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# Frequency effect in short-beam shear fatigue of a glass fiber reinforced polyester composite

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The effect of loading frequency on short-beam shear fatigue behavior of a glass fiber reinforced polyester laminated was studied. Surface specimen temperature increase and macroscopic specimen damage were also evaluated. The tests were performed employing a short-beam device with three amplitude stress levels, four frequencies between 1 and 10 Hz and a shear stress ratio $R = 0.1$. Specimens with the smallest stress amplitude showed a fatigue life between $10^5$ and $10^6$ cycles and the largest stress amplitude endured approximately $10^4$ cycles. The high stress amplitude tests produced increases in specimen temperature up to 7 °C, 4 °C and 1 °C for 10 Hz, 6 Hz and both 3 and 1 Hz respectively, while no temperature changes were measured in low amplitude tests. According to the statistical analysis performed, the changes in fatigue life were not significant for the frequency range employed in this study.



## 1. Introduction

Fatigue tests are time-consuming, especially in high cycle fatigue. High loading frequencies are desirable as long as no significant change occurs in the fatigue behavior. Selecting the optimal testing frequency for composite tests is not an easy task because of its frequency sensitivity. There are no clear guidelines, although some directions, as no significant change of specimen temperature, are widely used [1]. Nevertheless, these directions sometimes do not consider influential variables as the principal fiber orientation or the type of fiber and matrix, among others.

The change in fatigue life due to frequency variation has been associated with two effects [2]. The first one is self-generated heating due to the high damping factor and the low heat conductivity of the matrix. The second one is the effect of rate dependence. Nijssen [3] included a third effect, the frictional heating generated between the specimen and the test device. These effects are linked to the specimen geometry, the material system, load direction in the laminate, etc. [1]. For example, when the load is applied in the principal fiber direction, the composite usually is less sensitive to changes in loading frequency than in directions where matrix or fiber–matrix interface control the mechanical behavior. The latter is the case of interlaminar shear properties that are dependent of matrix and fiber–matrix interface behavior.

Interlaminar shear fatigue behavior is of special interest in laminate composites of large thickness (>20 mm) and flexure cyclic loads, as can be found in wind turbine blades. Different tests have been proposed to measure this behavior [4–9], many of which are adaptations of quasi-static tests. Short-beam shear (SBS) test is one of the proposals and it has the advantages of small specimens and simple test device, together to no grip problems. The quasi-static SBS test is widely used to compare materials or in quality control. Although the specimens do not present a pure shear stress state, the stress state promotes the interlaminar failure of the specimens [10]. This test has been used by several researchers [4,11–13] to measure predominant interlaminar shear fatigue of composites and ASTM Committee D30 has been working in its normalization [14]. The selection of a loading frequency in SBS fatigue tests is not simple just as in other fatigue tests in composites. The frequencies employed in fatigue tests of polymer matrix composites are usually below 25 Hz [15]. The public databases of SNL/MSU/DOE [16] and Knowledge Centre WMC [17] were consulted with the aim to know usual frequency values in composite fatigue of glass and carbon reinforced polymers. The histograms of loading frequencies are shown in Figs. 1 and 2. Data correspond to results of specimens tested with different lay-ups, geometries, production processes, fiber/resin ratios and directions of load application with regard to principal fiber direction. Tests were carried out at

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**Nomenclature**

| | |
|---|---|
| $b$ | specimen width |
| CLD | constant life diagrams |
| $CV$ | sample coefficient of variation |
| $E^{chord}$ | tensile chord modulus of elasticity |
| $f$ | loading frequency |
| $F^{sbs}$ | quasi-static short-beam strength |
| $F^{tu}$ | ultimate tensile strength |
| $h$ | specimen thickness |
| $l$ | specimen length |
| $N$ | number of cycles |
| $N_f$ | number of cycles at failure or SBS fatigue life of a specimen |
| $P$ | force |
| $P_{(i)}$ | force at $i$th data point observed during the fatigue test |
| $R$ | shear stress-ratio |
| $R^2$ | coefficient of determination |
| $S$ | standard deviation |
| SBS | Short-beam shear |
| $\alpha$ | significance level |
| $\delta$ | displacement of the loading nose |
| $\delta$max ratio | stiffness loss of the specimen |
| $\Delta\delta$ ratio | variation in displacement at each load cycle/variation in displacement at the first cycle ratio |
| $\delta max_N$ | maximum displacement of the loading nose at $N$ cycles |
| $\delta max_1$ | maximum displacement of the loading nose at the first cycle |
| $\delta min_N$ | minimum displacement of the loading nose at $N$ cycles |
| $\delta min_1$ | minimum displacement of loading nose at the first cycle |
| $\nu$ | Poisson's ratio |
| $\tau_a$ | shear stress amplitude |
| $\tau^{sbs}_{(i)}$ | SBS stress value observed at ith data point in one cycle |
| $\tau^{sbs}_{max}$ | maximum SBS stress value observed in one cycle |
| $\tau^{sbs}_{min}$ | minimum SBS stress value observed in one cycle |

constant amplitude loading, different stress levels and uniaxial tension–tension, tension–compression and compression–compression loads. The associated published papers in both databases [16,17] give more information about the test programs. No interlaminar shear tests are included in the cited databases.

