EXPERIMENTAL METHODOLOGY FOR LIMIT STRAIN DETERMINATION IN A CARBON/EPOXY COMPOSITE UNDER TENSILE FATIGUE LOADING

A. C. Ancelotti Jr.[1*], V. O. Gonçalves [2], L. C. Pardini[2]

[1]*Institute of Mechanical Engineering, UNIFEI - Federal University of Itajuba, Av. BPS, 1303*
Pinheirinho CEP 37500-903 Itajubá – MG, Brazil
[2]*Institute of Aeronautics and Space, DCTA, Av. Brigadeiro Faria Lima, 1.941 - Parque Martim Cererê*
CEP12.227-000 São José dos Campos - SP - Brazil
**e-mail address of the corresponding author: ancelotti@unifei.edu.br*

Keywords: composites, fatigue, limit strain, damage

Abstract

This work proposes a methodology to obtain the carbon fiber/epoxy composite limit strain for structures surviving 120000 cycles. The damage progression was also evaluated using stiffness reduction and hysteresis loop analysis in order to obtain dynamic and secant modulus. The results provide information about composite fatigue behavior. This approach determined a limit strain range from 0.83 to 0.87%, a fatigue stress limit of 0.8% of the static strength, stiffness degradation (damage index) of about 5% (within the limit strain). The methodology presented herein may be used for determining of material design allowable when fatigue is key consideration.

1. Introduction

Historically, airframe design has been dominated by metallic materials. Currently, carbon graphite composite materials are being used to produce primary aircraft structures such as fuselages and wings. The allure of using composite material in aerospace structures is related to its high strength-to-weight ratio, fatigue resistance and high modulus which promise cost savings to aircraft operators in terms of fuel and maintenance. Also, the introduction of composites has brought other benefits related to fatigue resistance, such as the opportunity to increase inspection intervals, improvements on window frame design, and reduced damage growth. Although composite materials are less sensitive to fatigue than metallic materials, these materials are generally anisotropic and inhomogeneous so that the fatigue behavior is more complex. In composite materials, fatigue life is dependent on materials design features such as fiber and matrix selection, fiber orientation, fiber/matrix interface [1], fiber and void volume content [2,3], and fiber arrangement in the pre-preg material [4]. In general fatigue fracture may happen in several modes and can lead to different results.

Nevertheless, due to the inherent difficulty in understanding and analyzing fatigue phenomenon in composites, aircraft design for composite materials has been mostly limited to static design allowable properties. Fatigue behavior has not been considered an issue. Limit strain is determined from static properties (B-basis) and any uncertainties in durability are accounted for in high safety factors applied to the design. As a result composite parts tend to be heavier and more costly than necessary [5,6]. Typical ultimate strain levels allowed on composite parts are maintained around 4000$\mu\varepsilon$ or 0.4% [5]. Such levels do not allow the full potential of composite materials to be realized. There is an opportunity to improve composite design and reduce weight and costs; however, an accurate and safe methodology for developing composite fatigue properties design is needed to accommodate such designs.

Most studies related to fatigue in composite materials utilize stress degradation or S-N curves (Stress-Number of cycles) in order to determine the endurance limit. They do not take in consideration the damage growth in the composite during its operating lifetime which is very important in terms of design. Several techniques have been proposed to monitor composite degradation caused by fatigue. Potential techniques include acoustic emission, thermographic monitoring [7,8], microscopic analysis, radiography [9], pulse echo ultrasonics and hysteresis loop measurements [10]. The advantage of measuring hysteresis loop information is that it supplies a wide range of information for subsequent analysis. Damping behavior, secant modulus, dynamic modulus and damage accumulation as a function of the number of cycles are easily determined [10, 11]. Good predictions for fatigue life were obtained by several authors [8, 12, 13] by relating hysteresis loop responses and thermographic monitoring techniques.

