Polish Society of
Composite Materials
Polskie Towarzystwo
Materiałów Kompozytowych

19: 3 (2019) 100-106

COMPOSITES
THEORY AND
PRACTICE
ISSN: 2084-6096
ISSN (online): 2299-128X

Djamel Djeghader[1]*, Bachir Redjel[2]

[1] *Civil and Hydraulic Engineering Department, Mohammed Sedik Benyahia University, 18000, Jijel, Algeria*
[2] *Civil Engineering Department, Badji Mokhtar University, 23000, Annaba, Algeria*
**Corresponding author. E-mail: djameldjeghader@yahoo.fr*

Received (Otrzymano) 28.08.2019

FATIGUE LIFE PREDICTION OF GLASS REINFORCED COMPOSITE MATERIALS USING WEIBULL DISTRIBUTION

Cyclic bending fatigue tests were conducted on randomly oriented short multidirectional glass fiber-reinforced polyester matrices. Standard test specimens were manufactured in rectangles with a volume fraction of 40% glass fibers. The experimental fatigue life results were fitted using S-N curves, which are based on power function equations. S-N curves, which are characterized by important and significant scatter over the lifetime, were correlated using the two-parameter Weibull distribution function to determine the probability of failure and to plot the S-N curves at different reliability levels. These curves are of considerable design value in practical applications of composite materials and predict the sample response at the time of service depending on the degree of reliability.

Keywords: glass, polyester, fatigue life, Weibull distribution, mean life, survival probability

INTRODUCTION

The endurance properties of composite materials are much greater in contrast with metallic materials, especially light alloys. These exceptional properties of these materials justify their use in the aeronautical and naval industry for parts subject to stress fatigue. However, the anisotropy of composite materials directly influences their strength and stiffness and also renders very complex failure mechanisms under static and cyclic stresses. There have been many investigations into the mechanical properties of composite materials in fatigue tests in order to identify and explain the physical basis of the damage mechanism in cyclic load [1-4]. However, most of the manufacturing processes of fiber reinforced composite materials result in a heterogeneous material that can generate, in a given part, regions that have different mechanical properties. This is true in particular for parts manufactured using the contact molding process. This process can lead to a wide scatter of mechanical properties, especially fatigue resistance. The scatter of mechanical properties in fatigue test results directly from the nature and physiology of the composite material, the nature and mode of action relating to the preparation of the environment surrounding the specimen, uncertainty of the setting within the test machines, adjustment of the applied loading, cycle frequency and structure heterogeneities [5].

It is necessary to use statistical methods to analyse experimental data and predict the mechanical properties of these materials. One of the analysis methods is Weibull statistics, which has frequently been used to determine the mechanical properties of materials and to analyse fatigue scattering problems. Weibull distribution has the capability to model the experimental data of extremely different characters because of its excellent applicability and accuracy [6, 7]. Moreover, the results of recent research studies have proved that Weibull's statistical analysis will be very useful in the evaluation of fatigue data reliability in composite materials [8]. For example, when shape parameter (β) is equal to 1, it becomes a two-parameter exponential distribution [9]. For β values near 3, its coefficient of skewness approaches zero and the function is capable of approximating normal distribution [9]. Hanif et al. [10] employed Weibull distribution to incorporate the failure probabilities into the fatigue life of laminated cementitious composites. Sohel et al. [11] presented a statistical constitutive model at a given stress level to explain the fatigue life of an ultra-lightweight cement composite and lightweight aggregate concrete. Noel [12] used a statistical approach to optimize the Weibull distribution parameters fitting experimental fatigue data to develop S-N curves for any probability of failure of fiber reinforced polymer composites. The results show that the model is versatile and can be calibrated to describe the probabilistic nature of fatigue response.

