends of the specimens. Before testing, all specimen edges were sanded down to P1200 and then polished in order to avoid crack initiation or delamination due to machining.

2.2. Testing procedure

All tests were carried out under laboratoratory conditions (23°C, 50% r.h.) on a 100 kN servo-hydraulic material testing system (MTS 810, MTS Systems GmbH, D). The load ratio, R ($=\sigma_{min}/\sigma_{max}$), was fixed to 0.1. Cycle dependent mechanical properties were measured by evaluating the material's Young's modulus at fixed numbers of cycles. Therefore the test machine unloaded the specimen to 0 N after a defined number of sinusoidal cycles under load control. This was followed by a monotonic tensile test up to a relative axial strain of 0.25% at a crosshead rate of 0.5 mm/min. Then the test machine returned to cyclic loading.

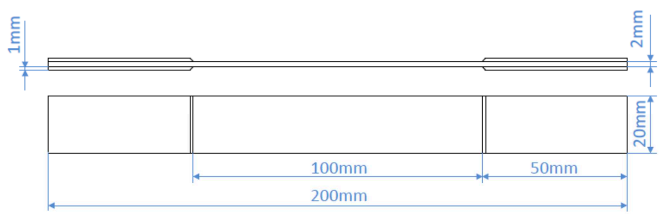


Figure 1. Specimen dimensions.

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

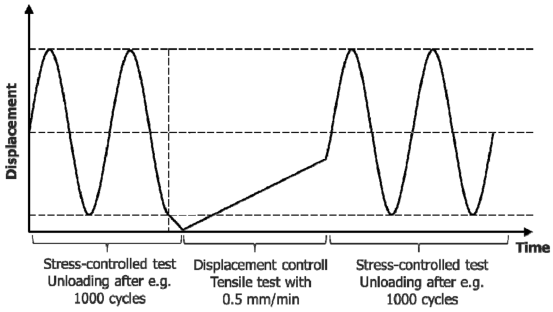


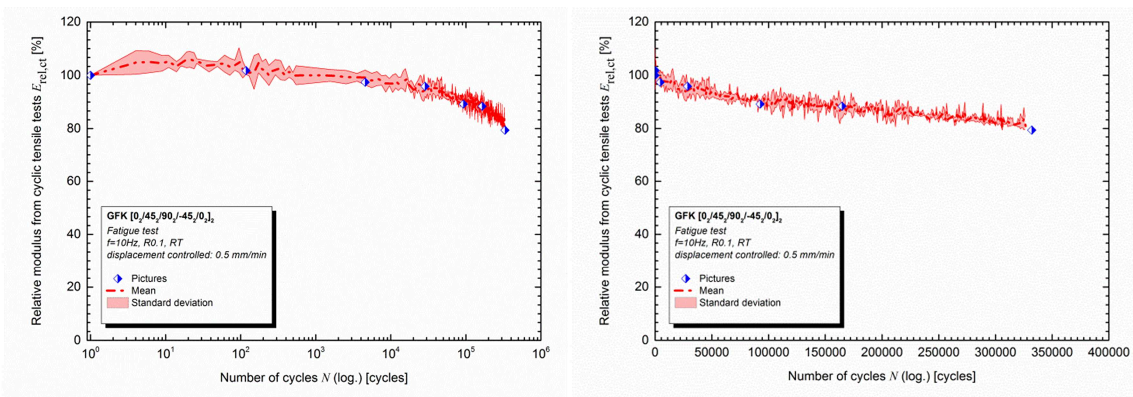
Figure 2. Testing procedure for measurement of cycle dependent Young's modulus, E(N) [12].

The evolution of cracks was monitored with two transmitted light non-destructive testing systems. One detailed high resolution camera system was used to record crack initiation and propagation of a detail of the specimen and one camera system recorded both longitutinal strains in the specimen and damage evolution in the whole specimen. This allowed to correlate mechanical performance drops to damage mechanisms in the composite material.

Furthermore it made possible to stop the test right after the appearance of specific fracture phenomena (like e.g. first 90° or 45° cracks) and to dismount the specimen for further investigations of the fracture processes with non-destructive and destructive testing methods.

3. Results

Figure 3 shows the evolution of the Young's modulus during fatigue tests on the multiaxial composite material (mean and standard deviation of 5 specimens). The damage evolution in one specimen is shown in Table 1 as representative of the five tested specimens. The specimen failed after 332 043 cycles at a maximum stress level of 100 MPa. The relative Young's modulus decreased throughout the test due to the initiation, propagation and coalescence of microcracks in the various layers of the composite.

