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Fatigue behaviour of a GFRP laminate by thermographic measurements

C. Colombo[a], F. Libonati[a]*, F.Pezzani[b], A. Salerno[b], L. Vergani[a]

[a] *Politecnico di Milano, Department of Mechanics, Via La Masa 1, 20156 Milano, Italy*
[b] *Politecnico di Milano, Energy Department, Via Lambruschini 4, 20156 Milano, Italy*

Abstract

Composite materials are widely used to build structural components, thanks to their mechanical properties. Those are generally considered 'engineering materials', since they are tailored to meet specific requirements. Due to their use for structural components, it is important to know their mechanical behaviour, especially under cyclic loads. At present, there is a common interest, among researchers, to study the mechanical behaviour of composites, by means of both traditional and innovative techniques, with the final purpose of making previsions regarding their service life. In fact, due to their composite nature, they behave in a different mode compared to homogeneous materials. This study is focused on a glass fibre-reinforced plastic (GFRP); the aim of this work is to study its fatigue behaviour, from both the mechanical and the thermal points of view. The main reason is that there is a lack of knowledge, in the literature, about the fatigue of composites. In this study, a GFR laminate was characterized under static and dynamic loading conditions; during the experimental tests, thermal measurements were carried out by means of an IR-thermal camera. Temperature measurements were done during the static tests, whereas in the dynamic tests the dissipated energy was measured, by using the dissipation method (D-mode). Then, various criteria for fatigue life estimation were applied fitting the experimental data. Since different thermographic techniques have been used to estimate the fatigue behaviour, a final comparison between the experimental data and the predicted fatigue behaviour is proposed and discussed, showing a good agreement.

Keywords: Glass fibre-reinforced plastics (GFRP); laminate; fatigue; thermoelasticity; D-mode.

* Corresponding author. Tel.: +39-02-2399-8667; fax: +39-02-2399-8263.
E-mail address: flavia.libonati@mail.polimi.it.

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Nomenclature

α_0	constants of the model in Eq. (1), to be experimentally estimated
α_1, β_1	constants of the model in Eq. (2)-(3), to be experimentally estimated
θ	angle between the fibres and the axis of load application
σ_{max}	maximum stress applied during fatigue loading
σ_u	ultimate static strength, averaged from experimental tests
f	frequency of the fatigue tests
N_f	number of cycles to failure
R	stress ratio

1. Introduction

In the last years, the use of composite materials for structural applications has widely spread, replacing other more common and homogeneous materials (i.e. steel), thanks to their interesting strength/weight ratios. Different composite materials have been developed: considering fibre reinforced composites, a particular category is the glass fibre reinforced plastics (GFRP), object of the present work. This kind of composite has long glass fibres as reinforcement and a polymer matrix.

In light of their use as structural components, it is certainly very important to study their static and fatigue behaviour. Indeed, since the fatigue of composite components is often not known, these structural elements are generally designed using very high safety factors. Hence, the potential of these materials is not exploited, losing the advantage of weight reduction and causing waste of materials.

Moreover, the knowledge of the fatigue behaviour is important not only in the structural design stage, but also for a proper planning of non-destructive testing. It is, therefore, important to provide theoretical models for fatigue life estimation.

The aim of the present work is to evaluate the progressive damage of a fibre-reinforced composite under static and dynamic loads. For this reason, IR-thermography was also used to monitor the damage, which is directly related to an increase in the surface temperature field. Different methods, both mechanical and energetic, are proposed to give an estimation of the fatigue behaviour of the composite. Comparisons among the life estimations are shown in a final discussion of the results.

2. Theory

Before describing the material and the experimental tests, carried out on the composite laminate, a brief introduction on the mechanical fatigue models, developed in the literature and used in the following data analysis, is presented. Also, the theoretical formulation of the thermoelasticity is introduced.

