FATIGUE CRACK NUCLEATION AND PROPAGATION IN BONDED JOINTS

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ABSTRACT

The fatigue failure of bonded joints has been studied in this work. Tests have been conducted on single-lap shear joints bonded with a structural adhesive. The joint length has been taken higher than in standard fatigue tests in order to better distinguish between nucleation and propagation phases. The crack length evolution has been monitored with the compliance method and the crack growth velocity has been correlated with the range of strain energy relaease rate, *G*. Three different thicknesses of the bondline have been considered.

The results showed that the nucleation phases is practically absent, while the propagation is characterized by a constant velocity for about 80% of the total life. It is therefore believed that a fracture mechanics approach is of fundamental importance to design bonded joints undergoing fatigue.

1. INTRODUCTION

The design and/or verification of bonded joints subjected to fatigue loading traditionally relies on the calculation of the stress acting along the bondline. That stress is then compared with a fatigue strength, possibly evaluated from the tensile strength through a series of coefficient depending on the adhesive/adherend system and the environmental conditions [1].

Such approach may be questioned in the case of bonded joints for two fundamental motivations: i) the difference between stress conditions in a given joint and in the standard fatigue test joint; ii) the absence of fatigue failure analysis, i.e. the distinction between nucleation and propagation of a defect.

The results of fatigue tests performed in [2] on different kind of joints, when elaborated using a stress-based approach showed a great scatter depending on joint geometry. The tests made in [3] on double-lap shear joints showed an increase of the fatigue strength with the length of the bondline. This latter means that the contribution of the propagation phase of the defect leading to rupture is not negligible. An attempt to discriminate the relative importance of initiation and propagation phases of a fatigue defect was made in [2] and [3] and it turned out that it depends on both stress level and the joint geometry.

From these studies it turns out that an approach to fatigue durabilty without uncertanties on the application to different geometries and/or stress levels would be of great importance in the design of bonded joints. The aim of this work is therefore to: i) study the fatigue failure mechanism of bonded joints, ii) discriminate between initiation and propagation of the defect leading to failure and, iii) evaluate the kinetics of such defect.

2 EXPERIMENTS

2.1 Testing equipment and conditions

Tests have been conducted on 80mm-long, 35mm-wide single-lap shear joints. The length was chosen much higher than the one suggested in the ASTM D 3166 standard fatigue test (25mm) in order to better distinguish nucleation and propagation phases. The 5mm-thick aluminum alloy adherends were bonded with Loctite 330®, a structural adhesive used by the authors also in previous studies [4-6]. The standard shear and tensile strength is about 20MPa [1]. Thicknesses t_a = 0.1, 0.25 and 0.5mm of the bonding layer were tested.

The compliance has been determined every 500 cycles from the signal of two clip-gages placed at the ends of the joint, see Fig. 1. In some of the tests the crack evolution has been followed also optically by means of a CCD camera mounted on an optical microscope.

Constant load amplitude tests were conducted at load ratio $R = P_{min}/P_{max} = 0.1$ and frequency f = 10 Hz.

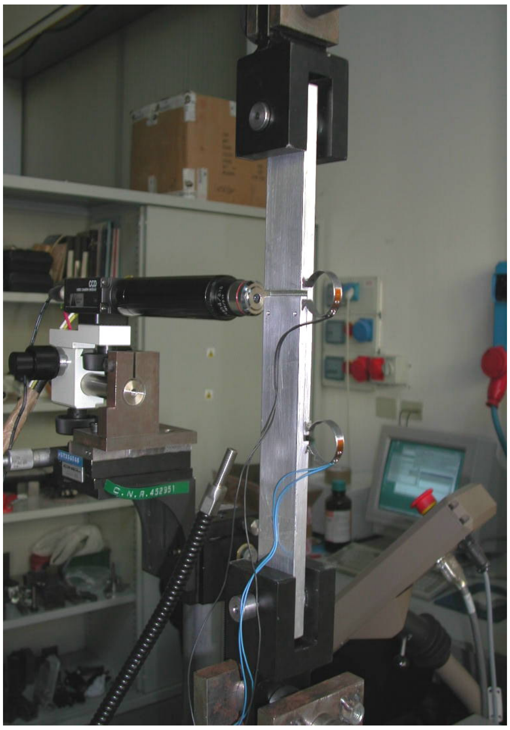

Fig. 1: testing equipment.

