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Experimental Stress Analysis

Mechanical properties degradation of a glass fibre laminates under cyclic tension

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Abstract: Composite materials are used in a wide range of applications such as automotive, aerospace or power generation industry. Most structural parts are dynamically loaded; thus, fatigue must be taken into consideration during the design process even in the case of composite laminates. The most promising way how to predict the fatigue deterioration and reduce necessary experimental input data at the same time seems to be the micro mechanics of failure. However, even this approach requires necessary experimental input data. This paper deals with the woven fabric E-glass epoxy matrix composite. Static and fatigue test were performed. The influence of aluminium shims attached to the specimen on static mechanical properties and fatigue life is shown. Residual tensile strength and residual longitudinal modulus of the woven fabric laminated composite specimens after cyclic loading were investigated.

Keywords: Composite, Woven fabric, Fatigue, Experiment, Residual strength

1. Introduction

Composite materials are used in a wide range of applications such as automotive, aerospace or power generation industry. These materials are so popular because of their beneficial strength to weight ratio. Another advantage is that the “custom made” material can be created for a certain application. Most structural parts are dynamically loaded. Even though composite material can sustain certain amount of fatigue damage (it is damage tolerant) its mechanical properties decline. Thus, fatigue must be taken into account during the design process.

In contrast to the conventional materials such as steel, more phenomena are involved in the process of composite fatigue. Deterioration of composite constituents (usually matrix and fibres) and the deterioration of the interface are involved. Both matrix and fibre can be of several types, fibres can have any orientation, laminate can consist of dozens of plies and many other variables play a role. This makes the problem much more complicated than metal fatigue. Due to this complexity it is not possible to deduce a generally valid fatigue criterion for computational prediction of fatigue damage. Nevertheless, there exist methods how to predict fatigue deterioration but their application is in most cases limited to very specific conditions or require vast amount of experimental data. The most promising approach of predicting fatigue damage seems to be the method called micromechanics of failure (MMF) [1, 2]. MMF tries to reduce the amount of necessary experimental input data and to simplify

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the experimental testing. However, the experimental input data are still necessary for any computational prediction.

The present paper deals with the woven fabric glass fibre reinforced epoxy matrix composite. This material is widely used because it is stiff and strong in tension and compression and cheap at the same time. The disadvantage is that the glass fibre composite is weak and compliant in shear. Woven fabric composites are typical for their impact resistance, damage tolerance and the ease of manufacturing [5]. A typical glass fibre laminated component is a thin-walled construction.

2. Fatigue damage in composites

In contrast to the homogenous materials, where a single crack initiates and propagates in a direction perpendicular to the loading axis, the fracture behavior of the composite material is characterized by multiple damage modes that are spatially distributed. Because of the fact that the fatigue damage is interspersed throughout the composite volume instead of the predominant single crack, composites are exceptionally resistant to fatigue failure.

Fatigue of composites is a complex process because the failure of the individual constituents and the failure of the interfaces between constituents are involved. Micro damage of the constituents as well as changes in material properties of a particular constituent affects global mechanical properties such as stiffness or strength and consequently it influences life. Therefore, stiffness or residual strength can be used as a non-destructive parameter to monitor fatigue damage. Various failure mechanisms can occur during cyclic loading in the case of unidirectional composites such as matrix micro-cracking, fibre/matrix debonding, transverse rupture, fibre rupture, delamination, and so forth, [3]. The damage accumulation is followed by the stiffness decrease [4]. The process of damage accumulation can be devided into three stages. During the first stage of damage accumulation, increasing matrix cracks density is followed by the steep fall of the normalized stiffness. In the second stage, steady decline of stiffness is caused predominantly by debonding and fibre bridging. The last stage is characterized by unstable fibre fracture and delamination. The individual damage mechanisms take place simultaneously; matrix cracking may dominate during stage one, debonding and delamination during stage two and final damage including unstable fibre fracture take place during the later stage.