2.1. Fatigue damage models for composite materials

With the aim of understanding the mechanical behaviour of a GFRP laminate and proposing an estimation of the fatigue life, two criteria were selected from the literature to fit experimental data in the σ_{max}-N_f plot. In particular, the first one is the classical linear regression, also known as Wöhler curve. In the case of homogeneous materials, such as steel, this trend line shows a linear plateau starting from the static strength, then a linear finite life part, and finally a fatigue limit; in the case of composites, this is not evidenced from literature studies. In particular, the decrease in σ_{max}-N_f plot is evident from the earlier stage of the fatigue life. Studies in the literature have also evidenced that a real fatigue limit does not exists for composites, but instead the damage is progressive during all the life of the material. [1] In the latter case, the linear Whöler curve has the following formulation:

$$\sigma_{max} = \sigma_u + \alpha_0 \cdot logN_f \tag{1}$$

A second model, able to estimate fatigue life for this kind of materials, was proposed by Epaarachchi and Clausen. [2] It describes the progressive damage of a fibre-reinforced composite under a cyclic load with a constant amplitude and frequency, in terms of residual strength. Its equation is:

$$\sigma_u - \sigma_{max} = \alpha_1 \left(\frac{\sigma_{max}}{\sigma_u}\right)^{0.6-R|sin\theta|} \left[\sigma_{max}(1-R)^{1.6-R|sin\theta|}\right] \frac{1}{f^{\beta_1}} \left(N_f^{\beta_1} - 1\right) \tag{2}$$

From Eq. (2), and defining the damaging parameter D as follows, it is possible to estimate the fatigue life:

$$D = \left(\frac{\sigma_u}{\sigma_{max}} - 1\right)\left(\frac{\sigma_u}{\sigma_{max}}\right)^{0.6-R|sin\theta|} \frac{1}{(1-R)^{1.6-R|sin\theta|}} f^{\beta_1} \quad \Rightarrow \quad N_f = \sqrt[\beta_1]{\frac{D}{\alpha_1} + 1} \tag{3}$$

2.2. Infrared thermography

Infrared thermography (IR-thermography) is a non destructive technique (NDT) widely used in the mechanical and structural fields for damage assessment. It allows for the contactless measurement of the surface temperature distribution of an object. Indeed, after a thermal stimulation, for instance with a lamp, the local surface temperature increments of an object can reveal internal defects and material inhomogeneities. This technique is used for the non-destructive inspection (NDI) of components, especially in the aeronautical field, as it allows quick inspections of large areas. Besides NDI, the IR-thermography is used for damage monitoring, on in-service components, and for stress analyses. In fact, it is a valid tool for the Thermoelastic Stress Analysis (TSA), an experimental method for the stress evaluation, based on the thermoelastic effect. When a homogeneous and isotropic solid is cyclically loaded with a sufficiently high frequency, there is a local variation of the volume, substantially in adiabatic conditions, and a temperature variation arises; the latter is linked to the first stress invariant according to the equation (4):

$$\frac{\delta T}{T_0} = -K_0 \delta\sigma \tag{4}$$

where T_0 is the average temperature of the solid, $K_0=\lambda/\rho C_p$ is the thermoelastic constant, λ is the linear thermal expansion coefficient, ρ the mass density, C_p the specific heat at constant pressure and $\sigma=\delta(\sigma_I+\sigma_{II}+ \sigma_{III})$ is the variation of the first stress invariant. [3]

The general thermoelastic equation for orthotropic materials, in terms of stress components, can be expressed as follows, with the presence of more thermoelastic constants [4]:

$$\delta T = -\frac{T_0}{\rho C_p}\sum_{i=1}^{6}\lambda_i \delta\sigma_i \qquad (5)$$

Moreover, composite materials normally present a surface resin rich layer, few microns thick, which attenuates the thermal waves mainly generated in the fibers, creating a frequency dependency of the thermoelastic constants. [5]

In case of elastic behaviour, the temperature variation is not associated with the irreversible conversion of mechanical power into heat, while in case of inelastic behaviour there is always an irreversible conversion of mechanical power into heat. Therefore, a ductile material, tested in a displacement control mode, presents a first temperature decrease (i.e. increment of the volume) due to the thermoelastic effect in the elastic region, and a subsequent temperature increment due to the heat generation under plastic deformations. Composites show a similar temperature trend, but the latter part (i.e. temperature increment) is due to other dissipation mechanisms, which are in turn relating to their composite nature.

