EAN 2018
56th conference on experimental stress analysis

Stiffness Reduction of Glass/Epoxy Laminate Under Fatigue Loading

KRÁL Michal[1, a] and CABRNOCH Bohuslav[1, b]

[1]Czech Aerospace Research Centre, Department of Composite Technologies, Beranových 130,199 05 Praha - Letňany, Czech Republic

[a]kral@vzlu.cz, [b]cabrnoch@vzlu.cz

Keywords: fiber reinforced plastic, cycling loading, fatigue damage, stiffness reduction, test specimen

Abstract. The importance of proper dimensioning of machines parts and assemblies is well-known. The assessment of fatigue strength and determination of lifetime is a necessary part of the design process of most components including composite structures. The main objective of this paper is to describe the behavior of Glass/Epoxy laminate under tensile fatigue loading. The emphasis was placed on observation of stiffness reduction during lifetime. Three stacking sequences were tested to get a satisfactory overview of laminate behavior. In one case unexpected stiffness increasing was observed and further investigated in order to determine the effect on real structures. It was necessary to propose methodology for residual modulus estimation before experimental measurement. The description of used methodology based on standards ASTM D3039 and ASTM D3518 is also the objective of this paper.

Introduction

Despite a long term research of fatigue of composite materials a satisfactory methodology which can describe this phenomenon including outer signs of damage has not been found yet. Stiffness and strength reduction can be included between outer signs of damage affecting the structure very distinctly. In general, the reduction of mechanical properties causes that design reserve factors are not valid during a whole lifetime. Stiffness also affects other properties of the structure such as resistance against buckling or natural frequencies.

The motivation for the research of methodology for measurement of laminates stiffness reduction under cycling loading stems from the requirements of customers from many industrial sectors. In the case of structures which must have sufficient stiffness during their lifetime it is necessary to estimate residual stiffness after defined number of cycles. As an example of typical composite structures with defined requirements on stiffness properties which are subjected to cyclic loading can be mentioned e.g. blades of axial fan, composite springs of loom and blades of wind turbines.

Basic review of current state of research

Research and modeling of fatigue in composite materials has been the objective of research for more than 40 years. In comparison with metal materials, fatigue damage in composites is more complicated and worse describable. Fatigue damage in laminates is cumulated in a whole volume of material and is accompanied by more damage mechanisms. The consequence of the development of these damage mechanisms is the reduction of mechanical properties.

Growth of damage mechanisms and therefore also stiffness reduction is dependent on many factors. These factors can be divided to three main groups. The first group can be called material factors and includes e.g. stacking sequence or type of reinforcement (unidirectional, fabric, NCF). The second group can be called the parameters of loading and includes e.g. frequency of loading, type of cycling loading (alternating, tensile only, compressive only), randomness of loading and character of loading (force controlled, deformation controlled loading). The third category can be called external influences and includes temperature, humidity etc.

The division of models for fatigue life prediction is always a question of personal opinion, but generally prediction models can be divided into several basic categories according to used approach of modeling. Division proposed by well-known experts in material science can be found e.g. in [1], [2] and [3]. Models based on residual stiffness are usually classified as phenomenological models of residual material properties. It must be mentioned that stiffness of material in degradation models is very often expressed through Young's modulus. These models are capable to estimate damage parameter D like in the following model (1) proposed by Liu and Lessard [4]. Damage parameter D is usually expressed using equation (2).

$$\frac{dD}{dN}=\frac{A.(\sigma_{max})^{c}}{B.D^{B-1}}. \tag{1}$$

$$D=\frac{E}{E_0}. \tag{2}$$

Symbol D is damage parameter, σ_{max} is peak stress, A, B and C are model coefficients, E is residual modulus and E_0 is virgin modulus of material. In general, damage parameter can take values from 0 to 1. As already mentioned, stiffness reduction under sufficient level can be defined as limit state. In this case, the knowledge of residual stiffness can be directly used for dimensioning.

Frequently discussed question is the measurement of residual stiffness. During unidirectional tensile experiments is possible to measure residual Young's modulus because the stress field in test specimen is uniform and can be expressed using one value. In the case of test specimens with complex shape or loading conditions, it is necessary to measure residual stiffness because the value of Young's modulus can be different in each point of the structure. This paper is focused on the measurement of residual stiffness during unidirectional tensile experiments and therefore related methods will be discussed. The measurement of residual modulus during loading depends on the character of loading. Considering deformation controlled loading, the force needed for defined deformation achieving is measured. This force decreases due to modulus reduction. The situation is more complicated in the case of force controlled loading. This type of loading is also less used by research teams and proposed methodology is described in following text.