The material of interest is the 7-layer woven fabric E-glass epoxy matrix composite. The weave type is the biaxial plain weave that is formed by interlacing warp and fill strand (fibre bundles) in a regular sequence. The plain weave fabric is balanced; hence, the lamina has same mechanical properties in longitudinal and transverse directions. All laminate layers have same 0°/90° orientation. The laminate is bridged (nested).

As mentioned, it is not possible to set up a generally valid fatigue criterion for computational prediction of fatigue damage. However, the most promising way how to predict fatigue deterioration is the micromechanics of failure (MMF) [1]. MMF takes into account the micro- (matrix-fibre level) and meso-structure (bundle-matrix level) and the failure modes as the reason for mechanical properties deterioration. Hence, a clear understanding of the damage mechanisms is necessary.

The damage accumulation in woven fibre composites is similar to the one in unidirectional composites. However, the damage accumulation rate is steeper in the early stage of fatigue life because of the stress concentration in the unit cell. Micro structural damage inside the strand or transverse cracks in the fill can be formed during the first stage. When the cracks attain an equilibrium or saturation spacing size the stage one ends. This state of damage is called the characteristic damage state (CDS) [5]. The latter stage is characterized by shear failure in the warp, cracks in pure matrix regions and the delamination between fill and warp as well as the adjacent layers. Because of the interlacing nature of the woven fabric composite, damage growth during this stage would be slow and gradual. During the last stage strand fracture occurs at the locations of stress concentration because of over-straining or over-stressing. This leads to the failure of the whole laminate.

Data obtained from the experimental measurement will be used as the input data and calibration tool into the micromechanical criteria of composite static and fatigue damage.

3. Experiment

The material used for specimen fabrication is the 7-layer woven fabric E-glass epoxy matrix composite. Epoxy resin MGS LR385 and hardener MGS LH 385/386 were used. Laminate was cured at 50°C for 8 hours. Volume fraction of fibres is 40% - 41%. The value of fibre volume fraction was determined equally by two methods. Density of the laminate is 1730 kg/m^3. The dimensions of the specimen are 240x20 mm. Thickness of the specimens was between 2.1 and 2.23 mm

3.1. Static testing

In order to obtain orientation values of the static properties (i.e. longitudinal tensile modulus, Poisson's ratio, static longitudinal tensile strength) tensile test of woven fabric composite specimens was performed. Two sets of specimens were measured. In the first set the specimens were not were not equipped with aluminium shims that should prevent specimens from being influenced by the pressure of clamping jaws. These specimens after static testing are shown in Fig. 1.

All three specimens of the first set (number 1-3) were equipped with strain gauges measuring longitudinal and transverse deformation. Specimens 2 and 3 were additionally equipped with extensometers. The extensometers were removed at a loading level at approximately 60% of the tensile strength to avoid damage of the extensometers. Tensile test confirmed expected nonlinear behaviour of the woven fabric composite. Hence, the longitudinal tensile modulus E_1 was determined as a piecewise linear function in the strain range of 0.1-0.3%, 0.2-0.4% and 0-0.3%. The results are shown in table 1. Static strength is defined as the maximum force transmitted by the specimen divided by the nominal cross section area.

In the second set the specimens (number 4-6) were equipped with aluminium shims to prevent jaws-induced damage. The photograph of damaged specimens is shown in Fig. 2.

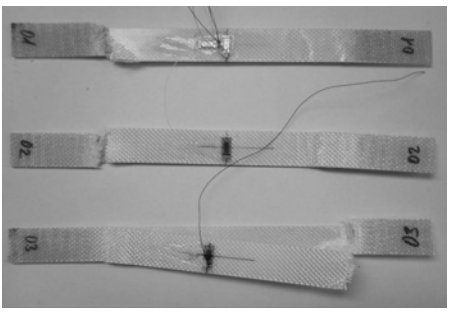

Fig. 1. Damaged specimens after static testing – set 1 (without aluminium shims)

