FATIGUE OF UNIDIRECTIONAL CARBON FIBER REINFORCED EPOXY COMPOSITES

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Abstract

This paper presents the results of current research on the fatigue of carbon/epoxy laminate composites involving layers of unidirectional prepreg, manufactured by an autoclave method. The stacking sequence of the laminate was $[0]_4$ and $[\pm45]_4$. Tension-tension fatigue tests were performed at room temperature under load control mode with different amplitude. The sinusoidal load with a frequency of 5-20Hz was applied. The specimens were fatigue tested for up to 10^7 cycles. The strong dependence of maximum stress on stocking sequence of layers is observed under tension-tension test. It is the highest fatigue strength for the [±45] laminate in comparison to the [0] laminate. However for the both composites the applicable stress ratio stays to the interval 0,45 – 0,85. For [±45] laminate the failure occurred in the form of delamination in successive interlayer planes and the creep of matrix is observed. In [0] laminate the partially axial delamination of layers is observed.

1 Introduction

Carbon fiber reinforced polymer matrix composites (CFRP’s) have been widely used for aerospace components, aircraft, structural applications in automobiles, ships, sporting goods etc., because of their advantageous properties such as stability, high strength, stiffness and good chemical resistance [1]. Particularity in aircraft industry the use of these materials is associated with structural weight reduction and the consequential fuel saving and improved performance.

The strength and durability of carbon composites are an important aspect to be considered in the designing and manufacturing process as well as in the service life of composite structures. The degradation process in composite materials under static and dynamic loadings is complex and progressive. It is a combination of various damage modes. The damages of reinforcing fibres and matrix, delamination as well as degradation of fibre / matrix interface are observed [2,3,4].

Particularly important are the static and fatigue strength tests under the influence of shear stress and the determining role of matrix which may lead to significant reduction of strength properties of composite materials [5]. The theory of fatigue and experimental results for various composites are described in recent years [4,6-12], especially for carbon/epoxy composites. Composite materials under fatigue are typically characterised by a constant degradation in strength and/or stiffness due to damage accumulation with number of cycles

[6]. The orientation of the fibers influences greatly the behaviour of the composite. The damage development pattern in an angle-ply laminate is different from that described above for cross-ply laminates [4,6]. The temperature, environment and fatigue test parameters are the other factors which have influence on fatigue life and process of failure [7-12].
Nowadays finite elements analysis (FEA) are wilder used to obtain the quickly information about stress distribution and cracking in composites under static load and impact [12-16]. The modeling of fatigue process of composites by FEA method is a new problem but very interesting because of possibility to shorten time of experiments [17].
This paper presents the results of current research on the fatigue of carbon/epoxy composites involving unidirectional prepreg layers ([0], [±45] sequance) and the assumptions to FEA modeling of fatigue.

2 Materials and testing methods

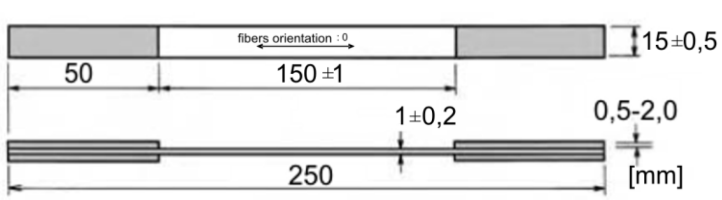
The research subject was carbon/epoxy composite made of unidirectional prepreg (UD) tape of the HexPly system (Hexcel, USA). The stacking sequence of the laminate was $[0]_4$ and $[\pm 45]_4$. The composite matrix was made of epoxy resin (density 1240 kg/m^3, T_g: 402 K; R_m: 64 MPa; ν: 0.4; E: 5.1 GPa), while AS7J12 K carbon fibers constituted reinforcement. The nominal volume content of reinforcing fibers was 57%. Composites were made using autoclave technology. The tensile properties of composites were determinate according to ASTM D 3039 standard [18] and they are presented in table 1.

