ACCELERATED FLEXURAL FATIGUE TEST RIG TO CHARACTERIZE HIGH STRENGTH COMPOSITE MATERIALS

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Keywords: fatigue test rig, five-point bending setup, composite materials.

Abstract

An accelerated flexural fatigue test rig was developed in which imposed displacements are mechanically controlled. For bending tests, frequencies up to 20 Hz and large strains are simultaneously possible. The innovative feature of the test is the design of a five-point bending (5PB) setup with rotating supports, which allows applying bidirectional deformation with boundary conditions similar to a clamped one allowing to apply high strain values with small displacements of the load points. Test rig description and the control program which permits changing the load rate and the speed are presented. Geometrical corrections in bending test setups are presented taking into account the specific boundary conditions of the aforementioned supports. The test rig is validated by comparison with a universal fatigue testing machine. The application of a fatigue statistical model is presented to correlate different fatigue tests, reducing the required amount of tests to obtain the material fatigue properties. Finally, composite T700 fatigue properties are presented applying the proposed test setup and statistical model.

1. Introduction

Composite materials exhibit in addition to high rigidity and specific strength, high fatigue resistance. Technologies as wind-turbine demanding to use composite materials a stringent knowledge of fatigue behaviour [1]. Large time are required to fatigue characterization of the composite material using the conventional machines and numerous efforts have been dedicated to develop commercial machines, test rig and techniques to accelerate the process of characterization, for example [2, 3]. Frequently flexure configurations are used for the study of composite materials which is appreciated in [4-9]. With the goal of reduce the long-time tests to predict the fatigue life, statistical models as [10, 11] have been proposed.

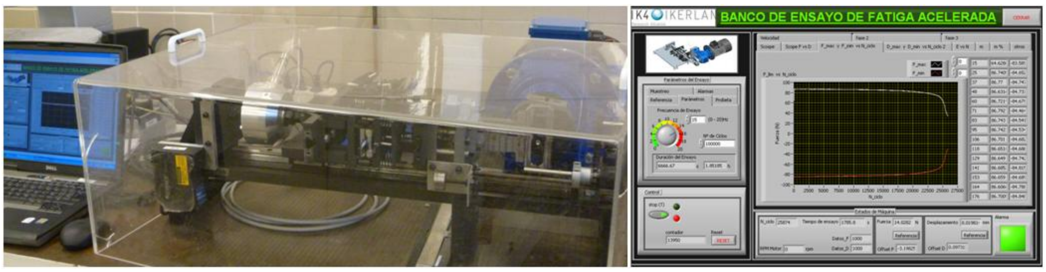


Figure 1. Accelerated flexural fatigue test rig.

In present work an accelerated flexural fatigue test rig, designed and built in IK4-IKERLAN, allowing to accelerate this type of testing is proposed (Figure 1).

2. Test rig description

2.1. Overview

The test rig consists of four different parts: the motion generation system, the motion transmission mechanism, the measuring system and the test fixture. In Figure 2 is represented a simple scheme of the work principle of the test rig.

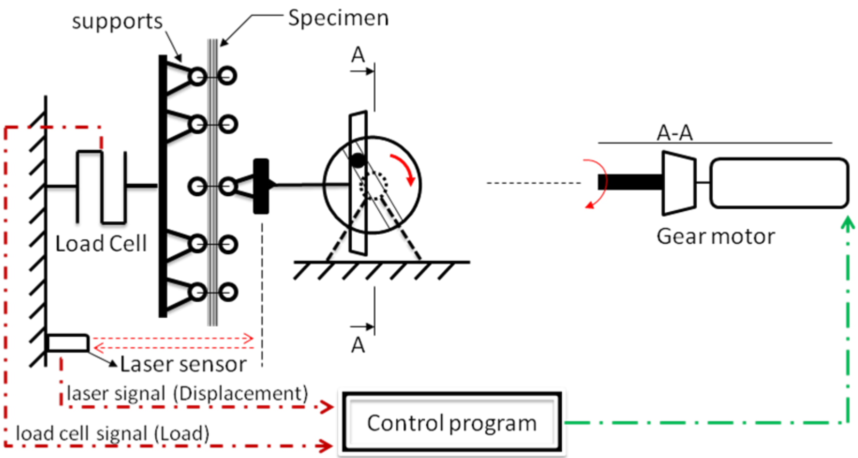


Figure 2. Basics of test rig operation

According to the installed power, the frequency of testing that allows the test rig are between 0 to 20 Hz, and it is independent of the magnitude of load and displacement applied due to the displacement control is purely mechanic allowing to apply large displacements and high frequencies simultaneously.