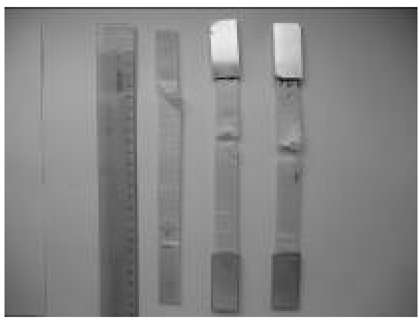

Fig. 2. Damaged specimens after static testing – set 2 (with aluminium shims)

The test data from set 2 were evaluated in the same way as the previously mentioned data. Longitudinal strain was measured using extensometer. Transversal strain was not measured; thus, Poisson’s ratio could not be evaluated. The results obtained are shown in Table 1.

Table 1. Static properties of the woven fabric composite specimens

specimen number	E_1 [MPa] (0.1-0.3%)	E_1 [MPa] (0.2-0.4%)	E_1 [MPa] (0-0.3%)	υ_{12}	tensile strength [MPa]
1 (strain gauge)	20774.37	18241.05	21071.61	0.13	423.42
2 (strain gauge)	19799.51	18691.98	19989.39	0.1	432.19
3 (strain gauge)	17842.60	17234.37	20186.25	0.12	425.81
2 (extensometer)	19548.28	18128.08	19647.65	0.12	-
3 (extensometer)	18126.13	17055.00	20999.15	0.14	-
4 (extensometer)	19362	18100	20179	-	457,3
5 (extensometer)	17409	17514	17815	-	449,9
6 (extensometer)	20281	18414	21486	-	472,6

The results of static tests clearly show that the stiffness measured without aluminium shims is the same as the stiffness measured using shims (within the deviation of 3%), whereas the measurements differ in terms of strength. The strength measured with shims is significantly higher. The presumable reason is that the results of set 1 were influenced by the pressure of clamping jaws. This presumption can be legitimized by comparing Figs. 1 and 2. Therefore, it is strongly recommended to use aluminium shims when measuring the strength of composite specimens.

3.2. Cyclic testing

Cyclic straining leads to fatigue damage that gives rise to the changes in mechanical properties. The material fails at lower stress levels than would be required under monotonic loading. The fatigue damage results in a reduction of composites stiffness and strength and consequently in a reduction of the load carrying capacity of the structure. Therefore, it is important to take fatigue into account when designing any dynamically loaded structure. To be able to predict/compute fatigue deterioration the experimental data using simple specimens are necessary as the input into the computational methods.

3.2.1. Cyclic testing methodology

Cyclic tension test of woven glassfibre specimens was performed. The testing machine used is depicted in Fig. 3. The specimen (bright stripe) is clamped in jaws that are placed in linear guides. The specimen is statically prestrained using screwed bolt (right). A particular prestrain and strain amplitude is directly measured using extensometer to avoid the influence of the manufacturing tollerances of the testing machine. The desired strain amplitude is set up by adjusting circular cam (left). Rotating circular cam is powered by the electric engine (top left). The accelerometer is attached to the specimen. If the specimen fails the vibrations exceed the threshold level and the machine stops.

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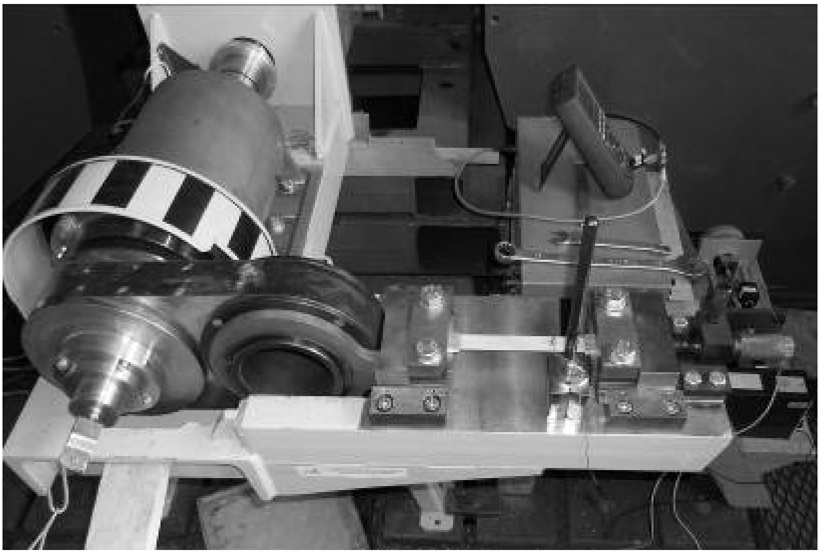