Tensile strength F_{TU} [MPa]		**Young modulus in tension E_T [GPa]**		**Poisson ratio ν**		**Shear strength F_{SU} [MPa]**	**Shear modulus G [GPa]**	**Compressive strength F_{CU} [MPa]**	
0°	90°	0°	90°	0°	90°	±45°	±45°	0°	90°
1867.2	25.97	130.71	6.36	0.32	0.02	100.15	4.18	1531	214

Table 1. Mechanical characteristics of carbon/epoxy composites (average values)

Tension-tension fatigue tests were performed at room temperature with servo-hydraulic machine (MTS 25kN) under load control mode with different amplitude. The sinusoidal load with a frequency of 5 – 20 Hz and a stress ratio of R = 0.1 was applied. The specimens were fatigue tested for up to 10^7 cycles. The procedure for the specimens dimensions (Fig.1) was carried out according to ASTM D3039 standard [18]. The fatigue test was determinate according to ASTM D3479 standard [19].

a)



b)

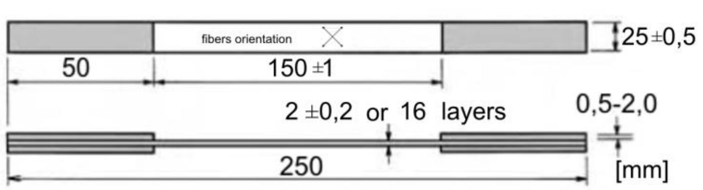


Figure 1. Specimens geometry and dimensions for static and fatigue tests with layers sequence of $[0]_4$ (a) and $[\pm 45]_4$ (b)

The frequency of 10 Hz was selected to fatigue test because of a good correlation between temperature of samples and time of experiments.

Fracture surfaces obtained from fatigue tests were analyzed in Zeiss Ultra scanning electron microscopy.

Numerical analysis by FE method to describe the tensile and fatigue properties was carried out. Above analysis was based on typical in the scientific literature strength criterions of the composite materials. In carried out research a stress criterion was used to estimate degrees of effort in composite. A tensor Tsai-Wu's criterion was a basic to specify the strength in studying composite structure. Abaqus/Standard software was the applied numerical tool.

3. Results and discussion

3.1 Fatigue analysis

The fatigue date for both type of composites can be seen in Figure 2. The S - N graph indicates the strong dependence of maximum stress on stocking sequence of layers. The maximum stress values for 0^0 angle-ply laminate are about order of magnitude higher than for $\pm45^0$ angle-ply laminate. It is a consequence of tensile properties of materials with different configuration of UD tape (see Tab.1).

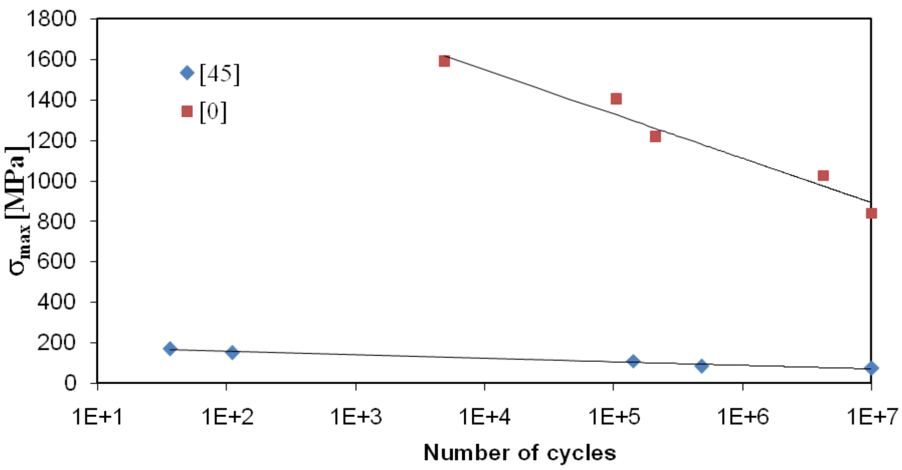


Figure 2. S–N curves for maximum stress versus number of cycles to failure

Figure 3 compares the axial fatigue strength values obtained for both materials and presents the normalized S - N curves in which the number of fatigue cycles is represented as a function of the ratio between maximum applied stress and the ultimate tensile strength of the tested materials. It is the highest fatigue strength for the $\pm45^0$ angle-ply laminate in comparison to the 0^0 angle-ply laminate. However for the both composites the applicable stress ratio stays to the interval 0,45 – 0,85.

