CARBON-EPOXY COMPOSITE FATIGUE STRENGTH – EXPERIMENT AND FEM NUMERICAL ESTIMATION

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Abstract

The development of composite materials characterized by the constant amelioration of their mechanical properties (stiffness and strength) has widened their application for structural elements, mainly in aeronautical, naval and automobile industries. The possibility of tailoring the composite's properties appropriately to the applied load (by changing the direction of the fibre alignment and applying a corresponding matrix) results in the growing importance of the design process. The paper presents a numerical technique of determining the fatigue strength of the laminated carbon–epoxy composite. The experimental investigations were carried out to determine the complete set of the stiffness characteristics E_{ij}, G_{ij}, v_{ij}, the strength characteristics $\sigma_{i,n}$, $\varepsilon_{i,n}$. and the S-N fatigue curves. The static and fatigue numerical calculations were carried out for the material anisotropic model of the particular composite layers. Eight-node 3D finite elements with the composite's properties were used to develop the specimen's numerical model. The contact problem between the composite layers enabling the reflection of a mutual interaction was taken into account. The numerical investigation also included the state of effort analysis and the fatigue life assessment of the composite. The assessment of the composite's fatigue life was performed using the MSC.Fatigue code. The verification of models and numerical analysis was carried out for composite specimens made of the CE 8201-245-45/120 prepreg. The experimental verification confirmed that the places of the lowest fatigue life, found out in numerical analysis, are located in the area of the gauge part.

Keywords: fatigue strength, carbon-epoxy composite, FEM

1. Introduction

The use of composite materials is advantageous due to the cost saving and weight reduction. The carbon fibre is used in the aircraft industry because of low weight, high strength and high stiffness. The resin component is used to maintain fibre orientation and carry loads. The basic resin in the aircraft industry is epoxy [7, 8].

Components of the composite material are joined together to form complete structure and the strength of any complete structure evidently depends on the way the components are attached to each other as well as an strength of the individual components. As a general rule, the stiffness and strength of a laminate will increase in proportion to the fibre volume fraction.

Tensile, compression and shear properties of the composite are heavily influenced by the resin matrix, in which the woven fabric is placed. This anisotropic feature of the composite requires that twenty one constants are necessary to describe elastic properties of materials. However, the woven fabric used to manufacture the laminate has the same properties in two directions. Therefore, only nine constants need to be obtained.

Mechanical tests are useful for determining material characteristic of the specimen but it is not possible to perform mechanical tests for each structure. Therefore, numerical analyses have wide applications [10, 14]. Composite materials need special mathematical procedure to properly describe the composite characteristics [13]. The strain/stress state at the interfaces between two

laminated plies or grip and composite plays a critical role in determining the mechanical behaviour of a laminated composite [15]. Therefore, it should be modelled as two separate surfaces.

The mechanical test and numerical analysis comparison results allow preparing an accurate material model of the composite.

The specificity of the fatigue of composites depends on many factors such as thickness, delamination and debonding [2]. The tensile and fatigue failure of the composites is sudden, without visible matrix cracks or delamination of plies [9].

2. Mechanical tests

The composite specimens for static and fatigue tests were made of CE 8201-245-45/120 prepreg (KDK8042 carbon fabric impregnated with E201 epoxy resin) which is characterized by the same volume fraction and mechanical properties of fibres in the warp and weft directions (an orthotropic material). The mechanical properties of the composite were determined in accordance with ASTM standards [1].
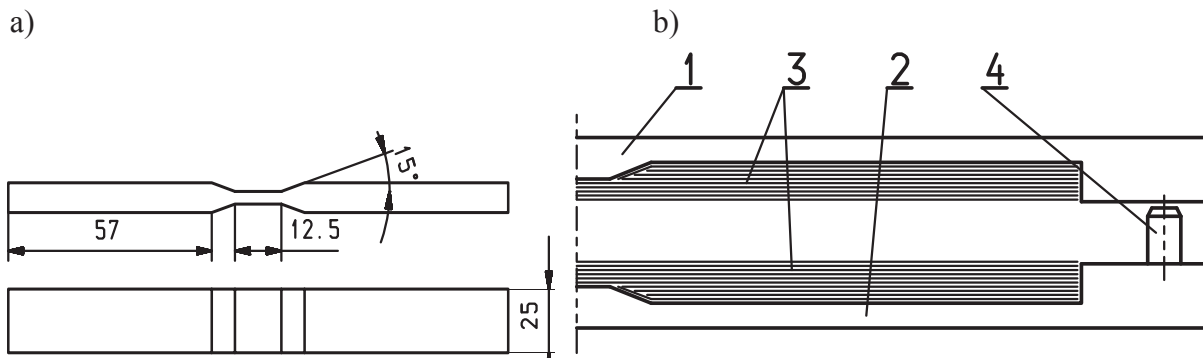

