THE EFFECT OF FREQUENCY ON TENSION-TENSION FATIGUE BEHAVIOR OF UNIDIRECTIONAL AND WOVEN FABRIC GRAPHITE-EPOXY COMPOSITES

J. C. Marin, J. Justo*, F. París, J. Cañas

Grupo de Elasticidad y Resistencia de Materiales, Escuela Técnica Superior de Ingeniería,

Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

**jjusto@us.es*

Keywords: Fatigue life, Fatigue testing, Composites, Unidirectional, Woven fabric.

Abstract

In this paper, the effect of different values of load frequency on the evolution of the stress versus number of cycles to failure curve for a graphite-epoxy composite is studied. Two types of materials have been considered: unidirectional tape and woven fabric laminates. Fatigue tension-tension tests at different orientation angles and several frequency values have been carried out. The results show there is almost no effect of the load frequency in the S-N curve of unidirectional laminates. For woven fabric laminates, only under off-axis tension, the effect of frequency becomes a remarkable parameter in the fatigue behavior.

1. Introduction

The present use of graphite-epoxy composites in aircraft primary structures causes the knowledge of their fatigue behavior to become an important task. The knowledge of fatigue behavior in composite materials is certainly more limited than that in metallic materials [1]. The fatigue analysis approach adopted for composite materials is an extension of the established approach for metallic materials, taking into account the peculiarity of composite laminates. A fatigue analysis requires, besides a detailed description of the load spectrum, a deep knowledge of the fatigue behavior of the material [2]. Fatigue behavior of composite materials is usually characterized by stress vs. number of cycles to failure (S-N) experimental curves. This information, obtained by dynamic tests, is used as basis to perform fatigue failure analyses of composite material structures [3]. A significant parameter in the performance of the dynamic tests is the frequency of the applied load, as can be revealed by several works devoted to this topic [4 - 12]. 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 [4] and glass/epoxy [5] 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 fact has been associated to a thermal degradation of the matrix, and has been observed in graphite/epoxy quasi-isotropic [6, 7] and graphite/PEEK, both angle-ply [8, 9] and quasi-isotropic [9] laminates. The last effect has also been observed in fabric laminates, for glass-vinylester [10] in both orientations cross-ply and angle-ply, and for graphite-epoxy [11] only in angle-ply configurations.

All previous works were based on studying multi-angle laminates. In the case of unidirectional laminates, Chen et al. [12] performed fatigue tests of 0º and 90º carbon/epoxy specimens at different frequencies. The results show that the fatigue life increases as the load frequency increases. The authors point out that a possible reason for this effect is the decrease in the stable maximum strain with the increase in the load frequency, due to the viscoelastic behavior of polymer matrix composites. In addition, it is notable, in this case, that the considered frequency range is higher than 5 Hz, unlike works in references [4, 5], which obtain the same results for frequencies below 5 Hz.

The aim of this work is to elucidate if the load frequency affects the fatigue behavior of some (most popular) graphite-epoxy laminas from pre-pregs, tapes or fabrics. The results obtained might help to understand the behavior of laminates fabricated from the laminas here studied and to elucidate if the fatigue behavior of a laminate can be extrapolated from the behavior of its component layers. The results will also help to check if it is possible to use (without modifying the results) frequencies higher than the usual 10 Hz, in order to accelerate this kind of tests. 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 of the material at several frequencies and for different fibre orientation angles, in order to observe the influence of frequency. For this purpose, for unidirectional laminates oriented at 0, 15 and 45 degrees, fatigue tests under tension-tension loads have been carried out for several values of frequency (10 Hz, 15 Hz and 18 Hz). Then, results for different orientations have been compared using a dimensionless representation (Kawai [13]). In the second part of this work, a graphite-epoxy fabric laminate has been considered. Fatigue tests under tension-tension loads, on laminates at 0º/90º and ±45º degrees, have been carried out for several frequencies (10 Hz and 15 Hz for 0º/90º, and 2 Hz and 8 Hz for ±45º). Furthermore, results for different orientations have been compared using the same dimensionless representation employed in the above configuration.

2. Specimens and test preparation

Two types of tests have been carried out: static and dynamic tension tests. In order to obtain the specimens for these tests, several panels have been manufactured. 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 with a diamond disc saw to obtain the specimens with the correct dimensions. Previously to this step, tabs have been bonded to the sides of the panels to improve the grip of the clamps to the specimens during the tests. The material of the unidirectional coupons is a carbon fibre (AS4) epoxy matrix (8552) prepreg from Hexcel, with 1.58 g/cm^3 of density, 57.42% of nominal fibre content and moduli of E_{11}=141 MPa and E_{22}= 10 MPa. The material of the woven fabric coupons is also a carbon fibre (AS4) epoxy matrix (8552) prepreg from Hexcel, with 1.57 g/cm^3 of density, 55.29% of nominal fibre content and moduli of E_{11}=68 MPa and E_{22}= 66 MPa [14].

In the case of the static test, the objective is to obtain the maximum strength of the specimens 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 carried out 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:

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

where σ_{min} is the minimum stress applied and σ_{max} is the maximum stress applied.

During fatigue tests, a thermocouple has been placed on the specimens 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, 200 mm length and 1 mm thickness, according to the standards ASTM D3039 [15] for the static tests and ASTM D3479 [16] 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 specimens have been tested for each orientation and for each kind of test.

The frequencies used in the tests have been 10 Hz, to have a reference for all configurations, and a higher frequency (15 Hz in the case of the 0º specimens and 18 Hz in the case of the 15º and 45º specimens), to observe the effect of the frequency increase.

A view of the failure of three coupons after testing under static load is shown in figure 1.

2.2. Fabric laminates

The dimensions of the specimens for fabric laminates are: 14 mm width, 200 mm length and 1 mm thickness, according to the standards ASTM D3039 [15] for the static tests and ASTM D3479 [16] for the dynamic tests. To obtain these specimens 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 reference level and 15 Hz for the higher level. The reason for this choice is the evidence pointed by Reis et al. [17], 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 reference level and 8 Hz for the higher level, because, as were shown by Kawai and Taniguchi [11], 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, firstly for unidirectional tape, and secondly for fabric laminates. For each kind of material, after all the results are presented, they are analyzed together in their corresponding subsection.