In the past, the experimental study on the thermoelastic effect were carried out by means of contact techniques (e.g. thermocouples), while over the past years, thanks to innovative thermal cameras, it is possible to rapidly obtain a full field thermal map, without any contact need.

The most recent thermal cameras are also endowed with a lock-in amplifier, a useful tool for the TSA. This tool allows the processing of an image sequence, acquired in a modulated load cycle, to determine the amplitude variation and the phase shift of the temperature with respect to the load. In fact, in elastic and adiabatic conditions, a cyclically loaded specimen, presents a cyclic temperature variation with amplitude depending on the amplitude of the load, and a 0° or 180° phase shift with respect to the applied load. In case of non adiabatic conditions, for instance when there is a non uniform stress distribution, the material presents a high thermal diffusivity and the load is applied at a low frequency, there is a heat flow inside the specimen, which attenuates the temperature peaks and produces a phase shift of the modulated temperature. In case of non elastic behaviour, the Fourier analysis of the modulated temperature shows components at frequencies different from those of the modulated load.

3. Materials and experimental setup

The tests were performed on a GFRP made of E-glass/epoxy with a 50% vol. fibre content. Specimens were cut from a laminate plate made of non-crimp fabrics (NCF) with a stacking sequence of $[\pm 45°]_{10}$. The geometry and the dimensions were chosen according to the standard ASTM D 3518/D3518M-94 [6] (Fig 1.a). In order to avoid a localized damage in the grip areas and to ensure a correct load transfer, GFRP tabs were glued at the end of the specimens, , by using an acrylic adhesive.

In most of the tests, henceforward called IR-monitored tests, infrared images of the samples surface were acquired using an IR camera FLIR Titanium working in the waveband 2-5 μm, endowed with a 320*256 Focal Plane Array InSb sensor with a 25 mK thermal sensitivity. The IR camera was endowed with a lock-in module able to analyze a sequence of IR images acquired during a modulated load cycle, in order to determine, pixel by pixel, the amplitude of the modulated temperature and its phase shift with respect the modulated load. This function is normally used to perform a Thermoelastic stress analysis.

In order to have a reference signal, lower than 5 Volt, allowing the Lock-in module to filter the background noise, the camera was connected to the testing machine. The camera was placed approximately 300 mm far from the surface of the specimens; therefore, it was possible to obtain full-field thermal maps of the specimens during the tests. Furthermore, the use of image analysis and the study of the temperature field allowed us to access to more information about the damage of the material under static and dynamic loading conditions.

Damage analyses of this material under static and dynamic loads were carried out by performing three types of tests: 1) IR-monitored static tests; 2) IR-monitored dynamic tests; 3) Fatigue tests.

Then, the experimental data were interpolated with different theoretical models: i) the Wöhler model for composites [1], ii) the Epaarachchi-Clausen model [2], iii) an experimental equation obtained by interpolating the GFRP data of the Mandell's database [7,8]. A final comparison of the obtained results is made to give an estimation of the fatigue behaviour of the studied material in the finite life region.

3.1. IR-monitored static tests

Static tests were carried out using a universal tensile testing machine (MTS Alliance RF150) with a load cell of 150 kN. The experimental setup is shown in Fig.1.b. All the tests were performed in displacement control mode, choosing a cross-head speed of 2 mm/min and a stress-strain data acquisition frequency of 5 Hz. For each specimen it was possible to evaluate, during the test, the temperature trend of the scanned surface. In this case, the thermal data acquisition frequency was set at 1 Hz.

