THE EFFECT OF FREQUENCY ON FATIGUE BEHAVIOUR OF GRAPHITE-EPOXY COMPOSITES

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Keywords: Graphite-epoxy, fatigue, frequency, testing.

Abstract

The present use of graphite-epoxy composites in aircraft primary structures causes the knowledge of their fatigue behaviour to become an important task. Fatigue behaviour of these materials is usually characterized by S-N experimental curves. A significant parameter in the performance of the dynamic tests is the frequency of the applied load.
The objective of this paper is to study the effect of different values of frequency on the configuration of the S-N curve for a graphite-epoxy composite. For this purpose, two types of materials have been considered: unidirectional tape and fabric laminates. Fatigue tests under tension-tension at different orientation angles and for several frequency values have been carried out. The results show that, only in the case of fabric laminates under off-axis tension, the effect of frequency becomes a remarkable parameter in the fatigue behaviour.

1. Introduction

As related literature suggests, load frequency has a dual effect on the fatigue behavior of composites. When the rise in temperature associated with hysteretic heating is not significant, fatigue life can increase with increasing frequency. This fact has been observed in graphite/epoxy [1] and glass/epoxy [2] angle-ply laminates for frequencies lower than 5Hz, and has been associated to a creep phenomenon. On the other hand, when the rise in temperature is significant, fatigue life can decrease with increasing frequency. This has been associated to a matrix thermal degradation, and has been observed in graphite/epoxy quasi-isotropic [3,4] and graphite/PEEK angle-ply [5] laminates. The last effect has been observed also in fabric laminates, for glass-vinylester [6] in both orientations cross-ply and angle-ply, and for graphite-epoxy [7] only in angle-ply configurations.

The aim of this work is to elucidate why the load frequency affects the fatigue behaviour of some graphite-epoxy laminates at some frequency ranges. In the first part of this paper the characterization of a unidirectional carbon fibre composite material under fatigue loads is presented. The objective of the study is to obtain the S-N curve (stress vs. number of cycles to failure) of the material at several frequencies and for different fibre orientation angles, in order to allow to observe the influence of frequency. For this purpose, for unidirectional laminates oriented at 0, 15 and 45 degrees, fatigue tests under tension-tension for several frequencies (10 Hz, 15 Hz and 18 Hz) have been carried out. Then, results for different orientation have been compared using a non-dimensional representation (Kawai [8]). In a second part of this work a graphite-epoxy fabric laminate has been considered. Fatigue tests under tension-tension at 0º/90º and ±45º degrees for several frequencies (10 Hz and 15 Hz for 0º/90º, and 2 Hz and 8 Hz for ±45º) have been carried out. Also, results for different orientations have been compared using the same non-dimensional representation employed in the above configuration.

2. Coupons and test preparation

Two types of tests have been carried out: static and dynamic tension tests. To obtain the coupons for these tests several panels have been manufatured. The manufacturing of the panels have been done using a vacuum bag for the compaction of the layers and an autoclave for the curing process. Once cured, the panels have been machined in a diamond disc saw to obtain the coupons with the correct dimensions. Previously to this step, tabs have been adhered to the sides of the panel to improve the grip of the clamps to the coupons during the tests.

In the case of the static test, the objective is to obtain the maximum strength of the coupons for each fibre orientation. Once the ultimate strengths are obtained, these values are used to define the stress levels for the dynamic tests, calculated as a percentage of the maximum strengths. The dynamic tests will show the number of cycles that the material is capable to resist at each stress level. The curve that approximate these values is called the S-N curve of the material.

The static tests have been done in an Instron 4482 electromechanical testing machine controlling the displacement at a speed of 0.5 mm/min. The dynamic tests have been done in an Instron 8801 hydraulic testing machine controlling the load, using a sinusoidal function with a parameter *R* of 0.1, *R* being:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{1}$$

As said before, $\sigma_{\max}$ is calculated as a percentage of the maximum tensile static strength.

During fatigue tests, a thermocouple has been placed on the coupons to measure the temperature of the material.

2.1. Unidirectional tape

In both cases, static and dynamic tension tests, the dimensions of the coupons are the same, i. e., 10 mm width and 200 mm length and 1 mm thickness, according to the standards ASTM D3039 [9] for the static tests and ASTM D3479 [10] for the dynamic tests. To obtain these coupons of a graphite/epoxy (AS4/8552) material, three panels of 4 layers each have been manufactured, one for each fibre orientation (0º, 15º and 45º). Two coupons have been tested for each orientation and for each kind of test.

