INFLUENCE OF THE TEMPERATURE IN THE DELAMINATION UNDER MODE I OF FRACTURE AND DYNAMIC LOADING OF TWO CARBON-EPOXY COMPOSITES.

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Abstract.

This paper experimentally analyzes the influence of temperature and type of matrix on the delamination process of two composites subjected to fatigue loading through the study of their fracture under mode I. The chosen temperatures for the experiments were 20 (room temperature), 50 and 90ºC. The experimental study determines the influence that temperature has on the onset of delamination for the entire range of fatigue life of the material, from the low number of cycles zone to the high number of cycles zone. That is, it enabled the plotting of fatigue curves, represented as GImax-N, for an asymmetry coefficient of 0.2

The experimental data obtained were treated with a probabilistic model based on a Weibull distribution which allowed the identification of relevant aspects of the fatigue behavior of the materials such as the estimation of fatigue strength for periods greater than the tested values and the analysis of the reliability of the results.

1. Introduction.

Composite materials manufactured by the overlapping of sheets present the drawback of the possible generation and growth of cracks between these sheets, which, depending on the type of loading applied to the material, may result in a separation between sheets and an important loss in strength. This phenomenon, known as delamination, is one of the failure modes which most limit the life of composite materials [1-4]. The matrix of a fiber-reinforced composite material has the basic function of joining the fibers, acting as an element of distribution of loads between them and protecting them from the surface deterioration which can be caused by mechanical, chemical or environmental actions. This deterioration can, in turn, result in surface defects, leading to cracks which are likely to propagate by the action of cyclic loads. On reaching a critical value, these small defects thus give rise to different failure modes in the material, even for relatively low loading values in comparison with the strength of the material. The matrix prevents or slows down the propagation of cracks of one fiber to another; in other words, it acts as a barrier that prevents crack propagation. Although some individual fibers break, the overall failure of the composite will not occur until a sufficient number of fibers have broken; i.e., until the damaged area reaches a critical size. It is essential for the adhesion between fiber and matrix to be optimal in order to minimize the drawing out of the fibers. The composite material's resistance to delamination depends on the magnitude of this adherence. Proper adhesion is thus essential to optimize the transmission of loads from matrix to fibers [5-9]. Although the possible thermal degradation suffered by these materials under service conditions and its influence on the delamination phenomenon has thus been studied for more than one decade, the number of papers related to this topic is still not very extensive. Some of the first studies in this field [10] analyzed the behavior to fracture under mode I loading of a composite subjected to thermal degradation. The behavior to fatigue of carbon-epoxy composites has likewise been studied [11, 12], concluding that the ductile behavior of material increases with increasing temperature. Other authors [13] have analyzed the delamination process in carbon-epoxy composite under modes I and II and mixed mode I/II under static as well as fatigue loading at different temperatures. The results show that the values of the energy release rate under mode I and a static regime do not vary significantly with temperature, while the energy release rate under mode II is lower at a high temperature than that obtained at room temperature. The behavior of a composite with carbon reinforcement and a PEEK matrix has been studied when subjected to interlaminar fracture under modes I and II at high temperatures (from 20 to 200ºC) [14]. The authors analyzed the elastic properties of the material at different temperatures in order to evaluate the stress intensity factor. Other authors [15-20] have analyzed the effect of temperature on composites under static and fatigue loading for different modes of fracture with thermal and moisture effects. Several papers have been published on the influence of the evaluation models used in the characterization to fatigue in composite materials subjected to delamination [21-25]. The advantage that these models represent in the interpretation of results is evidenced in these studies. The present paper aims to take a step further in this field, analyzing one of the phenomena associated with the progress of delamination, namely the influence of temperature and the type of matrix on the evolution of the phenomenon of delamination in two composite materials reinforced with the same type of unidirectional carbon fiber at different temperatures, corresponding to the onset of delamination fatigue. That is, the goal is to determine the number of cycles required for the generation of a crack preceding delamination for different release energy rates. The results have been evaluated using a probabilistic model based on a Weibull distribution proposed in [26, 27] that provides a full description of the entire range of fatigue life in the low and high number of cycles zones. It likewise allows the estimation of the value of the real limit of the fatigue life or endurance limit; i.e., the level of loading under which a given element is capable of supporting an unlimited number of cycles. This endurance limit is independent of the failure probability and of the size effect.