3.1. Unidirectional tape

3.1.1. Static tests

The means of the tensile strength of the material for the different orientation angles obtained from the static tests are summarized in table 1. These values have been used to obtain the loads for the dynamic tests.

3.1.2. Dynamic tests

0º specimens 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 differences in the percentages are motivated by the fact that, at 70% load level, the coupons of the 15 Hz frequency did not fail in the time the equipment was available for the tests (the supported more than 10^5 cycles). Thus, it was decided to rise the percentage of load for these configurations. At the end of the tests, the number of cycles needed to reach the failure in the specimens at these stress levels were obtained. The number of cycles until failure, for the two frequencies tested (10 Hz and 15 Hz), and the trend lines that approximate best these points (least squares adjustment) are depicted in figure 2. Note that the highest frequency chosen (15 Hz) is different from that of the following configurations (18 Hz). The reason is that, for 0º specimens, the testing machine did not allow to increase the frequency in more than 15 Hz, due to mechanical limitations.

As in the previous case, the number of cycles achieved and the trend lines for the 15º coupons are presented in figure 3, 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. A view of a dynamic test for a 15º orientation specimen is shown in figure 4.

The number of cycles until failure and the trend curves for the 45º specimens are presented in figure 5, 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

In sight of the curves of Figures 2, 3 and 5, it can be assumed that the results follow a linear law in logarithmic coordinates:

$$\sigma = \mathrm{A} \log N + \mathrm{B} \tag{2}$$

where σ is the stress level, N is the number of cycles, A and B being constant values. The results show a low scattering from this trend. The evolutions presented in figures 2, 3 and 5 show that there is almost no effect of the frequency in the S-N curve of unidirectional laminates. Only in the case of the 0º orientation angle, a small difference can be appreciated, in the sense that the fatigue life increases as the load frequency increases. These results are qualitatively in agreement with the results obtained by Chen et al. [12]. The mean values of the coefficients A and B for the different orientation angles are shown in table 2.

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

In order to compare the different fiber orientations, a dimensionless parameter (Kawai [13]) has been chosen, given by the stress (σ) divided by the maximum strength (σ_{max}) for each orientation angle. The evolution of the fatigue life with this dimensionless parameter is presented in figure 6. 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 6. From the knowledge of fatigue behavior of a 0º orientation lamina, a very approximate estimate of the fatigue behavior of any unidirectional laminate could be obtained. However, the correct band is always wider than that associated with the zero degrees case.

3.2. Fabric laminates

3.2.1. Static tests

The means of the tensile strength of the material for the different orientation angles obtained from the static tests are shown in table 3. These values have been used to obtain the loads for the dynamic tests.

3.2.2. Dynamic tests

0º/90º specimens 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. As in the previous case, with these tests, the values of the cycles needed to reach the failure in the specimens at these stress levels were obtained. The number of cycles until failure for the two frequencies tested (10 Hz and 15 Hz) and the trend lines that approximate best these points (least squares adjustment) are shown in figure 7. A view of all tested 0º/90º specimens is shown in figures 8 and 9 for 10 and 15 Hz, respectively. All the failures observed show a fracture plane perpendicular to the load direction, without section width shortening.

As in the previous case, number of cycles and the trend lines for the ±45º fabric laminates are presented in figure 10, 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. A view of all tested ±45º specimens is shown in figures 11 and 12 for 2 and 8 Hz, respectively. The corresponding failures show ±45º fracture planes, with some shortening of the section width. This effect is more pronounced for the highest frequency value.

3.2.3. Analysis of the results

As in unidirectional tape case, results for 0º/90º fabric laminates can be adjusted by the law described in equation (2). These results (figure 7) show that there is no effect of frequency on the fatigue behavior for this configuration. Furthermore, the configuration of the failures observed in specimens (figures 8 and 9) is the same for the two frequencies considered.

Figure 10 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 (figure 13) shows higher increments at 8 Hz tests (between 20 ºC and 40 ºC) than at 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 [13]) 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 14. The adjustment dimensionless curves for 0º/90º fabric coupons show a linear trend and no effect of the frequency used in the tests. Nevertheless, the adjustment dimensionless curves for ±45º fabric specimens show a nonlinear trend and a remarkable effect of the load frequency.

4. Discussion and conclusions

The objective of this work has been to study the influence of the frequency in the fatigue behavior 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 composites for the different orientations (0º, 15º, 45º) tested. This fact has been confirmed by controlling the temperature of the coupons during the tests, which have not shown relevant variations. A first consequence of this fact, is that there is no restriction in the choice of load frequency to apply on tests (into the analyzed range of frequency). Hence, the S-N curve obtained from these tests could be representative of the fatigue behavior of the unidirectional layer considered. Nevertheless, the results reported by other authors in graphite-epoxy multi-angle laminates [4, 6, 7], and also in other composite materials [5, 8, 9], show that load frequency applied affect the fatigue life of these laminates. It implies that these effects of frequency, observed on laminates manufactured by the lay-up of unidirectional tapes at different orientations, have to be associated with mechanisms of interaction between layers. In this sense, Rotem [6] 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 the origin of the phenomenon. A major consequence of this fact is that, in general, the fatigue behavior of a laminate can not be extrapolated from the behavior of its component layers, because the fatigue behavior of a laminate could be affected by the value of frequency used, while the component layers isolated can not be affected by them.

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. As a consequence of this, the characteristic S-N curve corresponding to this case, that shows a linear trend, could be representative of fatigue behavior of fabric layer considered, at 0º orientation angle. Conversely, for an angle-ply configuration (±45°), it has been shown that an increase in 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 nonlinear. A main question in this case, is to establish what the appropriate value of load frequency to apply in tests is, in order to obtain a characteristic S-N curve of fatigue behavior. Some authors [9], in the case of multi-angle laminates, recommended to limit the frequency to low values where matrix thermal degradation does not occur. Although, following this recommendation, in this case, could generate a non-conservative characteristic curve, because a component constituted by the fabric laminates tested in this work may be subjected in service to high load frequencies. Hence, a deeper study about this question must be necessary to clarify the proper method to follow in the evaluation of representative S-N curves, in the off-axis fatigue behavior of fabric laminates.