3.2. IR-monitored dynamic tests

Dynamic tests were performed using an MTS 810 hydraulic machine with a load cell of 100 kN. The IR-monitored dynamic tests consisted of applying the load at different load levels for a certain number of cycles (i.e. 10^3 cycles for each load step). Those tests were performed in load control mode, starting from a low load level (σ_{max} = 16 MPa) and stepwise increasing the load, by 2 MPa, until the stress of 44 MPa has been reached. A schematic representation of the load history is given in Fig.3.b. For all the tests, the stress ratio was equal to 0.1 and the frequency was set to 20 Hz. For each load step, the specimen surface was scanned by using the dissipation measurement mode (i.e. D-mode), a tool of the thermal camera to evaluate the intrinsic dissipation of an object under dynamic loading conditions. In fact, the lock-in module of the IR camera, besides being able to carry out a thermoelastic stress analysis, allows you to perform the so called D-mode analysis, which shows pixel by pixel a result different from zero, if the temperature has components at frequencies different from those of the applied load. The D-mode signal should not be interpreted as a signal proportional to the energy dissipated in a cycle. It is just an indication that in the frequency domain there are components at frequencies different from those of the applied load. The D-mode signal becomes higher when these components become more important.

3.3. Fatigue tests

On the basis of the first results, obtained from the static and dynamic tests, it was possible to plan a series of fatigue tests to characterize the fatigue behaviour of the studied material. Fatigue tests were performed, according to the standard ASTM D 3479/D 3479M-96 [9], at different load levels to determine the σ_{max}-*LogN* curve of the material in the finite life region. In this case, we considered as finite life region the one between 0 and $5 \cdot 10^6$ cycles. The limit $5 \cdot 10^6$ cycles was chosen as an average value, considering those found in the literature. [1] The correspondent stress, henceforward called *fatigue strength*, is not the fatigue limit of the material, but the stress at the end of the estimated finite life region. In all the tests, the stress ratio was equal to 0.1 and the frequency was set to 10 Hz.

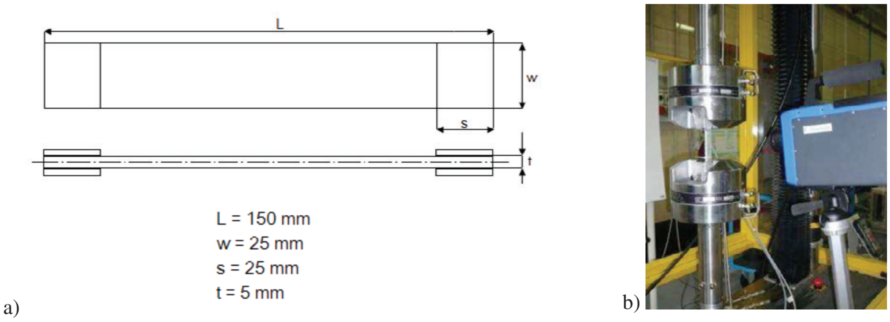


Fig. 1. (a) Geometry and dimension of the specimens; (b) experimental set-up.

4. Results and discussion

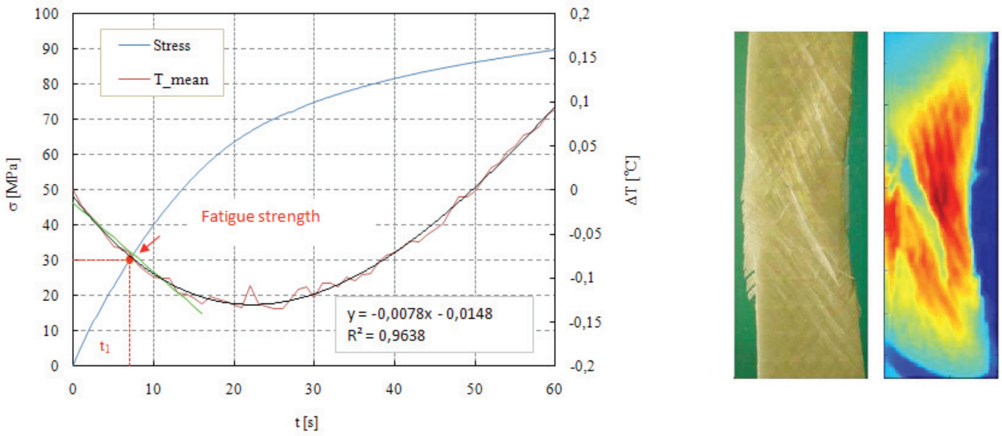
The results of all the tests had a good repeatability and a low scattering. The experimental data were firstly analysed and then used to make estimations, by means of different mechanical models, of the fatigue behaviour of the studied material. These results, obtained from the three types of tests, are presented in the following paragraphs.