2. Experimental procedure.

2.1. Materials, specimens and testing equipment.

The two composite materials were manufactured with the same AS4 unidirectional carbon fiber though with two types of matrix: a modified 8552 epoxy prepreg and an unmodified 3501-6 epoxy. Double Cantilever Beam (DCB) specimens were used to characterize delamination under mode I fracture according to ASTM Standard D5528 [28]. In order to avoid environmental conditions influencing the results, all samples were subjected to a pre-conditioning process to remove any moisture. Tests were conducted on a servohydraulic dynamic testing machine equipped with a thermal chamber and a load cell of 5 kN.

2.2. Fatigue characterization.

The aim of this experimental program was to determine the G_{Imax}-log N fatigue curves (release energy rate vs. number of cycles) of the tested materials when subjected to delamination fracture processes under mode I dynamic loading. The goal of fatigue characterization was thus to determine the required number of loading cycles to failure, understanding this to be the onset of a crack in the material.

The tests were carried out according to ASTM Standard D6115 [31]. Under mode I, the loading levels applied to the specimens were adjusted for each test based on data obtained from static characterization of the material in the initiation phase at the different temperatures under consideration. All tests were carried out under displacement control, defining the maximum displacement, δ_{max}, as a percentage of the critical displacement obtained from the static characterization carried out prior to the fatigue tests and calculating the minimum displacement as $\delta_{max} \cdot R$, for R=0.2. The energy release rate, G, in mode I was calculated using the modified beam theory proposed in ASTM Standard D5528. Crack initiation was considered to exist when it was visually observed using a 100× travelling microscope located to one side of the specimen. An extensometer was also placed in front of the specimen in order to analyze the changes in compliance suffered by the specimen and thus verify that delamination had occurred. Mechanical systems were used to position this extensometer.

3. Statistical model of evaluation of results.

The Weibull regression model developed by Castillo et al. [32] was used to evaluate the fatigue test results obtained in the experimental program. This model allows statistical normalization of all the data obtained and increases the reliability of this evaluation. According to this model, the G-N probabilistic field for a sample of test results under dynamic loading of constant amplitude can be formulated by the expression:

$$P_f = F(N;G) = 1 - exp\left[\left(\frac{\log(N/N_0)\cdot\log(G_{Imax}/G_0) - \lambda}{\delta}\right)^{\beta}\right] \tag{1}$$