An immediate reason for differences in tensile and fatigue properties of examined materials is a mechanics of failure. Figure 4 illustrates the macroscopic image of carbon / epoxy composites after fatigue test. In $\pm45^0$ angle-ply laminate, the failure occurred in the form of delamination in successive interlayer planes as well as damage of reinforcing fibers (Fig.4a). This type of failure is characterised as shear fatigue. In 0^0 angle-ply laminate the partially axial delamination of layers is observed (Fig.4b).

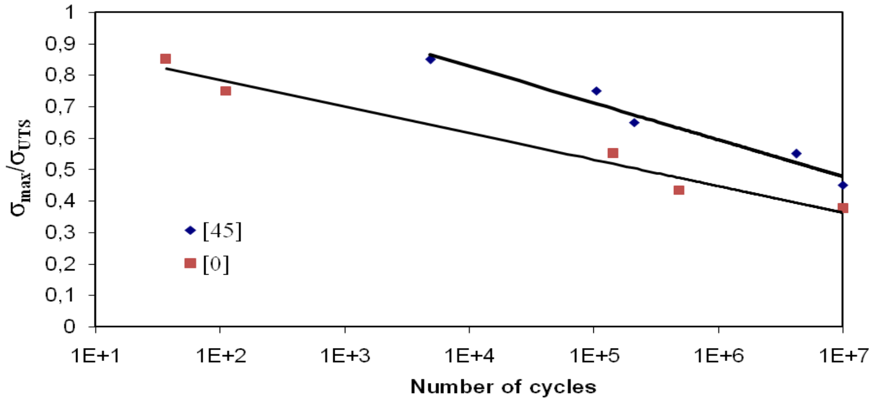


Figure 3. Normalized stress versus number of cycles to failure

a)

b)

Figure 4. Macroscopic image of specimens after fatigue test: a) composite with sequence of [±45], b) composite with sequence of [0]

The fractography of fractures is applied as one of principal methods as well as interpretation of the results obtained in strength and fatigue tests. Essential data on composites behaviour relating to the fractographic analysis of damage in composite structures are contained in the studies elaborated by Greenhalgh [20]. Figure 5 illustrates the typical fracture of fiber and matrix obtained in performed tests [21].

a) b)

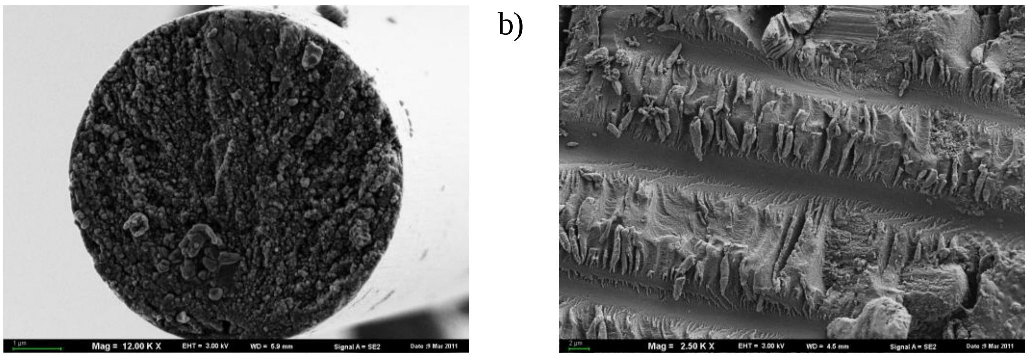


Figure 5. Fatigue fracture of carbon/epoxy composite: a) fracture of fiber, b) fracture of matrix in [±45] laminate; SEM

A characteristic crack initiation zone has been observed in fibers (Fig.5a). Radially propagating crack growth direction lines are the symptoms of brittle cracking phenomenon occurred in fibres in course of structure damage [20]. Figure 5b illustrates a characteristic morphology of matrix rolling and the creation of resin “flakes” inclined to surface. This effect is characteristic for damage as a result of fatigue processes with high number of cycles and under the impact of shear forces. The number of cycles and the strength of fibre / matrix bonding are the factors affecting such behaviour of the matrix material. Under fatigue loads, the matrix plasticity is increased and its deformation takes place (Fig. 5b). Petermann and Schulte [22] observed that for $\pm 45^0$ angle-ply laminates of carbon / epoxy tested in tension-tension fatigue at high stress ratios and maximum stresses below the endurance limit, the damage evolution was dominated by creep. In fact the mean load can be considered as static load and consequently the material creeps under its effect. On the other hand, the 0^0 angle-plies laminates of carbon / epoxy do not exhibit creep.