The purpose of this paper is to introduce a methodology to determine the limit strain of composite laminate structures by using the material's response over a defined fatigue life of 120000 cycles which corresponds to approximately two lives of typical commercial aircraft. A hysteresis loop method was developed to demonstrate damage evolution of composites when loaded within their limit strain.

2. Materials and testing methods

The material selected for this investigation was a widely-available woven, carbon fiber composite prepreg T300/F584 [14] which is supplied by Hexcel Composites Corp. This material is frequently utilized in the aircraft industry for parts manufacturing. The material was manually laid up in a typical composite laminate $(0°,90°)_8$ and, after being debulked, was cured in an autoclave according to the supplier-recommended cure cycle. The fiber volume content of the resulting composite laminate was determined using ASTM 3171/ASTM 792 specifications. The fiber volume content was about 57% and the void volume measured less than 0.3%. In order to assure the quality and homogeneity of the entire composite panel used in this study; it was inspected by a pulse-echo ultrasonic C-scan method. The nominal thickness of each composite panel after consolidation was 3 mm. Test specimens for tensile testing were prepared according to guidelines provided in the ASTM D3039 standard. The specimens were cut such that the 0° or warp direction matched the load direction. End tabs were bonded to all specimens to eliminate stress concentrations in both static and fatigue testing.

Quasi-static and fatigue tensile testing were carried out in a laboratory with controlled environmental conditions, 23±5°C and 50±10% relative humidity. Both quasi-static and fatigue tensile testing were conducted in a computer-controlled, servo-hydraulic testing machine with hydraulic jaw grips.

The quasi-static tests were conducted in accordance with ASTM D3039 specification. The cross-head speed was set to 1mm/min and an extensometer was fixed on the gage-length section of the specimen. Ten specimens were tested in order to obtain ultimate tensile strength and modulus mean values. The ultimate tensile strength results were treated statistically to obtain the B-Basis value, which means 95% lower confidence bound on the tenth percentile of the population measured [15]. This B-basis value was used as a reference for the residual tensile strength of the composite specimens that survive 120000 cycles of tensile-tensile fatigue loading.

All fatigue tensile testing was performed under load control condition with a sinusoidal waveform. Fatigue testing was conducted at a frequency of 12 Hz and a stress ratio of R = 0.1 was applied for a maximum of 120000 cycles. All specimens were monitored by an infrared camera during the tensile-tensile fatigue cycling to avoid overheating caused by hysteretic heating. For this work, the maximum temperature allowed on the specimen surface was 60°C in order to avoid degradation of properties. Figure 3 presents a flow chart of the methodology used to determine limit strain.