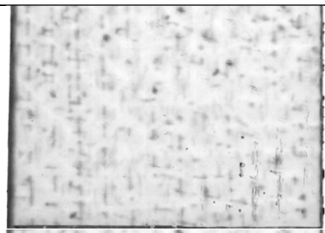
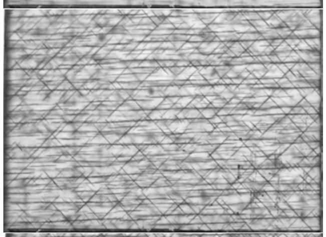
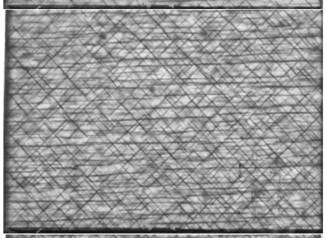
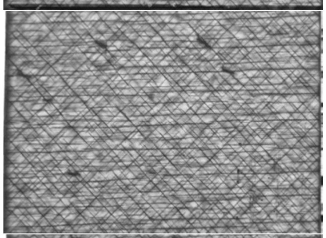
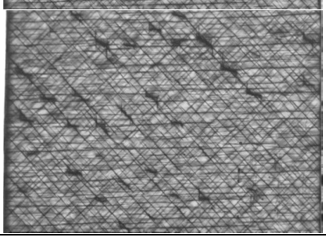


(a) (b)

Figure 3. Relative Young's modulus versus number of cycles. (a) logarithmic diagram, (b) linear diagram.

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

Table 1. Number of loading cycles and associated Young's moduli and damage states.

Number of loading cycles [-]	Specimen photograph	Young's modulus [GPa]	Comments
1		30.84	No visible damage in the specimen.
118		31.41	Microcracks in the 90° plies have initiated and begun to grow.
4 552		30.06	First microcracks in the 45° plies have initiated.
28 588		29.57	Microcracks have initated in the 45° and -45° plies and start to coalescence.
92 684		27.51	Cracks in the 90°, 45° and -45° plies are saturated.
164 792		26.11	Delaminations have started to grow from damage hotspots (dark spots on the specimen's surface).
332 043		24.51	Damage hotspots occur throughout the specimen and coalesced.

Cracks initiated in the specimen at an early stage of testing. After 118 cycles, the 90° layers started to fail. This was caused by the stresses perpendicular to the fiber direction present in the 90° layers. These are relatively high compared to the strength of the laminaes in 90° direction. The Puck's factor of safety for the 90° layers amounted to 1.42. The 45° and -45° Layers, which failed next, had a Puck's factor of safety of 1.49 and the 0° layers a safety factor of 4.49. The multiaxial composite laminate had an average factor of safety of 2.73.

Crack density saturation occurred after approximately 87 200 cycles (evaluated by visual observation of all recorded pictures). Thereafter, 'damage hotspots' developed by coalescence of 90° and +/-45° micro cracks at small manufacturing imperfections. Coalescencing damage hotspots led to the formation of delaminations and finally to tensile fracture of the specimen. A detailed representation of the different damage states in the specimens and the related Youg's moduli and load cycle numbers is shown in Table 1.

4. Conclusion and outlook

Fatigue tests on multiaxial glass fibre reinforced polymer composites showed that a combined non-destructive-destructive approach can help to understand the underlying damage mechanisms that cause the decrease of mechanical properties in GFRP during fatigue loading.

Fatigue tests will be carried out on a variety of stacking sequences that cause different types of damage in the material. Additionally, accompanying non-destructive testing at selected partner institutes, will help to select non-destructive testing methods that can be applied for online non-destructive testing during GFRP- and in a later stage CFRP-fatigue.

References

[1] Reifsnider KL (ed.). Fatigue of composite materials. Amsterdam, New York. Elsevier, 1991.

[2] R. Talreja. *Fatigue of Composite Materials*. Technomic Publishing Inc., 1987.

[3] B. Harris. *Fatigue in Composites*. Woodhead Publishing Limited, 2003.

[4] A. P. Vassilopoulos, B. D. Manshadi and T. Keller. Piecewise non-linear constant life diagram formulation for FRP composite materials. *International Journal of Fatigue*, 32:1731–1738 2010.

[5] M. Kawai and K. Yano. Anisomorphic constant fatigue life diagrams of constant probability of failure and prediction of P–S–N curves for unidirectional carbon/epoxy laminates. *International Journal of Fatigue*, 83:323–334 2016.

