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On the use of thermographic technique to assess the fatigue performance of bonded joints

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ABSTRACT

The thermographic technique is based on the heat released during dynamic loading cycles, correlating the temperature variation on specimen's surface with the applied stress amplitude. An abrupt temperature variation under a specific stress level reveals the presence of an irreversible phenomenon inside the material, which could be associated with fatigue damage process. In this work, the fatigue performance of bonded joints is assessed by carrying out fatigue tests in a servo-hydraulic machine monitored continuously by a thermographic acquisition system, with the utilization of end notched flexure specimens composed by two steel plates of ASTM A36, bonded together with epoxy adhesive. The results confirm that the thermographic technique is quite promising as an alternative approach to estimate the bonded joint fatigue strength.

1. Introduction

The fatigue performance is a very important issue in design of structures submitted to dynamic loading. The fatigue of bonded joints has been studied by many authors in order to understand what happens with substrates and adhesive when they are subjected to variable loading [1–6].

Abdel Wahab [7] did an extensive review of fatigue in adhesively bonded joints, defining two main approaches for fatigue analysis: stress-life and fatigue crack initiation/propagation. In fact, according to the author, there is a clear search to find a fatigue threshold for materials, as a fatigue limit; however, this is not the case for adhesively bonded joints and the fatigue threshold for this type of structures is usually specified at a certain number of cycles, for instance, one million cycles. For fatigue crack initiation, damage models can be used, based on empirical assumptions, as the models of plastic or principal strains, or based on scientific observations, as the models related to the theory of continuum damage mechanics. For fatigue crack propagation, the idea is to combine a fracture parameter, such as strain energy release rate (G) and the crack growth rate (da/dN) using fracture mechanics tests.

Chaves et al. [8] did an interesting review of fracture mechanics tests for adhesively bonded joints. The characterization of adhesive joints fracture was divided in three basic approaches: continuum mechanics, fracture mechanics and damage mechanics. In the continuum mechanics approach, stresses and deformations of the bonded parts were described to define the maximum force that can be applied to the joint in four different loading types: normal, shear, peeling and cleavage. The fracture mechanics assumes the material non-continuity, recognizing delamination, debonding, cracking and other imperfections. Indeed, fracture mechanics can be divided into two basic approaches: stress intensity factor criterion and energetic criterion. The energetic criterion has been more utilized in adhesive joints and is based on the comparison between the strain energy release rate (SERR) and the critical energy value (G_{Ic}), which is a material characteristic. Even the damage mechanics is divided in continuum damage models (CDM) and cohesive zone models (CZM), which a geometric interpretation is shown in Fig. 1, as in Chaves et al. [8], where the area inside the lines is the value of G_{IIc} (G_c in shear loading mode).

Blackman et al. [9] used Linear Elastic Fracture Mechanics (LEFM) to estimate values of the mode II adhesive fracture energy for bonded joints, through the utilization of various forms of beam theory corrections. Also, the concept of an effective crack length was introduced and then used to calculate corrected values of G_{IIC}. Romanos et al. [10] presents a stress-life approach to predict fatigue properties of adhesively bonded joints by using structural adhesives. A butt-bonded hollow cylinders test procedures based upon ISO 11003-1 [11] have been used, with a torsion test, to provide a very uniform shear stress in the adhesive layer with negligible variation across the adhesive ring. The article intended to prove the transferability of fatigue data evaluated using standard specimens, to bonded structures and components tested in fatigue.

Allen et al. [12] proposed that only using the Wohler approach,

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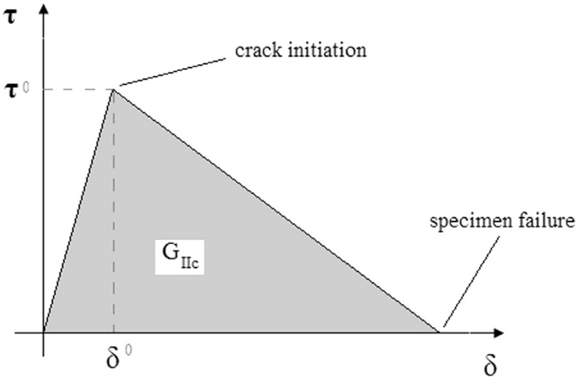

Fig. 1. Bilinear cohesive law (Chaves et al. [8] – adapted).

which is expensive and time consuming, it could be checked if fatigue limit of bonded joints exists or not. On the other hand, it was proposed the utilization of Prot [13] approach to do an estimative of fatigue limit without explicitly addressing the correspondent number of cycles.

De Barros et al. [14] studied the influence of mechanical surface treatment on fatigue of bonded joints, running fatigue tests on three-point bending fixture. End notched flexure specimens composed by two plates of steel ASTM A36 bonded together with the adhesive Novatec Primer NVT-1 were used. Three different surface treatments were considered for substrate: sand blasting, grit blasting and bristle blasting. It was observed that mechanical surface treatment has much influence on fatigue behaviour of bonded joints, which is not so characteristic in static loading condition. Grit and sanding blasting presented higher fatigue performance compared to the bristle one, having a fatigue life overcoming 10^6 cycles under 50% of loading level (applied load / load which the substrate yields).