3.2 Numerical analysis
Abaqus offers a general capability for modeling the progressive damage and failure due to stress reversals and the accumulation of inelastic strain energy when the material is subjected to sub-critical cyclic loadings.
The methodology of numerical modeling of fiber reinforced composite was proposed earlier [23]. The discrete models of composite specimens performed in layup-ply layer configuration were created on the basis of eight-node shell finite elements Continuum Shell type, designation as SC8R.
The estimation of effort state for failure load was carried out with the use of Tsai-Wu criterion and experimental mechanical parameters (Tab.1). Figure 6 shows the example of maps for tested composites in static condition.

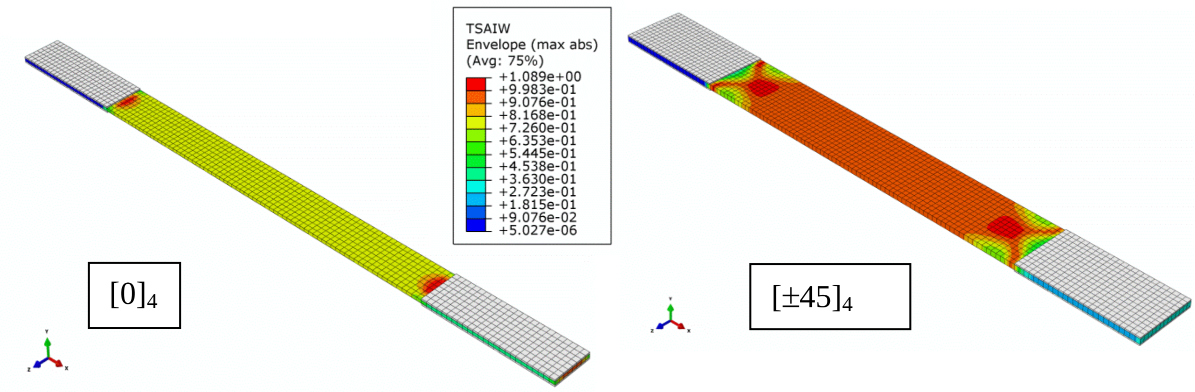


Figure 6. Composites effort by Tsai-Wu criterion

On the base of discrete models of composites and the results of tensile simulation an attempt to analyze fatigue was made according to Direct cyclic procedure in Abaqus program but the first results are unsatisfactory.

Conclusions
In this paper, fatigue of carbon/epoxy composites were experimentally investigated. The results may be summarized as follows:
The strong dependence of maximum stress on stocking sequence of layers is observed under tension-tension test. The maximum stress values for 0^0 angle-ply laminate are about order of magnitude higher than for $\pm 45^0$ angle-ply laminate. It is in good correlation with tensile properties of composites.
It is the highest fatigue strength for the $\pm 45^0$ angle-ply laminate in comparison to the 0^0 angle-ply laminate. However for the both composites the applicable stress ratio stays to the interval 0,45 – 0,85.

The shear fatigue is characteristic for ±45^0 angle-ply laminate, the failure occurred in the form of delamination in successive interlayer planes. In 0^0 angle-ply laminate the partially axial delamination of layers is observed.
The creep of matrix is observed in ±45^0 angle-ply laminate.

