Experimentální Analýza Napětí
2010
Experimental Stress Analysis

Degradation of mechanical properties of composite caused by cyclic loading

Vladislav Laš, Petr Měšťánek, Aziz Rustamov[1]

Abstract: The paper deals with the fatigue of composite materials with a focus on reduction of mechanical properties of the composite under displacement controlled bending cyclic loading. The research is concerned about fatigue of carbon/epoxy composite material with three stacking sequences: $[0^0]_8$, $[90^0{}_2/0^0{}_2]_s$ and $[0^0{}_2/90^0{}_2]_s$. Displacement controlled bending cyclic loading experiments were performed to observe stiffness degradation. Rectangular specimens were used in bending tests in several stress amplitudes; stress ratio ranging from 0.02 to 0.06. During experiments the changes of composite stiffness were recorded. These records were evaluated by FEA. Residual strength was measured after cyclic loading.

Keywords: Composite materials, Stiffness degradation, Bending experiments, Damage, Fatigue

1. Introduction

Composite materials are widely used in a several branches of industry due to profitable strength and stiffness to weight ratio. By choosing the appropriate combination of reinforcement and matrix material, it is possible to obtain properties that exactly fit the requirements for a particular structure for a particular purpose.

Some applications of composite materials are subjected to cyclic loading. Under cyclic loading composite material changes its mechanical properties (stiffness, strength …) and damage occurs in a cumulative manner. It is important to predict the damage and the mechanical properties degradation accurately to ensure that the structures operate with high reliability during their lives. It is also important to evaluate the performance of the structure in advance so that the maintenance or replacement of components can be scheduled before catastrophic failure.

Composite material's behavior is more complicated than the behavior of conventional materials like metal, due to their inhomogeneous and anisotropic nature. While in metals damage can be observed in one mode (represented by initiation and growth of the main crack), in composite material damage can be observed in more modes: fibre fracture, matrix cracking, fibre buckling, fibre – matrix interface failure, delamination. These damage modes can interact and grow in

---

[1] *Prof. Ing. Vladislav Laš, CSc., Ing. Aziz Rustamov, Ing. Petr Měšťánek;*
Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia;
Univerzitni 22, 306 14 Pilsen, Czech Republic; las@kme.zcu.cz

Experimentální analýza napětí 2010, Petr Šmíd, Pavel Horváth, Miroslav Hrabovský, eds.,
May 31 - June 3 2010, Velké Losiny, Czech Republic (Palacky University, Olomouc; Olomouc; 2010).

different rate. Damage performance can be affected by these parameters: fibre type, matrix type, type of reinforcement (unidirectional, mat, braiding,…), laminate stacking sequence, environmental conditions (mainly temperature and moisture absorption), loading conditions (stress ratio R, cycling frequency,…) and boundary conditions [1,7,8].

Stiffness is the most suitable property for damage metric of composite. Because, stiffness is sensitive parameter and its measurement can be performed nondestructively in contrast to residual strength and life. It is commonly accepted, that fibre-reinforced material's modulus decay can be divided into three stages: initial decrease (stage I), approximately linear reduction (stage II) and final failure (stage III) (Fig.1) [2]:

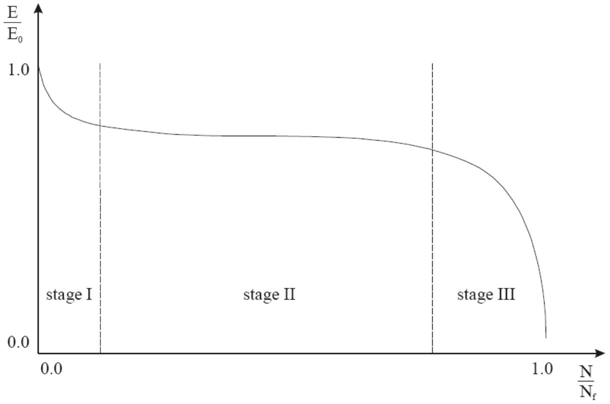

Fig. 1. Typical stiffness degradation curve for wide range of fibre-reinforced composite materials (from [2]).