It is of interest to note that the two-parameter Weibull function has several advantages [13]: (a) the distribution is expressed in a simple function form and is easy to apply; (b) the distribution accurately describes composite static strength and fatigue life and is widely accepted for composite statistical data analysis; (c) standard tables and computing routines are available; (d) data can be interpreted on a sound physical basis so that the A-Basis and B-Basis allowables determined for static strength and fatigue life are more reliable; and (e) the hypothesis-testing methods for statistical significance are available and verified. Selmy et al. [14] used the two-parameter Weibull distribution function to obtain the scatter in experimental results and to construct reliability graphs for fabricated hybrid composites. These graphs can be considered as reliability or safety limits in identifying the first failure time of a component under any stress amplitude. Djeghader and Redjel [15] correlated the number of cycles to failure of a jute-reinforced polyester composite using the two-parameter Weibull distribution function to determine the probability of failure and to plot the S-N curves at different reliability levels.

The main objective of the present paper is to study the fatigue behavior of randomly oriented short multidirectional glass fiber reinforced polyester composites using the power function equation. The experimental results from a fatigue test will be analyzed statistically using the two-parameter Weibull distribution function.

EXPERIMENTAL TECHNIQUES

Materials

Randomly oriented short multidirectional glass fiber reinforced polyester matrix composites were manufactured by the contact molding method in the form of rectangular plates with dimensions of 600 x 300 mm, with a mean thickness of 4 ±0.5 mm and a volume fraction of 40% glass fibers [16]. The unsaturated polyester resin (Polylite 420-852) has a tensile strength of about 45 MPa, a density at ambient temperature of 1110 kg/m^3, and viscosity around 20 dPa·s, the breaking stress is 72 MPa and the bending modulus is about 2350 MPa [15]. Glass fiber reinforcement (*E*) has density of 2540 kg/m^3, an elastic modulus of 72 GPa, breaking stress of 3.5 GPa and an elongation at break of about 4.4% [16, 17]. The average value of the ultimate flexural strength of a glass/polyester composite specimen is: σ_r = 180 MPa, and Young's modulus: E_f = = 5670 MPa [17]. The value of σ_r is necessary to perform the cyclic fatigue test of the composite material.

Fatigue test

The specimens for the cyclic fatigue tests were in a prismatic form of 80 mm in length, 15 mm in width and 4 mm in thickness (Fig. 1). The cyclic bending fatigue tests (3-point bending fatigue) were carried out using a ZWICK ROEL test machine with a ±20 KN capacity and controlled by the computer software "test expert" (Fig. 2). The loading type is sinusoidal with a constant amplitude of 1.25 Hz frequency. The choice of low frequency allows any side effects mainly due to heating of the material to be avoided. The fatigue life was measured for different stress levels S ($S = \sigma/\sigma_r$; where σ is the maximum stress; and σ_r is the bending failure stress) of 0.8, 0.7, 0.6, 0.55, 0.45, 0.35 and 0.25. For each level load, a minimum of three test specimens were tested. The criterion adopted in this study is complete fracture of the specimen. However, it should be noted that after 10^5 cycles, and for practical reasons in the laboratory, the test is stopped even if the specimen is not broken. We also consider the fact that there is no fracture. The limit of endurance is therefore fixed at 10^5 cycles [16].

Fig. 1. Specimens used in cyclic load

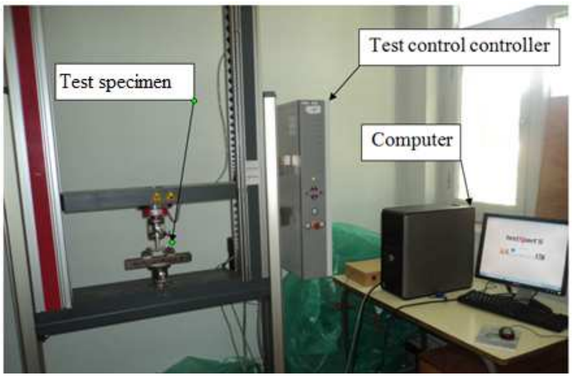

Fig. 2. All devices employed in cyclic fatigue test

THEORETICAL ANALYSIS

Many alternative statistical approaches are available to express engineering data. These approaches allow us to determine the relationship between the parameters, design the experiment, as well as predict and estimate, among others, the fatigue resistance for a certain load level and number of cycles, using the mathematical model or the probability distribution [18]. One of the approaches to analyze the fatigue-life data results involves the use of the two-parameter Weibull distribution function. The probability density function *f*(*x*) (PDF) of two-parameter distribution is indicated in equation (1). This PDF equation is the most popular definition of two-parameter Weibull distribution [15, 18-20].