References

[1] R. C. Alderliesten, Critical review on the assessment of fatigue and fracture in composite materials and structures, Eng. Fail. Anal., vol. 35, pp. 370-379, 2013.

[2] H. J. Sutherland, J. F. Mandell, Effect of mean stress on the damage of wind turbine blades, ASME Wind Energy Symposium, AIAA/ASME, pp. 32-44, 2004.

[3] J. C. Marin, A. Barroso, F. Paris, J. Cañas, Study of fatigue damage in wind turbine blades, Eng. Fail. Anal., vol. 16, pp. 656-668, 2009.

[4] G. C. Tsai, J. F. Doyle and C. T. Sun, Frequency effects on the fatigue life and damage of graphite/epoxy composites, J. Compos. Mater., vol. 21, pp. 2-13, 1987.

[5] D. Perreux and E. Joseph, The effect of frequency on the fatigue performance of filament-wound pipes under biaxial loading: experimental results and damage model, Compos. Sci. Technol., vol. 57, pp. 353-364, 1997.

[6] A. Rotem, Load frequency effect on the fatigue strength of isotropic laminates, Compos. Sci. Technol., vol. 46, pp. 129-138, 1993.

[7] G. Minak, On the determination of the fatigue life of laminated graphite-epoxy composite by means of temperature measurement, J. Compos. Mater., vol. 44, pp. 1739-1752, 2010.

[8] X. R. Xiao, Modeling of load frequency effect on fatigue life of thermoplastic composites, J. Compos. Mater., vol. 33, pp. 1141-1158, 1999.

[9] D. C. Curtis, D.R. Moore, B. Slater and N. Zahlan, Fatigue testing of multi-angle laminates of CF/PEEK, Compos., vol. 19, pp. 446-452, 1988.

[10] M. R. Kharrazi and S. Sarkani, Frequency dependent fatigue damage accumulation in fiber-reinforced plastics, J. Compos. Mater., vol. 35, pp.1924-1953, 2001.

[11] M. Kawai and T. Taniguchi, Off-axis fatigue behavior of plain weave carbon/epoxy fabric laminates at room and high temperatures and its mechanical modeling, Compos. Part A, vol. 37, pp. 243-256, 2006.

[12] H.-S. Chen, S.-F. Hwang, H.-S. Chen, Accelerated fatigue properties of unidirectional carbon/epoxy composite materials, Polym. Compos., vol. 27, pp. 138-146, 2006.

[13] M. Kawai, A phenomenological model for off-axis fatigue behavior of unidirectional polymer matrix composites under different stress ratios, Compos. Part A, vol. 35, pp. 955-963, 2004.

[14] Hexply 8552 epoxy matrix product data sheet. Hexcel Corporation, 2016.

[15] ASTM D3039 / D3039M - 08. Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM, 2008.

[16] ASTM D3479 / D3479M - 12. Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials, ASTM, 2012.

[17] P. N. B. Reis, J. A. M. Ferreira, J. D. M. Costa and M. O. W. Richardson, Fatigue life evaluation for carbon/epoxy laminate composites under constant and variable block loading, Compos. Sci. Technol., vol. 69, pp. 154-160, 2009.

Tables:

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

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

Table 2. Values of the coefficients for the S-N curve.

Orientation angle (deg)	**A**	**B**
0	-42.712	1955.15
15	-13.707	371.08
45	-2.730	95.33

Table 3. Mean values of the static tensile strength for cross-ply and angle-ply configurations.

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

Figures:

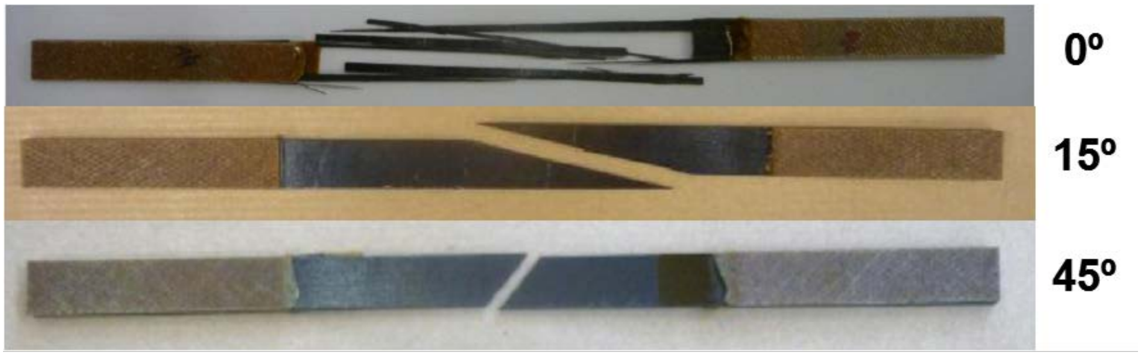

Figure 1. View three specimens after testing, one of each orientation.