2. Material and experimental setup

2.1. Material

Material used in bending cyclic experiments is carbon/epoxy composite with three types of stacking sequences: $[0^0]_8$, $[90^0{}_2/0^0{}_2]_s$ and $[0^0{}_2/90^0{}_2]_s$ Rectangular specimens used in the bending experiments were cut from thin plates. All material parameters for composite lamina are introduced in Table 1. In Tab.1 E_L is Young's modulus of elasticity in fibre direction, E_T is Young's modulus of elasticity in direction perpendicular to fibres, G_{LT} is shear modulus of elasticity, υ_{LT} is Poisson's ratio direction; X^T is tensile strength in the fibre direction, X^C is compressive strength in the fibre, Y^T is tensile strength in perpendicular direction to the fibres, Y^C is compressive strength in perpendicular direction to the fibres and S^L is shear strength. All these parameters except of υ_{LT} are presented in MPa.

Table 1. Material properties

Lay – up	E_L	E_T	G_{LT}	υ_{LT}	X^T	X^C	Y^T	Y^C	S^L
$[0^0]_8$	107950	7590	450	0.3225	1190.5	1160	43	200	62.3
$[0^0{}_2/90^0{}_2]_s$	120000	8000	400	0.377	1480	900	50	220	82
$[90^0{}_2/0^0{}_2]_s$	120000	8000	400	0.377	1480	900	50	220	82

2.2. Experimental setup

Although cyclic loading experiments in pure tension and compression are most often used in fatigue investigations, bending cyclic loading experiments was chosen. Because, bending loading has several advantages over pure tensile experiments [3]: i) bending loading occurs more frequently in real components, ii) there are no buckling complications in compressive loading iii) torsional or flexural stiffness may be more affected by material deterioration than tensile stiffness. An inspiration of this experimental way was obtained from V. Wan Peapegam's [4-6] works. Purpose of this experimental investigation is to study the mechanical properties degradation of composite materials under cyclic loading. Experimental procedure consists of two parts: first part is cyclic loading of composite specimens and second part is measuring the stiffness degradation in composite specimens after each exact number of cycles. In the first part of experimental procedure two composite specimens were set up to the test machine (Fig.2) and cyclically loaded by deflecting the upper end of the composite specimens to the maximum $u_{\max}$ and minimum $u_{\min}$ deflections. In the second part of the experimental procedure the upper ends of composite specimens were released from connecting rod and by means of block and stiff wire were deflected to the constant deflection u_0 and the force required to that deflection was measured. "Force gauge FG-5100" was used to measure the force. The experimental setup for displacement – controlled cantilever bending tests is schematically illustrated in Fig.2.

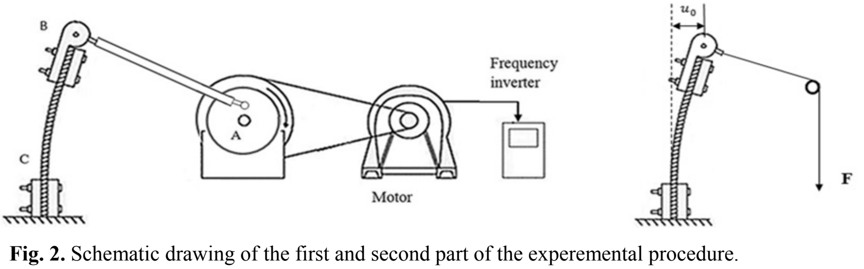

Fig. 2. Schematic drawing of the first and second part of the experemental procedure.

The shaft (point A in Fig.2) bears a mechanism with connecting rod. The hinge (point B in Fig.2) connects the connecting rod with moving clamp of the composite specimens. At the lower ends composite specimens are clamped (point C in Fig.2).

The stress level in lower end of the specimens was adjusted by changing the length of specimens. All deflections were measured using optoNCDT2200 laser sensor. Loading frequency was adjusted using the control transformer. Stiffness decrease was measured at a constant temperature and the constant environmental conditions. Loading frequency for $[0^0]_8$ specimens was 11.25 H. While for $[0^0{}_2/90^0{}_2]_s$ specimens the loading frequency was three times les, stress ratio was ranging from 0.02 to 0.06.