An important aspect to consider is the reliability of the results that can give the test rig and to ensure it, quasi-static tests are performed and compared with trials in the Universal Testing Machine, Figure 3.

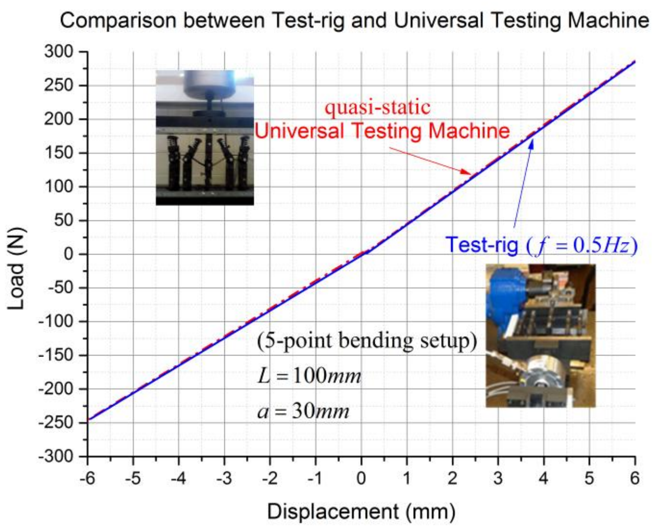


Figure 3. Comparison of the measurements obtained with the Test rig and a Universal testing machine.

In Figure 3 can be seen that the results obtained with the acquisition system of the Test rig are similar to those obtained by the Universal Testing Machine. The same test has been repeated for frequencies until 20Hz and no hysteric behaviour or heating of the test specimen has been appreciated, obtaining the same response of the force displacement curve for the whole range.

2.2. Boundary conditions setup

As was previously commented, bending setup is commonly used for fatigue characterization of composite materials. In [7] is performed a comparison between three and four points bending setup.

In present work is proposed a five point bending setup using supports designed at IK4-Ikerlan which can be seen in Figure 4. Five point bending setup is an intermediate alternative between the 3-point and clamped setup that present some advantages:

- Allow bidirectional testing.
- It can be considered partially clamped support, reducing high concentrations that produce a pure setup clamped.
- The bending test configuration by 5 points allows greater forces to apply the same levels of imposed displacements, in comparison with 3 and 4 points setup. It can be almost assimilated to a clamped boundary condition.
- As the cycle displacement is reduced, small displacement hypothesis can be used to post process the data. Also strain rate deformation is the test specimen is kept at a low level.
- In addition, the designed supports have free rotations around its axle, and one of the supports can rotate around a fixed axle. This feature allowing the supports to follow the curvature of the test specimen under load condition and assuring only a normal force contact against the specimen. This feature assures that no axial load are applied to the test specimen.