The frequencies used in the tests have been 10 Hz for the reference configuration and a higher frequency (15 Hz in the case of the 0º coupons and 18 Hz in the case of the 15º and 45º coupons) to observe the effect of the frequency increase. The difference in the highest frequencies has been caused due to the limits of the testing machine.

A view of a dynamic test and of three coupons after testing is shown in figure 1.

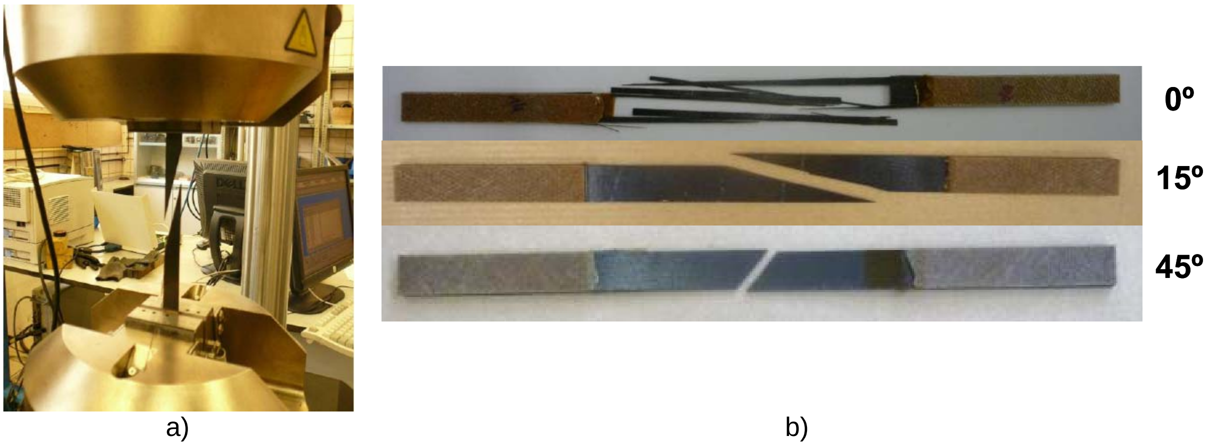


Figure 1. a) View of a dynamic test. b) Three coupons after testing, one of each orientation.

2.2. Fabric laminates

The dimensions of the coupons for fabric laminates are 14 mm width and 200 mm length and 1 mm thickness, according to the standards ASTM D3039 [9] for the static tests and ASTM D3479 [10] for the dynamic tests. To obtain these coupons of a graphite/epoxy (AS4/8552) material, four panels of 6 layers each have been manufactured, two for each orientation (0º/90º and ±45º).

In the case of the 0º/90º coupons, the frequencies used in the tests have been 10 Hz for the low level and 15 Hz for the high level. The reason for this choice is the evidence pointed by Reis et al. [11], who observed that no heating appeared in graphite-epoxy 0º/90º fabric specimens during fatigue tests at 10 Hz. In the case of the ±45º coupons, the frequencies used in the tests have been 2 Hz for the low level and 8 Hz for the high level, because, as is shown by Kawai and Taniguchi [7], angle-ply fabric laminates can be affected by the load frequency at lower values than cross-ply.

3. Test results and analysis

The results of the tests are presented next for unidirectional tape, and then for fabric laminates.

3.1. Unidirectional tape

3.1.1. Static tests

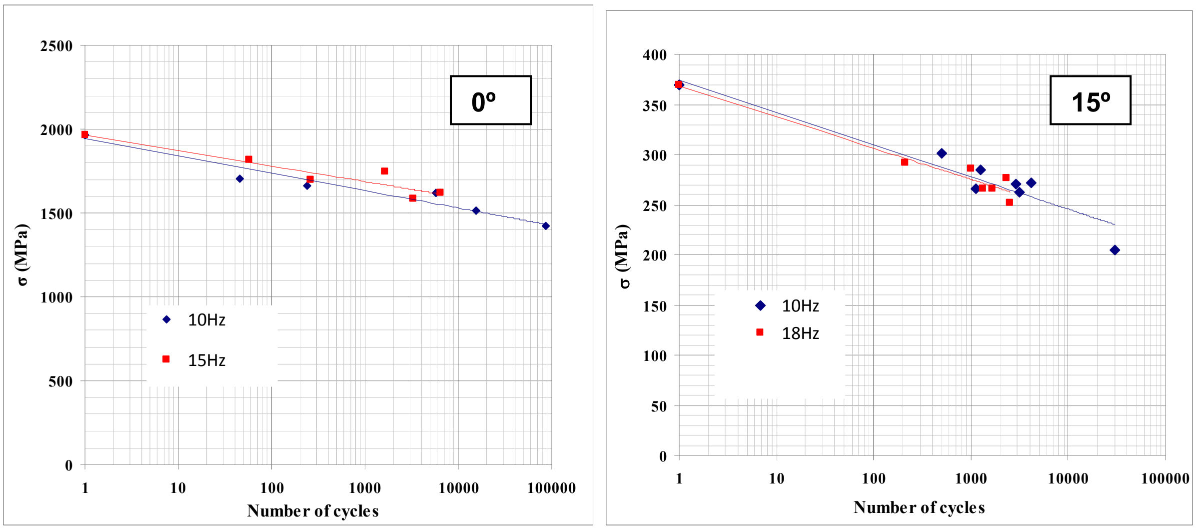
The mean values obtained from the results of static tests are shown in table 1. These values have been used to obtain the loads for the dynamic tests.