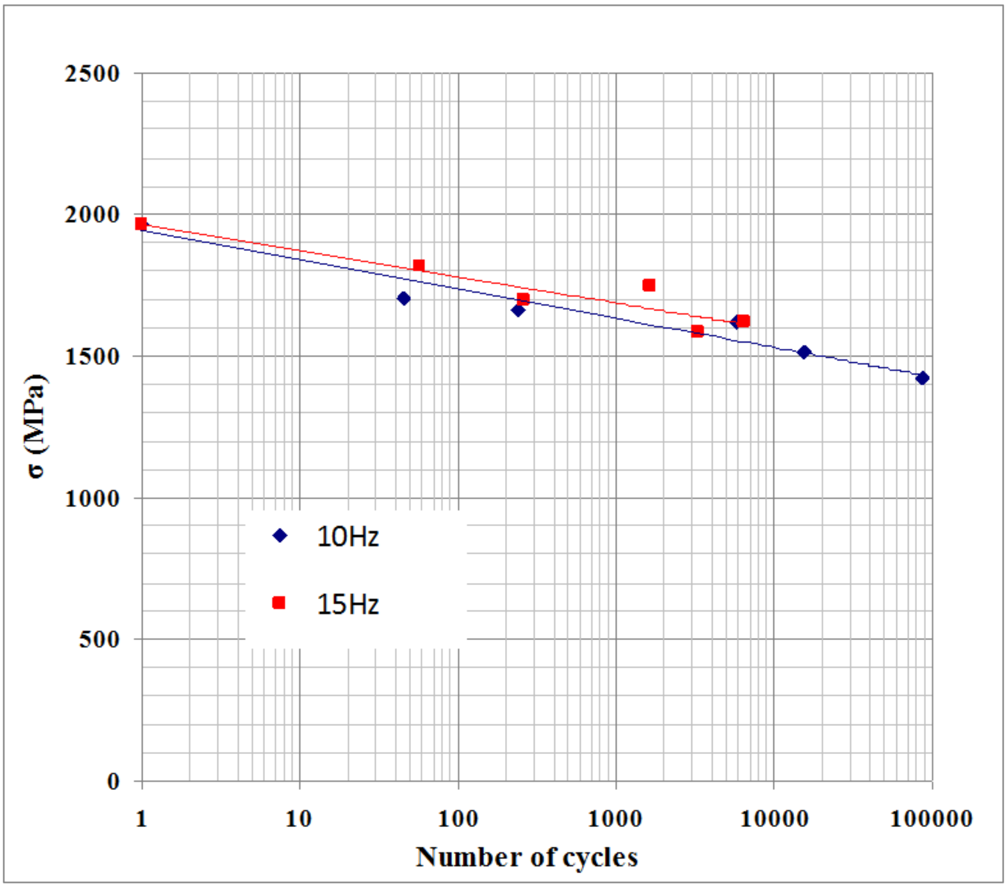

Figure 2. S-N curves for 0º orientation angle at 10 Hz and 15 Hz.

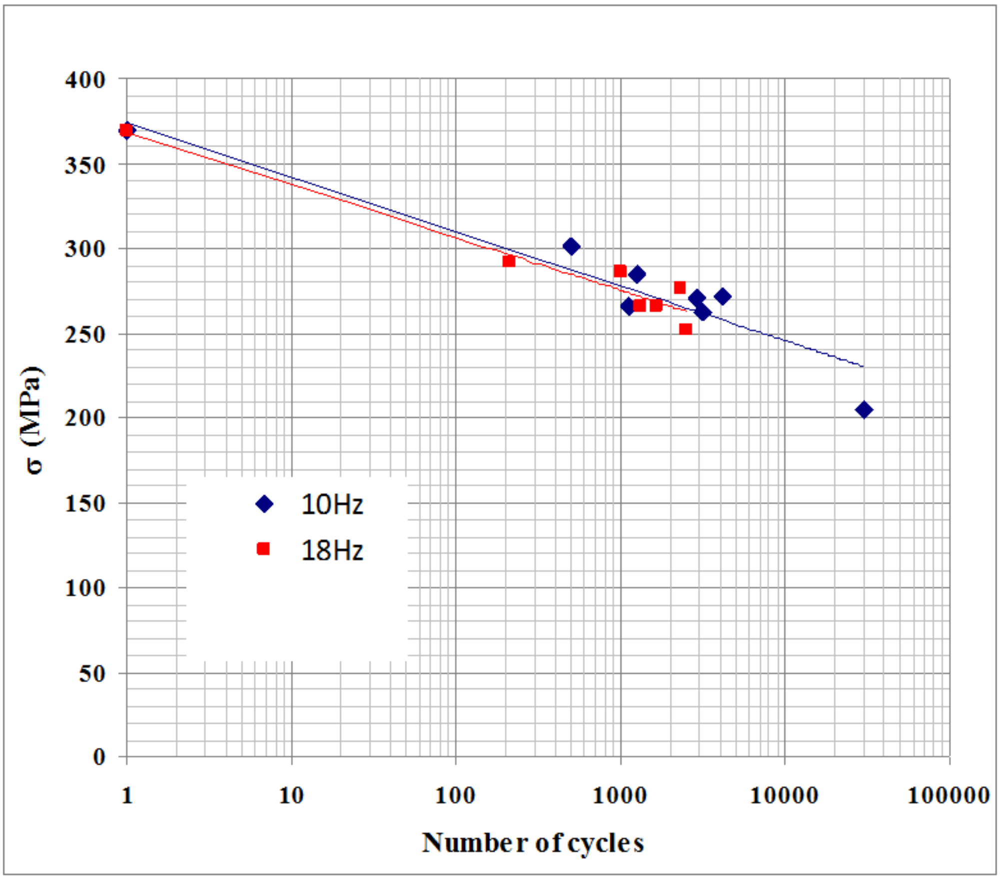

Figure 3. S-N curves for 15º orientation angle at 10 Hz and 18 Hz.

Figure 4. View of a dynamic test for 15º orientation angle of the fibres.