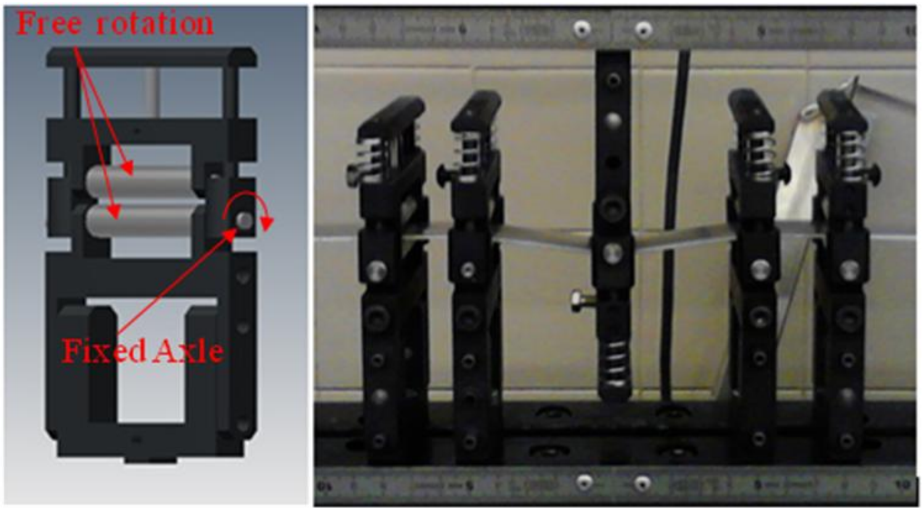


Figure 4. Rotating support and 5-point setup proposed

2.3. Evaluation of the specimen degradation

Change in the flexure modulus of the specimen is proposed to evaluate the degradation during life fatigue test. This value depends on the young modulus of the material under test and the setup geometry, and can be obtained from the measured force displacement curve. In paper [9] was discussed the influence of the rotation and the distance variations at supports and load rollers due to the variation of the contact zone between the specimen and the support. A methodology was developed to consider this effect in 3 and 4 point setup and the necessary corrections were determined in these cases.

The proposed setup with rotating supports exhibit a non symmetric behaviour in positive and negative displacement caused mainly by the rotation around a fixed support. This lead to the necessity of correcting the analytical formulas to take into account the non linear behaviour due to the geometric displacement and calculating the instant flexural modulus along the force displacement curve.

Following a similar procedure proposed in [9], Figure 5 an analytical formula, is obtained for the five point bending setup to obtain the flexural modulus by an arithmetic average equation (1). This allows taking into account these geometric effects and obtaining the flexural modulus during the fatigue test from the experimental measurement

$$\bar{E} = \frac{1}{n}\sum_{1}^{n} E_{\mathrm{i}} \qquad (1)$$

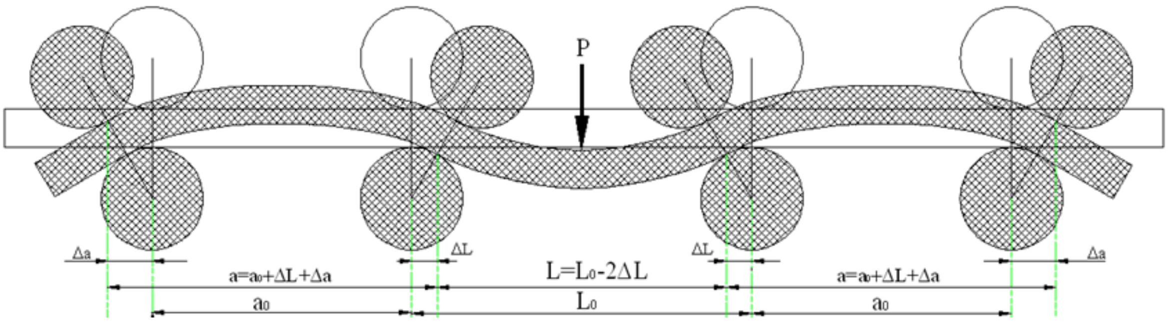


Figure 5. Scheme for the analysis of the necessary geometric correction.

The instantaneous modulus of bending E_{i} is obtained by (2).

$$E_{\mathrm{i}} = \frac{P_i\left(\psi_1 + \psi_3 P_i + \sqrt{\psi_3^2 P_i^2 + \left(2\psi_1\psi_3 - 4\psi_2\psi_4\right)P_i + 4\psi_2\delta_i + \psi_1^2}\right)}{2\left(\delta_i - \left(\psi_4\right)P_i\right)} \qquad (2)$$

where: P_i, δ_i are load and displacement instantaneous during the fatigue cycle;

$$\psi_1 = \frac{L^3}{48I}\left(\frac{3L+8a}{12L+8a}\right); \quad \psi_2 = \frac{L^4 a}{48I^2}\left(\frac{aR\left(480a+144L\right) - 27L^2\left(R+t\right)}{32\left(3L+10a\right)\left(3L+2a\right)\left(9L+2a\right)}\right)$$

$$\psi_3 = \frac{3L^2}{10AIG}\left(\frac{Ra}{36L+8a}\right); \quad \psi_4 = \frac{3L}{10AG}$$

L : initial span length; a : distance to external supports; R : Radius of the cylindrical supports; t :specimen thickness; I, A :moment of inertia and area of cross section on specimen; G : shear modulus.

The equation (1) and (2) is used by the control program to determine the flexure modulus in real time, which is used as material degradation criteria during fatigue tests.