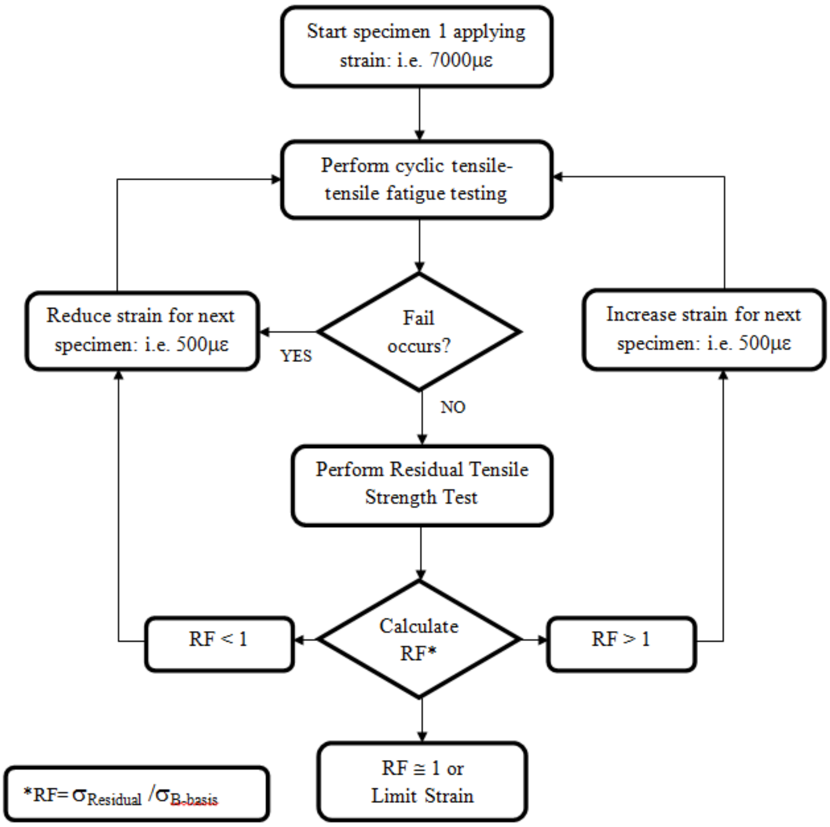

Figure 3: Flowchart for Fatigue Limit Strain Determination

The method iterates on approximately 28 test specimens until a confident limit strain is determined. During each test, the specimen is initially pre-loaded to about 50% of ultimate tensile strength. This procedure eliminates involuntary movement of the extensometer and avoids any loss of reference due to the eventual rupture of misaligned carbon fibers in the specimens. Previous studies have determined that a pre-load of 50% of ultimate tensile will not have any influence on the fatigue life [9, 16].

The specimen was loaded to a prescribed strain and level then submitted to fatigue cycling. If the specimen fails, the number of cycles is recorded and the next specimen is tested at a different maximum strain level. If the specimen survives 120000 cycles (two aircraft lifetimes), a residual strength test is performed and the factor relating the residual tensile strength, after cycling fatigue, and the ultimate tensile strength, reduced statistically to a B-basis value, is calculated. This ratio factor (residual strength/ultimate strength) is named as RF (Ratio Factor). A RF factor greater than 1 means that residual tensile strength is higher than the B-basis value. Consequently, the strain level applied to the next specimen must be increased. Conversely, if the residual tensile strength is lower than the B-basis value, the strain applied for the next specimen must be decreased. The limit strain corresponds to the point where the RF factor is approximately equal to 1.

As a mean to assess damage level in composite structures operating within the limit strain, hysteresis measurements were made. The hysteresis test consisted of loading the specimen up to the limit strain and conducting the fatigue test at this level. The fatigue test was interrupted each 30000 cycles in order to obtain the stress-strain (Young's Modulus) curves. At least 60 load cycles were monitored at each interval. The data acquisition frequency was set to 1 Hz to avoid noise and loss of signal. From the resulting hysteresis curve measurements, secant and dynamic modulus were calculated according to equations (1) and (2) respectively [10]:

$$E_{1S} = (\sigma_{1max}/\varepsilon_{1max}) \quad (1)$$

$$E_{1Dyn} = [(\sigma_{1max} - \sigma_{1min})/(\varepsilon_{1max} - \varepsilon_{1min})] \quad (2)$$

This change in material modulus has been used to express the state of damage in composite materials [1, 8, 17]. In this study, stiffness degradation or accumulated damage (damage index), *D(n)* was evaluated according to the following equation (3) at the same interval defined for the hysteresis loop (each 30000 cycles up to 120000, monitoring at least 60 cycles to each interval):

$$D(n) = 1 - E(n)/E_o \quad (3)$$

Where E_0 is the initial Young's Modulus of the composite material, E_f is the Young's Modulus at the end of fatigue cycling, and *E(n)* is the Young's Modulus after (*n*) fatigue cycles.

3.Results and discussion

3.1 Quasi-Static Properties

The quasi-static tensile test results are summarized in Table 1. The tensile Strength B-basis value was determined to be 808 MPa. Most of the specimens presented similar failure types which were the Lateral Gage Bottom (LGB) type according to ASTM D3039 specification. The LGB failure type is characterized by the rupture of sample on the transversal direction (orthogonal to the load direction), located on the gage area on the bottom of sample.