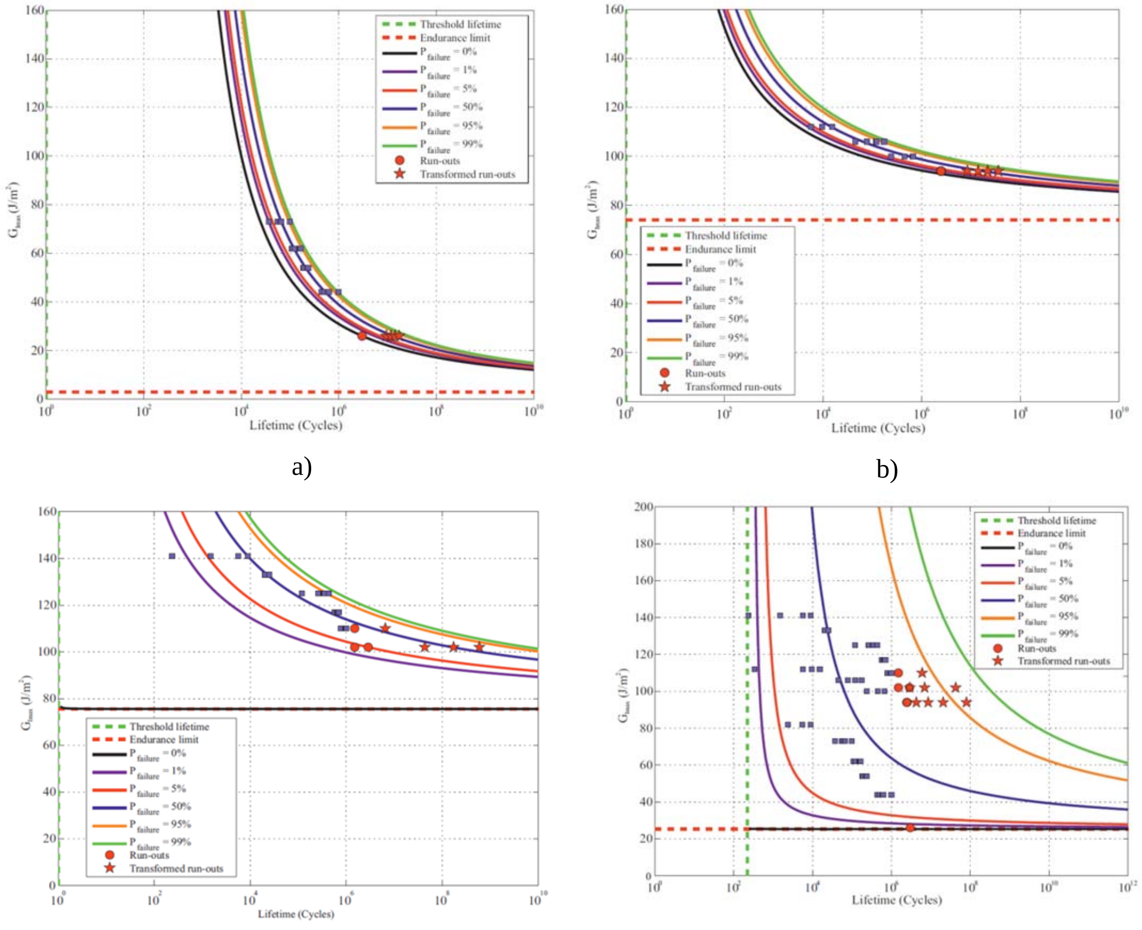
$$with\colon \log(N/N_0)\cdot\log(G_{Imax}/G_0) \geq \lambda$$

Where N is the fatigue life in cycles, G is the energy release rate, P_f is the failure probability; and Go, No, β, λ and δ are the model parameters with the following meaning:
No is the threshold value or limit number of cycles; Go, the limit value of the energy release rate; λ, the Weibull location parameter determining the position of the limit curve associated with the zero probability of failure; δ, the Weibull scale parameter, representing associates to a probability of failure P=0.62; and β is the Weibull shape parameter.

4. Experimental results.

This section presents the experimental results obtained in the study of the fatigue behavior for both materials as a function of temperature.

Figures 1a), b) and c) show the percentiles curves for AS4/3501-6 material which represent the probability of failure fatigue according to the Weibull model, plotting the maximum fracture energy versus the number of cycles required for initiation of a fatigue crack tested under mode I at 20, 50 and 90ºC, respectively. Figure 1d) shows the entire range of fatigue life for the same material considering the experimental results that would represent the overall behavior of the material under service conditions in which thermal fluctuations occur.