Fig. 3. Testing machine

The scheme of the measuring chain is depicted in Fig. 4. The graphical user interface and the illustrative visualisation was created using National Instruments graphical environment LabView®.

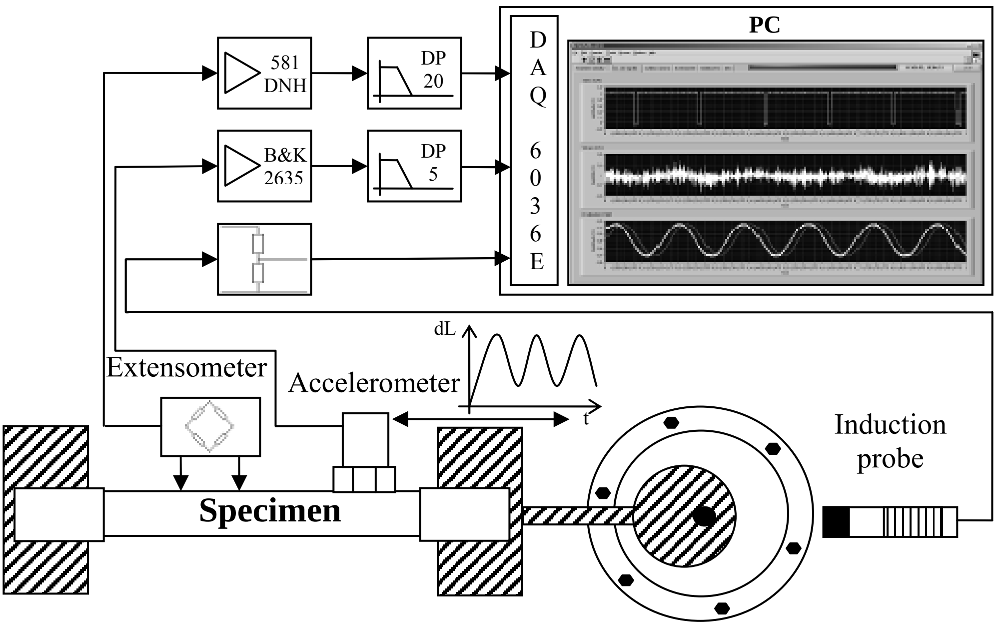

Fig. 4. The scheme of the measuring chain

Frequency and the number of cycles is measured employing the induction probe 872C-D4CP12-E2. Number of cycles was calculated from the measured frequency. There was no need to use the hardware counter of the DAQ card. The signal from the extensometer was processed with the strain gauge amplifier Peekel 581 DNH. The extensometer was calibrated using MTS 650.03 calibration kit. The specimen failure is detected employing accelerometer B&K 8307. The signal from the accelerometer is processed by amplifier B&K 2635. Fig. 5 shows the example of the visualisation on the operator screen.