Material T650/F584	Tensile Strength Ultimate σ_{SU} [MPa]	E-Modulus [GPa]	Tensile Strain [mm/mm10^{-6}]
Mean Value	930.2 ± 19.2	73.1 ± 2.4	12735

Table 1: Quasi-Static Tensile Strength and Modulus Results

3.2 Fatigue Tensile Test Results

The results for limit strain are shown in Figure 4.

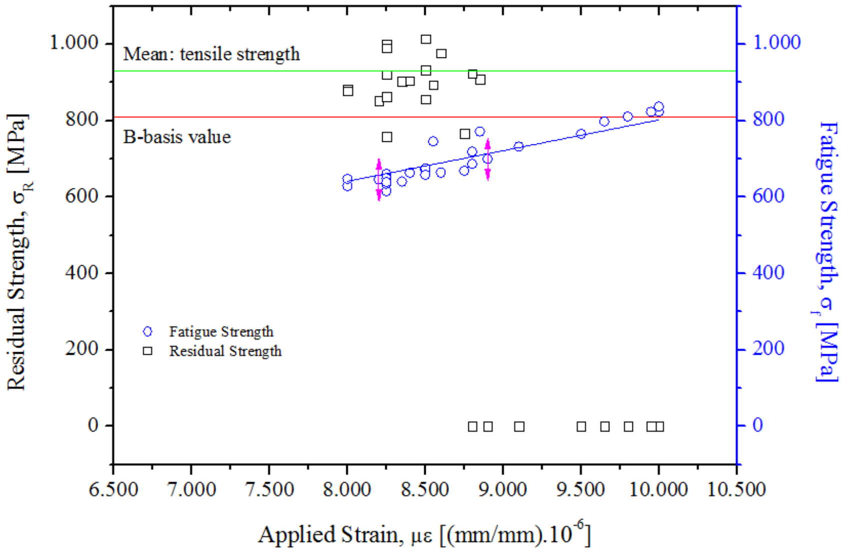

Figure 4: Residual tensile strength as a function of applied fatigue strain levels.

Two distinct regions in the figure are noteworthy. The first region, which ranges from 7500 to approximately 8650με, represents the fatigue strain levels where the specimens survived 120000 cycles. Residual strength values were determined for these specimens. The second region, which ranges from approximately 8600 to 10000με, represents the fatigue strain levels where most of the specimens failed prior to reaching 120000 cycles. The large scatter of results in the first region, related to the residual tensile strength, made it impossible to clearly determine the limit strain. Thus, the relationship between the residual strengths and B-basis value was not consistent enough to determine limit strain. However, the strain level transition from the specimens that survived fatigue cycling and those that failed prior to two fatigue lifetimes is very clear. Thus, it is possible to assume that the limit strain can be set in the range of 8300 to 8700με. The vast majority of the results in the first region exceed the B-Basis value. This means that the material retains its fatigue resistance even when loaded near the limit strain. Previous studies quantified the number of cracks in a similar composite material as a function of the applied strain from tensile loading [18]. They found the threshold strain needed to produce significant cracking ranged from 5000 to 9000με. Also, if the Poisson’s ratio was measured as a function of applied strain, the authors found a sharp decrease in Poisson´s ratio for applied strains over 5000με.

Figure 5 shows the normalized tensile strength (fatigue tensile strength/static mean ultimate strength or $\sigma_{fatigue}/\sigma_{US}$) as a function of the number of cycles (S-N) before specimen failure. At high stress levels, the specimens failed at low number of cycles. When the fatigue loads were kept constant at 80% of the normalized tensile strength, there was a wide range in the number of cycles to failure. This behavior agrees with the sensitivity of the limit strain determination, where a small increase in the strain leads to more rapid failure of specimen.