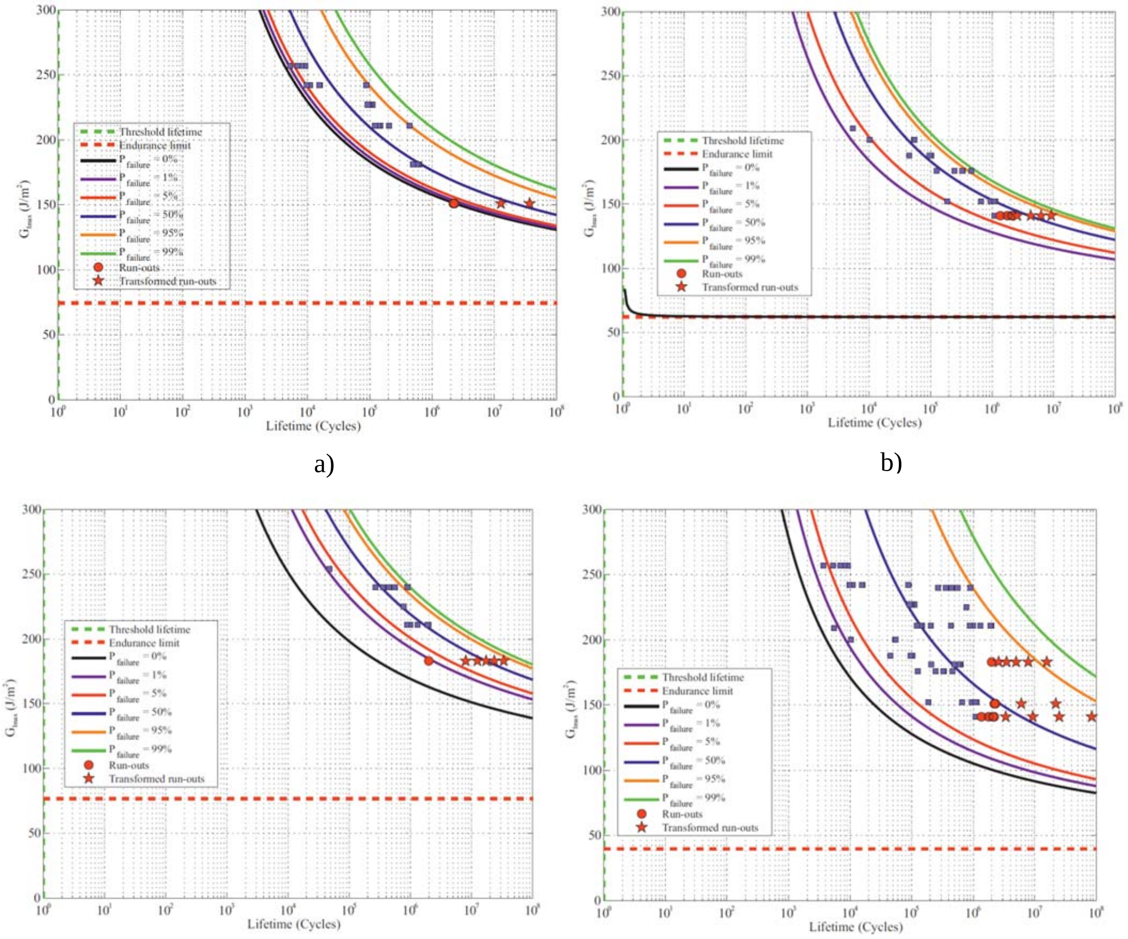
a) b) c) d)

Figure 1. Percentile fatigue curves for the 3501-6 matrix for different failure probabilities at: a)20, b)50, c)90ºC and d) for tests at all temperatures assuming a single sample of results.

An improvement in fatigue behavior can be observed with increasing temperature, showing a significant increase in the fatigue limit at 50 and 90ºC, which was not obtained at room temperature (20ºC). This finding may be justified by a possible increase in the ductility of the matrix with temperature. When all results obtained at different temperatures are considered as a single sample of results, which enables overall information on the fatigue behavior of the material to be obtained, the estimated fatigue limit is seen to be higher than that obtained at room temperature and significantly lower than that obtained at 50 and 90ºC.

Figures 2a), b) and c) show the percentile curves representing different probabilities of fatigue failure according to the Weibull model for the materials with the modified AS4/8552 matrix tested to dynamic fracture under mode I at 20, 50 and 90ºC, respectively. Figure 2d) shows the entire range of fatigue life for the same material considering the experimental results obtained at all the temperatures as a single sample of results.

In this material, AS4/8552, greater dispersion can be observed at the different temperatures and less dependence of the fatigue limit on temperature, although when all the temperatures are considered as a single sample, the fatigue limit is once again significantly lower than that obtained when each temperature is considered independently. From the point of view of safety, this would indicate the need to perform tests in all the entire range of service temperatures of the material.



a) b)

c) d)

Figure 2. Percentile fatigue curves for the 8552 matrix for different failure probabilities at: a)20, b)50, c)90ºC and d) for tests at all temperatures assuming a single sample of results.