4.1. IR-monitored static tests

In the static tests, all the specimens had a similar temperature trend characterized by three zones: i) an initial decreasing zone, ii) a zone of minimum, iii) an increasing zone until the final rupture. An example of this trend, referred to the scanned area of one of the specimens, is given in Fig.2.a. Generally, a hot region on the surface of the sample was clearly visible in the first seconds of the test; therefore, it was possible to locate the damaged area, since the beginning, by observing the thermal maps, so as to make previsions about the zone of failure. In addition, the thermographic technique allowed a qualitative analysis of the failure modes. In fact, during the tests, it was possible not only to see the hottest regions, but also subsequent flashes of lighting, probably due to the energy release at the fibre-matrix interface. Hence, it was likely to have an idea of the modes of failure (mainly due to delamination and fibre-matrix disbonding), later confirmed by microscopic analyses. In Fig.2.b a comparison between the picture of the final failure of the specimen, and the correspondent surface thermal map is given.

Moreover, the damage evolution could be monitored by studying the thermal profile. This analysis allowed the identification of an initial trend, linearly decreasing with a certain slope, and a temperature limit, which represents the end of the linear thermoelastic part. By using regression analysis, the temperature limit was determined and then correlated with a stress value, by overlapping the two curves (see Fig.2.a). A linear regression analysis was performed on the experimental data, to define the initial linear trend and the end of this part. The data in the linear region were chosen as those giving the highest correlation coefficient, which is also shown in Fig. 2.a. From the Fig.2.a, it is clear that the end of the linear trend corresponds, on the time scale, to t_1; the temperature value, which corresponds to t_1, was called temperature limit, while the stress correspondent to t_1 was called fatigue strength. In this way, a first estimation of the fatigue strength was given. This value could be related to the beginning of the first micro-damages in the material.

Then, after an accurate analysis of the stress-time and the temperature-time curves, an estimation of the σ_{max}-N_f curve in the finite life region could be proposed. Indeed, according to the literature [10,11] it is possible to determine, by means of one static test coupled with an IR-thermographic analysis, the fatigue limit for homogeneous materials. This value corresponds, on the surface temperature profile, to a temperature limit, which coincides with the end of the linear thermoelastic behaviour of the studied material. In this case, being the tests performed on a heterogeneous material, this cannot be considered as the fatigue limit, but the fatigue strength (i.e. the stress correspondent to a life of $5{\cdot}10^6$ cycles).



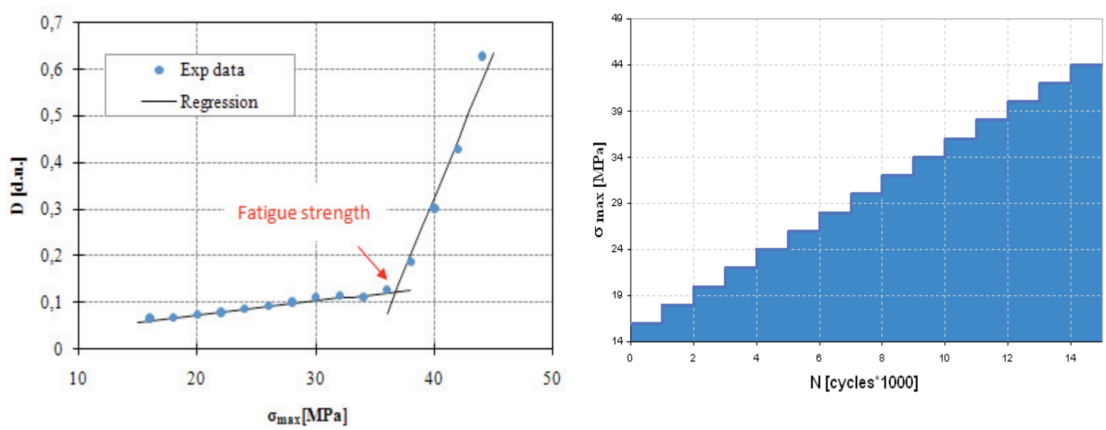
a) b)

