Materials Science and Engineering A 534 (2012) 594–602

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of substrate modulus on the fatigue behavior of adhesively bonded joints

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ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form 22 October 2011
Accepted 6 December 2011
Available online 13 December 2011

Keywords:
Finite element method
Toughened epoxy
Adhesive joint
Fatigue
Residual stresses

ABSTRACT

The effect of the substrate material on mode-I fatigue behavior of a toughened epoxy adhesive system was examined in terms of the substrate stiffness and curing residual stress. It was found that a change in adherend material from aluminum to steel caused a reduction in the fatigue performance; i.e. the threshold energy release rate decreased and the crack growth rate increased for a given applied energy release rate. The possibility that these observations were a result of adhesive curing residual stresses was studied experimentally and analytically, but it was found that such effects were relatively small. Finite element modeling showed that the fatigue results could be explained in terms of an increase in the crack tip stresses and an enlarged plastic zone due to the greater modulus of steel compared with aluminum. The local influence of the adherend modulus proved to be much more significant than the global effect of the adherend stiffness (product of modulus and moment of inertia). The effects of adherend modulus are expected to diminish as the phase angle increases.

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1. Introduction

Cyclic loads can produce fatigue failure in adhesive joints at stress levels much lower than they can withstand under monotonic loading. Consequently, there has been extensive research on the fatigue crack growth of adhesive joints under mode-I [1–4] and mixed-mode loading [5–7]. However, the effect of adherend material on fatigue crack growth in adhesive joints has received very little attention, although recent data suggested that the adherend material can affect fatigue cracking through a mechanism unrelated to the strength of the adhesive bond [7]. In contrast to fatigue crack growth, the effect of the adherend material on adhesive joint fracture has been the subject of several studies. Yan et al. [8] observed that the mode-I quasi-static, steady-state critical energy release rate, G_c^s, for a DCB (double cantilever beam) joint with steel adherends was about 30% less than that for the same adhesive with aluminum adherends. The lower fracture energy of the steel joints was attributed to elevated stress levels in the crack tip region of the stiffer steel joint. However, the equation used for the energy release rate (G) calculation did not consider the presence of the adhesive. Changing the substrate stiffness in an adhesive system alters the relative contribution of the adhesive layer to the total joint compliance, and thus the calculated G [7]. Therefore, the error of ignoring the adhesive in steel joints will be higher than in aluminum joints [7]. This might be the reason why the difference between the steel and aluminum joints decreased to 13% when the critical J-integral, J_c^s, was used as the basis of comparison, since the J-integral will account for the presence of the adhesive layer [8].

In agreement with the trend of [8], Azari et al. [9] found that G_c^s for steel joints was approximately 20% less than that for aluminum fracture specimens of the same thickness under mode-I and mixed-mode loading. However, it was unclear if this was a result of substrate modulus or an unrelated change in the interfacial bond strength and crack path, since the fracture surfaces of the aluminum joints were fully cohesive, but were partially interfacial in the steel joints, under both mode I and mixed-mode loading. Similarly, Choupani [10] found lower mode-I, mixed-mode and mode-II G_c^s for steel joints compared to the aluminum. However, this was attributed to the difference in the failure pattern of the two systems, from a cohesive fracture for the aluminum joints to a crack path at the substrate-adhesive interface for the steel joints [10]. Therefore, the bond strength may have played a larger role than differences attributable to a changed crack tip stress state. In contrast, Bell and Kinloch [11] compared the mode-I G_c^s of aluminum, steel and CFRP (carbon fiber-reinforced polymer) joints and found that G_c^s increased with adherend stiffness. This was attributed to the shape and the size of the plastic zone ahead of the tip and within the adhesive layer which was believed to be affected by the transverse elastic modulus of the adherends. Later however, the difference between the CFRP and the metallic adherend specimens was attributed to water absorbed by the CFRP substrates [12].

Recently, the present authors examined the effect of loading phase angle on the fatigue behavior of aluminum and steel joints [7]. Under mode-I loading, the threshold energy release rate, G_{th},

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doi:10.1016/j.msea.2011.12.014