Figure 3 shows the fracture energy for both materials and the three temperatures under study versus the number of fatigue cycles that the material can withstand. This fracture energy has been estimated for a failure probability of 1%, according to the proposed model.

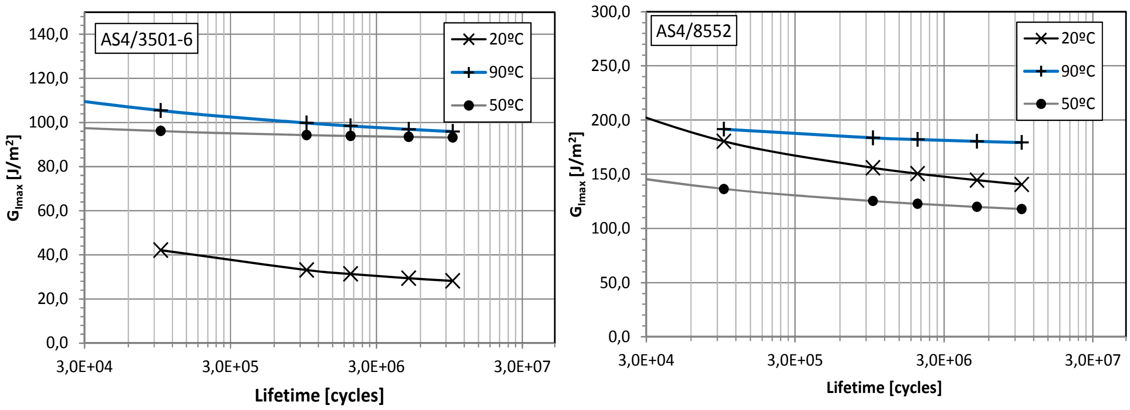


Figure 3. Estimated fracture energy for each material versus fatigue life for the temperatures considered and a failure probability of 1%: a) 3501-6 matrix, b) 8552 matrix.

As previously stated, it is evident that the performance of the unmodified 3501-6 matrix improves markedly with temperature, showing little difference between 50 and 90ºC, for a fatigue life of the element of around five million cycles. For a fatigue life of the element of less than a million of cycles, the best results are found for the highest temperature, 90ºC. The same trend is not observed for the modified, tougher resin, however, which performs worse at 50ºC than at room temperature. In the low number of cycles zone, the behavior of the material is similar at room temperature and at 90ºC, while the best results in the high number of cycles zone were obtained at 90ºC.

Figure 4 shows the energy amplitude, expressed as the % of the energy of delamination obtained in the static characterization, which it would be possible to apply to an element subjected to fracture under mode I and cyclic loading according to the model used versus fatigue life for a probability of failure of 1% for each of the studied temperatures.

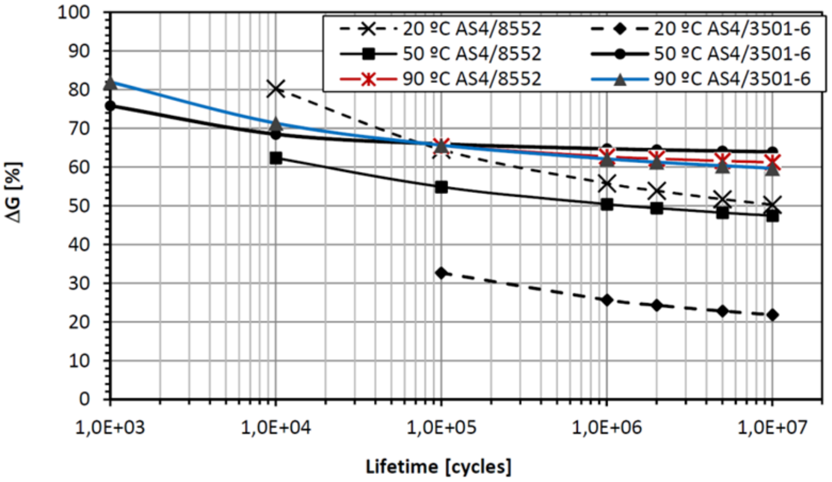


Figure 4. Energy amplitude versus number of cycles for P_f 1%, all temperatures.