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{1}$$

In the context of this study, α is the scale parameter at a certain stress level (characteristic life); β is the shape parameter of the two-parameter Weibull distribution at a certain stress level (the inverse measure of the dispersion in the fatigue life results); and x is the variable parameter (denoting, the random variable value of cycles to failure).

Integrating the probability density function (PDF) in equation (1) gives the cumulative density function (CDF) or the probability of failure, $P_f(x)$, in equation (2) [21, 22].

$$P_f(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{2}$$

The survival probability (the reliability function), $P_s(x)$, is defined as $P_s(x) = 1 - P_f(x)$, which indicates that the sample test is not subjected to any dangerous damage for a specific period of time. By substituting this value of $P_f(x)$ in equation (2), it is converted to the following equation:

$$P_s(x) = e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{3}$$

The values of scale parameter α and shape parameter β are determined by taking the logarithm twice on both sides of equation (3), which can be rewritten in the following form:

$$ln\left(ln\left(\frac{1}{1-P_f(x)}\right)\right) = \beta ln(x) - \beta Ln\,(\alpha) \tag{4}$$

It can be seen in equation (4) that the relationship between Ln(Ln(1/1 – $P_f(x)$)) and Ln(x) is a linear one. Therefore, the slope of the straight regression line presents shape parameter β. Scale parameter α can be obtained from the second term of equation (4) [14].

Survival probability $P_s(x)$ for each cycle number at a given stress level in the fatigue test is calculated from the median ranking method using the following equation [14, 22, 23]:

$$P_s(x) = 1 - \left(\frac{i-0.3}{n+0.4}\right) \tag{5}$$

Where n is the total number of samples and i is the failure serial number. According to Equations (4) and (5), it is very easy to plot a graph with Ln(Ln(1/1 – $P_f(x)$)) against Ln(N) in order to determine the values of scale parameter α and shape parameter β.

The scatter in the fatigue life can be determined and analyzed using the following equations [24, 25]:

$$[MTTF] = \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{6}$$

$$[SD] = \alpha\sqrt{\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)} \tag{7}$$

$$[CV] = \frac{[SD]}{[MTTF]} = \frac{\sqrt{\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)}}{\Gamma\left(1+\frac{1}{\beta}\right)} \tag{8}$$

Where $MTTF$ is the mean life time to failure (the mean fatigue life) (eq. (6)), SD is the standard deviation (eq. (7)), CV is the coefficient of variation of the two-parameter Weibull distribution (eq. (8)), and Γ is the gamma function.

RESULTS AND DATA ANALYSIS

S-N diagram

In this part, S-N curve models developed directly to characterize the experimental fatigue data subjected to a constant load amplitude will be fitted by the power function equation (see eq. (9)):

$$\sigma = A\left[log\left(N_f\right)\right]^{B} \tag{9}$$

A and B are material constants linked to the material properties. These two constants were calculated from the experimental data using least-squares curve fitting.

The repetition of stress loading creates damage in the glass fiber and polyester matrix of the composite material. When the number of performed cycles is less than the lifetime, it is important to quantify these damages in order to estimate the residual lifetime. Therefore, the residual stress of the glass fiber reinforced polyester composite decreases as the fatigue test progresses [26]. Comparisons between the experimental results and the power function fit of applied stress in the fatigue test with the number of cycles are presented in Figure 3.