Fig. 1. a) Geometry and dimensions of the fatigue test specimen, b) method of production: 1 - top mold, 2 - bottom mold, 3 - prepreg layers, 4 - dowel pin

The equipment and the production method of the semi-finished product for fatigue test specimens making are shown in Fig. 1b. After 4 prepreg layers had been laid up in the space of gripping area 10 prepreg layers were laid up shaping the gauge and gripping areas of the specimens. The curing process was carried out for 2 hours at the temperature of 130°C and under the required pressure. Next, the semi-finished product was cut and ground in order to obtain the required width of the specimens. Two types of specimen were used in the tests. Specimen geometry for the purpose of tension test and compressive test were prepared in accordance with ASTM D3039/D3039M-07 and ASTM D 3410, respectively. To avoid buckling phenomena short (modified) specimens were used in the fatigue test (Fig. 1).

The INSTRON 8802 universal testing machine was used for determining the material properties of the composite as well as for fatigue testing. The composite elastic material characteristics are shown in Tab. 1. The stress-strain curve in the direction 1 is presented in Fig. 2a. Shear properties of composite material by the V-notched beam method were obtained in accordance with ASTM D5379/D5379M-98.

Tab. 1. Orthotropic elastic constants for the composite

E_{11} [MPa]	E_{22} [MPa]	E_{33} [MPa]	G_{12} [MPa]	G_{23} [MPa]	G_{31} [MPa]	ν_{12}	ν_{23}	ν_{31}
58093	58093	9759	3545	2564	2564	0.0154	0.5356	0.1575

The stress ratio R=-0.5 was applied for the fatigue tests of the composite [9]. The fatigue tests were carried out for stress levels equal to 0.5, 0.6, 0.7 and 0.8 of the minimal value of the failure stress $\sigma_{f,\ min}$=530 MPa obtained in the static tests of the modified specimens. The applied stress levels resulted in low and medium-cycle fatigue tests. During pre-tests the test frequencies were determined for each level of load to avoid self-generated heating. Finally, the test frequencies amounting to 1 and 3 Hz were applied to the stress levels of 0.8, 0.7 and 0.6, 0.5, respectively, which resulted in temperature increase less than 5°C. The temperature of the investigated specimen was measured with the Raytek THERMALERT MI pyrometer.

The S-N curve was found on the basis of fatigue tests carried out in the range of the applied load levels from 0.5 to 0.8. The actual experimental data and regression curve are presented in Fig. 2. During these tests the modified specimens failed in the gauge area irrespective of the stress level.
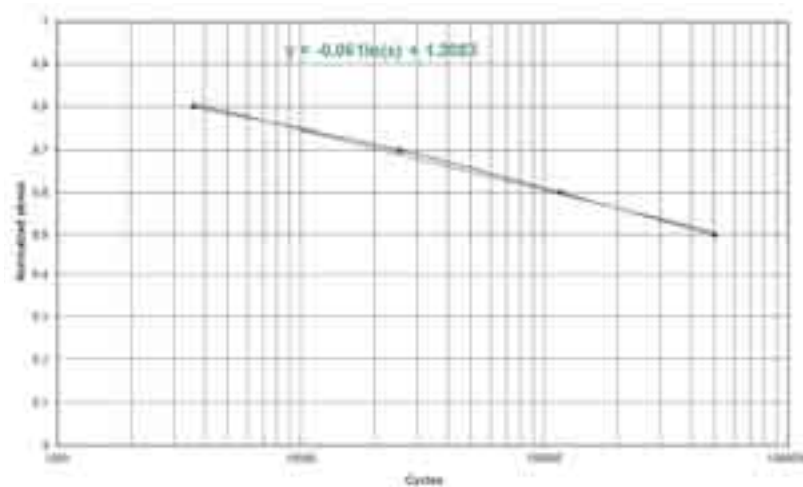