A typical shape of residual stiffness curve is shown in Fig. 1. It can be seen, that stiffness reduction during lifetime is divided into three stages and forms a typical S shaped curve [5]. Each stage is characteristic by development of certain failure modes. The size of individual stages is dependent on more factors but the most important is the level of cyclic stress. On low levels, the third stage may not arise. On high levels the first stage passes to the third stage very fast and the second stage is very short.

The main goal of a number of authors is a modeling of stiffness reduction using finite element method. This approach is based on implementation of degradation models to FE code. A long-term research of this method is performed e.g. by Degrieck and Paepegem, see [6] and [7]. FE modeling is limited by the complexity of fatigue damage in composites and

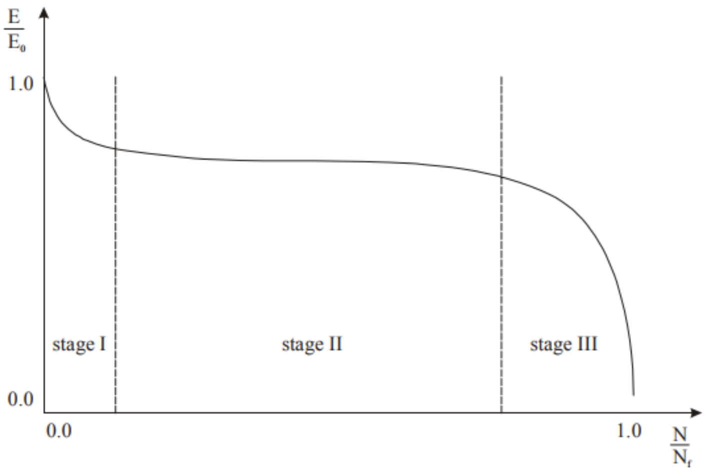

Fig.1 A typical shape of residual stiffness curve [5]

a very bad possibility of generalization. Identified model implemented in FE code will always be useable only for certain conditions which are usually similar to the conditions applied during measuring of data used for identification of implemented model.

Description of proposed methodology for residual stiffness measurement

As already mentioned, the motivation for this research stems from the requirements to structures which must have sufficient stiffness during their lifetime. Between these structures designed at the Composite Technologies Department in Czech Aerospace Research Centre it is possible to include e.g. blades of axial fan. It is generally known that the properties of composite structure can be programmed by the stacking sequence. In the case of non-autoclave technologies, fabrics are generally used as reinforcement. The orientation is usually 0/90°, ±45° and their combinations. Therefore, during experiments three stacking sequences [$(0/90)_8$], [$(\pm 45)_8$] and [(0/90, ±45, 0/90, ±45) s] were tested in order to get a sufficient review of material behavior and effect of the layers with individual orientations.

Using stacking sequence [$(0/90)_8$] was possible to determine Young's modulus and using stacking sequence [$(\pm 45)_8$] was measured shear modulus. Test specimens were subjected to shape optimization to prevent from tab failures. Finally, the shape of dog bone was chosen as optimal, see Fig. 2. Glass / Epoxy composite was selected as a material of tabs. The reason is relatively small stiffness and resulting low stress concentration at the end of tabs.

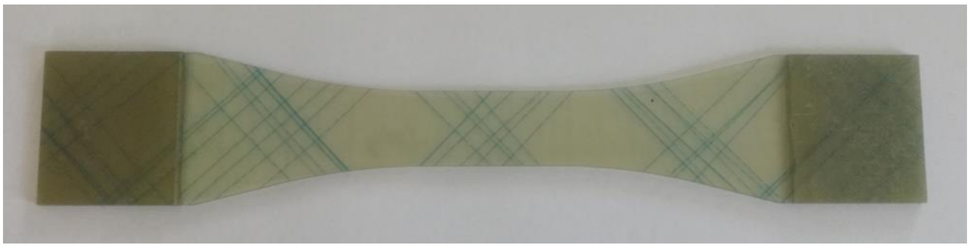
Fig.2 Proposed test specimen with the shape of dog bone

The loading was realized as unidirectional tension with frequency of 10 Hz. With respect to structures, usually designed at the Composite Technologies Department, was necessary to use force controlled loading. Cyclic loading was performed on servo-hydraulic machine MTS with hydraulic grips modified for flat specimens.