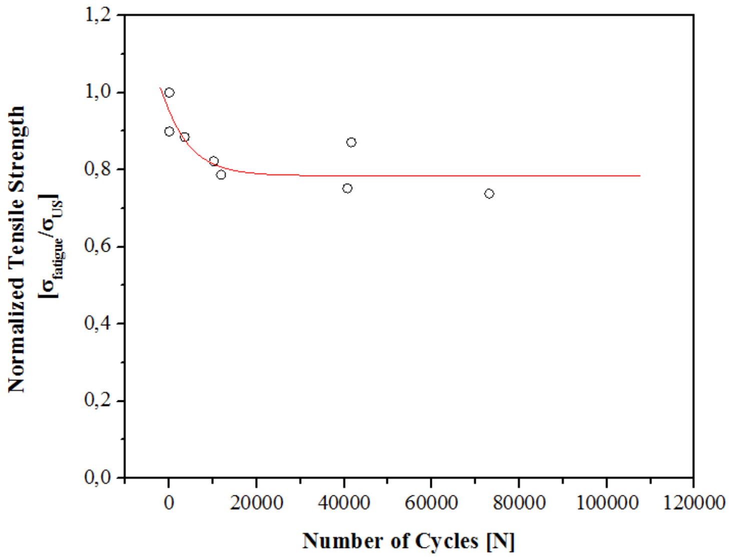

Figure 5: Normalized Tensile Stress as a Function of Number of Cycles to Failure

3.3 Hysteresis Measurements

Figure 6 shows a sample hysteresis curve for a composite specimen cycled within the observed limit strain of 8300με. As the number of load cycles increases, an increase in the global strain is observed. After 120000 cycles the maximum strain measured at the maximum tensile load of 650 MPa was 8650με. This increase in strain is due to accumulated fatigue damage in the composite laminate.

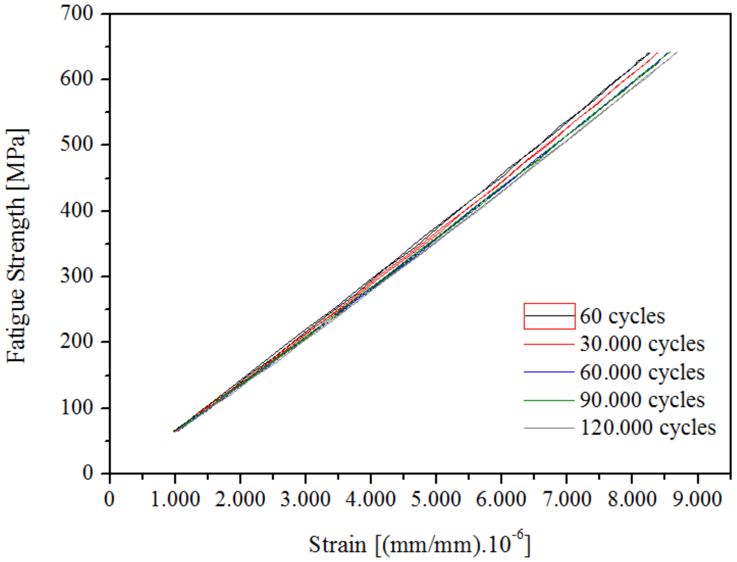

Figure 6: Hysteresis Loop Measurements within the Limit Strain Range

Dynamic modulus, secant modulus and the damage index calculates using these hysteresis curves are presented in Figure 7.