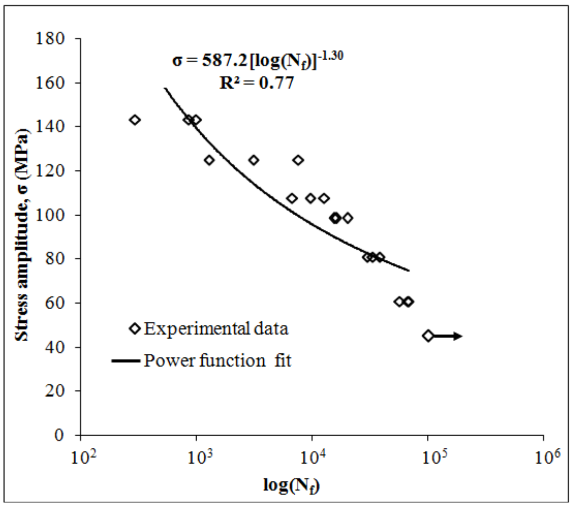

Fig. 3. S-N diagram of glass reinforced polyester composite material

The figure clearly shows that cyclic fatigue failure number (N) of the glass-reinforced composite material decreases with an increase in the value of applied stress. However, evaluation of the experimental data using the linear function has a low value of coefficients of linear correlation ($R^2 = 0.77$), which indicates the importance of the dispersion of lifetimes, which is essentially due to the heterogeneous nature of the studied composites and the nature of the test specimens that seldom have comparable characteristics. Indeed, the volume fraction, the length and orientation of the fibers, the density and the defects of the distribution, as well as the physical and mechanical characteristics, differ from one test specimen to another and from one region to another of the same specimen [16]. Thus, it is clear that in addition to the structural defects of the glass fiber reinforced polyester composite material, the fatigue behavior of the material under cyclic loading allowed clean dispersion, like a physical fact of the fatigue phenomenon. Moreover, it is generally far too difficult to entirely remove some of the causes of experimental error, even if it is possible in theory. The simultaneous action of these two kinds of causes, both experimental and physical, leads to a scatter of test results that are rarely negligible with regard to the amounts being measured [5].

Weibull distribution

The fatigue life of the specimens was assessed using the two-parameter Weibull distribution, as shown in equation (4). Figure 4 shows the Weibull plot for the different stress levels. However, because none of the specimens tested at a 0.25 loading level corresponding to $\sigma = 45$ MPa failed, this data cannot be used further in the analysis.

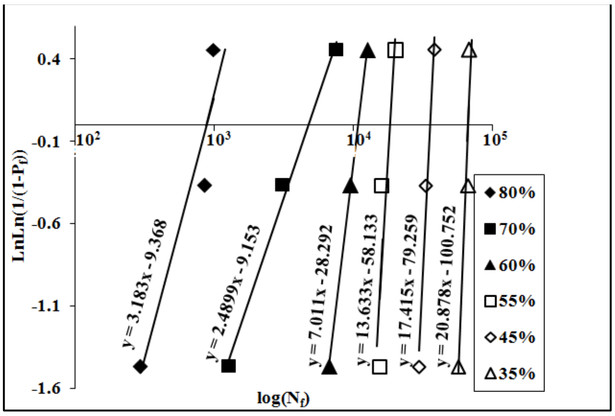

Fig. 4. Weibull lines for glass reinforced polyester composite samples

It is evident from the data depicted in Figure 4 and reported in Table 1 that the slope of the linear regression lines (shape parameter β) presents important values for the minimum loading levels, indicating that these lines are approximately vertical with minimum variation (scatter) in fatigue life data (on the abscissa) and vice versa for a lower value of β, except for loading 0.7, which has a value of (β) at about 2.5, indicating that the dispersion result is greater compared to the other loading levels of the fatigue test (Table 1). However, it is important to note that all the plots displayed good linearity with reliability index $R^2 > 0.78$, signifying a reasonable Weibull distribution fitting. Therefore, it is possible to conclude that the (β) slopes of the regression lines effectively represented the scatter in the fatigue life data of the studied material.

