Numerical/phenomenological model for fatigue life prediction of hybrid laminates

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Abstract

In this article, the fatigue stress-cycle (*S-N*) curves of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) were investigated. Experimental fatigue tests were performed on unidirectional specimens. The*S-N*curves for GFRP and CFRP materials were determined. Obtained *S-N* curves were next described by phenomenological model (PM) based on mathematical function containing convexity and concavity ranges. Based on the PM and numerical static analyses performed in ABAQUS/Standard on hybrid glass-carbon fiber reinforced polymer, the fatigue *S-N* curve was predicted for this material. Finally, the slight residual CFRP fatigue life region was found in the estimated *S-N* curve of hybrid glass/carbon composite.

Keywords: fatigue life prediction model, residual fatigue life, hybrid laminates

1. Introduction

Fiber reinforced polymers are characterized by advantageous properties such as low density and high mechanical durability. However, depending on the reinforcing material, their utility properties may vary in a great extent. Generally, carbon fiber reinforced polymers (CFRP) are strong and stiff, while the glass fibers reinforced polymers (GFRP) are more flexible [1]. The glass fiber reinforced polymers can dissipate more energy in a fracture process due to higher deformations than carbon reinforced polymers, which was observed by Bieniaś et al. [1]. The CFRP's are still finding new applications, majorly because of their superior resistance for mechanical fatigue [2,3]. However, in some applications, the usage of two types of reinforcing fibers is desirable to meet the suitable mechanical properties and utility. For that reason it is necessary to determine not only the general mechanical static properties like stiffness and strength of the hybrid material, but also its fatigue characteristic – the *S-N* curve of resulting laminate. Experimental fatigue tests are generally considered to be expensive, time-consuming and difficult to simulate by the numerical analyses. For that reason, this article presents methodology for fatigue life prediction of general hybrid laminate materials, on the basis of the manufacturing process data, static mechanical properties, as well as fatigue properties of monolithic CFRP and GFRP materials.

2. Materials and Methods

Experimental tests were performed on monolithic CFRP and GFRP laminates with unidirectional composite layer orientation [0°] along sample axis. The materials selected for composite manufacturing were unidirectional layers of fibers pre-impregnated with epoxy matrix resin (Hexply System, Hexcel, USA). Total laminates thickness was equal to 1.55 mm. The laminates were manufactured by the means of autoclave method (Machinenbau Scholz, Germany) in the Department of Materials Engineering at Lublin University of Technology. The following process parameters were employed: curing temperature of 135°C, curing time of 2 h, heating and cooling gradient 2°C/min, 4.5 bar pressure, 0.8 bar vacuum pressure.

2.1. Fatigue tests

Experimental fatigue tests were performed with the use of tension-tension method and the INSTRON 8801 Fatigue Testing Systems 100 kN (UK). Fatigue tests aimed to establish the *S-N* characteristics were conducted by defining the constant values of mean cycle force F_{mean} and the force amplitude F_{amp}. Maximum force value in the fatigue cycle equalled $F_{max} = F_{mean} + F_{amp}$. The values of maximum stress in fatigue tests were established at percentage values of ultimate static tensile strength of GFRP and CFRP monolithic laminates. A sinusoidal shape of fatigue cycle was employed. The testing frequency was 10 Hz, with a stress ratio R = 0.1. The fatigue tests were conducted until all the laminate components underwent total failure or up to 10^7 fatigue cycles.

2.2. Function describing stress-cycles fatigue curves

On the basis of the experimental tests, the phenomenological models (PM) were defined for each monolithic material in order to predict *S-N* curve of hybrid glass-carbon laminate. The PM is based on function (Eq.1) proposed by Kohout and Vechet [4].The function proposed by Kohout and Vechet was transformed in the way which allows calculating number of fatigue cycles to material failure, for specified stress level of particular material in hybrid laminate.

$$\sigma(N) = \sigma_1 \left(\frac{1+N/B}{1+N/C}\right)^b \tag{1}$$

$$\sqrt[b]{\sigma(N)} = \sqrt[b]{\sigma_1}\,\frac{1+N/B}{1+N/C} \tag{2}$$

$$\sqrt[b]{\sigma(N)} + \sqrt[b]{\sigma(N)}\,\frac{N}{C} = \sqrt[b]{\sigma_1} + \sqrt[b]{\sigma_1}\,\frac{N}{B} \tag{3}$$

$$N\left[\left(\frac{\sqrt[b]{\sigma(N)}}{C}\right) - \left(\frac{\sqrt[b]{\sigma_1}}{B}\right)\right] = -\sqrt[b]{\sigma(N)} + \sqrt[b]{\sigma_1} \tag{4}$$

$$N = \frac{-\sqrt[b]{\sigma(N)} + \sqrt[b]{\sigma_1}}{\left(\frac{\sqrt[b]{\sigma(N)}}{C}\right) - \left(\frac{\sqrt[b]{\sigma_1}}{B}\right)} \tag{5}$$

The PM model parameters employed in the present study are provided in Table 1.

Table 1. PM parameters of monolithic CFRP and GFRP.