Fig. 2. (a) Stress and thermal profile during a static test; (b) comparison between the final failure and the correspondent thermal map.

4.2. IR-monitored dynamic tests

Another estimation of σ_{max}-N_f curve in the finite life region was given by performing dynamic tests: indeed, by using the obtained value of the stress limit (30 MPa), it was possible to plan a series of stepwise dynamic tests, choosing an appropriate sequence of load-steps to apply. These dynamic tests were IR-monitored and the value of the intrinsic damage was calculated, for each load-step, by using a specific algorithm of the camera, as explained in the previous paragraphs. In fact, the camera is able to give the value of this dissipation (D) for each load level. Generally, if the material is in the elastic field, the increase in the D-signal is negligible, whereas, in case of damage the increase in the D-value is considerable. According to the literature [12], the D-mode can be used to assess the fatigue limit of most material; the stress, which corresponds to a sudden increase of the D-signal, can be considered a good estimation of the fatigue limit of homogeneous materials. Nevertheless, in the case of composites we are not sure if this can be considered a fatigue limit. [1]

All the data were collected in a graph; then, by means of a bi-linear interpolation, as shown in Fig.3.a, it was possible to determine the point of intersection and find the correspondent value of the stress, which was equal to 36 MPa. This value, which corresponds to a sudden increase of the dissipation, was used to make another estimation of the fatigue strength of the studied material. It should be noted that this value is not so different from the one found by means of the static tests.

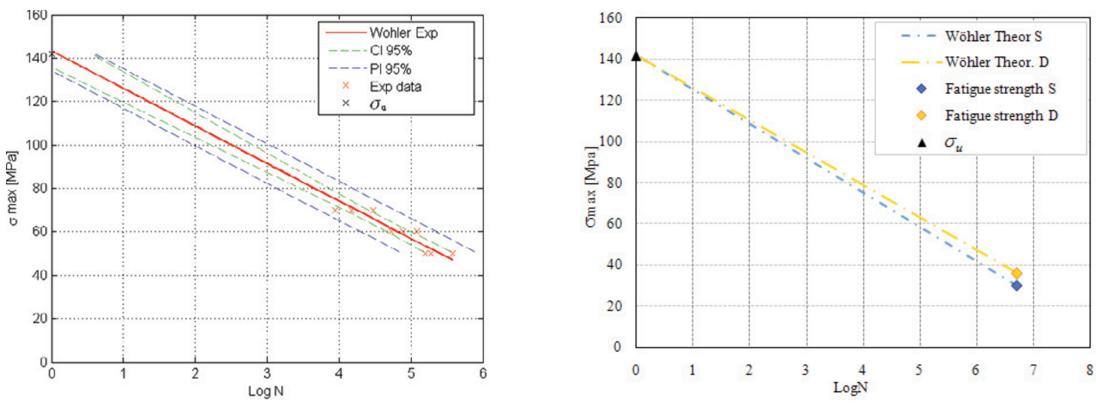


a) b)

Fig. 3. (a) Bi-linear interpolation of the experimental data of dynamic tests; (b) schematic representation of the stepwise dynamic tests: load history.