In this article, the fatigue performance of bonded joints is assessed using the thermographic technique proposed by Risitano [15], which is also considered an accelerated method as the one proposed by Prot [13]. Specimens, as used in De Barros et al. [14] with sanding blasting surface treatment, were tested under three-point bending fixture, monitored continuously by an infrared camera. To define the fatigue performance of bonded joints, the nomenclature used in the ASTM D3166-99 [16] was adopted: adhesive joint fatigue strength, which address the situation where it is considered that the adhesive joint has reached a limit condition of crack initiation process could occur.

2. Experimental methodology

In this section, a brief description of the thermographic technique and all experimental resources used in the development of this research are presented.

2.1. Thermographic technique

The thermographic technique is mainly characterized by the use of thermo elasticity principles, through the measurement of the temperature variation on the external surface of specimens during variable loading application. It is known that a body subjected to variable loading experiences a changing on its temperature, where irreversible damage can be produced in material for larger temperature variation. This approach can be used to assess the fatigue behaviour of materials, proposing the hypothesis that fatigue failure occurs when the plastic deformation energy reaches a constant value (E_c), characteristic of each material, as in Fargione et al. [17] and Risitano et al. [15]. This assumption allowed a prompt correlation between the temperature increasing and the number of loading cycles, since fatigue damage is an energy dissipation process, as in Hou et al. [18]. Fig. 2 shows, schematically, the temperature behaviour (T) on specimen surface during fatigue cycles (N) under a loading amplitude large enough to initiate and propagate cracks.

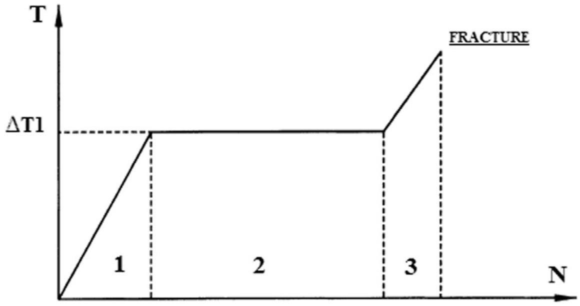

Fig. 2. Relationship ***T*** vs ***N*** during fatigue loading.

Fig. 2 schematically shows the three thermal phases (1, 2 and 3), which could be associated, respectively, with crack initiation, crack propagation and unstable failure process. The temperature variation of phase 1 (ΔT_1) increases as higher is the loading level relatively to the material fatigue strength (FS). Although Fig. 2 shows no temperature variation ($\partial T/\partial N_2 = 0$) in phase 2, there are also materials with a temperature increasing rate constant. This phase is responsible for the majority of test cycles. Finally, the number of cycles spent in phase 3 is relatively small if compared to others phases because the damage is quite significative culminating in unstable crack growth. The temperature in this last phase can reach more than 100 °C depending on the material and loading level tested.

Risitano [15] proposed to determine the temperature variation (ΔT) for only phase 1, in homogeneous materials, since it can represent the crack initiation process, for different stress amplitude (σ_a) in order to obtain the relationship ΔT_1 x σ_a. This relation has a bilinear profile with different slopes $d(\Delta T_1)/d\sigma_a$, characterizing a transition region from no fatigue damage (lower slope) to fatigue damage (higher slope). With this relation, the material fatigue limit can be determined (for materials, as ferrous alloys, which present this behaviour) by the extension of the straight line with higher slope until it across σ_a-axis, where $\Delta T_1 = 0$, representing no crack initiation and, consequently, no perceptible fatigue damage process. In the present work, there is an adaptation of this process, instead of using a ΔT_1 x σ_a graphic used for homogenous materials it was used ΔT x Q % graphics (shown in Figs. 10 and 11) adapted to non-homogeneous materials, where Q % is defined as a relation of the applied load in three points bending fixture and the load that begging to yield the substrate.

2.2. Experimental apparatus

Three specimens (*SP*) were submitted to fatigue tests in a servo hydraulic machine, using a three-point bending fixture. Sinusoidal loading was used with a frequency $f = 20Hz$ and a loading ratio of $R = P_{min}/P_{max} = 0.1$, where P is the applied transversal load. Fig. 3 shows a specimen on the testing fixture and its main dimensions.

The specimen dimensions are the same used in De Barros et al. [14], with pre-crack length $a_0 = 25$ mm, width $b = 25$ mm, total length $l = 190$ mm and substrate thickness $h = 6$ mm. The distance between lower and upper rollers was stated as $L = 80$ mm. The adhesive used was the Novatec Primer NVT-1, semi-flexible epoxy-based adhesive (epoxy + polyamine) with polymerization time of two hours, with high abrasion resistance, anticorrosion protection and high adhesion, with 0.5 mm thickness.

In order to guarantee thickness of the adhesive, spacers were used. Also, polypropylene plastics, with waxed surfaces, were used to form the pre-crack length.

Table 1 provides material mechanical properties of the cured adhesive.

The fatigue loading was applied as a percentage of the load