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Fatigue behaviour of epoxy-steel single lap joints under variable frequency

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ABSTRACT

This work investigates the loading frequency effects on the fatigue behaviour of adhesively-bonded steel lap joints. *S*–*N* diagrams of fatigue tests, under constant amplitude loading, were obtained for frequencies ranging between 2 and 40 Hz. The fatigue life for variable frequency tests was estimated based on constant frequency *S*–*N* curves, using a linear cumulative damage rule. It is possible to conclude that, for the higher shear stresses, the frequency presents only a marginal effect on fatigue life. On the other hand, for the lower shear stresses, the fatigue life of the adhesive joints is very dependant on the frequency level. Good correlations were obtained between fatigue life predictions and experimental results.

1. Introduction

Most of the research into fatigue behaviour of adhesive joints has been conducted at constant amplitude loading. However, many of the structures that utilise adhesive bonding are subjected to complex fatigue load histories characterized by changes in the amplitude, stress ratio (R), frequency and waveform of the cycling stresses.

Several methods to predict variable amplitude fatigue life can be found in the literature generally classified as: Palmgren–Miner (P–M) based models, phenomenological models and progressive damage models [1]. In the P–M rule, the damage calculated from the different blocks is added linearly and for many materials this tends to over-predict fatigue life, mainly when there are load interaction effects (overloads, load sequencing, etc.) [2]. However, the intensity of these effects is material dependant. In ductile materials (such as aluminium) the presence of overloads can lead to crack retardation, while in brittle materials (adhesives and composites) it can cause crack growth acceleration [3]. In the case of bonded joints, some studies conducted under variable amplitude loading have reported an accelerated failure [2,4–6]. Crack growth acceleration was mainly attributed to spectrum mean stress variations but overloads also proved to be important in crack initiation.

The variation of strength and stiffness can be used to measure the damage accumulation during fatigue loading. Stiffness wearout has the advantage of being non-destructive, although it is not directly linked to a failure criterion and may not be sufficiently sensitive during the early stages of damage [7]. On the other hand, the strength wearout approach is an empirical equation, linear [2] or non-linear [8], which is fitted to the experimental results (residual strength against the number of fatigue cycles). The failure occurs when the residual strength equals the maximum stress of the spectrum [7,9–10]. The main disadvantage of this method is that an extensive number of destructive tests are required [7].

The fracture mechanics (FM) approach for studying the fatigue crack growth behaviour of adhesive bonds was first used by Mostovoy and Ripling [11] and, nowadays, several works can be found in the open literature, where the crack growth rate is normally related to the strain energy release rate [1,3–5,12–15]. However, because FM approaches only consider the fatigue crack propagation phase, they may under-predict the fatigue life [1] if the initiation phase is dominant. Therefore, a more mechanistically representative method of predicting fatigue initiation life is through the application of damage models, which can be categorised into two groups: cohesive zone models (CZMs) and continuum damage mechanics (CDM) based models [1].

As previously referred, the bibliography presents some discussion about the methodology of fatigue life prediction under variable amplitude loading. However, in the case of fatigue loading under variable frequency of adhesive joints, the available studies are not sufficient to acquire complete knowledge about this subject. The time required to generate fatigue data is the reason why the relatively high frequencies, between 5 and 10 Hz are normally used [16]. However, frequency effects on the fatigue life should be considered as a consequence of the viscoelastic nature of

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polymeric adhesives. For example, some studies show that the frequency effects are sensitive to the different adhesive systems [11,16]. According to Pirondi and Nicoletto [15] and Ashcroft et al. [17], when the adhesives present a strong viscoelastic behaviour, the influence of the loading frequency is markedly temperature dependant. Supported on a fracture mechanics (FM) approach, Al-Ghamdi et al. [18] proposed a simple damage accumulation method, based on the Paris Law, to predict crack growth as a function of the number of cycles or time. Linear relationships were established between log frequency and log G_{th}, D or n, which can be used to construct a FCP (Fatigue Crack Propagation) curve and, hence, predict crack growth at any frequency [18].

This work aims to investigate loading frequency effects on the fatigue behaviour of adhesively-bonded steel lap joints. *S*–*N* diagrams, under constant amplitude fatigue tests, are obtained for the frequencies of 2, 10 and 40 Hz. Experimental tests composed of two blocks with the same loading amplitude but changing from a low frequency level to a higher frequency level (L–H sequence) or vice versa (H–L sequence), are also analysed. Finally, the fatigue life is estimated based on the *S*–*N* curve at the appropriate stress and frequency, using a linear cumulative damage rule, and the predictions are compared with experimental results.

2. Material and experimental procedure

Docol 1000 high elastic limit steel plates with 1.5 mm thickness were used as the material for the adherends of the studied single-lap joints. More details about Docol 1000 high elastic limit steel can be found in Refs. [19–20] and Table 1 shows the main mechanical properties.