Orientation angle (deg)	Tensile Strength [MPa]
0	1948
15	369
45	95

Table 1. Mean values of the static tensile strength for on-axis and off-axis orientations.

3.1.2. Dynamic tests

The 0º coupons have been tested at 90, 85, 75 and 70% (for the frequency of 10 Hz) and 90, 85, 82 and 80% (for the frequency of 15 Hz) of the maximum static strength. The values of the cycles needed to reach the failure in the coupons at these stress levels were obtained. All these values for the two frequencies tested (10 Hz and 15 Hz) and the trend lines that approximate best these points are shown in figure 2(a).



(a) (b)

Figure 2. S-N curves for: (a) 0º coupons at 10 Hz and 15 Hz, (b) 15º coupons at 10 Hz and 18 Hz

As in the previous case, the values and the trend lines for the 15º coupons are presented in figure 2(b), for load levels of 85, 75, 70 and 65% (for the frequency of 10 Hz) and 80, 75, 70 and 65% (for the frequency of 18 Hz) of the maximum static strength.

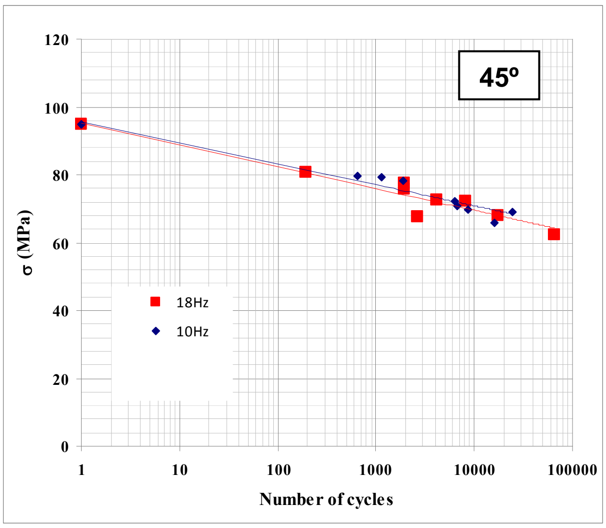


Figure 3. S-N curves for the 45º coupons at 10 Hz and 18 Hz

The values and the trend curves for the 45º coupons are presented in figure 3, for load levels of 85, 80, 75 and 70% (for the frequency of 10 Hz) and 90, 85, 80, 75, 70 and 65% (for the frequency of 18 Hz) of the maximum strength.

3.1.3. Analysis of the results

It can be seen that the results follow a law

$$\sigma = A \log N + B \quad (2)$$

A and B being constant values. The results show a low scattering from this trend.

The evolutions presented in figures 2-3 show that there is almost no effect of the frequency in the S-N curve of the unidirectional laminates. Only in the case of the 0º coupons a little influence of the frequency can be appreciated.

As said before, a thermocouple was used to measure the temperature of the coupons during the tests. After completing the test campaign, it can be asserted that no rise in the temperature of the coupons in the unidirectional composite parts under fatigue loads in the range of life studied was appreciated.

To compare the different orientations, a dimensionless parameter (Kawai [8]) has been chosen, given by the stress (σ) divided by the maximum strength (σ_{max}) for each orientation. The evolution of the fatigue life with this dimensionless parameter is presented in figure 4. Due to the distribution of the experimental results when representing them with the dimensionless parameter, a relatively narrow band covering all of these values can be drawn, as shown in figure 4. In this way, the fatigue behavior of unidirectional laminates can be approximately estimated, for any orientation, from the knowledge of the fatigue behavior of a 0º orientation laminate.