2.4. Statistical processing

For the fatigue behaviour, statistical procedures are implemented for the purpose of processing the experimental data and estimate the characteristic parameters. Has been selected the model proposed in [11] and implemented the equation (3).

$$p_f\left(N,\Delta\sigma\right)=1-e^{-\left(\frac{(logN-B)(log\Delta\sigma-C)-\lambda}{\phi}\right)^{\beta}};\left(logN-B\right)\left(log\Delta\sigma-C\right)\geqslant\lambda \tag{3}$$

where: p_f -probability of failure; N -number of cycles to failure; $\Delta\sigma, \Delta\varepsilon$ - level of stress / strain imposed; B -threshold value of lifetime; C -endurance limit; λ -parameter defining the position of the zero percentile; ϕ -scale factor; β -shape parameter of the Weibull distribution.

The statistical model proposed by [11] minimizes the number of samples needed to study the fatigue life of materials through experimental tests due it considers different compatibility conditions, the principle of the weakest link and some statistics and physical considerations.

3. Material properties

The material studied was a composite laminate $\left[0,45,90,-45\right]_S$ with carbon fibber (T700s) and epoxy matrix. Specimens were used as shown in Figure 6.

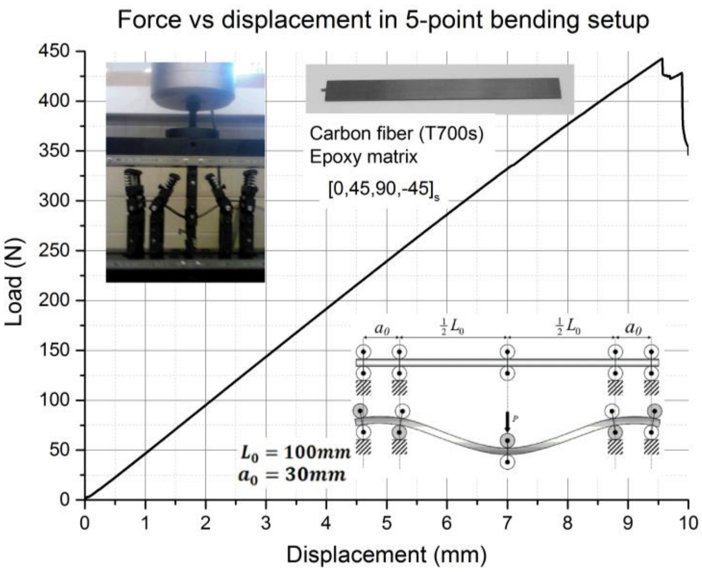


Figure 6. Static five point bending test until failure.

The geometric properties of the setup for the five point bending and the specimen are given in Table 1.

Parameter	Value [mm]
Specimen width (b)	25
Specimen thickness (t)	1.5
Span between supports (L)	100
Distance outside support (a)	30

Table 1. Geometric parameters used during the tests.

The Young modulus obtained was $E = 68884$ MPa. The shear modulus also was obtained previously and result $G = 26200$ MPa.

3. Materials fatigue life testing

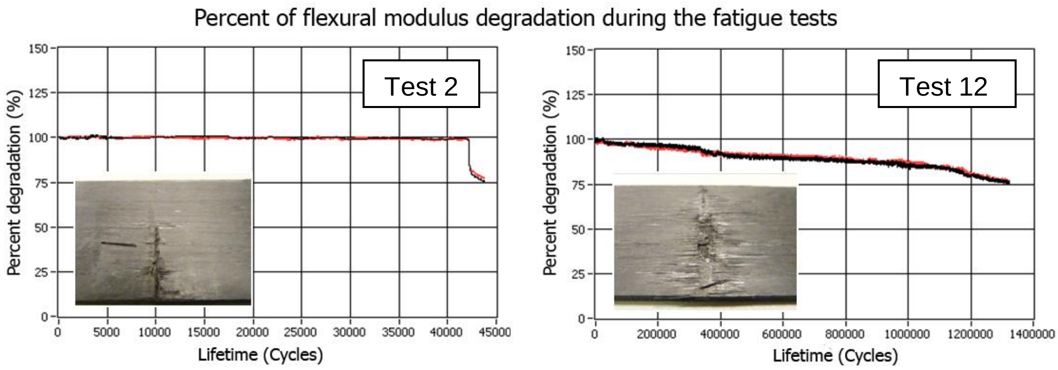
To obtain the fatigue behaviour, fifteen specimens of composite material were tested for six different load levels using the test rig. The fatigue experimental results are shown in Table 2.