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References

[1] Morgan P. *Carbon fibers and their composites*. Taylor and Francis Group, New York. (2005)
[2] Gamstedt E.K., Talreja R. Fatigue damage mechanisms in unidirectional carbon-fibre reinforced plastics. *Journal of Materials Science*, **34**, pp. 2535-2546 (1999)
[3] Wu F., Yao W. A fatigue damage model of composite materials. *International Journal of Fatigue*, **32**, pp. 134-138 (2010)
[4] Harris B. *Fatigue in composites*. CRC Press, Boca Raton (2000)
[5] Hodgkinson J.M. *Mechanical testing of advanced fibre composites.* CRC Press, Cambridge. (2000)
[6] Talreja R. *Fatigue of polymer matrix composites.* in: “Comprehensive composite materials”, edited by Kelly A. and Zweben C. Elsevier Science Ltd., **2**, pp. 529–52 (2000)
[7] Jen M-H.R., Tseng Y-Ch., Kung H-K., Haung J.C. Fatigue response of APC-2 composite laminates at elevated temperatures. *Composites: Part B*, **39**, pp. 1142-1146 (2008)
[8] Putic S., Uskokovic P. S., Aleksic R. Analysis of fatigue and crack growth in carbon - fiber epoxy matrix composite laminates. *Strength of Materials*, **35**, pp. 500-507 (2003)
[9] Franco L.A.L., Graca M.L.A., Silva F.S. Fractography analysis and fatigue of thermoplastic composite laminates at different environmental conditions. *Mater. Sci. Eng.* **A 488**, pp. 505–513 (2008)
[10] Cioffi M.O.H., Voorwald H.J.C., Camargo J.A.M., Rezende M.C., Ortiz E.C., Ambrosio L. Fractography analysis and fatigue strength of carbon fiber/RTM6 laminates. *Materials Science and Engineering,* **A 527**, pp. 3609–3614 (2010)
[11] Reis P.N.B., Ferreira J.A.M., Costa J.D.M., Richardson M.O.W. Fatigue life evaluation for carbon/epoxy laminate composites under constant and variable block loading. *Composites Science and Technology*, **69**, pp. 154 - 160 (2009)
[12] Koyanagi J., Yoneyama S., Nemoto A., Melo J. D. D. Time and temperature dependence of carbon/epoxy interface strength. *Composites Science and Technology,* **70**, pp. 1395-1400 (2010)
[13] Bonhomme J., Arguelles A., Vina J., Vina I. Fractography and failure mechanisms in static mode I and mode II delamination testing of unidirectional carbon reinforced composites. *Polymer Testing*, **28**, pp. 612–617 (2009)
[14] Ogasawara T., Onta K., Ogihara S., Yokozeki T., Hara E. Torsion fatigue behavior of unidirectional carbon/epoxy and glass/epoxy composites. *Composite Structures,* **90**, pp. 482–489 (2009)
[15] Shin K.C., Lee J.J. Effects of thermal residual stresses on failure of co-cured lap joints with steel and carbon fiber–epoxy composite adherents under static and fatigue tensile loads. *Composites: Part A*, **37**, pp. 476–487 (2006)
[16] Mikhaluk D.S., Truong T.C., Borovkov A.I., Lomov S.V., Verpoest I. Experimental observations and finite element modelling of damage initiation and evolution in

carbon/epoxy non-crimp fabric composites. *Engineering Fracture Mechanics*, **75**, pp. 2751-2766 (2008)
[17] Yamaguchi T., Okabe T., Yashiro S. Fatigue simulation for titanium/CFRP hybrid laminates using cohesive elements. *Composites Science and Technology*, **69**, pp. 1968–1973 (2009)
[18] *ASTM D3039. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* (2008).
[19] ASTM D3479. *Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials* (2007).
[20] Greenhalgh E.S. *Failure analysis and fractography of polymer composites*, Woodhead Publishing in Materials, CRC Cambridge. (2009)
[21] Bieniaś J., Ostapiuk M., Surowska B. Fractography and damage analysis of carbon/epoxy composites under static and dynamic loads at elevated temperatures. *Acta mechanica et automatica*, **6(1)**, pp.17-20 (2012)
[22] Petermann J, Schulte K. The effects of creep and fatigue stress ratio on the long-term behaviour of angle-ply CFRP. *Composite Structures*, **57**, pp. 205-210 (2002)
[23] Bieniaś J., Dębski H., Surowska B., Sadowski T. Analysis of microstructure damage in carbon/epoxy composites using FEM. *Comput. Mater. Sci.*, http://dx.doi.org/10.1016/ j.commatsci.2012.03.033 (2012)