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Fatigue Threshold Analysis of Adhesives: Displacement Control vs. Load Control Strategy

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Abstract

The aim of this paper is to study the response of a two-part polyurethane-resin adhesive under quasi-static and fatigue loading conditions, to compare load control and displacement control approaches for the mode I fatigue threshold analysis of the tested material. To achieve this, double cantilever beam (DCB) joints were manufactured and tested. For the post-processing of the raw data, a compliance-based beam method was used. Out of this analysis, R curves and Paris law curves were obtained.

Both approaches showed a similar Paris law slope meaning a low sensibility of the crack growth rate between them. As the displacement control load decreases gradually during the test, it can give more precise threshold energy than the load control technique.

1. Introduction

Adhesives as a structural bonding method offer a more uniform stress distribution along the bondline compared to the traditional joining techniques. They also reduce the weight of the structure, increase the flexibility of the joints, and allow the joining of dissimilar materials (da Silva, Öchsner, and Adams 2011). These advantages justified the significant ascension of their use over the past decades among the most common fastening methods, such as riveting, and welding (Antelo et al. 2021).

In real practice, bonded joints are often subjected to fatigue loading conditions. The fatigue life can be separated into two main parts, crack initiation and crack propagation. The fracture mechanics approach has been widely used to investigate the mechanical behavior of adhesive joints for fatigue crack propagation in bonded joints. Rocha et al. (A.V. Rocha, Akhavan-Safar, et al. 2020) investigated the fatigue behavior of one epoxy-based, one acrylic, and one rubber-like adhesive, with different bondline thicknesses. For fatigue crack growth tests, under pure modes I, II, and mixed-mode, a frequency of 10Hz was used with an R-ratio of 0.1. Monteiro et al. (Monteiro et al. 2020) evaluated the fatigue behavior of a structural epoxy adhesive for different R-ratios (0.1 and 0.3) and load levels and also stated that the use of a higher load amplitude leads to faster crack growth and shorter life, pointing out that the effect of load level on crack propagation is higher at lower R-ratios and G_{th} could be approximately constant throughout mode I condition with different load levels while it is a function of mode mixity.

However, within the context of the current demand and despite the enhanced fatigue strength, their mechanisms of long-term cyclic behavior are not yet completely defined. Therefore, it is essential to study and better understand the behavior of adhesive joints under a high cycle fatigue regime which corresponds to 50% to 90% of the mechanical failures of the structures (Parvez et al. 2019). Also, for a safe design against fatigue crack growth, it is necessary to know the fatigue threshold energy (G_{th}) of the adhesive used to bond the structural components. Several techniques have been considered by authors to analyze the threshold energy of adhesive materials. A displacement control approach keeps maximum and minimum displacement constant. This causes the strain energy release rate, G, and the crack speed to decrease with fatigue cycles. In this approach, the test begins at the maximum desired crack growth rate and terminates at the threshold region. However, in force control fatigue tests, the load is constant during the test while the displacement increases by crack propagation. This increase in crack size increases the fracture energy cycle by cycle until it reaches a critical value where the unstable crack growth region begins. Accordingly, in this kind of test, the crack growth usually starts at the threshold zone and accelerates to the maximum desired crack speed leading to the complete failure of the joint. Azari et al. (Azari et al. 2010) evaluated the effect of Paris law relation on the fatigue threshold of bonded joints loaded in mode I. They considered both load control and displacement control techniques. They found that using a proposed Paris law relation, the threshold energy would be less sensitive to the load ratio (displacement ratio). They also found that the increase in load ratio will increase the threshold energy of the adhesive.

Despite the few studies published by authors, the fatigue threshold energy analysis of bonded joints is still an open research topic. Different techniques considered by authors and different parameters that influence the results have made the fatigue threshold analysis of adhesives more challenging.

Accordingly, the aim of the current study is to investigate the difference between different strategies (load control and displacement control) used to assess the threshold energy of adhesive materials under pure tensile loading conditions.

2. Experimental Details

In the experimental part, double cantilever beam (DCB) specimens were manufactured and tested under fatigue loading conditions.