From the point of view of the influence of the type of resin on the behavior of the composite material versus delamination under mode I and fatigue loading, the 3501-6 resin, in principle less tough, performs worse at room temperature, whereas at 50ºC the tougher resin presents worse results. Both resins perform similarly at 90º. It should be noted that these statements are made without taking into account the resistant capacity of each resin, as only the loading level which each can withstand was taken into account.

5. Conclusions.

This study has experimentally analyzed the influence of temperature and the type of matrix on carbon/epoxy composite materials in the fatigue delamination process under mode I loading. For the best interpretation of the results, a probabilistic regression model based on a Weibull distribution was applied which has been used with other types of materials. The most relevant conclusions may be summarized as follows:

Thermal fluctuations modify the behavior of these materials when they are subjected to mode I fracture delamination under dynamic loading. These modifications in behavior depend on the type of matrix used in the composite.

Overall, the less tough resin presents better fatigue behavior with increasing temperature, while a decrease in fatigue resistance capacity was observed in the case of the tougher resin with respect to room temperature for relatively small increases in temperature. When the loading state favors the delamination phenomenon, it is convenient to characterize the material to fatigue in the entire range of service temperatures, especially in those applications where the required safety level is very high.

The use of a statistical model for the interpretation of results is necessary in studies that analyze the fatigue behavior of these materials.

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7. References.

[1] A. Launay Y. Marco, M.H. Maitournam, I. Raoult. Modelling the influence of temperature and relative humidity on the time-dependent mechanical behaviour of a short glass fibre reinforced polyamide. Mechanics of Materials, 56: 1–10, 2013.

[2] B. Landry, G. LaPlante, L. R. LeBlanc. Environmental effects on mode II fatigue delamination growth in an aerospace grade carbon/epoxy composite. Composites Part A, 43: 475–485, 2012.

[3] M. Miura, Y. Shindo, T. Takeda, F. Narita. Interlaminar fracture characterization of woven glass/epoxy composites under mixed-mode II/III loading conditions at cryogenic temperatures. Engineering Fracture Mechanics, 96: 615–625, 2012.

[4] A. Argüelles, Fernández Canteli A., J. Viña, M.A. García. Evolution of the impact strength of carbon fiber-reinforced PEI following exposure to mechanical, hygrothermal and hygrothermomechanical aging. Journal of Composite Materials, 41, No 19: 2337-2346, 2007.

[5] M. Kawai , S. Yajima, A. Hachinohe, Y. Kawase. High-temperature off-axis fatigue behaviour of unidirectional carbon-fibre-reinforced composites with different resin matrices. Composites Science and Technology, 61: 1285–1302, 2001.

[6] Chiara Colombo, Laura Vergani. Influence of delamination on fatigue properties of a fiberglass composite. Composite Structures, 107: 325–333, 2011.

[7] J. Mohan, A. Ivankovic´, N. Murphy. Effect of prepreg storage humidity on the mixed-mode fracture toughness of a co-cured composite joint. Composites Part A, 45: 23–34, 2013.

[8] A. Argüelles, J. Viña, A.F. Canteli, J. Bonhomme. Influence of resin type on the delamination behavior of carbon fiber reinforced composites under mode-II loading. International Journal of Damage Mechanics, 20: 963-978, 2011.

[9] A. Argüelles, J. Viña, A. Fernández-Canteli, I. Viña, J. Bonhomme. Influence of the matrix constituent on mode I and mode II delamination toughness in fiber-reinforced polymer composites under cyclic fatigue. Mechanics of Materials, 43: 62–67, 2011.

[10] P. Hutapea, F.G. Yuan. The effect of thermal aging on the Mode-I interlaminar fracture behavior of a high-temperature IM7/LaRC-RP46 composite. Composites Science and Technology, 59: 1271-1286, 2011.

[11] A. Sjögren, Leif Asp. Effects of temperature on delamination growth in a carbon/epoxy composite under fatigue loading. International Journal of Fatigue, 24: 179–184, 2002.