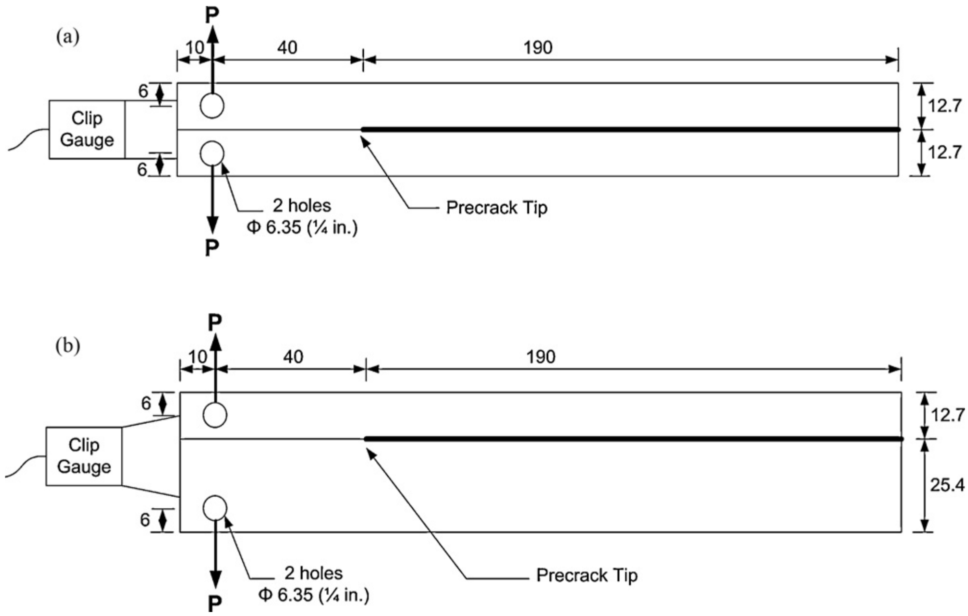

Fig. 1. Geometry and the loading condition of (a) DCB and (b) ADCB joints used in [7]. All dimensions in mm unless stated. Specimen width was 19 mm (3/4″).

for steel joints was slightly lower than that for aluminum joints, and the difference was statistically significant. This was consistent with the trend observed in fracture; i.e. steel joints were weaker [9]. However, G_{th} was the same for steel and aluminum asymmetric DCB joints (phase angle of 18°), and G_{th} for steel cracked-lap-shear (CLS) joints (phase angle of 50°) was about 30% greater than that for aluminum joints. Similar trends existed for crack growth rates. The trend for the CLS joints was explained in terms of changes in the relative fractions of cohesive failure due to variations in the bond strength, rather than differences in adherend stiffness or modulus [7]. This explanation was somewhat similar to that in [9,10] for the differences in the mode-I and mixed-mode fracture strengths of steel and aluminum joints.

The present paper uses finite element modeling to relate differences in the crack tip stresses and the plastic zones in steel and aluminum adhesive joint fatigue specimens to measured differences in the crack growth rates. The possibility that these differences are due to variations in the residual curing stresses is investigated. The effect of loading phase angle on the fatigue behavior of adhesively bonded joints with different substrate materials has also been examined.

2. Experimental approach

2.1. Fatigue experiments

The mode-I fatigue data of [7] showed a significant increase in the mode-I fatigue crack growth rate and a reduction in the mode-I G_{th} when the substrate was changed from aluminum to steel. Moreover, these mode-I fatigue data exhibited cohesive failure in both the steel and aluminum joints and so the confounding influence of differences in the interfacial bond strength can be eliminated. The details of the fatigue experiments may be found in [7]; therefore, the following provides only a brief summary of the key features of these earlier tests. Double cantilever beam (DCB) specimens (Fig. 1(a)) were used for testing under mode I conditions. Aluminum specimens were fabricated from 12.7 mm × 19.05 mm (1/2″ × 3/4″) AA6061-T651 flat bars which were abraded and pretreated using the P2 etching process [13]. The steel joints were made from 12.7 mm × 19.05 mm (1/2″ × 3/4″) AISI 1018 steel bars with a standard Zn-phosphate pretreatment [7], and had the same geometry as the aluminum joints. A single-part, heat-cured, highly toughened epoxy adhesive was used with a bondline thickness of 0.38 mm (0.015″).

The fatigue experiments were at a cyclic frequency of 20 Hz, in a dry environment (11–15% relative humidity), under force control with a constant force ratio, $R = P_{min}/P_{max} = 0.1$ [7]. It was previously shown that testing under force or displacement control does not significantly affect the fatigue behavior [14]. The unloading joint compliance approach [15] was used to measure the fatigue crack length [7].

The energy release rate, G, for the DCB joint was calculated from the measured force and crack length using an analytical beam-on-elastic-foundation model [7] as follows:

$$G = 12(Pa)^2(A + B) \quad (1)$$

where

$$A = \frac{1}{2E_u h_u^3}\frac{1}{(1-t_l/h_u)^3}\left[1 + 0.677\{(1-t_l/h_u)^3[1 + t_l/h_u(2E_u/E_a - 1)]\}^{0.25}\frac{h_u}{a}\right]^2$$
$$B = \frac{1}{2E_l {h_l}^3}\frac{1}{(1-t_u/h_l)^3}\left[1 + 0.677\{(1-t_u/h_l)^3[1 + t_u/h_l(2E_l/E_a - 1)]\}^{0.25}\frac{h_l}{a}\right]^2 \quad (2)$$

and P is the force per unit width, E is the elastic tensile modulus, t is the adhesive thickness and h is the adherend thickness. The subscripts a, u and l refer to the adhesive, and the upper and lower substrates, respectively. The calibration constant of 0.677 was suggested by Hutchinson and Suo [16] based on a comparison between finite element results and analytical considerations.

For crack lengths of 40–120 mm, the G values for the aluminum and steel DCB joints were within 2% of those predicted from a two-dimensional elasto-plastic finite element model [7]. In the FE model, G was calculated using a virtual crack extension technique. To investigate the effect of plastic deformation near the crack tip on the calculated G using FEA, results from a fully elastic FE model were compared to the elasto-plastic model. The average difference between the calculated G using the two models for the $200\ \mathrm{J/m^2} < G < 1000\ \mathrm{J/m^2}$, typical range for the current fatigue tests, was less than 1%.

2.2. Residual curing stress measurements

Differences in fatigue crack growth behavior in steel and aluminum adhesive joints may be attributable to the differences in the

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