2.1. Materials

The substrates used in this work were machined from high-strength steel, to ensure the absence of plastic deformation during the tests, bonded with a 2-part polyurethane adhesive. This material has a characteristic low viscosity (7000 mPa.s and 20 mPa.s for the resin and hardener, respectively, and 1100 mPa.s mixed), it is semi-flexible and has good thermal conductivity. In terms of the specific gravity, it shows 1.57 g/cm^3 and 1.22 g/cm^3 for the resin and hardener, respectively.

2.2. Geometry

The joints used for the static and fatigue tests were DCB specimens manufactured based on the ASTM D-3433 standard (D-99 1999) as shown in Figure 1.

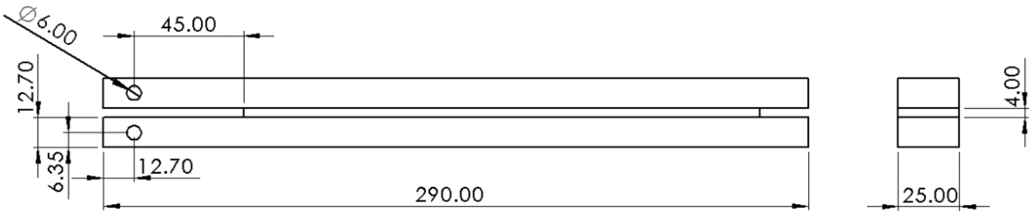

Figure 1: Specimens' geometry adapted from ASTM D-3433-99.

2.3. Manufacturing

To improve adhesion in the joint, the surfaces of the specimens were sandblasted, and cleaned with acetone, and then a very thin coat of primer was applied to the surfaces. To guarantee the 4mm bondline thickness considered in this study, besides using the metal spacers, as the low viscosity is a characteristic of this adhesive, a specific mold system was also developed using 3D printed Polycarbonate specimens (see Figure 2). To maintain a consistent pre-crack, thin blades were used between the spacers at the front of the specimen.

According to the manufacturers, the curing process was 24h at room temperature followed by a post-curing step at 80°C for 4h.

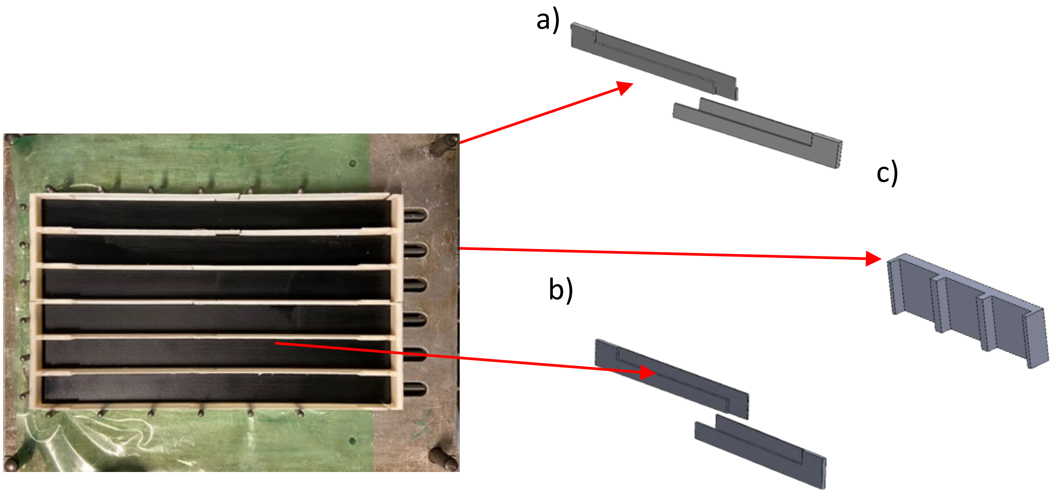

Figure 2: Mould assembly with 3D printed Polycarbonate specimens that are the white parts shown in the mould. a) middle, b) lateral and c) end lock.

2.4. Test Approach

An INSTRON 8801 servo-hydraulic machine was used for fatigue crack growth tests and an INSTRON 3367 was employed for the quasi-static tests. A displacement rate of 0.2 mm/min was used for the quasi-static tests. Static tests were conducted to obtain the maximum strength and the compliance of the joints. These data were used as a reference for setting the fatigue test parameters.