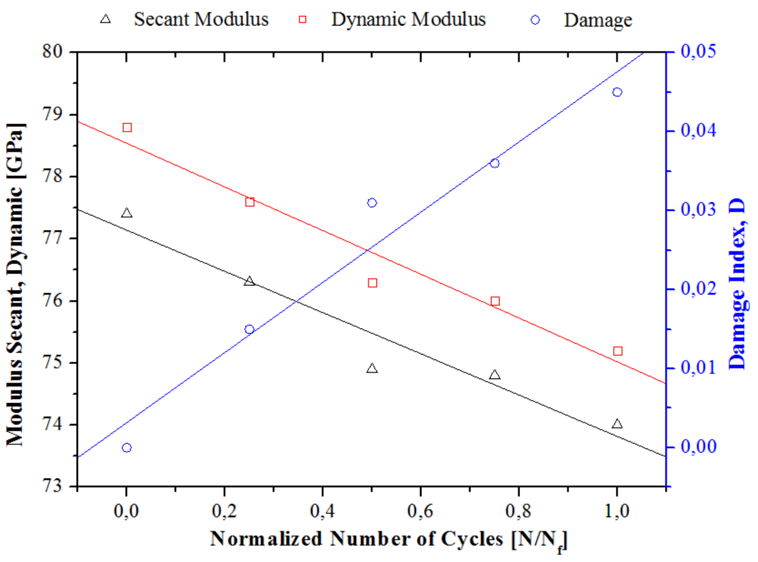

Figure 7: Dynamic and Secant Modulus and Damage Index as a Function of the Number of Fatigue Cycles (N_f=120000 cycles)

Both moduli's decrease as the number of fatigue cycles increase. This decrease is slightly more pronounced for the secant modulus and this is related to the amount of cumulative damage in the material. Related studies pointed out that for thermoset polymers; the secant modulus is lower than the dynamic modulus due to visco-elastic effects [10]. The results show that in composite materials, the visco-elastic effect, although it exists, is less pronounced than in neat polymers; however, the effect is similar. After 120000 cycles, the stiffness reductions in both dynamic and secant modulus were about 4-5% at a load level of 70% of ultimate load.

The damage index is a parameter to indicate the amount of accumulated damage within the material, which varies from 0 to 1. The damage index parameter (D) was quantified by the measurement of modulus each 30000 cycles (up to 120000). Results for damage index are also plotted in Figure 7. The damage index exhibits a sharp increase over the fatigue lifetime. Results from several authors [5, 17, 19, 20] indicate that there are three stages of damage evolution in composites. During the first stage, fatigue damage grows rapidly due to the occurrence of multiple damage modes within the material. The damage increases steadily and slowly during the second stage corresponding to resin matrix failure. Finally in the third stage, the damage grows rapidly due to fiber fracture [20, 21]. In this study, the composite specimens were loaded within the limit strain so only the first stage is observed.

4. Conclusions

This study produced a methodology for determining the limit strain of composite materials based on the results from fatigue tensile tests. Although limit strain could not be accurately identified by relating the residual strength and B-basis values, this approach does define a range of strain values where the limit strain of a material may be obtained. This region is easily identified by observing a change in the material behavior, which is governed by a transition between the survival and failure of specimens during fatigue cycling. The fatigue limit strain observed for the prepreg composite material evaluated was around 8300 to 8700με. This demonstrated the possibility of increasing the typical load level applied to composite structures which is normally in the vicinity of 4000με. Despite limited data points, the S-N curves generated in this work show that the stress limit is around 80% of the normalized ultimate tensile stress level. Hysteresis curves generated from modulus tests conducted at discrete intervals during the fatigue tests, revealed a stiffness reduction of 5% for dynamic and secant moduli. It was determined that hysteresis measurements, acquired during fatigue tests within the limit strain, provide a reliable method for quantifying damage accumulated from fatigue of composite materials. This methodology may be used as a basis for determining material design allowables when fatigue is a critical issue.

5. Acknowledgements

The authors gratefully acknowledge EMBRAER – Empresa Brasileira de Aeronáutica by donation of materials and DCTA by the mechanical testing performed.

6. References

[1]. S. Subramanian, K. L. Reifsnider, W. W. Stinchcomb, A Cumulative Damage Model to Predict the Fatigue Life of Composite Laminates including the Effect of a Fibre/Matriz Interphase. *International Journal of Fatigue,* 17 (1995) 343-351.

[2]. A.R. Chambers, J.S. Earl, C.A. Squires, M.A. Suhot, The Effect of Voids on the Flexural Fatigue Performance of Unidirectional Carbon Fibre Composites Developed for Wind Turbine Applications. *International Journal of Fatigue,* 28 (2006) 1389-1398.

[3]. M. J. Salkind, Fatigue of Composites. *Composite Materials: Testing and Design (Second Conference).* s.l. : American Society for Testing and Materials, 1972, 143-169.