3. Experimental data evaluation

As an output of above described experimental procedure force versus number of cycles data were obtained. In order that the results of different measurements can be compared, the force must be recalculated into residual stiffness. Modulus of elasticity in fibre direction was used as a measure of stiffness. The residual modulus was determined in the iterative calculation using combination of the finite element software MSC.Marc and numerical computing software Matlab. The finite element model is built in the MSC.Marc software as 3D problem. The composite specimens were modeled with shell quadratic elements. Material was modeled as a layered material where each layer has orthotropic properties. The hinge was modeled as a node connected with upper end edge nodes of the specimens with rigid RBE2'S links. Fixed displacement boundary condition was applied to the lower end of the specimens. Large strain (displacement) analysis option was chosen, because the large displacements occur; the problem is nonlinear. In the beginning of the iteration process, the measured force was applied and the initial modulus in fibre direction was set by the controlling macros written in Matlab. During the iterative process modulus was being changed until the calculated deflection was equal to the measured one (Fig.3). The result of this process is the residual stiffness/number of cycles relation for each experiment. In Fig.3 u_n is calculated deflection (calculated by FEA), $u_{\exp}$ is measured deflection in experiment, δ is a residue given in advance and E_L is modulus in fiber direction.

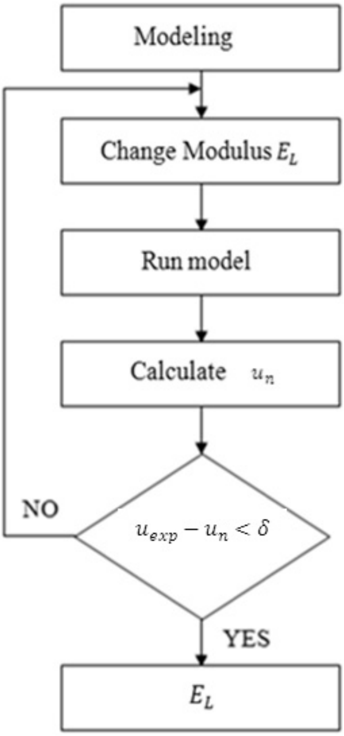

Fig. 3. Flow chart of calculation.

4. Results and discussion

As a result of this investigation, the stiffness degradation of composite material with different layups was obtained. The results are presented here in form of normalized stiffness (current value the modulus/initial value of the modulus: E / E_0) to number of cycles. Fig. 4 shows normalized stiffness – cycle history for $[0^0]_8$ the specimens loaded with 70%, 60% and 55% of the bending strength.

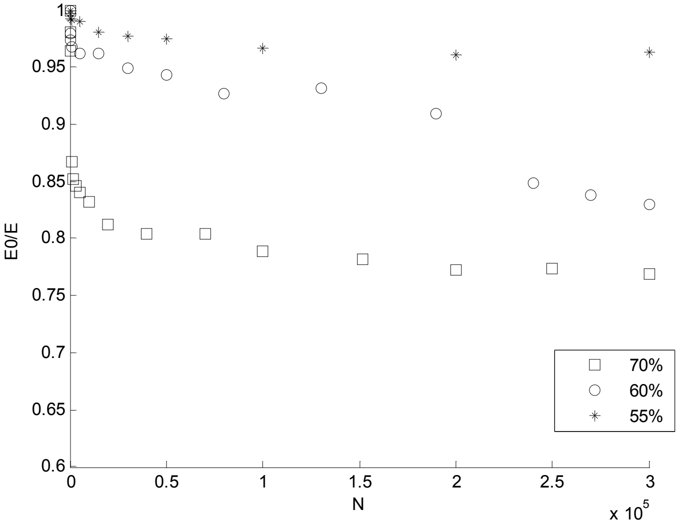

Fig. 4. Normalized stiffness – cycle history for $[0^0]_8$ specimens loaded with 70%, 60% and 55% of the bending strength.

Obtained results represented in Fig. 4 are as expected (see Fig. 1). At the beginning of cyclic loading modulus decay is rapid (stage I). Development of transverse matrix crack dominates. In the stage II steady decline of modulus takes place. Development of edge delaminations dominates. Transverse micro cracks and delamination of the outer layer appeared at the lower clamped ends of the specimens at the site of bending (at the site facing to motor (see Fig.2), where is the bigger compression loading) (see Fig.7). The investigation of third stage was not an interest of this research, because in real constructions (or its parts) it is important to stay in second stage as long as possible for full functionality of the construction. The higher stress level applied to the higher modulus decay can be observed (Fig.4).

Fig. 5 shows normalized stiffness – number of cycles graph for $[0^0{}_2/90^0{}_2]_s$ specimens in two bending cyclic experiments. It is observable that $[0^0{}_2/90^0{}_2]_s$ specimen's modulus degradation has different behavior from $[0^0]_8$ specimens. After rapid decay of modulus it stays unchanged. It can be explained by damage of composite's the 90^0 plies and reducing composite specimen's stiffness.