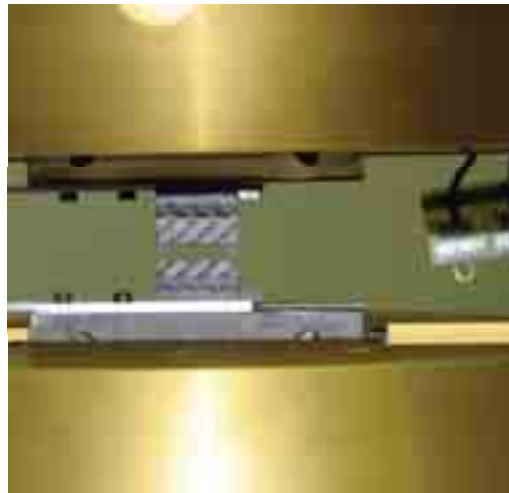*Fig. 2. S-N curve of the investigated composite*

Fig. 3. Specimen after the fatigue test

3. Numerical analyses

The numerical fatigue life estimation process requires: material properties, loading in the form of load time histories and local stress strain information from the linear/nonlinear elastic/elastic-plastic analysis. Therefore tensile and compression tests for the short specimen are modelled and nonlinear analysis is performed.

Eight-node, isoparametric composite brick finite elements are used to model the laminated composite. One element layer models two prepreg plies. These elements allow defining the layer-by-layer material identifications, layer thicknesses, and orientation angles for a laminated composite material. The second Piola-Kirchhoff stresses and Green strains are output at each integration point for the case of large deformations [12].

A failure mechanism-based progressive damage analysis was postulated for analysing the tension failure of the composite specimen. To estimate the specimen failure the maximum stress criterion is used:

$$F = \max\left(\frac{\sigma_1}{X_t}; -\frac{\sigma_1}{X_C}; \frac{\sigma_2}{Y_t}; -\frac{\sigma_2}{Y_C}; \frac{\sigma_3}{Z_t}; -\frac{\sigma_3}{Z_C}; \left|\frac{\sigma_{12}}{S_{12}}\right|; \left|\frac{\sigma_{23}}{S_{23}}\right|; \left|\frac{\sigma_{31}}{S_{31}}\right| \right). \tag{1}$$

The failure material parameters are shown in Tab. 2.

Tab. 2 Failure material parameters for the composite

Parameter	Symbol	Value [MPa]
Maximum tensile stress in x-direction	X_t	650
Maximum absolute value of compressive stress in x-direction	X_C	555
Maximum tensile stress in y-direction	Y_t	650
Maximum absolute value of compressive stress in y-direction	Y_C	555
Maximum tensile stress in z-direction	Z_t	10
Maximum absolute value of compressive stress in z-direction	Z_C	500
Maximum absolute value of shear stress in xy-plane	S_{12}	181
Maximum absolute value of shear stress in yz-plane	S_{23}	132
Maximum absolute value of shear stress in zx-plane	S_{31}	132