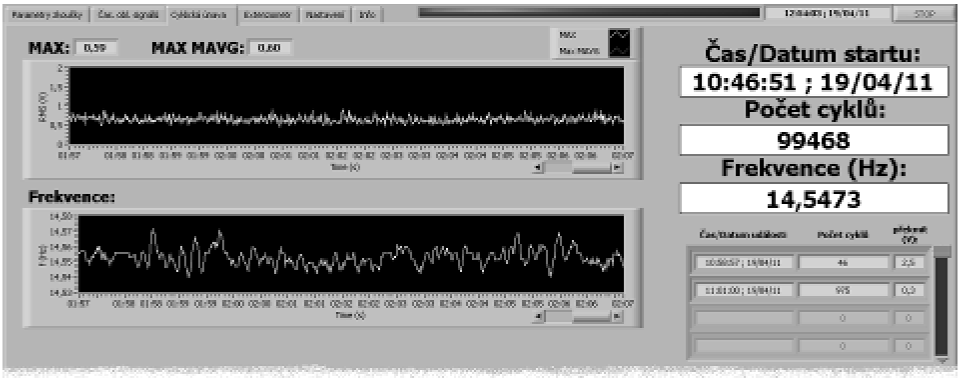

Fig. 5. Example of the visualisation

3.2.2. Specimens series A and B

The strain controlled cyclic straining was carried out at the constant strain amplitude $\varepsilon = 0.2\%$, frequency 15Hz at the room temperature 20°C in air. The mean strain varied in the range from 0.2% to 0.8%. Number of cycles to fatigue failure of the specimens was recorded. Two sets of specimens were tested – with and without dural shims. The main objective of the testing was to quantify the influence of stress concentration at the contact edge between clamping jaws and the specimen without shims (series A) and with shims (series B). Hence, to quantify the influence of the dural shims on the fatigue life. The results are plotted in Fig. 6. The fatigue life improves as the mean strain decreases as expected.

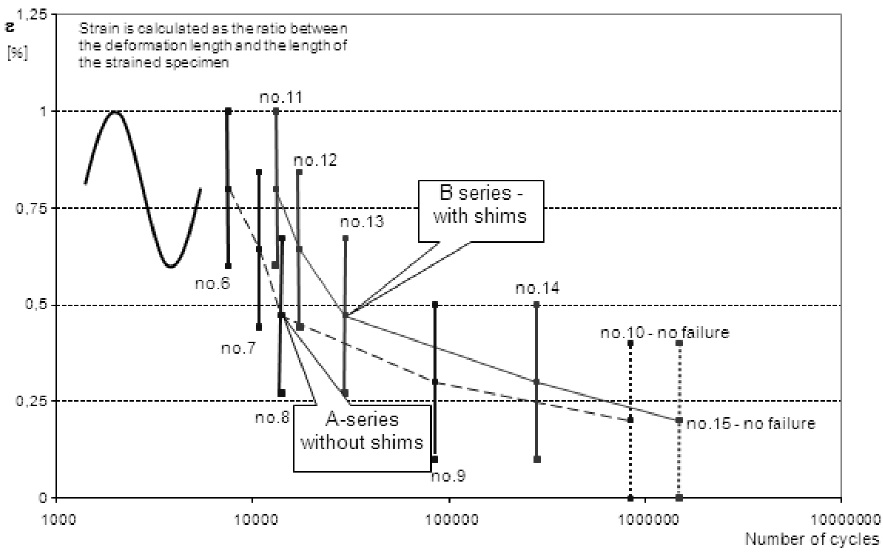

Fig. 6. Number of cycles to fatigue failure for different mean strain (without shims (dashed line); with shims (solid line))

It can be concluded that the presence of dural shims strongly influences the fatigue life. The specimens equipped with shims endure much more cycles to failure. Hence, only specimens equipped with the shims should be used for fatigue tests. The comparison of ruptured specimens is shown in Figs. 7 and 8.