The displacement control fatigue tests were performed at a frequency of 12Hz, with a displacement ratio of 0.04. The R ratio in displacement control tests was tried to be kept around 0.1. A maximum displacement corresponding to the load level of 60% of the maximum static strength was considered in this test.

For the load control approach, the same parameters as the displacement control tests were used, except for the maximum fatigue load, which was 35% of the maximum static strength.

3. Results and Discussion

The quasi-static results obtained from the data reduction using CBBM (compliance-based beam method) and the fracture surface are shown in Figure 3.

The static load-displacement curve is used to obtain the maximum load supported, which is used as a reference for fatigue tests. After this point in the curve, it is possible to notice a load decrease that represents the start of crack propagation. The resistance curve (R curve) represents the energy release rate for pure mode I as a function of equivalent crack length. Mode I fracture energy was used to normalize the strain energy release rate obtained at each loading cycle in the fatigue test.

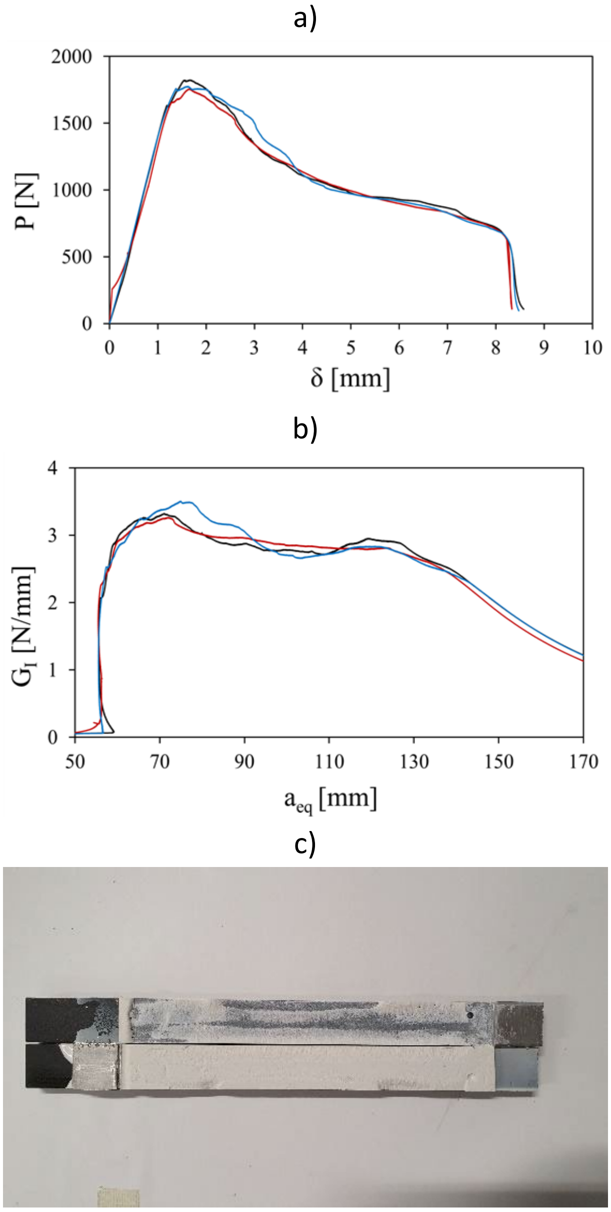

Figure 3: Results from the quasi-static fracture tests for 3 samples: a) Load vs. displacement (P-δ) curve, b) R – curve, and c) Fracture surface.

According to the Paris law equation, the region of stable crack propagation can be described as follows:

$$\frac{da}{dN} = C\left(\frac{G_{maxI}}{G_{Ic}}\right)^{m} \tag{1}$$

The damage parameter can be G_{max}, G_{min}, G_{th}, or a combination of them as $\Delta G = G_{max} - G_{min}$ as studied by Rocha et al. and Wang et al. (A. Rocha, Akhavan-Safar, et al. 2020; Wang, Slomiana, and Bucinell 1985). In this study, a normalized damage parameter was used, defined as $\frac{G_{maxI}}{G_{Ic}}$ where the G_{Ic} is the mode I fracture energy for quasi-static loading conditions and G_{maxI} is the maximum strain energy release rate at each loading cycle corresponding to the maximum fatigue load. Figure 4 compares the results of the fatigue fractures tests for both load control and displacement control strategies.