TABLE 1. **Weibull parameters in fatigue test**

σ/σ_r	α	β	R^2	[CV](%)	Weibull mean life (N_0)
0.80	877	3.183	0.892	34	785
0.70	4744	2.490	0.992	43	4209
0.60	10851	7.010	0.999	17	10151
0.55	18375	13.633	0.784	9	17688
0.45	35577	17.415	0.977	7	34508
0.35	66952	20.878	0.870	6	65247

The obtained scale parameter values (β) were greater than 1 ($\beta > 1$), meaning that the fatigue loading damage was distributed throughout the stressed region. Although this phenomenon often reduces the stiffness of a composite material, it does not always lead to an immediate reduction in strength. Strength reductions typically occur in the wear-out zone following small stress-induced, viscoelastic, or creep deformations in the matrix [27].

The values of scale parameter α of the Weibull distribution function were calculated based on the above-mentioned equations (eq. (3) and (4)). These values are listed in Table 1, and it is worth noting that they are related in an inversely proportional way to loading in the fatigue test.

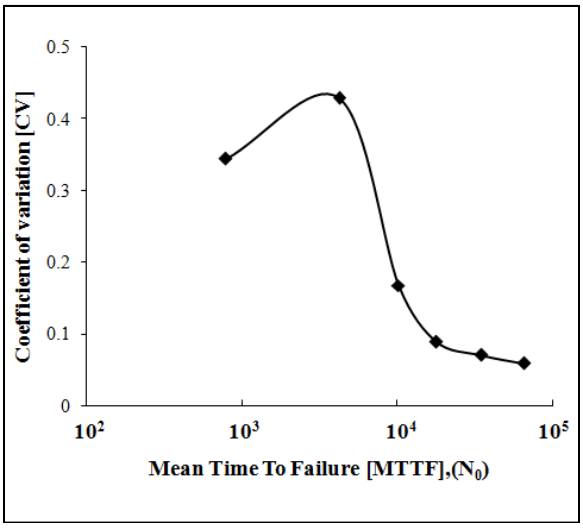

Fig. 5. Effect of mean fatigue life on coefficient of variation [CV]

To evaluate the relative dispersion of the fatigue test data, it was necessary to use equation (8) to calculate the relative coefficients of variation (CV) for each mean life ($MTTF$). Figure 5 shows the effect of $MTTF$ on CV. According to these results, the scatter in the fatigue life values was the widest between 10^2 and 10^4, where SD

was approximately 43% of the mean life. This observation was made due to the presence of structural defects that at the beginning of a test can emerge in response to the increased level of stress. However, for the other values of mean life (low stress level) the data has relatively low variability, where the SD is between 6÷9% of the mean life. This tendency in the dispersion of the fatigue life at different loading levels is extremely important to the designer and deserves much attention for the application of this type of composite materials [20]. The line of connection between the data points in Figure 5 simply serves to suggest a trend in the data.

The probability of functional performance of a structural element or part of an element under current service conditions and in a defined period of time is known as reliability or the probability of survival [28]. The reliability graph corresponding to each stress alue of glass reinforced polyester composite samples is shown in Figure 6. This graph was plotted using equation (3).

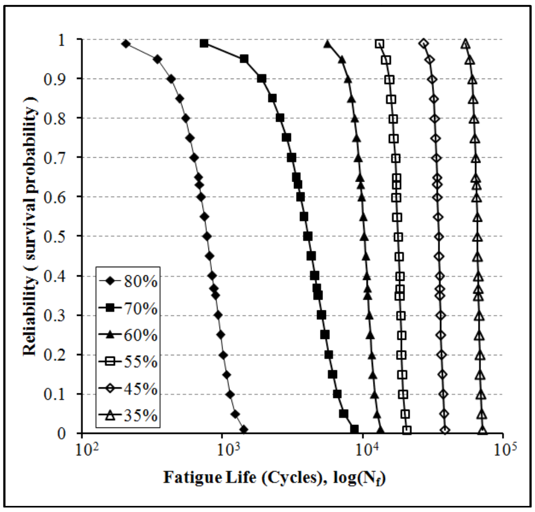

Fig. 6. Survival probability graphs for glass reinforced polyester composite material