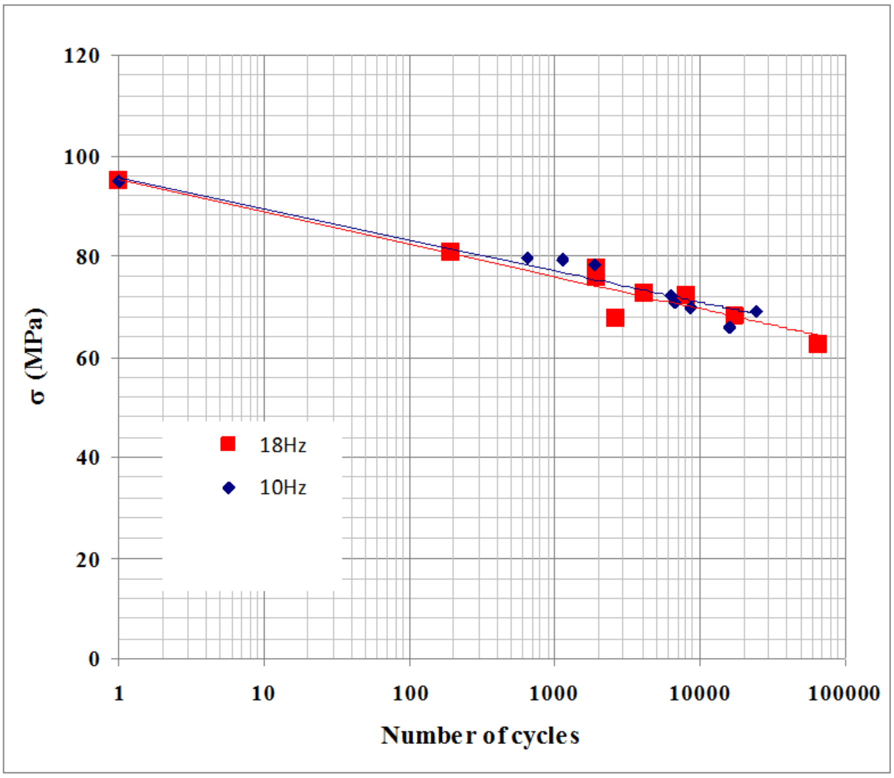

Figure 5. S-N curves for the 45º orientation angle at 10 Hz and 18 Hz.

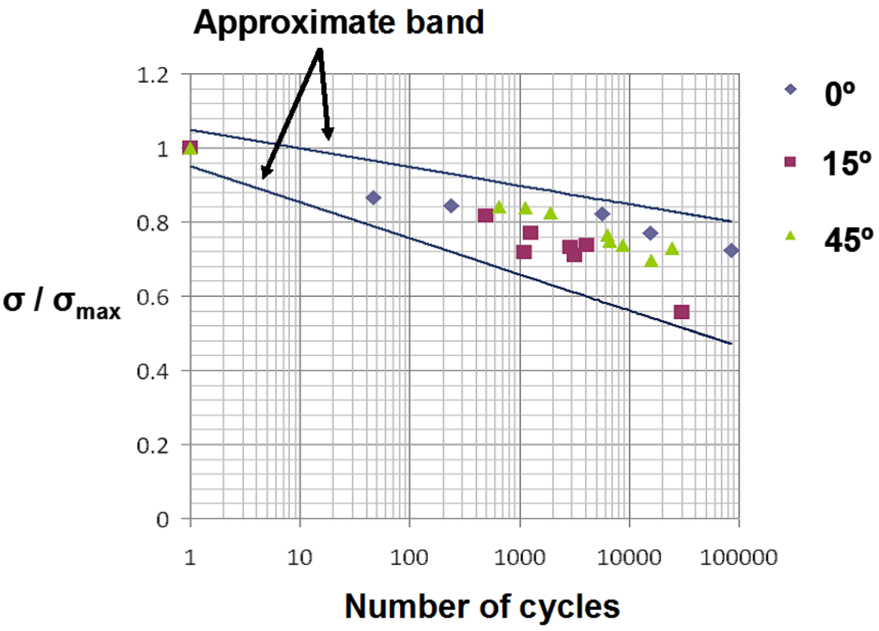

Figure 6. Dimensionless comparison of the S-N curves for the 0º, 15º and 45º orientation angles.

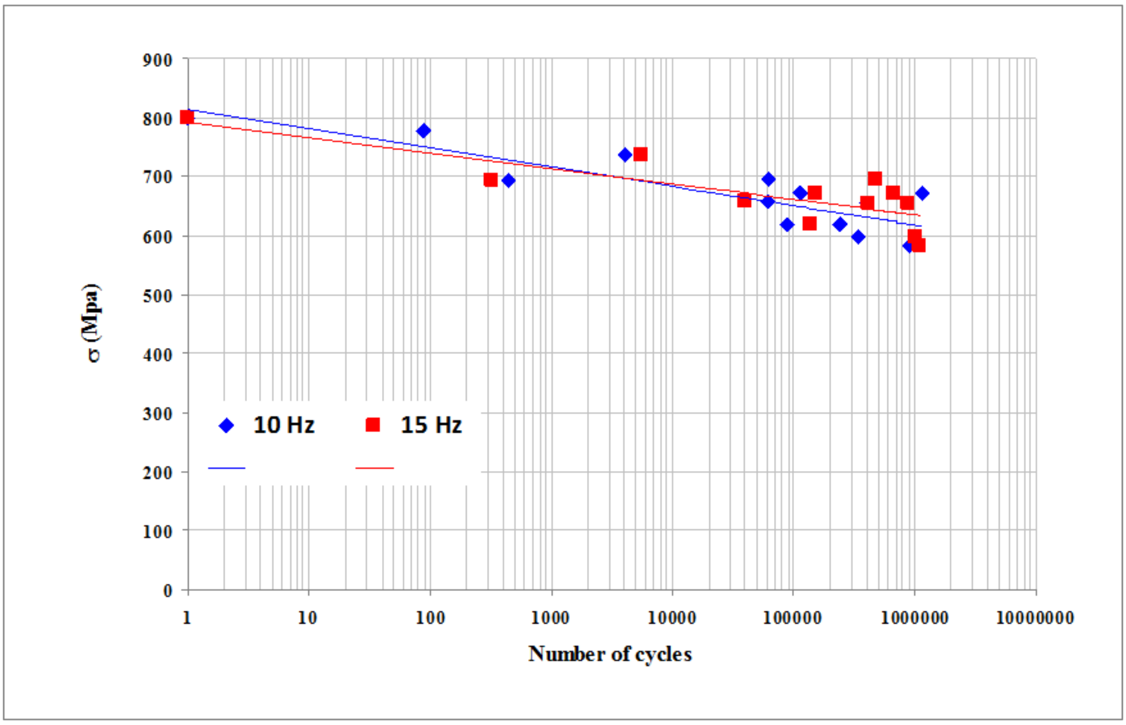

Figure 7. S-N curves for the 0º/90º fabric laminates at 10 Hz and 15 Hz.