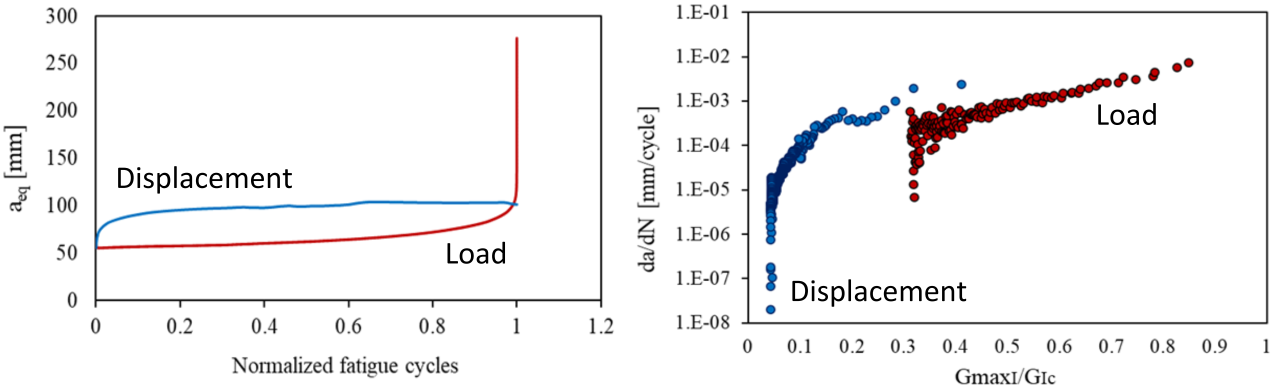

Figure 4: Results from the load control fatigue fracture tests.

Table 1: Gth and Paris law slope comparison between.

	G_{th} [N/mm]	Paris law slope, m
Load Control	0.93	3.57
Displacement Control	0.14 ± 0.04	3.17 ± 0.47

In the displacement control tests, the load drops significantly after the crack initiation and finally close to the threshold region the load is usually very low. Due to this very low load level, the load cell usually introduces noises into the measured load values that must be filtered during the processing of the results. However, due to the constant load level, less significant noises are observed in load control tests. Also, the difference between the equivalent crack length vs. normalized cycles (Figure 4, left graph) is substantial between the two approaches. The load control test starts at the threshold region of the Paris law curve, so it takes a lot of energy and cycles to start the crack propagation, but the crack size rapidly increases at the end. However, the displacement control test starts at the third region of the Paris law curve with unstable crack propagation, and then crack growth stabilizes, and finally it reaches the threshold region. Although a similar slope was obtained for the stable crack propagation part, however, the results show that the two techniques give different fatigue threshold values. The load control test showed higher threshold energy than the displaced control test. Several parameters such as the fatigue displacement (load) level and the displacement (load) ratio can affect the results. To understand the role of each parameter further experimental studies are needed.

4. Conclusions

Two different techniques including load control and displacement control test have been considered by authors to measure the threshold energy of adhesives. An important aspect to distinguish between the two approaches used for the fatigue testing is that displacement control tests start at the 3^{rd} region of the Paris law curve, which corresponds to unstable crack propagation, and it ends at the threshold region. While, load control tests start at the threshold, with non-significant crack growth, then it progresses to the 2^{nd}, and finally ends at the the 3^{rd} region of the Paris law curve. Furthermore, load control fatigue tests usually end with joint failure, however, for displacement control, usually the joint doesn't fail and the end of the test.

A displacement control test is inevitable to achieve a threshold, once a displacement ratio that doesn't fracture the joint too quickly is set. Both load control and displacement control techniques showed similar Paris law slope (m) meaning the less sensitivity of the stable fatigue crack growth rate to the considered technique while for the threshold values different results were obtained from the two strategies. However, since the load is gradually reduced in a displacement control test until a threshold region is achieved, it can give more precise threshold energy than a load control test where the load is constant during the test and the displacement increases cycle by cycle. However, further studies are needed in this field.

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