The cyclic fatigue life of a glass/polyester composite can be easily determined at any survival probability using this graph. Therefore, the 50% survival probability of the tested samples is found in this graph by drawing a horizontal line from the y-axis to its intersection with the distribution curve. For example, for a 0.6 loading level corresponding to 108 MPa, the intersection of the horizontal line for a 50% survival probability gives a life cycle number of 10298 cycles (Fig. 6). This value becomes 65787 cycles for a 0.35 loading level corresponding to 61 MPa. Similarly, when the loading level is 0.8 (σ = 143 MPa), the intersection of the horizontal line for a 90% survival probability composite shows a lifetime of 432 cycles, while when a loading level of 0.3% (σ = 61 MPa) is used, the lifetime is 60111 cycles.

The results of the 3-point bending fatigue test of glass/polyester composite material showed significant variability because of the anisotropic structures and semi-brittle behavior of the materials. Thus, the reliability or safety limit is an important parameter in designing this type of structure.

The case of $P_s(x) = 0.368$ indicates that the part survived the characteristic life (with respect to the number of cycles). This survival probability value can be determined from equation (3) by substituting ($x = \alpha$). Therefore, the following equation (12) can be written [15]:

$$P_s(x) = 1 - P_f(x) = e^{-\left(\frac{\alpha}{\alpha}\right)^{\beta}} = 0.368 \qquad (12)$$

In Figure 7, the S-N curves are drawn for different reliability levels using equation (13) (derived from eq. (3)).

$$N_{P_x} = \alpha \qquad (13)$$

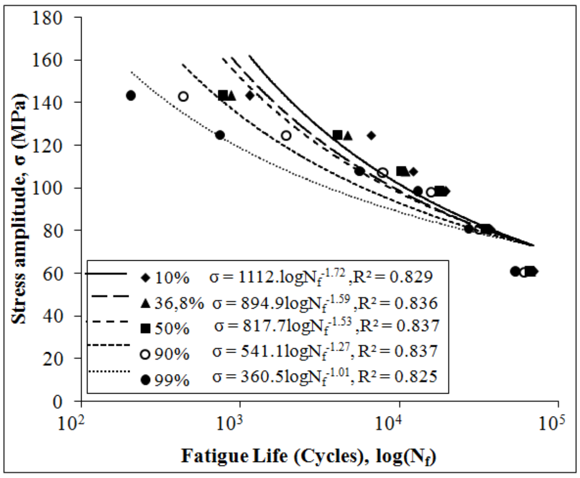

Fig. 7. S-N curves for different reliable levels for glass polyester composite material

The results obtained from equation (13) (cycle number) were fitted using a power function (eq. (11)).

It can be seen in Figure 7 that constant A decreases as the level of survival probability increases (the number of cycles in fatigue life decreases as the reliability increases). The curves in Figure 7 are of considerable value to the designer for the practical applications of this type of composite material. These curves can predict the response of the sample at the time of service depending on the degree of reliability. For example, if composite structural elements (structural components) contain a defect or a critical section which can be damaged under repeated load (where any failure is catastrophic), using the calculated lifetime at high reliability (99%) is strongly recommended.

CONCLUSIONS

Glass fiber reinforced polyester composite material was subjected to cyclic fatigue in order to plot the S-N curve and to calculate the endurance limit of this material using the power function approaches. The experimental data was collected to predict the lifetime using the statistical method based on the two-parameter

Weibull distribution. From the experimental results, theoretical and statistical analysis of the fatigue life data of the glass/polyester composite material, the following concluding remarks were drawn:

- The experimental results showed dispersion due to the anisotropy of material and operation of the cyclic fatigue test. This behavior makes predicting fatigue life very difficult.
- The residual stress of the glass fiber reinforced polyester composite decreases as the fatigue test progresses. Therefore, the endurance limit of this composite material can be estimated at a stress of 45 MPa with a failure cycle number at 10^5 cycles.
- The mean values of the experimental results from the fatigue test and the theoretical curve were in good agreement although there is a wide range of experimental data.
- Scatter in the fatigue life values was the widest between 10^2 and 10^4, where the SD is about 43% of the mean life (between 10^3 and 10^4). This observation is due to the presence of structural defects that can be significantly damaged under a high stress level at the beginning of the test.
- The fatigue life of glass/polyester composite material can be easily determined at any survival percent using fatigue life distribution diagrams constructed by the two-parameter Weibull cumulative function (probability of survival).
- The reliability or safety limit is an important parameter in designing semi-brittle elements. For this reason, S-N curves for several levels of reliability were presented to designers such as: $P_s = 0.99$, $P_s = 0.50$, $P_s = 0.368$ and $P_s = 0.1$ which can be considered as reliability or safety limits in the identification of the first failure time under any stress level.

REFERENCES

[1] Gassan J., A study of fibre and interface parameters affecting the fatigue behavior of natural fiber composites, Compos. Part A-Appl. S. 2002 March, 33, 3, 369-374, https://doi.org/10.1016/S1359-835X(01)00116-6.

[2] Nojavan S., Schesser D., Yang Q.D., A two-dimensional in situ fatigue cohesive zone model for crack propagation in composites under cyclic loading, Inter. J. Fatigue 2016 February, 82, 3, 449-461, https://doi.org/10.1016/j.ijfatigue.2015.08.029.

[3] Luo Z., Cao H., Ren H., Zhou X., Tension-tension fatigue behavior of a PIPSiC /Si Ccomposite at elevated temperature in air, Ceram. Int. 2002 February, 42, 2, 3250-3260, https://doi.org/10.1016/j.ceramint.2015.10.116.

[4] Gagani A.I., Monsås A.B., Krauklis A.E., Echtermeyer A.T., The effect of temperature and water immersion on the interlaminar shear fatigue of glass fiber epoxy composites using the I-beam method, Compos. Sci. Technol. 2019, September, 181, 107703, https://doi.org/10.1016/j.compscitech.2019.107703.

[5] Bathias C., Pineau A., Fatigue of Materials and Structures: Fundamentals, ISTE Ltd and John Wiley & Sons, Inc, 2010.

[6] Wang Y., Yu W., Wang F., Experimental evaluation and modified Weibull characterization of the tensile behavior of tri-component elastic-conductive composite yarn, Text. Res. J. 2017, March, 88, 10, 1138-1149, https://doi.org/10.1177/0040517517698991.

[7] Hwang W., Han K.S., Statistical study of strength and fatigue life of composite materials, Composites 1987, January, 18, 1, 47-53, https://doi.org/10.1016/0010-4361(87)90007-3.

[8] Sørensen B.F., Goutianos S., Micromechanical model for prediction of the fatigue limit for unidirectional fibre composites, Mech. Mater. 2019, April, 131, 169-187, https://doi.org/10.1016/j.mechmat.2019.01.023.

[9] Long M.W., Narciso J.D., Probabilistic Design Methodology for Composite Aircraft Structures, Repport Office of Aviation Research, Washington 1999.

[10] Hanif A., Usman M., Lu Z., Cheng Y., Li Z., Flexural fatigue behavior of thin laminated cementitious composites incorporating cenosphere fillers, Mater. Design 2018, February, 140, 267-277, https://doi.org/10.1016/j.matdes.2017.12.003.

[11] Sohel K.M.A., Al-Jabri K., Zhang M.H., Richard L.J.Y., Flexural fatigue behavior of ultra-lightweight cement composite and high strength lightweight aggregate concrete, Constr. Build. Mater. 2018, June, 173, 90-100, https://doi.org/10.1016/j.conbuildmat.2018.03.276.