Due to symmetry, only half of the specimen is modelled. Adequate boundary conditions are applied. The specimen is fully supported in one grip region and loaded in the second one.
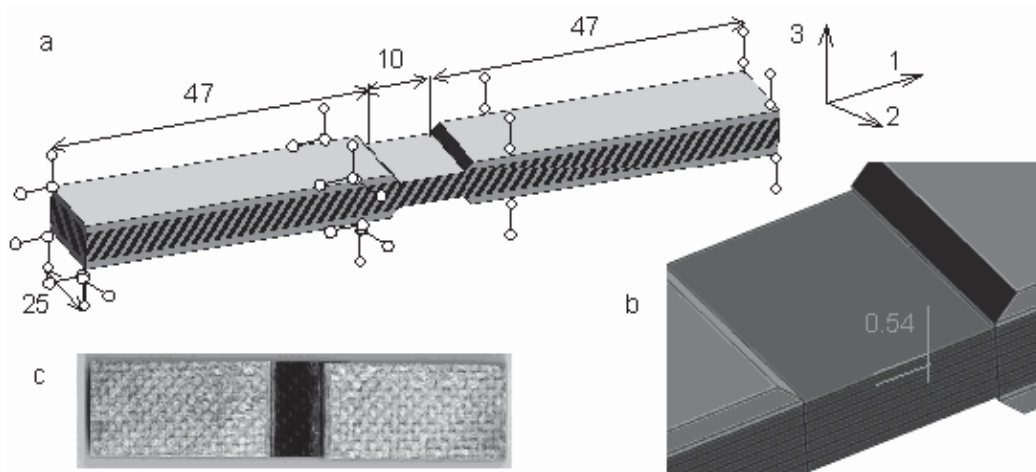

Fig. 4. Overall dimensions of the specimen

Preliminary numerical tests were performed for selection correctly method to generate composite model. The stress versus strain for experimental and numerical tests of short specimen is shown in Fig. 5.

The contact problem is modelled between composite layers and grips [3-5]. To perform contact analysis the penalty method was used [12]. This means that stresses are determined for each load step and the value of failure initiation can be observed.
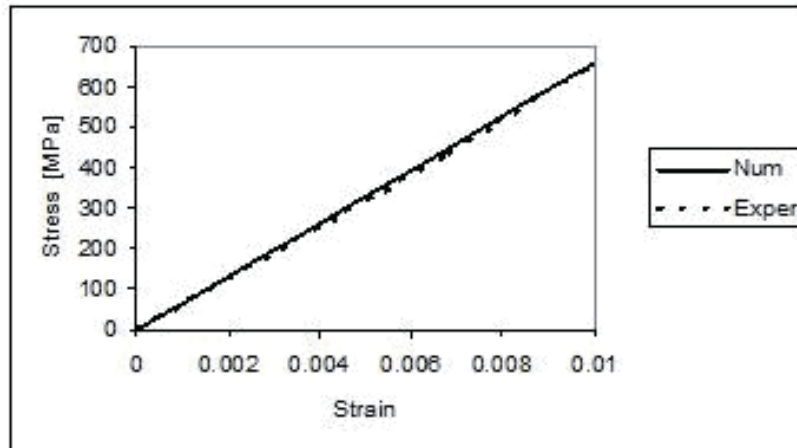