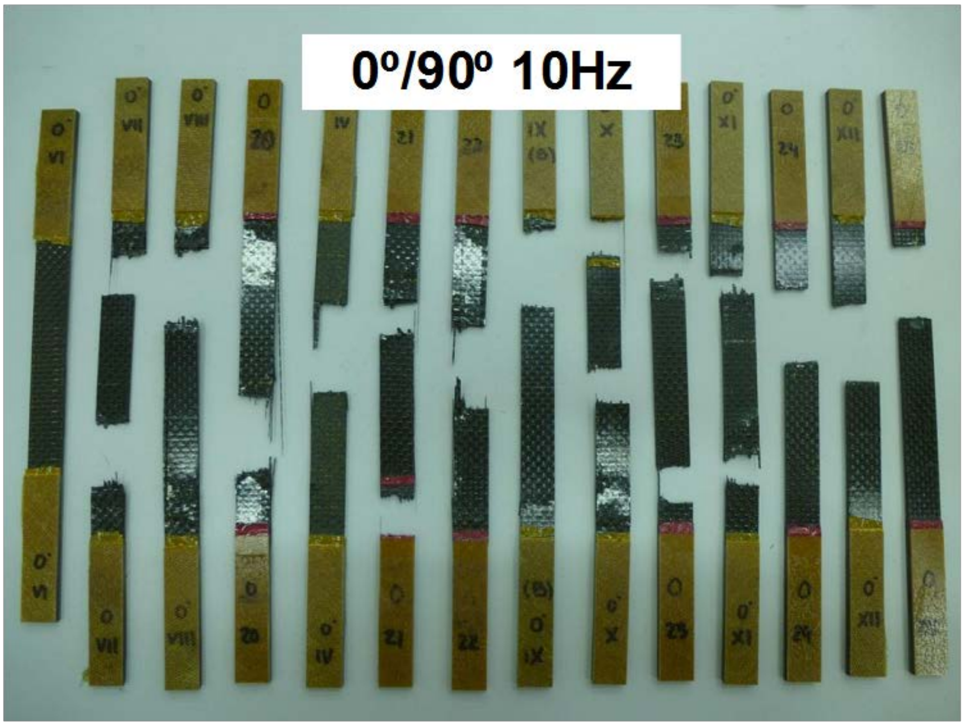

Figure 8. View of the 0º/90º tested specimens at 10 Hz.

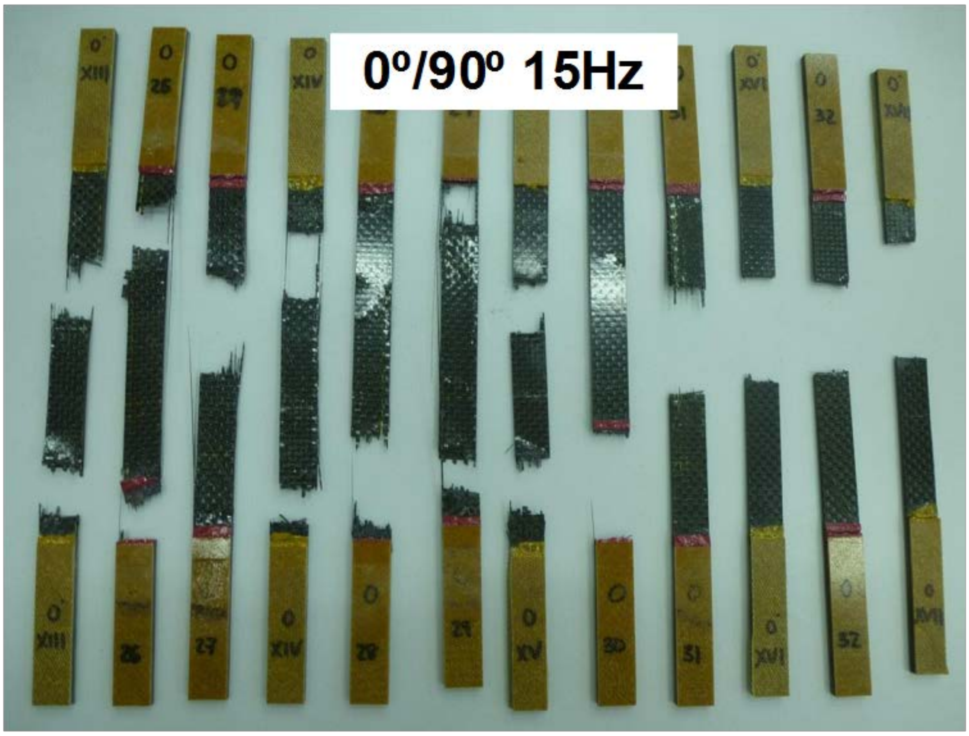

Figure 9. View of the 0º/90º tested specimens at 15 Hz.