[12] Noël M., Probabilistic fatigue life modelling of FRP composites for construction, Constr. Build. Mater. 2019, May, 206, 279-286, https://doi.org/10.1016/j.conbuildmat.2019.02.082

[13] Cohen D., Application of reliability and fiber probabilistic strength distribution concept to composite vessel burst strength design, J. Compos. Mater. 1984, December, 26, 13, 1984-2014, https://doi.org/10.1177/002199839202601307.

[14] Selmy A.I., Abd El-baky M.A., Azab N.A., Experimental study on flexural fatigue behavior of glass fibers/epoxy hybrid composites with statistical analysis, J. Reinf. Plast. Comp. 2013, July, 32, 23, 1821-1834, https://doi.org/10.1177/0731684413496879.

[15] Djeghader D., Redjel B., Effect of water absorption on the Weibull distribution of fatigue test in jute-reinforced polyester composite materials, Adv. Compos. Lett. 2019, May, 28, 3, 1-11, https://doi.org/10.1177/0963693519853833.

[16] Djeghader D., Redjel B., Fatigue resistance of randomly oriented short glass fiber reinforced polyester composite materials immersed in seawater environment, Mech. Ind. 2017, November, 18, 604, https://doi.org/10.1051/meca/2016087.

[17] Nechad H., Evaluation de l'endommagement et de la rupture de matériaux hétérogènes par ultrasons et émission acoustique: Estimation de la durée de vie restante, Ph.D. Thesis, Institut National des Sciences Appliquées de Lyon, Lyon, French 2004.

[18] Mohammad M., Abdullah S., Jamaludin N., Innayatullah O., Predicting the fatigue life of the SAE 1045 steel using an empirical Weibull-based model associated to acoustic emission parameters, Mater. Design. 2014, February, 54, 1039--1048, https://doi.org/10.1016/j.matdes.2013.09.021.

[19] Sakin R., Ay I., Statistical analysis of bending fatigue life data using Weibull distribution in glass-fiber reinforced polyester composites, Mater. Design. 2008, 29, 6, 1170-1181, https://doi.org/10.1016/j.matdes.2007.05.005.

[20] Khashaba U.A., Fatigue and reliability analysis of unidirectional GFRP composites under rotating bending loads, J. Compos. Mater. 2003, February, 37, 4, 317-331, https://doi.org/10.1177/0021998303037004680.

[21] Weibull W., A statistical distribution function of wide applicability, J. Appl. Mech. 1951, 18, 293-297.

[22] Hwang W., Han K.S., Statistical study of strength and fatigue life of composite materials, Compo. 1987, January, 18, 1, 47-53, https://doi.org/10.1016/0010-4361(87)90007-3.

[23] Haidyrah A.S., Newkirk J.W., Castano C.H., Weibull statistical analysis of Krouse type bending fatigue of nuclear materials, J. Nucl. Mater. 2016, March, 470, 244-250, https://doi.org/10.1016/j.jnucmat.2015.12.016.

[24] Bohoris G.A., Gamma function tables for the estimation of the mean and standard deviation of the weibull distribution, Qual. Reliab. Eng. Int. 1994, 10, 2, 105-115, https://doi.org/10.1002/qre.4680100205.

[25] Zhou G., Davies G.A.O., Characterization of thick glass woven roving / polyester laminates: 2. Flexure and statistical considerations, Compo. 1995, August, 26, 8, 587-596, https://doi.org/10.1016/0010-4361(95)92623-K.

[26] Liang S., Gning P.B., Guillaumat L., Properties evolution of flax/epoxy composites under fatigue loading, Inter. J. Fatigue 2014, June, 63, 36-45, https://doi.org/10.1016/j.ijfatigue.2014.01.003.

[27] Harris B., Fatigue in Composites, Woodhead Publishing, Materials Research Centre, University of Bath, UK, Part I. ISBN: 978-1-85573-608-5, 2003.

[28] Khashaba U.A., Aljinaidi A.A., Hamed M.A., Fatigue and reliability analysis of nano-modified scarf adhesive joints in carbon fiber composites, Compos. Part B-Ing 2017, July, 120, 103-117, https://doi.org/10.1016/j.compositesb.2017.04.001.