Fig. 7. Specimens without dural shims after cyclic testing

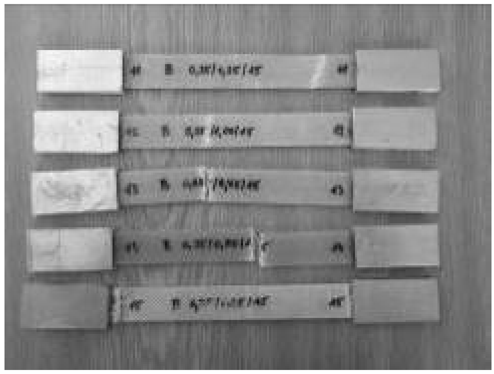

Fig. 8. Specimens equipped with shims after cyclic testing

3.3. Cyclic testing - specimens series C

Same specimens equipped with dural shims were cyclically loaded at the constant mean strain 0.3% and strain amplitude 0.2% i.e. peak stress approximately only 20% of the static strength. Mean strain and strain amplitude were accurately measured using extensometer. The straining conditions were chosen according to the results of testing series A and B. The intention was to measure the residual tensile strength decrease depending on the number of load cycles. The specimens were loaded by a certain but different number of cycles. Thus, each specimen suffered different amount of accumulated damage which reflected in different residual strength. The tensile test of each specimen was performed. Residual strength was plotted against the number of loading cycles in Fig. 9. It can be observed that most of the residual strength decline occurs during the first hundred thousand cycles. This confirms the expected behaviour.

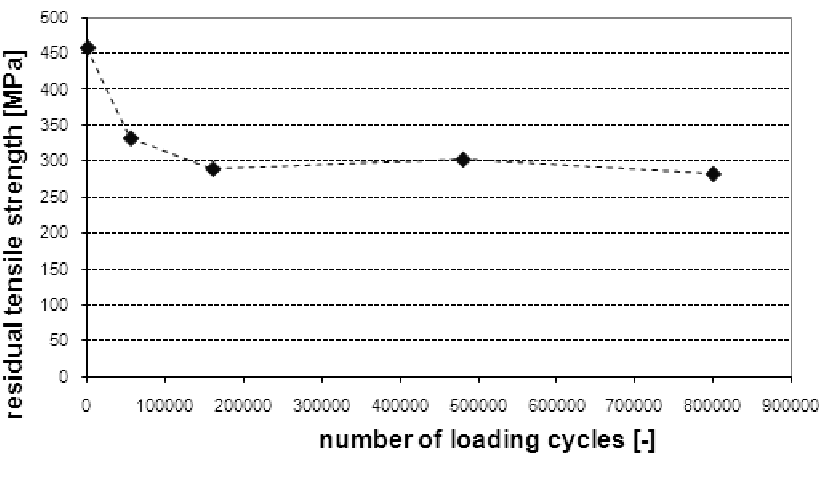

Fig. 9. Residual tensile strength degradation (ε_{mean} = 0.3%, ε_a = 0.2%)

Surprisingly, specimens of the C-series that were loaded equally to specimen number B-14 sustained much more loading cycles than specimen B-14. This can be explained by the scatter of the fatigue properties. The scatter can be caused by several factors acting during manufacture and hardening of the laminate.

The residual modulus of the specimens was recorded as well during previously described tensile tests. However, it has been observed that the values of the residual modulus fall within the scatter band of measured static modulus for this particular peak stress ratio. This observation is in agreement with the statements published in [1,4]. Online residual modulus measurement will be used during future fatigue tests.

4. Conclusions

The presented paper deals with the woven fabric E-glass-epoxy matrix composite. Static tensile test of two sets of specimens was performed (with and without aluminium shims). It has been concluded that while the measured longitudinal moduli did not differ from each other, tensile strength was influenced by clamping forces in the case of specimens without aluminium shims.

Same effect has been observed in the case of cyclic loading in terms of number of cycles to failure. The presence of dural shims significantly improves the fatigue behaviour and shifts the critical spot towards the centre of the specimens. Taking everything into account, the influence of specimen clamping should be eliminated for example by using the aluminium or dural shims.

The decrease of residual tensile strength has been investigated It has been concluded that the cumulated fatigue damage reduces the tensile strength. Most of the strength decline takes place during the early stage of cyclic loading. On the other hand, the longitudinal modulus is not affected by the fatigue damage caused by this particular type of loading.

The acquired data will be extended and used as the input and calibration tool into the micromechanical criteria of composite static and fatigue damage.

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