The specimens were manufactured as 20 mm wide bars cut from the plates and bonded with “Araldite® 420 A/B” adhesive. The main properties of the adhesive can be found in Table 1. The geometry and dimensions of the specimens are shown in Fig. 1. Abrasive polishing with silicon carbide paper type P220 (R_z=4.66 ± 0.34 μm) was used and, finally, the surface was cleaned with dry air and alcohol. In order to obtain a uniform adhesive thickness of 80 μm, the specimens were compressed with constant pressure.

The constant amplitude loading fatigue tests were carried out in tension using an E 10000 Instron Electropulse uniaxial fatigue test machine, equipped with a 10 kN load cell and controlled by a computer with data acquisition. Tests were performed at room temperature, under constant amplitude sinusoidal waveform loading, a stress ratio of R=0.05 and frequencies of 2, 10 and 40 Hz. Throughout the present study, the majority of the tests were replicated twice for each loading level. In order to measure the temperature variation during the fatigue tests, some specimens were instrumented with thermocouples type *K*. The thermocouples were placed at the edge of the patches (see Fig. 2), where the stress concentration and peel stresses are highest [21–23]. Therefore, to measure the temperature of the adhesive, a 1.5 mm diameter hole was machined in one of the adherends to fix the thermocouples. In order to verify if this hole has any effect on the fatigue life, preliminary tests were performed. It was possible to conclude that the results obtained are in good agreement with the dispersion observed, in terms of the fatigue life obtained with specimens without a hole.

Table 1
Mechanical properties of the adhesive and adherent.

Material	σ_{UTS} [MPa]	σ_{YS} [MPa] strain 0.2%	E [GPa]
Adhesive (Araldite® 420 A/B)	35	27	1.85
Docol 1000 high strength steel	1055	510	205

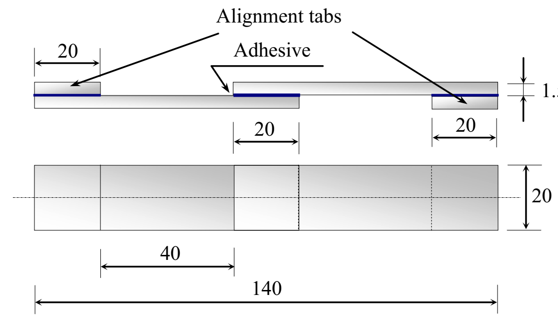

Fig. 1. Specimen geometry with 80 μm adhesive thickness (dimensions in mm).

A variable frequency-loading fatigue study was carried out using two and three-block loading sequences composed of different frequency levels. The two-block sequences were performed with transitions from low to high (L–H) and high to low (H–L) frequency levels. The load amplitudes used in these tests were chosen based on the fatigue *S*–*N* curves obtained at constant loading amplitude/frequency tests. The extension of the first block, in terms of number of cycles, was defined as one third of the constant frequency fatigue life. The second loading block was applied up to failure. In relation to the variable frequency-loading fatigue tests composed by the three-block loading sequence, as shown in Fig. 3, frequencies levels of 10, 2 and 40 Hz were used. The sequence length was ranged using blocks with a different number of cycles (N_i=1000, 2500 and 4000) in order to analyse the influence of the block extension on fatigue life.

3. Results and discussion

One of the main tools used to analyse fatigue test results, based on the stress-life approach, are *S*–*N* diagrams, representing the fatigue life dependence on stress [24]. The results of the constant amplitude tests for different frequencies are presented in Fig. 4, in terms of shear stress amplitude versus the number of cycles to failure. Fatigue tests were performed at three values of frequency: 2, 10 and 40 Hz. The mean curves obtained by linear relationship (least squares method) of the experimental results are also superimposed in Fig. 4. In the present study the total separation of the specimens were adopted as the failure criterion.

It is possible to observe that, for the higher shear stress amplitudes, the frequency presents only a marginal effect, since fatigue lives are very similar in the different frequencies. On the other hand, for the lower shear stress amplitudes, the fatigue life of the adhesive joints is highly dependant on the frequency. Fatigue tests performed at 2 Hz promote the lowest fatigue lives, while the higher fatigue lives were obtained at the frequency level of 10 Hz. At the frequency level above 10 Hz, the fatigue life decreases again but with higher values than the ones observed for 2 Hz. Therefore, the *S*–*N* curve obtained at 40 Hz is positioned between the curves of 2 and 10 Hz. These results agree with the studies developed by Marceau et al. [25] in lap-shear and double cantilever beam (DCB) joints, where they found that low frequency fatigue was more damaging to adhesive joints than high frequency fatigue. According to Althof [26] the fatigue failure is creep-controlled at low frequencies, provided no significant change of temperature occurs. On other hand, Pirondi and Nicoletto [15] report that the influence of loading frequency should be discussed in terms of temperature, especially for adhesives where the mechanical properties are markedly temperature dependant. Therefore, the results obtained can be explained by the predominance of the creep mechanism at