Test	Maximum Displacement [mm]	Maximum Load [N]	Number of cycles up to 25 % of degradation Nc
1	8.3	406.4	12135
2	8.15	399.1	21879
3	8.15	399.1	18645
4	7.3	357.4	64990
5	7.3	357.4	34982
6	7.3	357.4	51469
7	7.0	342.7	102473
8	7.0	342.7	91852
9	6.5	318.2	301453
10	6.5	318.2	195237
11	6.3	308.4	936402
12	6.3	308.4	661892
13	6.3	308.4	435599
14	6.3	308.4	1000000
15	6	293.8	1000000

Table 2. Experimental fatigue test results.

The tests were conducted at a frequency of 15 Hz and as frequency is independent of the load level, the duration of the all tests (machine time) is: 91,28 h (3,8days). It is an important aspect, because in a conventional dynamic machine with hydraulic control to high levels of loads, the frequencies tests are significantly reduced.

Using the flexural modulus as failure criteria when it has decreased 25 % respect the initial value are obtained results as shown in Figure 7.



a) high load level b) low load levels

Figure 7. Percent of flexural modulus degradation of the material.

In Figure 7 it can be noted that for high levels (a) of load fatigue breakage occurs suddenly in the 0º laminate, while lower levels (b) for the flexural modulus degradation occurs gradually.

Using the statistic program based on [11] methodology is obtained the statistical parameters that best fits the model given in Table 3. The convergence of the model is produced properly.

Statistic parameter estimated	Value
β	11.21
B	7.17
C	-4.92
ϕ	0.78
λ	0.45

Table 3. Statistical parameters obtained.

The results are represented graphically in terms of $\varepsilon - N$; it can be seen in Figure 8.

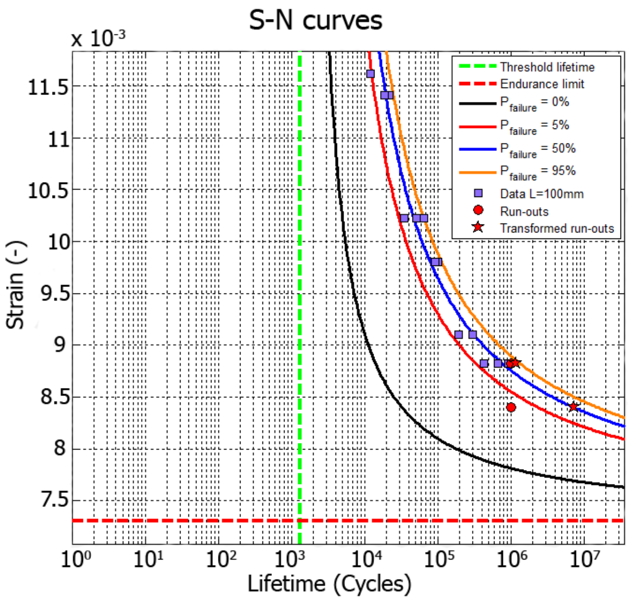


Figure 8. ε-N curve obtained.

The fatigue limit (endurance) of the material studied in deformations is $\varepsilon_{\lim} = 0.73\%$ and can be said to 1323 cycles (threshold lifetime) the specimen will not fail to fatigue.

3. Conclusions

1. The mechanical control used to loads applied, the configuration of a bidirectional five bending setup and statistical processing which was used, allowed a significant reduction of the time required to a fatigue characterization of a composite material using the test rig.
2. The proposed supports allow applying a high level of strains with a small displacement of the test specimen.
3. The corrections proposed for flexure configurations allowed proposed corrections for flexure configurations allowed the correction of the measured values achieving more accurate results over the entire force displacement curve.
4. The experimental characterization of the fatigue behaviour of composite materials studied, provided results in a relatively small time, showing the effectiveness of the Test rig for the characterization of materials fatigue.
5. A fatigue life curve for the laminate $[0,45,90,-45]_S$ with carbon fibber (T700s) is obtained.

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