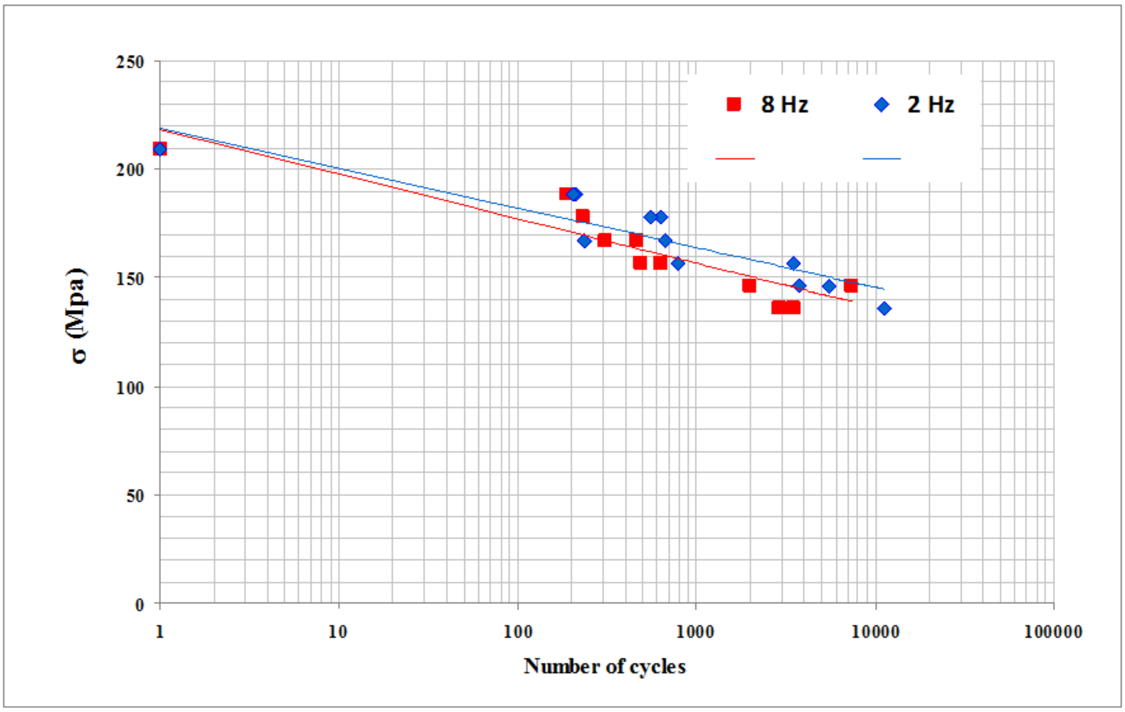

Figure 10. S-N curves for the ±45º fabric laminates at 2 Hz and 8 Hz.

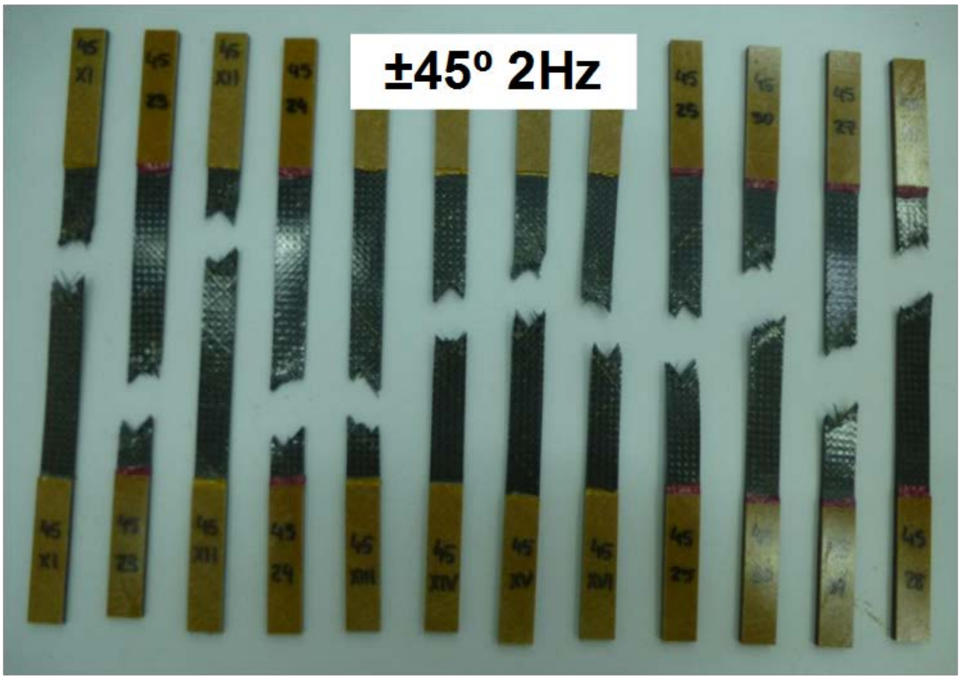

Figure 11. View of the ±45º tested specimens at 2 Hz.

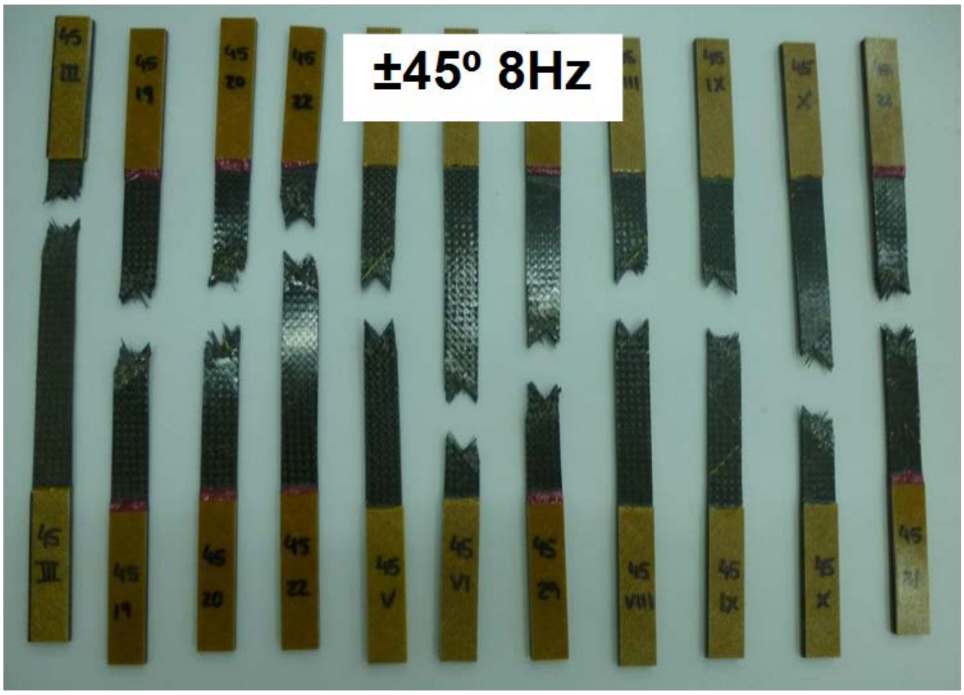

Figure 12. View of the ±45º tested specimens at 8 Hz.