2.2 Geometry calibration

The nucleation and propagation of defects has been monitored through the change in the compliance of the joint, C, which is evaluated as the slope of the best fit of the sliding displacement δ vs. load P data during the unloading part of the cycle. The sliding displacement δ is measured at both ends of the joint by means of clip-gages (see Fig. 1). The relationship between C and the crack length a has been developed on the basis of the work of [7] which modeled the joint as a beam on an elastic foundation.

$$C = \frac{\delta}{P} = \frac{1}{2}\frac{l}{Ebh} + 2a\frac{4}{Ebh} + \frac{t}{G_a}\frac{\lambda_\tau}{2b}\coth\left(\frac{\lambda_\tau l}{2}\right) + \frac{t}{E_a}\frac{h^2\lambda_\sigma^3}{2b}\frac{\cosh(\lambda_\sigma l) - \cos(\lambda_\sigma l)}{\sinh(\lambda_\sigma l) + \sin(\lambda_\sigma l)} \qquad (1)$$

where

$$\lambda_t = \left(\frac{8G_a}{t_a hE}\right)^{1/2}; \lambda_\sigma = \left(\frac{6E'_a}{t_a h^3 E}\right); \quad l = L - 2a \qquad (2)$$

being G_a the elastic shear modulus of the adhesive, b and h width and thickness of the adherends and L is the joint length. Eqn. (1) has been compared with the experimentally recorded values of C and a (this latter measured optically on the joint side) in Fig. 2. The experimental are relative to both the clip-gages and therefore, are representative of the two crack fronts the develops from the joint ends. The scatter is due to the surface measurement of crack length, where the crack tip is sometimes difficult to detect and which does not account for the curvature of crack front. The trend is however in good agreement with Eqn. (1).

The strain energy release rate is derived from Eqn. (1) as:

$$G = \frac{P^2}{2b}\frac{dC}{d(2a)} \qquad (3)$$

For values of the ligamente $l = L\text{-}a$ such that $\lambda_\tau l$ and $\lambda_\sigma l > 4$, G can be approximated by ($\sigma_0 = P/(bh)$):

$$G = 1.75\frac{h}{E}{\sigma_0}^2 \qquad (4)$$

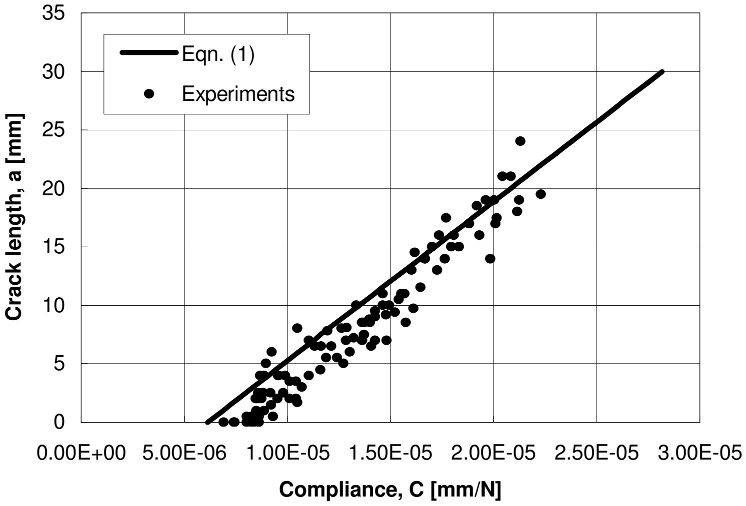

Fig. 2: comparison between Eqn. (1) and a-C data measured experimentally.

3 RESULTS AND DISCUSSION

3.1 Failure mechanism

The failure process has been monitored optically in some of the joints. The main phases are shown in Figs. 3a-d. The side of the joint not yet cycled is shown in Fig. 3a. The dark region is the adhesive layer (0.25mm thick in this case). After a small number of cycles (Fig. 3b) the adhesive "whitens" with respect to Fig. 3a, an indicator that some damage is taking place before a macroscopic defect appears. This latter then shows up at the at the end of the joint (Fig. 3c) and runs within the adhesive (cohesive propagation) or, more often in joints showing polimerization defects, at adhesive/adherend interface (adhesive propagation, Fig. 3d). It is worth to say that defects start almost simultaneously at the two ends of the bondline.

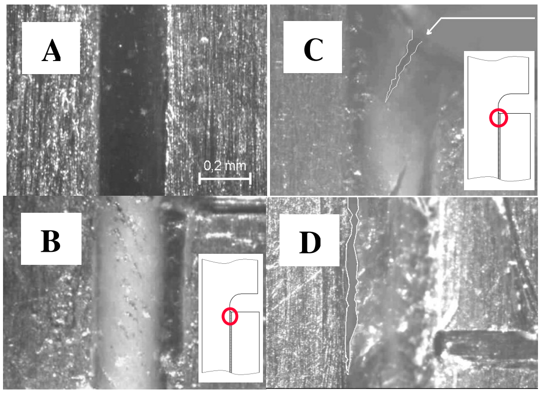

Fig. 3: a) undamaged joint; b) whitening after few cycles; c) nucleation; d) propagation.

3.2 Defect evolution

An example of the evolution of the defect length *a* against the number of cycles *N* is shown in Fig. 3. The first observation is that the initiation phase is practically absent, therefore the lifetime of the joint is dominated by the propagation. The trend of experimental data is linear for about the first 80% of life, while afterwards the increase is more than proportional. The linear trend corresponds to a constant propagation velocity (elongation per cycle, *da/dN*).