[6] M. Kawai, Y. Matsuda and R. Yoshimura. A general method for predicting temperature-dependent anisomorphic constant fatigue life diagram for a woven fabric carbon/epoxy laminate. *Composites Part A: Applied Science and Manufacturing*, 43:915–925 2012.

[7] S. Stelzer, A. J. Brunner, A. Argüelles, N. Murphy and G. Pinter. Mode I delamination fatigue crack growth in unidirectional fiber reinforced composites: Development of a standardized test procedure. *Composites Science and Technology*, 72:1102–1107 2012.

[8] A. J. Brunner, S. Stelzer, G. Pinter and G. P. Terrasi. Cyclic fatigue delamination of carbon fiber-reinforced polymer-matrix composites: Data analysis and design considerations. *International Journal of Fatigue*, 83:293–299 2016.

[9] R. Jones, S. Stelzer and A. J. Brunner. Mode I, II and Mixed Mode I/II delamination growth in composites. *Composite Structures*, 110:317–324 2014.

[10] G. B. Murri. Effect of data reduction and fiber-bridging on Mode I delamination characterization of unidirectional composites. *Journal of Composite Materials*, 48:2413–2424 2014.

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

[11] M. Hojo and T. Aoki. Characterization of fatigue R-curves based on Gmax constant delamination tests in CF/PEEK laminates. *Proceedings of the 20th International Conference on Composite Materials,* 19.07. -20.07.2015 2015.

[12] J. Brunbauer, F. Arbeiter, S. Stelzer and G. Pinter. Stiffness Based Fatigue Characterisation of CFRP. *Advanced Materials Research*, 891-892:166–171 2014.

[13] J. Brunbauer and G. Pinter. Technological approach to fatigue life prediction of CFRP. *Proceedings of the 16th European Conference on Composite Materials,* 22.06. - 26.06.2014 2014.

[14] F. Aymerich, P. Priolo and C. Sun. Static and fatigue behaviour of stitched graphite/epoxy composite laminates. *Composites Science and Technology*, 63:907–917 2003.

[15] T. Philippidis and A. P. Vassilopoulos. Fatigue design allowables for GRP laminates based on stiffness degradation measurements. *Composites Science and Technology*, 60:2819–2828 2000.

[16] J. Brunbauer and G. Pinter. Fatigue life prediction of carbon fibre reinforced laminates by using cycle-dependent classical laminate theory. *Composites Part B: Engineering*, 70:167–174 2015.

[17] J. Brunbauer and G. Pinter. Effects of mean stress and fibre volume content on the fatigue-induced damage mechanisms in CFRP. *International Journal of Fatigue*, 75:28–38 2015.

[18] J. Brunbauer and G. Pinter. On the strain measurement and stiffness calculation of carbon fibre reinforced composites under quasi-static tensile and tension-tension fatigue loads. *Polymer Testing*, 40:256–264 2014.

[19] G. Pinter, E. Ladstätter, W. Billinger and R. Lang. Characterisation of the tensile fatigue behaviour of RTM-laminates by isocyclic stress–strain-diagrams. *International Journal of Fatigue*, 28:1277–1283 2006.

[20] J. Brunbauer, H. Stadler and G. Pinter. Mechanical properties, fatigue damage and microstructure of carbon/epoxy laminates depending on fibre volume content. *International Journal of Fatigue*, 70:85–92 2015.

[21] M. Kawai. A phenomenological model for off-axis fatigue behavior of unidirectional polymer matrix composites under different stress ratios. *Composites Part A: Applied Science and Manufacturing*, 35:955–963 2004.

[22] M. Kawai and T. Taniguchi. Off-axis fatigue behavior of plain weave carbon/epoxy fabric laminates at room and high temperatures and its mechanical modeling. *Composites Part A: Applied Science and Manufacturing*, 37:243–256 2006.

[23] M. Quaresimin, P. A. Carraro, L. P. Mikkelsen, N. Lucato, L. Vivian and P. Brøndsted et al. Damage evolution under cyclic multiaxial stress state: A comparative analysis between glass/epoxy laminates and tubes. *Composites Part B: Engineering*, 61:282–290 2014.

[24] M. Ricotta, M. Quaresimin and R. Talreja. Mode I Strain Energy Release Rate in composite laminates in the presence of voids. *Composites Science and Technology*, 68:2616–2623 2008.

[25] M. Quaresimin, L. Susmel and R. Talreja. Fatigue behaviour and life assessment of composite laminates under multiaxial loadings. *International Journal of Fatigue*, 32:2–16 2010.

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