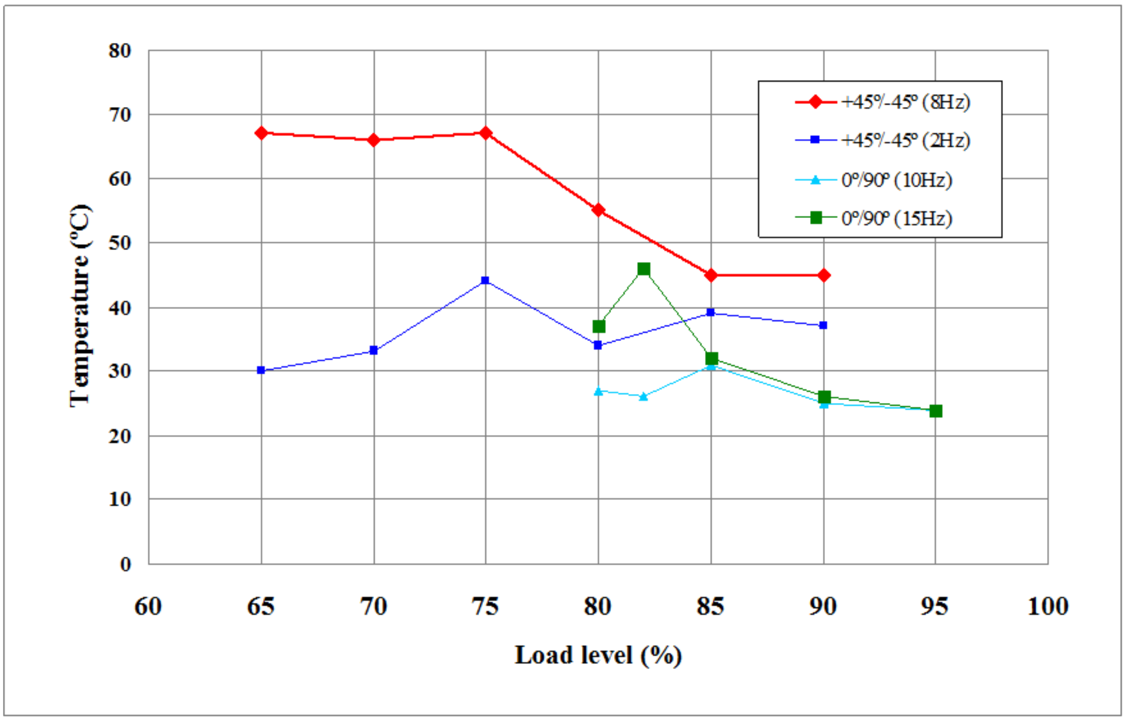

Figure 13. Temperature measured during tests.

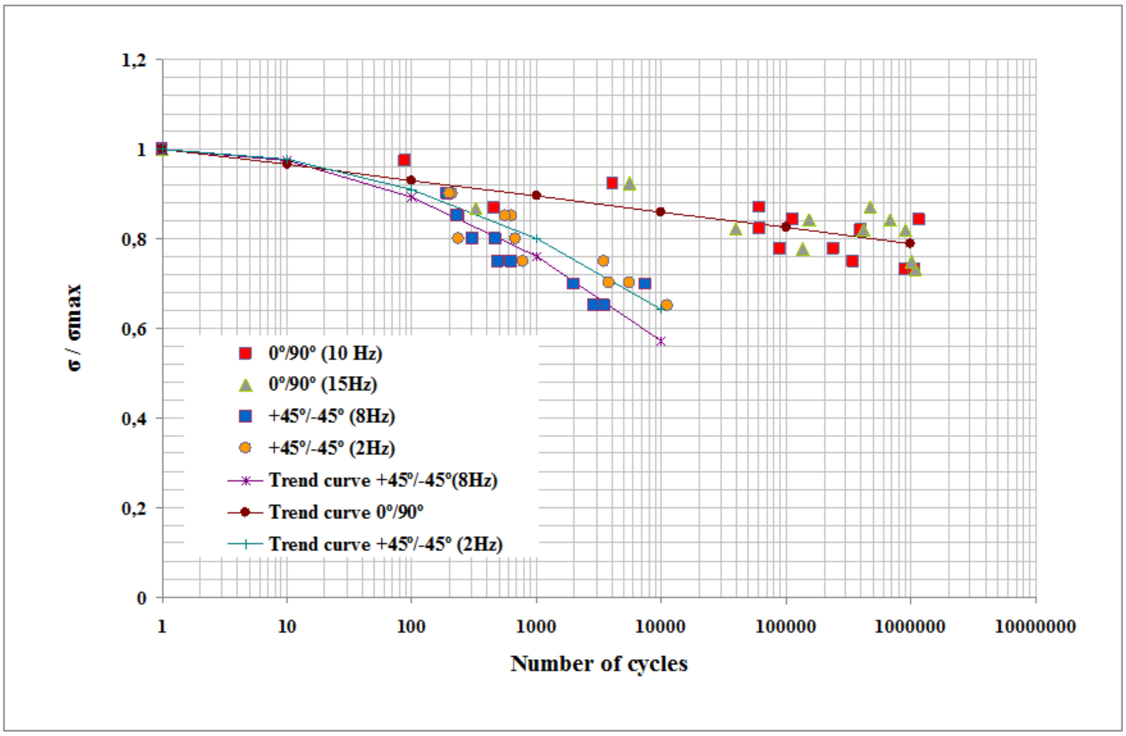

Figure 14. Dimensionless comparison of the S-N curves for the 0º/90º and ±45º fabric laminates.