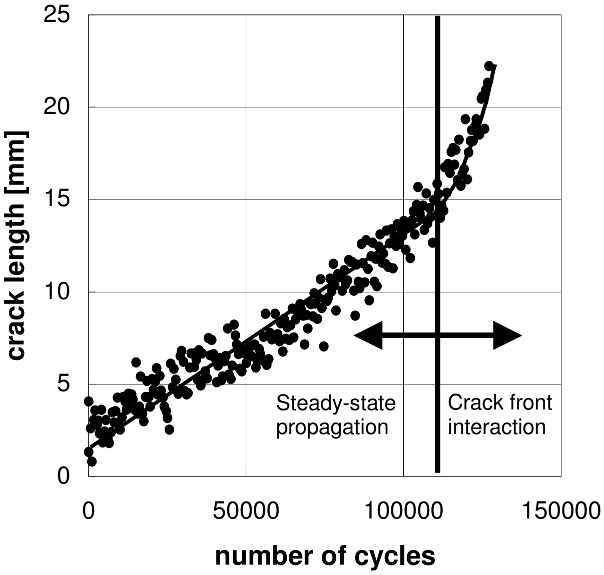

Fig. 4: Typical evolution of a defect during the test.

The slope of the linear trend (i.e a constant *da/dN*) has been plotted against ΔG in Fig. 5. It is worth to underline that in single-lap-shear joint ΔG is constant over a wide range of crack lengths. The solid lines represent the Paris-like equation:

$$\frac{da}{dN}=C(\Delta G)^m \tag{5}$$

used to fit the data. The exponent are very similar for all of the thicknesses considered, meaning that the crack propagation mechanism is not influenced by this parameter, while the constant C is slightly different only for $t_a = 0.1$mm.

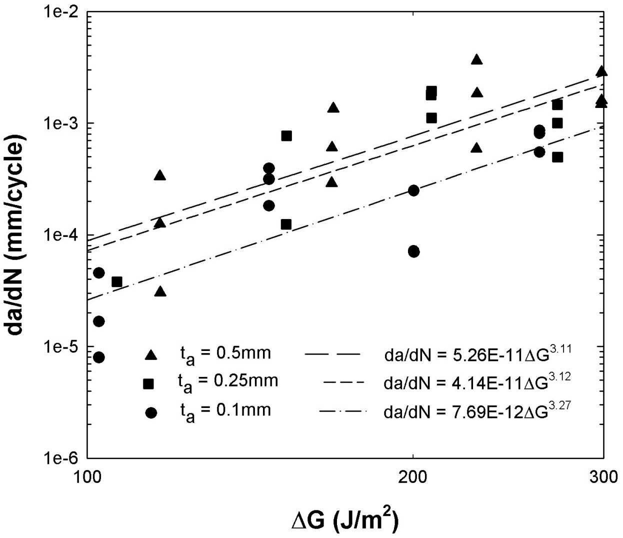

Fig. 5: FCG rate at different load levels and adhesive thickness t_a.

In all of the tests, the failure of the joints occurred at a crack length such that G was represented by Eqn. (4). Since the maximum load of the cycle is kept costant, the acceleration of the crack before rupture and the critical crack length cannot be explained using fracture mechanics arguments. Regarding the critical crack length, the ligament at fracture l_c is plotted as function of the maximum load P_{max} in Fig. 6.

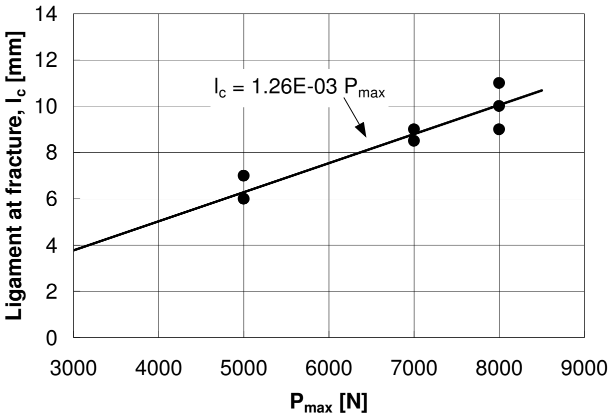

Fig. 6: ligament at fracture as a function of the maximum load of the cycle.

In the hypothesis that the collapse occurs when the average shear stress in the joint attains a critical value τ_R, one has:

$$l_c = \frac{P_{\max}}{b\tau_R} \tag{6}$$

The linear regression of the data shown in Fig. 6 gives a value τ_R = 22.6MPa which is very similar to the shear strength declared in the technical datasheet of the adhesive.

4 CONCLUSIONS

Fatigue failure of a bonded single lap-shear joint has been investigated monitoring the evolution of the defect(s) leading to rupture. The results showed that cracks nucleate from stress concentration regions at the ends of the joints in a very few cycles. The FCG rate can be correlated to the applied load range through a Paris-like relationship, while the collapse occurs when the average shear stress attains the adhesive strength. The duration of the joint is dependent essentially from the propagation phase and, therefore, fracture mechanics can be regarded as an important tool in the fatigue design of bonded joints.

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