[4]. P. T. Curtis, B. B. Moore, *A Comparison of the Fatigue Performance of Woven and Non-woven CFRP Laminates.* London : Royal Aircraft Establishement, 1985. Technical Report 85059.

[5]. B. Harris, *Fatigue in Composites.* Boca Raton, Florida USA : CRC Press LLC, 2003.

[6]. C. Bathias, An Engineering Point of View about Fatigue of Polymer Matrix Composite Materials. *International Journal of Fatigue, 28 (*2006) 1094-1099.

[7]. J. E. Lindhagen, L. A. Berglund, Temperature Changes in Polymer Composites During Tensile Loading. *Journal of Materials Science.* 32 (1997) 4071-4076.

[8]. L. Toubal, M. Karama, B. Lorrain, Damage evolution and infrared thermography in woven composite laminates under fatigue loading. *International Journal of Fatigue,* 28 (2006) 1867-1872.

[9]. H. T. Hahn, J. Bartley-Cho, S. G. Lim, *The Effect of Loading Parameters on Fatigue of Composite Laminates: Part II.* U.S. Department of Transportation, Federal Aviation Administration. 1997. DOT/FAA/AR-96/76.

[10]. G. Pinter, E. Ladstatter, W. Billinger, R.W. Langer, Characterization of the Tensile Fatigue Behaviour of RTM-laminates by Isocyclic Stres-strain-diagrams. *International Journal of Fatigue,* 28 (2006) 1277-1283.

[11]. V. Barron, M. Buggy, N. H. Mckenna, Frequency Effects on the Fatigue Behaviour on Carbon Fibre Reinforced Polymer Laminates. *Journal of Materials Science.* 36 (2001) 1755-1761.

[12]. G. Minak, On the Determination of the Fatigue Life of Laminated Graphite-Epoxy Composite by Means of Temperature Measurement. *Journal of Composite Materials.* 2010, Vol. 44, pp. 1739-1752.

[13]. R. Steinberger, T.I. Valadas Leitão, E. Ladstatter, G. Pinter,W. Billinger, R.W. Lang, Infrared Thermographic Techniques for Non-destructive Damage Characterization of Carbon Fibre Reinforced Polymers during Tensile Fatigue Testing. *International Journal of Fatigue.* 2006, Vol. 28, pp. 1340-1347.

[14]. Hexcel Composites. Material Data Sheet - F584. Duxford, UK : s.n., 1998.

[15]. Department Of Defense - U.S.A. *Composite Materials Handbook.* 1997. Vol. 1. MIL-HDBK-17-1F.

[16]. H. T. Hahn, J. L. Timmer, J. Bartley-Cho, S. Lee, S. Lim, *The Effect of Preloading on Fatigue Damage in Composite Structures: Part I.* U.S. Department of Transportation, Federal Aviation Administration. Washington, D.C. : s.n., 1996. pp. 1-36. DOT/FAA/AR-95/79.

[17]. H. Mao, S. Mahadevan, Fatigue damage modelling of composite materials. *Composite Structures.* 2002, Vol. 58, pp. 405-410.

[18]. F. Gao, L. Boniface, S.L. Ogin, P.A. Smith, R.P. Greaves, Damage accumulation in woven-fabric CFRP laminates under tensile loading: Part 1. Observations of damage accumulation. *Composites Science and Technology.* 59 (1999) 123-136.

[19]. T. F. Tan, C. K. H. Dharan, Cyclic Hysteresis Evolution as a Damage Parameter for Notched Composite Laminates. *Journal of Composite Materials.* 2010, p. INTERNET.

[20]. F. Wu, W. Yao**,** A Fatigue Damage Model of Composite Materials. *International Journal of Fatigue,* 32 (2010) 134-138.

[21]. C. Li, F. E. Ellyin, A. Wharmby, On Matriz Crack Saturation in Composites Laminates. *Composites: Part B,* 34 (2003) 473-480.