The lower stiffness at the clamped lower ends of composite specimen's the lower stress at the same place. This forbids the stiffness to reduce.

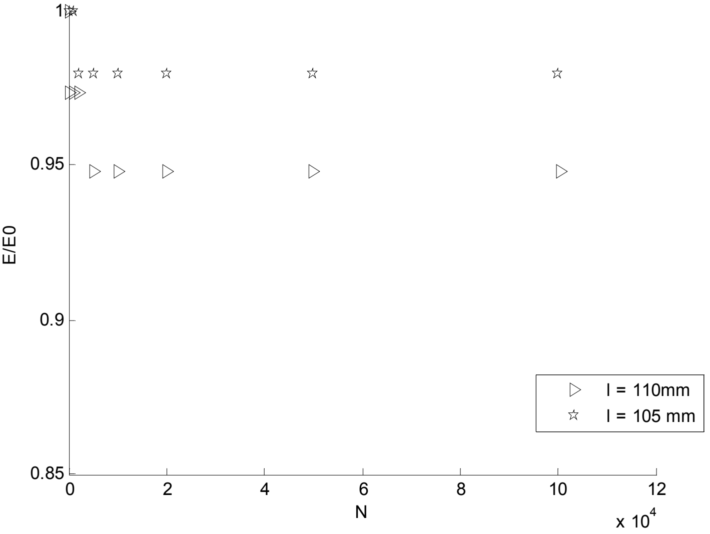

Fig. 5. Normalized stiffness – number of cycles graph for $[0^0{}_2/90^0{}_2]_s$ specimens.

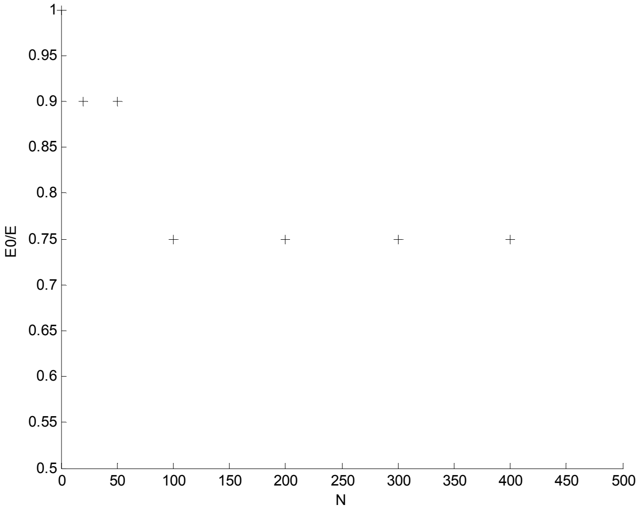

Fig.6. Normalized stiffness – number of cycles graph for $[90^0{}_2/0^0{}_2]_s$ specimens.

Fig. 6 shows normalized stiffness – number of cycles graph for $[90^0{}_2/0^0{}_2]_s$. Character of stiffness degradation of $[90^0{}_2/0^0{}_2]_s$ specimens is similar to $[0^0{}_2/90^0{}_2]_s$ specimen's stiffness degradation. However $[90^0{}_2/0^0{}_2]_s$ specimen's stiffness fell more in value. Because, $[90^0{}_2/0^0{}_2]_s$ composite's the 90^0 plies are outermost 90^0 plies and $[0^0{}_2/90^0{}_2]_s$ composite's 90^0 plies are internal plies. Outermost 90^0 plies of $[90^0{}_2/0^0{}_2]_s$ specimens more subjected to loading. bending load. This involves more damage of these plies and whole composite specimen.

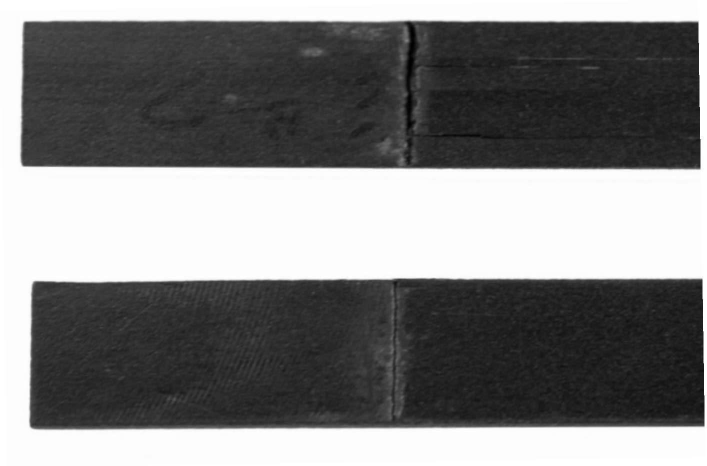

Fig. 7. Damaged composite specimens.