[12] Ashcroft I. A., Hughes D., Shaw S. J. Mode I fracture of epoxy bonded composite joints: part 1. Quasi-static loading. International Journal of Adhesion and Adhesives, 21: 87-99, 2001.

[13] Uematsu Y., Kitamura T., Ohtani R. Delamination behavior of a carbon-fiber-reinforced thermoplastic polymer at high temperatures. Composites Science and technology, 53: 333-341, 1995.

[14] K. Wang, B. Young, S. T. Smith. Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures. Engineering Structures, 33: 2154–2161, 2011.

[15] B.D. Davidson, M. Kumar, M.A. Soffa. Influence of mode ratio and hygrothermal condition on the delamination toughness of a thermoplastic particulate interlayered carbon/epoxy composite. Composites: Part A 40: 67–79, 2009.

[16] Cândido G.M., Costa M.L., Rezende M. C., Almeida S. F. M. Hygrothermal effects on quasi-isotropic carbon epoxy laminates with machined and molded edges. Composites. Part B: Engineering, 39(3): 490-496, 2008.

[17] L.A.L. Franco, M.L.A. Graca, F.S. Silva. Fractography analysis and fatigue of thermoplastic composite laminates at different environmental conditions. Materials Science and Engineering, 488: 505–513, 2008.

[18] Ramanujam N., Vaddadi P., Nakamura T., Singh R. P. Interlaminar fatigue crack growth of cross-ply composites under thermal cycles. Composite estructures, 85: 175-1870, 2008.

[19] P. Coronado, A. Argüelles, J. Viña, V. Mollón, I. Viña. Influence of temperature on a carbon–fibre epoxy composite subjected to static and fatigue loading under mode-I delamination. International Journal of Solids and Structures, 49: 2934–2940, 2012.

[20] Emin Ergun, Süleyman Tasgetiren, Muzaffer Topçu. Fatigue and fracture analysis of aluminum plate with composite patches under the hygrothermal effect. Composite Structures, 92: 2622–2631, 2010.

[21] M. Naderi, A.R. Maligno. Fatigue life prediction of carbon/epoxy laminates by stochastic numerical simulation. Composite Structures, 94: 1052–1059, 2012.

[22] A.I. Selmy, N.A. Azab, M.A. Abd El-baky. Flexural fatigue characteristics of two different types of glass fiber/epoxy polymeric composite laminates with statistical analysis. Composites Part B, 45: 518–527, 2013.

[23] John Montesano, Zouheir Fawaz, Kamran Behdinan, Cheung Poon. Fatigue damage characterization and modeling of a triaxially braided polymer matrix composite at elevated temperatures. Composite Structures, 101: 129–137, 2013.

[24] R. Sarfaraz, A. P. Vassilopoulos, T. Keller. A hybrid S–N formulation for fatigue life modeling of composite materials and structures. Composites Part A, 43: 445–453, 2012.

[25] Darshil U. Shah, Peter J. Schubel, Mike J. Clifford, Peter Licence. Fatigue life evaluation of aligned plant fibre composites through S–N curves and constant-life diagrams. Composites Science and Technology, 74: 139–149, 2013.

[26] Castillo E., Fernández Canteli A.: A general regression model for lifetime evaluation and prediction. Int J of Fracture, 107: 117-137, 2001.

[27] Castillo E., F. Canteli A., Pinto H., López Aenlle M.: A general regression model for statistical analysis of strain life fatigue data. Materials Letters, 62: 3639-3642, 2008.

[28] ASTM D 5528-01 Mode I Interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites; 2007.

[29] ASTM D 3039 Standard Test Method for Tensile Properties of Fiber-Resin Composites; 2006.

[30] ASTM D 3518 Standard Practice for Inplane Stress-Strain Response of Unidirectional Reinforced Plastics; 2007.

[31] ASTM D6115-97. Standard test method for mode I fatigue delamination growth onset of unidirectional fiber-reinforced polymer matrix composites; 2011.

[32] Profatigue code. Dept. of Construction and Manufacturing Engineering. University of Oviedo. Free-use software.