Measurement method for individual stacking sequences is in detail described in following text. Residual modulus was measured several times during cyclic loading up to 5.10^5 cycles. The load levels were chosen in order to achieve only the first and the second stage of stiffness reduction curve. With respect to the shape of this curve, the points of measurement were distributed unevenly with more points at the beginning of the curve. Residual modulus was measured with respect to stacking sequence using extensometer or biaxial extensometer. Modulus reduction was expected approximately 15% and it was necessary to measure residual values as exact as possible. At each point the modulus was measured three times to get greater statistical sample and estimate residual modulus in current point with low error. On each level three test specimens were tested. Using described procedure, residual modulus in each point was estimated on the basis of nine independent values.

Modulus reduction of stacking sequence [(0/90)$_8$]

Cyclic loading of specimens with stacking sequence [(0/90)$_8$] was realized on three stress levels with peak stress equal to 169 MPa, 135 MPa and 101 MPa. The behavior of material was in line with expectation and stiffness reduction was more pronounced on higher stress levels, see Fig. 3. The modulus was measured on the basis of standard ASTM D3039. For strain measurement an axial extensometer was used. Data obtained during these experiments can be directly used for FE calculations, because with this stacking sequence can be on the basis of standard ASTM D3039 determined mechanical properties of single layers.

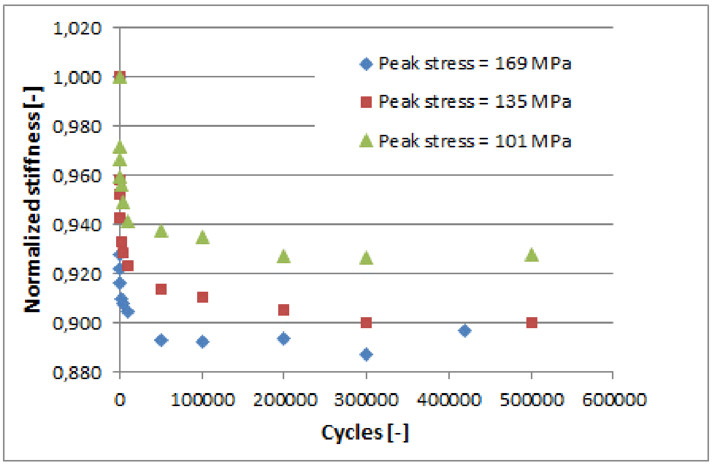

Fig.3 Stiffness reduction of test specimens with stacking sequence [(0/90)$_8$]

Modulus reduction of stacking sequence [(±45)$_8$]

Cyclic loading was expected also on three stress levels. Shear modulus was determined on the basis of standard ASTM D3518. Longitudinal and transversal moduli were measured using biaxial extensometer. During testing of the first stress level with peak stress equal to 40 MPa (relative to a cross-section of test specimen), the behavior was not in line with expectations. Shear modulus was increasing and after 5.10^5 cycles, residual modulus was 115% of the virgin value, see Fig. 4. The attention was focused on finding out the cause of this behavior.

In the case of stacking sequence with dominating layers oriented ±45°, matrix is more involved in transmission of forces. Possible change of mechanical properties of the matrix can therefore cause considerable change in mechanical properties of the whole composite. It is well known that composites get warm during cyclic loading.

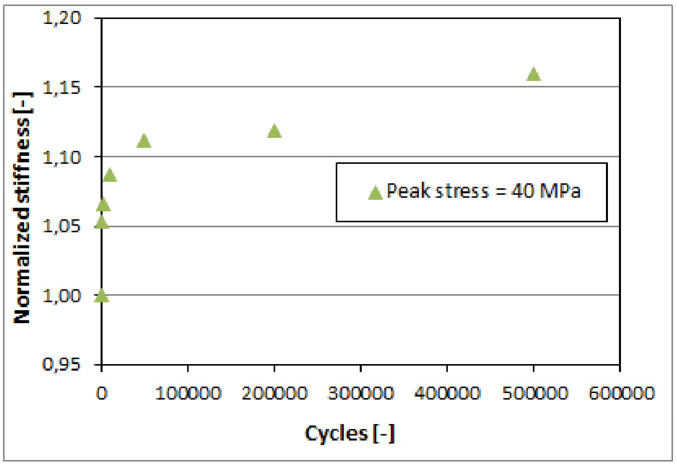

Fig.4 Stiffness change of test specimens with stacking sequence [(±45)8]

The possibility, if this warming can cause post-curing of the matrix, was verified using simple comparison of test results of test specimens cured at standard and significantly higher temperatures (matrix glass transition temperature was increased from 60°C to 120°C). The test results comparison shown no difference in test specimens behaviour and thus the effect of matrix post-curing has been ruled out. The situation is demonstrated in Fig. 5. The specimens post-cured at higher temperature exhibited higher modulus increase.