5. Conclusions

Experimental observations showed, that unidirectional $[0^0]_8$ composite specimen's stiffness degradation was as expected (see Fig.1). Furthermore, it has been concluded, that stiffness degradation rate depended on applied stress level (environmental conditions were the same).

While measuring force $[0^0{}_2/90^0{}_2]_s$ specimens showed smaller initial force, because of smaller stiffness, but stiffness degradation behavior is very different from $[0^0]_8$ composite specimens. Specimens with lay - up $[90^0{}_2/0^0{}_2]_s$ showed similar stiffness degradation behaviour like $[0^0{}_2/90^0{}_2]_s$ specimens with significant stiffness loss. The outer 90^0 plies damaged significantly in hundreds cycles, which led to significant stiffness loss. In pure tensile/compression fatigue experiments there would not be any difference between stiffness degradation of $[90^0{}_2/0^0{}_2]_s$ and $[0^0{}_2/90^0{}_2]_s$ composite specimens. But in bending fatigue experiments it is different. From these experimental observations it can be concluded that stiffness degradation of composite under bending cyclic loaded is influenced by composite lay-up. And it is not recommendable to put 90^0 plies like outer plies. It would lead to significant stiffness loss of the composite.

During cyclic loading transverse micro cracks appeared at the beginning at the lower clamped end of the specimens at the site of bending (at the site facing to motor (see Fig.2), where is the bigger compression loading). After exact number of cycles (see Fig.4) the outer layers started to delaminate (see Fig.7).

Strength was measured for six $[0^0]_8$ specimens cyclically loaded at 70% of the bending strength after 300000 cycles. Measurements showed that strength decreased approximately by 30%. From these measurements it can be conclude that micro cracks and delamination of layers lead to etiolating of composite.

Acknowledgements

This work has been supported by the research project of:

1) The Ministry of Education of Czech Republic no. MSM 4977751303
2) The research project MŠMT 1M05189 – Research Centre of Rail Vehicles.

References

[1] Degrieck J. and Van Peapegem W., “Fatigue Damage Modelling of Fibre – reinforced Composite Materials: Review,” *Applied Mechanics Reviews*, **54**(4), pp. 279-300, (2001). ISSN 0003-6900.

[2] Laš V., Měšťánek P. and Rustamov A., “Change of composite stiffness under cyclic loading,” *Metallurgy* **49**(2), pp. 366-370 (2010). ISSN 0543 – 8546.

[3] De Baere I., Van Paepegem W. and Degrieck J., “Comparison of different setups for fatigue testing of thin composite laminates in bending,” *International Journal of Fatigue*, **31**(6), pp. 1095-1101 (2009). ISSN 0142-1123.

[4] Van Paepegem W. and Degrieck J., “Fatigue degradation modeling of plain woven glass/epoxy composites,” *Composites: Part A*, **32**(10), pp. 1433-1441 (2001). ISSN 1359-835X.

[5] Van Paepegem W. and Degrieck J., “Modeling damage and permanent strain in fibre-reinforced composites under in plain fatigue loading,” *Composite Sciences and Technology*, **63**(5), pp. 667-694 (2003). ISSN 0266-3538.

[6] Van Paepegem W. and Degrieck J., “Simulating damage and permanent strain in fibre-reinforced composites under in plain fatigue loading,” *Composite Sciences and Technology*, (83), pp. 1930-1942 (2005). ISSN 0266-3538.

[7] Laš V. and Zemčik R., “Progressive damage of Unidirectional Composite Panels,” *Journal of composite Materials*, **42**(1), pp. 81-87 (2008). ISSN 0021-9983.

[8] Zemčik R. and Laš V., “Numerical and experimental analysis of delamination of cross – ply laminates,” *Materials and Technology*, **42**(4), pp. 171-174 (2008). ISSN 1580-2949.