4.3. Fatigue tests: prediction laws and final comparison

The two estimated values of the fatigue strength and the value of the static strength, experimentally determined in the static tests, were used to define two experimental linear prediction laws for the fatigue behaviour of this material in the finite-life region; these prediction laws, called ‘Wöhler Theor. S’ and ‘Wöhler Theor. D’ respectively, are shown in Fig.4.b. Thanks to these prediction laws, it was possible to schedule a series of fatigue tests to characterize the behaviour of the material in the finite-life region. The experimental data were interpolated by using the Wöhler model for composites (called Wöhler Exp.), as shown in Fig.4.a, and the Eparaachchi-Clausen model. In addition, another comparison was made by interpolating the data with an experimental law, determined by fitting all the GFRP-data included in Mandell’s database. [7,8] Finally, all the data were collected in a unique graph, with the aim of making a final comparison (see Fig.5). It is clear, from the graph shown in Fig.5, that there is a good agreement among all the methods used to estimate the fatigue finite life curve of the studied material. In particular, the Wöhler model for composites and the experimental law for GFRP [8] show a good agreement with the predictions made by using the experimental data of the IR-monitored static tests (i.e. Wöhler Theor. S). On the contrary, the Eparaachchi-Clausen model better agrees with the predictions made by means of the IR-monitored dynamic tests (i.e. Wöhler Theor. D).



a) b)

Fig. 4. (a) Experimental data of fatigue tests; (b) Experimental linear prediction laws for the fatigue behaviour of the material in the finite-life region.

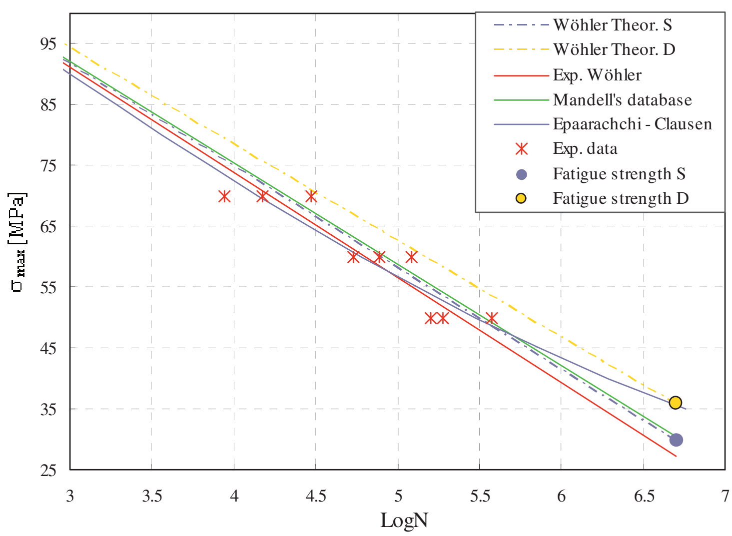


Fig. 5. Interpolation of the experimental data with different models: final comparison. Magnification in the region (3÷7) $*10^6$ cycles.

5. Conclusions

In this study, experimental tests on specimens from a GFRP laminate were presented. The aim of these tests was to study the fatigue behaviour of this material and to provide valid models for its fatigue life estimation in the finite life region. The estimation of the material life was proposed by three mechanical models and two thermal techniques. In light of the presented results, it is possible to assess that:

- The experimental tests showed a good repeatability and low data scattering;

- The fatigue strength was estimated by means of two thermal techniques, showing a good agreement;
- The estimations of the material life in the finite life region made by means of the IR-thermography showed a good comparison with those made by using literature models.

Therefore, we can consider the IR-thermography a valid tool for damage analysis of composites under various loading conditions. Moreover, this technique can be used to estimate the fatigue behaviour of GFRP composites.

As future perspectives we aim to deepen this study, to understand the physical meaning of the fatigue strength for this material. At present, we cannot ensure that this value represents the end of the finite life region, as it is not known if an infinite fatigue life exists yet; it can probably mean the beginning of a new finite life region correspondent to a higher number of cycles.

Perhaps the finite life region is not well described by a single line; two lines instead, may better describe this material high cycle fatigue behaviour. Therefore, the fatigue strength is likely to represent the beginning of damage on a different scale (e.g. for stresses lower than the fatigue strength damage happens at the mesoscale, while for higher stress values, damage is at the microscale).

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