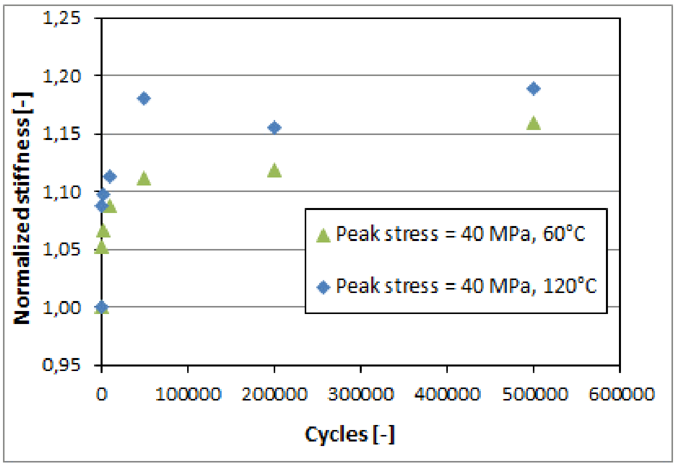

Fig.5 The comparison of stiffness change of two test specimens with stacking sequence [(±45)8] cured at different temperatures

Another evaluated reason of modulus increase was a creep strain. Creep strain in the case of stacking sequence ±45° can cause reorienting of fibers to lower angles than 45° and thus induced the change of test specimen stiffness in direction of loading. To verify a range of creep strain the observation of test specimen using optical microscope was performed. Prepared test specimen is shown in Fig. 6. Two sets of lines with defined distance of 25 mm and 50 mm were drawn on specimens. The distance between the lines was measured before and during cyclic loading at 2 000, 50 000 and 500 000 cycles.

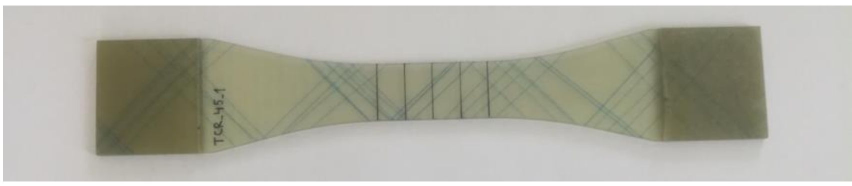

Fig.6 Test specimen proposed for creep strain measurement

Measured permanent strain was 2000 με on the base of 25 mm and 1000 με on the base of 50 mm. The peak strain of test specimens during cyclic loading is about 4000 με and therefore the permanent strain reaches 25 % and 50 % of this value. In Tab. 1 there is shown the comparison of distances measured before and after cyclic loading. Measured creep strain influences the behaviour of the tested material and causes stiffness increase.

Tab.1 The change of distance of two sets of lines caused by creep strain in specimens with stacking sequence [(±45)$_8$]

Distance	Virgin value	2 000 cycles	50 000 cycles	500 000 cycles	Resultant increase
25 mm	24.79 mm	24.81 mm	24.84 mm	24.84 mm	0.05 mm
50 mm	49.53 mm	49.56 mm	49.61 mm	49.58 mm	0.05 mm

Modulus reduction of stacking sequence [(0/90, ±45, 0/90, ±45)s]

Cyclic loading was realized on three stress levels with peak stress equal to 127 MPa, 102 MPa and 76 MPa (relative to a cross-section of test specimen). The behavior of test specimens was in line with expectations. Stiffness was measured again on the basis of ASTM D3039, but in the case of this quasi-isotropic stacking sequence, the resultant modulus was measured. It is impossible to estimate the behavior of single layers on the basis of these results. It can be seen that the stiffness reduction is between 2% and 13% in dependence on stress level, see Fig. 7.