Fig. 5. Comparison of experimental (Exper) and FEM analysis (Num) results

The interface is modelled as two individual surfaces: one of them belongs to the grip, and the other - to the composite. No relative motion occurs between these sticked surfaces. This approach allows modeling the debonding grip and composite, which is a large problem during mechanical tests of the composite materials. The longitudinal strains obtained from the numerical analyses for two models: with and without a contact surface for tensile and compressive tests are shown in Fig. 6.
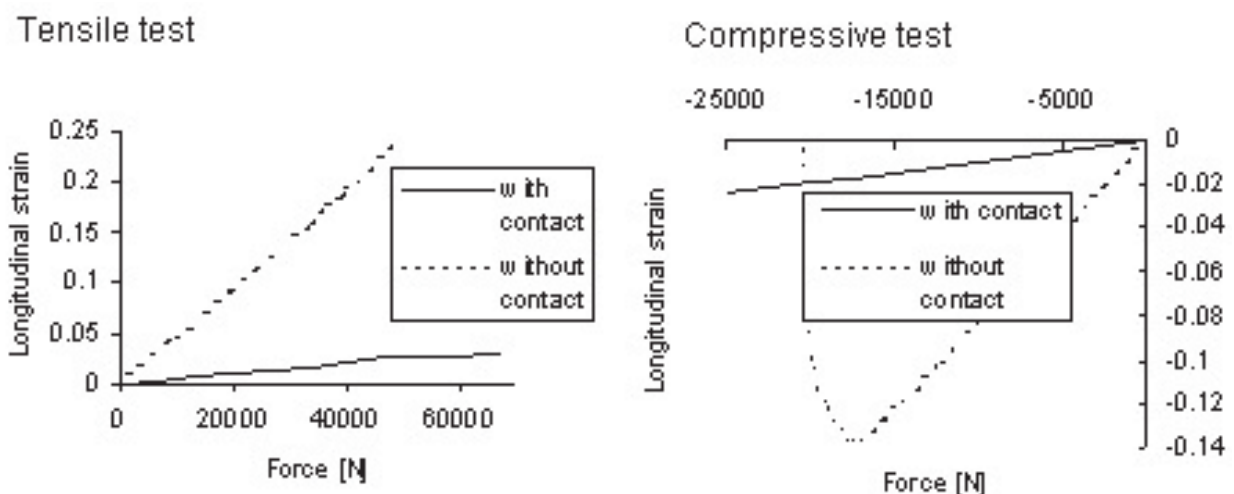

Fig. 6. Comparison of the results for models with and without contact

In the numerical analysis the failure of the composite specimen occurs for lower loading (about 80%) for the model without contact than for the one with the contact.

The fatigue life estimation is obtained by MSC.Fatigue code. The S-N approach is applied [11]. The S-N analyses are based on the nominal stress-life method using rain flow cycle counting and Palmgren-Miner linear damage summation. Fatigue calculations are based on local elastic

stresses calculated by FEM. Fatigue response for a material is the stress amplitude versus log cycles to failure curve (S-N curve). The basic equation for the S-N curve is:

$$\Delta S = SRI1\left(N_f\right)^{b1},$$ (2)

where:

ΔS — nominal stress range,
$SRI1$ — stress range intercept of the life line,
N_f — number of cycles,
$b1$ — the slope of the life line.

Values of those parameters were determined during experimental investigations. This curve is shown in Fig. 2b, where $SRI1$=530 MPa and $b1$=-0.0951. Material properties are updated for each iteration, reflecting any changes resulting from damage. The Hoffman-Seeger method makes a new set of parameters for each stress state and it also makes a Neuber correction in equivalent stress-strain space [8].

MSC.Fatigue carries out elastic-plastic transformation. The influence of the mean stress on the fatigue process is described by Goodman relationship in the form:

$$S_a = S_0\left\{1 - \left(\frac{S_m}{S_u}\right)\right\},$$ (3)

where:

S_a — allowable stress amplitude,
S_0 — allowable stress amplitude at zero mean stress,
S_m — mean stress,
S_u — ultimate tensile stress.

Loading time history is of a sinusoidal form. The calculation is done with 96% certainty of survival. This corresponds to a 4% failure rate.

MSC.Fatigue assumes the minimal damage to be 1E-20 [11]. The maximum principal stress and life for two load levels are shown in Fig. 7.

The most damaged node is located in the middle of the thickness of specimen in the gauge region. It means that this point is the weakest one in the structure.

4. Conclusions

Modern integrated virtual product development tools are useful to solve even very complicated engineering problems. The three-dimensional model allows determining failure and saving life of the structure under multiaxial loading. Application of the contact problem to interface modelling permits to evaluate the strain/stress fields at the interface.

Selection of the adequate type of finite elements to composite model is possible due to comparison of results from numerical analyses and mechanical tests. It is necessary to conduct a complete set of mechanical tests because of orthotropic properties. Experimental verification of the laminated composite model indicates that implementation of actual mathematic solvers of the contact problem and composite mechanics enables a numerical analysis without special interface element.

The contact model is applied between the plies in the composite. It permits to include all phenomena, which can be found there, for example, interlaminar stress produced during loading.