In the case of SNL/MSU/DOE database, the most employed frequencies changed with time: Up to 2006 more than 28% of the tests were performed with values higher than 10.5 Hz. In the following six years, around 0.2% of tests were performed above 10.5 Hz. This change is associated to testing programs with different objectives. Many of the test with frequencies above 10.5 Hz corresponded to very high cycles ($10^8$–$10^9$ cycles) testing programs. Moreover, many of these fatigue tests were performed varying the frequency to maintain similar load rate and reduce test time at high cycle fatigue. In the case of Knowledge Centre WMC's database, less than 1% of the tested values were over 10.5 Hz. Van Wingerde et al. [18] discussed these database results and commented that a larger than expected influence of the loading frequency was observed. Frequencies employed in some interlaminar shear fatigue tests are presented in Table 1. Recent papers dealing with high cycle fatigue have used 10 Hz or lower frequencies.

The selection of an optimum or, at least, adequate loading frequency for SBS fatigue test is affected by all the aforementioned aspects. Because of the lack of specific published information, this paper examines the effect of frequencies in the SBS fatigue life of a glass fiber reinforced polyester laminate. The range of frequencies covered values between 1 and 10 Hz, commonly employed in recent fatigue test. A variance analysis was performed to evaluate whether significant changes in fatigue life are present. The macroscopic damage and the temperature change in the specimen surface were also evaluated.

## 2. Material and methods

The studied material was a glass fiber reinforced polyester laminate. The reinforcement consisted in four unidirectional E-glass plies and the matrix was a dicyclopentadiene (DCPD) polyester resin. The coupon, with nominal dimensions of 450 × 400 × 3.23 mm, was produced by infusion and the fiber volume fraction was 58%. In-plane tensile properties of the coupon are listed in Table 2.

Specimens were cut using a diamond wheel cooled with ethyl alcohol and their dimensions were in agreement with ASTM

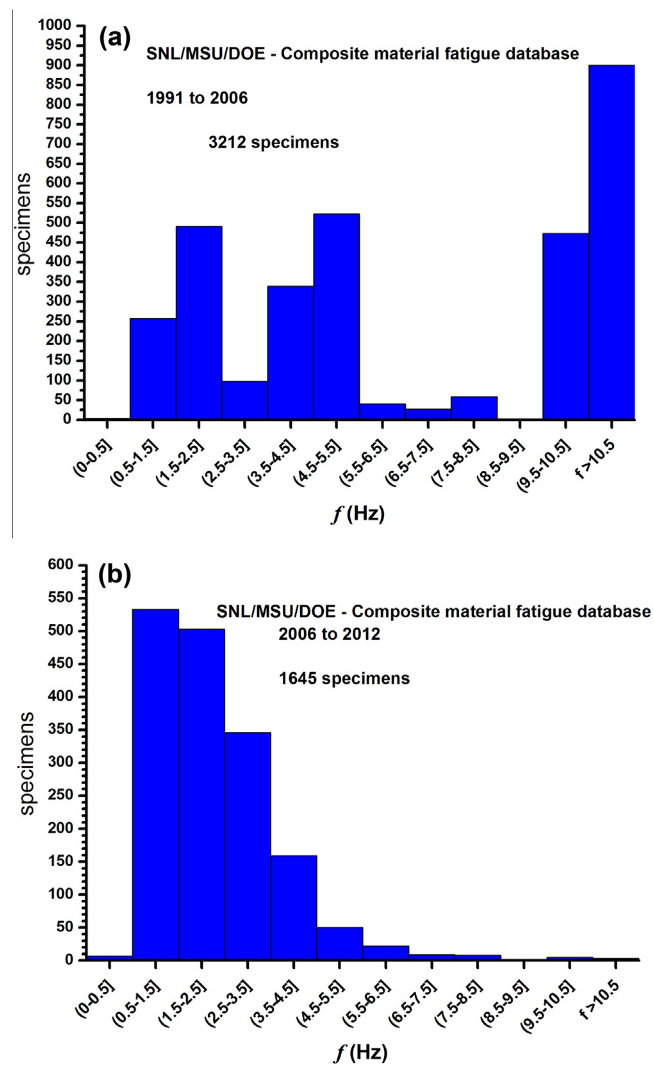


**Fig. 1.** Number of specimens of SNL/MSU/DOE database as a function of the loading frequency (a) from 1991 to 2006 and (b) from 2006 to 2012 [16].