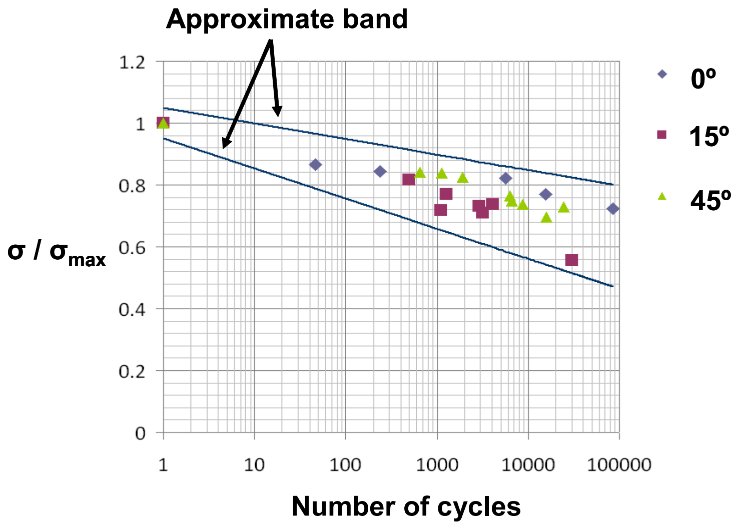


Figure 4. Dimensionless comparison of the S-N curve for the 0º, 15º and 45º coupons

3.2. Fabric laminates

3.2.1. Static tests

The mean values obtained from the results of static tests are shown in table 2. These values have been used to obtain the loads for the dynamic tests.

Orientation angle (deg)	Tensile Strength [MPa]
0/90	798.3
±45	209.2

Table 2. Mean values of the static tensile strength for cross-ply and angle-ply cofigurations.

3.2.2. Dynamic tests

The 0º/90º coupons have been tested at 95, 90, 85, 82, 80 and 75% (for the frequency of 10 Hz) and 95, 90, 85, 82 and 80% (for the frequency of 15 Hz) of the maximum static strength. The values of the cycles needed to reach the failure in the coupons at these stress levels were obtained. All these values for the two frequencies tested (10 Hz and 15 Hz) and the trend lines that approximate best these points are shown in figure 5.

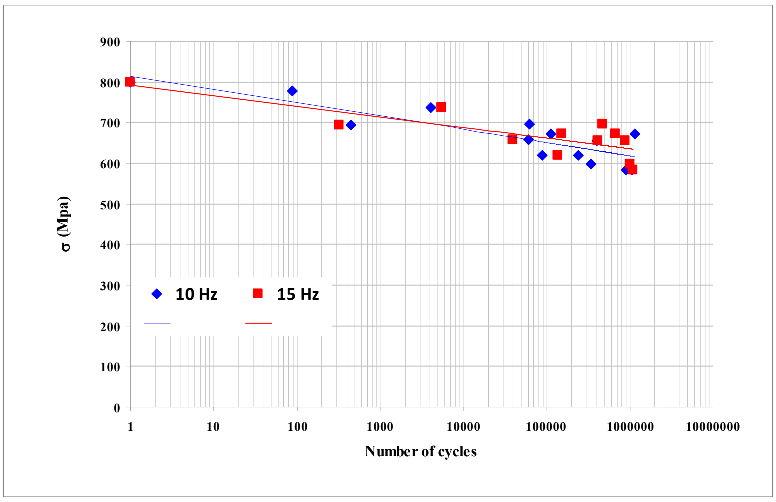


Figure 5. S-N curves for the 0º/90º coupons at 10 Hz and 15 Hz

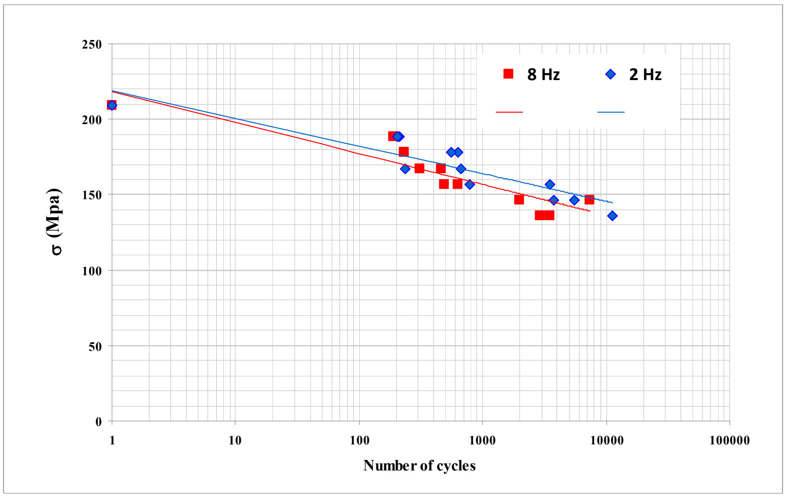


Figure 6. S-N curves for the ±45º coupons at 2 Hz and 8 Hz

As in the previous case, the values and the trend lines for the ±45º coupons are presented in figure 6, for load levels of 90, 85, 80, 75, 70 and 65% (for the frequency of 2 Hz) and 90, 85, 80, 75, 70 and 65% (for the frequency of 8 Hz) of the maximum static strength.