This study is intended to show an experimental-numerical 3D approach to predict the mechanical fatigue. MSC.Marc is used to determine the strain and stress distribution in the laminated composite including contact normal stress, whereas MSC.Fatigue is applied for life estimation.
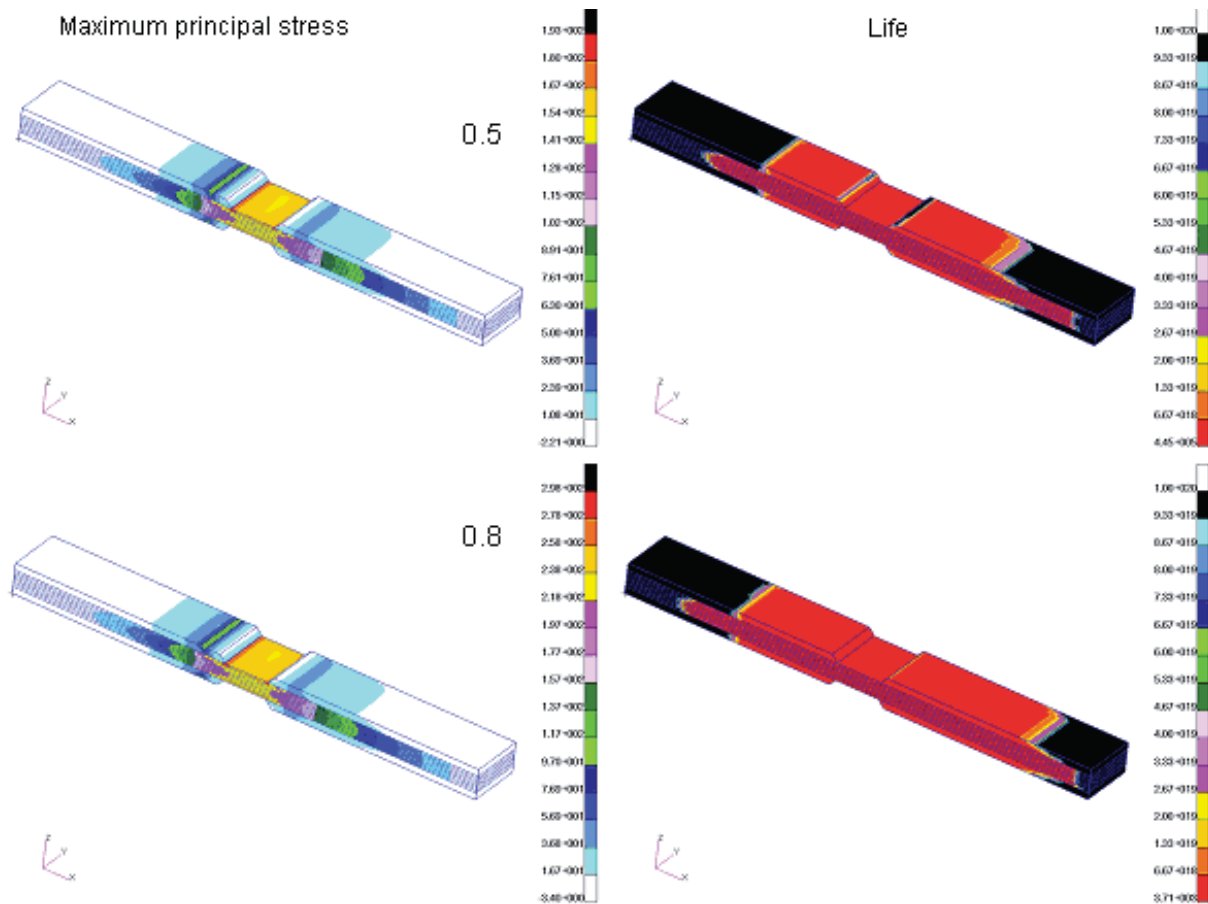
Fig. 7. Maximum principal stress and life

The presented method seems to be more suitable for structure optimisation than numerical analysis only.

Acknowledgements

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