	B	C	b	σ_1 [MPa]
GFRP	0.0001	575300	-0.168	1528
CFRP	100	50000000	-0.056	1875

Phenomenological model parameters B, C, b and σ_1 in Table 1 were found on the basis of experimental tests, by the least squares method.

3. Results and discussion

The preliminary fatigue test results are presented in Fig 1. Generally, the determined *S-N* curves for CFRP and GFRP monolithic materials are significantly different. Based on the shape and range of *S-N* curves, it can be observed, that CFRP material is much more resistant for mechanical fatigue, than GFRP. Obtained test results are consistent with research results revealed by Dai and Mishnaevsky [5] for monolithic carbon and glass fiber reinforced polymer composites.

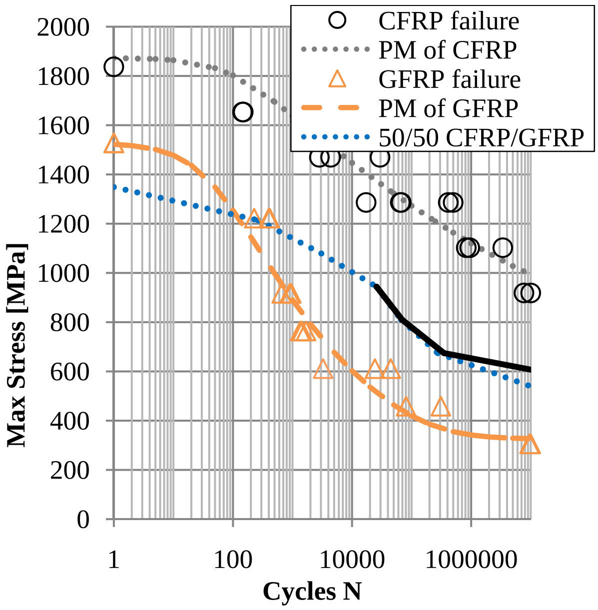

Figure 1: Stress-cycle curves of CFRP, GFRP and hybrid laminate.

In Fig.1, the predicted *S-N* curve for hybrid carbon/glass composite is presented. The hybrid composite has 1:1 volume proportion of carbon and glass fiber reinforced polymer.

First step do determine predicted *S-N* curve is to perform numerical analysis of hybrid laminate, taking into account the curing stresses which are induced in material by manufacturing process in the autoclave. These stresses are a result of mismatch between thermal expansion coefficient for glass and carbon fibers [2]. When the magnitude of curing stresses are known for specified glass/carbon fiber proportion, the next step is to find stress-strain curves, which will describe stress-strain behaviour of particular component in consistent loaded hybrid laminate. In this article, those stress-strain curves were found by numerical analyses in ABAQUS/Standard software, similarly as described in [2]. Finally, for known stress level of each component in hybrid carbon/glass laminate, the number fatigue cycles to material failure can be calculated based on the Eq.5 and parameters from Table 1. The detailed description described procedure for S-N curve determination is described in Dadej et al. [2] recent paper.

In hybrid laminates made of two different materials, the residual fatigue life may be observed, depending on the laminate configuration and fatigue strength of component material [2]. The revealed residual fatigue life region in *S-N* curve for considered hybrid carbon/glass laminate was marked in Fig 1. by black bold line. This region indicates incomplete failure of hybrid laminate. In hybrid 50/50% CFRP/GFRP laminate, according to performed analysis, for stress level 900MPa, after about $3*10^4$ cycles (Fig.1), the GFRP is supposed to fail, while the residual cross section of intact CFRP material is expected to still withstanding the specified maximum cycle load.

4. Conclusions

Experimental uniaxial fatigue tests, as well as analytical calculations were performed on CFRP, GFRP and hybrid CFRP/GFRP laminates. Experimental tests revealed, that CFRP material is much more resistant for mechanical fatigue than GFRP, which is described quantitatively by parameters of Eq.5 in Table 1. The determined points of fracture as a function of stress and number of fatigue cycles can be estimated by function proposed by Kohout and Vechet [4] with satisfactory accuracy. Basing on proposed transformed function, the *S-N* curve can be estimated for any hybrid laminates made of two different materials, for any volume ratio. Residual fatigue life of CFRP component was revealed for stress level below 900 MPa in considered 50/50% GFRP/GFRP hybrid laminate.

References

[1] Bieniaś J., Dadej K., Surowska B., Interlaminar fracture toughness of glass and carbon reinforced multidirectional fiber metal laminates, *EngFractMech*, Vol. 175(15), pp. 127–145, 2017.

[2] Dadej K., Bieniaś J., Surowska B., Residual fatigue life of carbon fibre aluminium laminates, *Int J Fatigue*, Vol. 100(1), pp. 94-104, 2017.

[3] Burianek D.A., Spearing S.M., Fatigue damage in titanium-graphite hybrid laminates. *Compos SciTechnol*, Vol. 62 pp. 607–617, 2002.

[4] Kohout J., Vechet S., A new function for fatigue curves characterization and its multiple merits, *Int J Fatigue*, Vol. 23, pp. 175–183, 2001.

[5] Dai G., Mishnaevsky L. Jr., Fatigue of hybrid glass/carbon composites: 3D computational studies, *Compos SciTechnol*, Vol. 94(9), pp. 71-79, 2014.