3.2.3. Analysis of the results

As in the case of unidirectional tape, the results for 0º/90º fabric laminates can be adjusted by a law as equation (2). This results (figure 5) show that there is no effect of frequency on the fatigue behavior for this configuration.

Figure 6 shows that experimental data for fabric laminates at ±45º do not adjust to a linear S-N curve in logarithmic coordinates. Moreover, a certain decrease in fatigue life can be appreciated with the increase in frequency. The rise in temperature measured during the tests shows higher increments at 8 Hz tests (between 20 ºC and 40 ºC) than at the 2 Hz tests (lower than 20 ºC).

As done in section 3.1.2, in order to compare the different frequencies at different orientations, a dimensionless parameter (Kawai [8]) has been chosen, given by the stress (σ) divided by the maximum strength (σ_{max}). The evolution of the fatigue life with this dimensionless parameter is presented in figure 7. Orientative trend curves have been represented in the graphic to remark the different behavior of the different orientations.

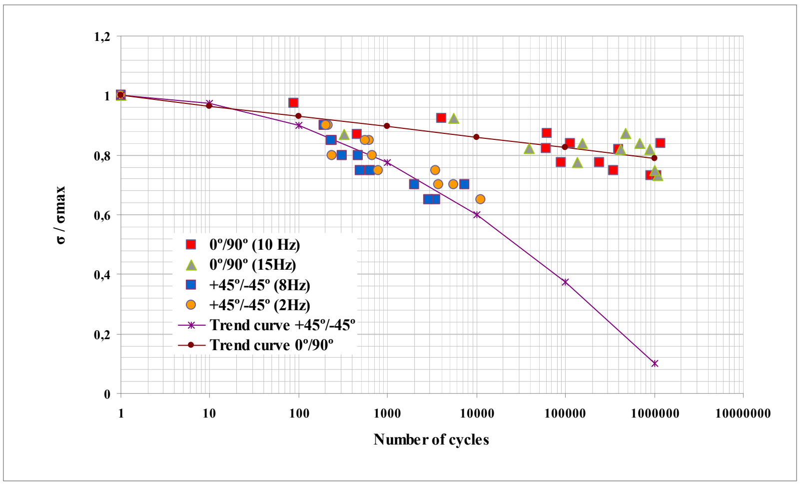


Figure 7. Dimensionless comparison of the S-N curve for the 0º/90º and ±45º fabric laminates

4. Conclusions

The objective of this work has been to study the influence of the frequency in the fatigue behaviour of both unidirectional and fabric composite laminates, for a graphite-epoxy material. For this purpose, static tension tests and fatigue tension-tension tests have been carried out.

The results have shown that frequency has a limited influence in fatigue behavior of unidirectional composite laminates. This fact has been confirmed by controlling the temperature of the coupons during the tests, which have not shown relevant variations.

This implies that the effects observed by other authors [1,3,4] on graphite-epoxy laminates manufactured by lay-up of unidirectional tapes at different orientations, have to be associated with mechanisms of interaction between layers. In this sense, Rotem [3] associated the effects of matrix thermal degradation to the appearance of interlaminar stresses, which are revealed through delaminations. Therefore, it would be necessary to study the effect of frequency on different types of laminates to establish what is the origin of the phenomenon. A major consequence of the results is that, in general, the fatigue behavior of a laminate can not be extrapolated from the behavior of its component layers.

In the case of graphite-epoxy fabric laminates, it has been shown that, for a cross-ply configuration (0º/90º), no effect of frequency is observed. The characteristic S-N curve corresponding to this case shows a linear trend. Conversely, for an angle-ply configuration (±45°) it has been shown that an increase of the frequency causes a decrease in the fatigue life. In this case, it can be seen that a significant thermal increase occurs, and that the trend of the characteristic S-N curve is not linear.

A possible explanation of why the frequency effect appears in some of fabric specimens, is that they are inherently laminates. The effect of frequency on angle-ply configurations could be related to the appearance of interlaminar phenomena, as was previously pointed out for unidirectional tape laminates.

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