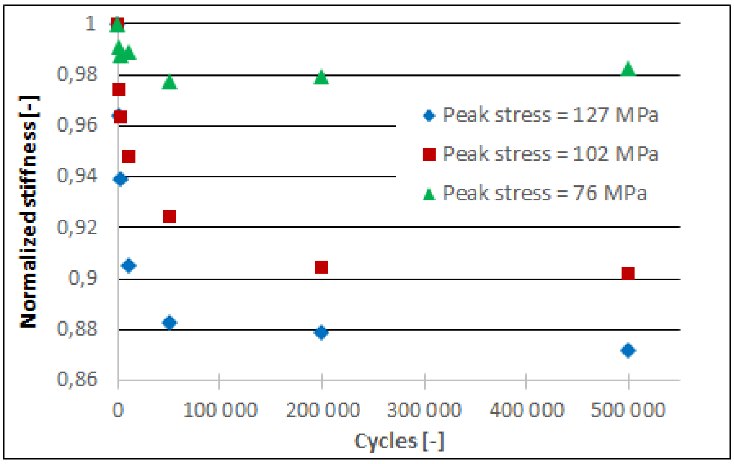

Fig.7 Stiffness reduction of test specimens with stacking sequence [(0/90, ±45, 0/90, ±45)s]

Conclusion

From presented results can be seen that behavior of composite materials under fatigue loading is quite complex issue. Results can be generalized only in the case of very similar boundary conditions. Stiffness reduction on stress levels which were tested in presented research is from 2% to 15%. Stress levels were chosen with respect to real engineering applications and all levels were under 60% of static strength. The question if stiffness reduction of 15% is for real structures danger is not easy to answer. In the case of structures which must be prevented from resonant stages and must have exactly defined natural frequencies, the change of stiffness within this range can be unacceptable.

It was expected to determine the reduction of shear modulus of tested material using stacking sequence [(±45)$_8$]. However, the results shown that the change of shear modulus is not easy to describe. It must be mentioned that behavior of single layer with this orientation may not be the same when the layer is embedded in laminate and when the layer is unrestrained like in discussed experiment. In stacking sequence where both orientations are combined, the layers with orientation 0/90° will not allow layers with orientation ±45° to reach so significant creep strain. During cyclic loading the layers with orientation ±45° will be influenced by two main mechanisms – creep strain and fatigue damage. Creep strain can cause increase of stiffness and fatigue damage can cause reduction of stiffness. Resultant behavior will be defined by the ratio of these two mechanisms and the ratio will be different for unrestrained layer and for layer embedded in composite.

Experiment with quasi-isotropic stacking sequence [(0/90, ±45, 0/90, ±45)s] was performed in order to verify above mentioned hypothesis, that in stacking sequence, where both orientations are combined, the effect of stiffness increase of layers oriented ±45° is not so expressive. To evaluate the behavior of layers oriented ±45°, the experiment, where the loading will be deformation controlled will be proposed. Loading with this character is closer to real loading of layer in final laminate.

Acknowledgements

The research was performed with financial institutional support from government budget through the Ministry of Industrial and Trade.

References

[1] J. Degrieck, W. van Paepegem, Fatigue damage modeling of fiber-reinforced composite materials: Review. Applied Mechanics Reviews. 2001, 54 (4) 279-300. ISSN 00036900.

[2] J. Montesano, J. K. Behdinan, Z. Fawaz, Ch. Poon, Considerations for Progressive Damage in Fibre-Reinforced Composite Materials Subject to Fatigue. In: High Performance Computing Systems and Applications. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, p. 148-164. ISBN 978-3-642-12658-1.

[3] G.P. Sendeckyj, Life Prediction for Resin-Matrix Composite Materials. Fatigue of Composite Materials. Composite Materials Series, 1991, p. 431-483. ISBN 9780444705075.

[4] B. Liu, L.B. Lessard, Fatigue and damage-tolerance analysis of composite laminates: Stiffness loss, damage-modeling, and life prediction. Composites Science and Technology. 1994, 51(1) 43-51. ISSN 02663538.

[5] W. van Paepegem, A new coupled approach of residual stiffness and strength for fatigue of fibre-reinforced composites. International Journal of Fatigue. 24(7) 747-762. ISSN 01421123.

[6] W. van Paepegem, J. Degrieck, Experimental set-up for and numerical modelling of bending fatigue experiments on plain woven glass/epoxy composites. Composite Structures. 2001, 51(1) 1-8. ISSN 02638223.

[7] W. van Paepegem, J. Degrieck, Modelling damage and permanent strain in fibre-reinforced composites under in-plane fatigue loading. Composites Science and Technology. 2003, 63(5) 677-694. ISSN 02663538.