Fracture Characteristics of Interfacial Crack in Epoxy Adhesive-bonded Dissimilar Materials

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1. Introduction

Adhesive joint is the best candidate to replace any conventional bonding methods (e.g. rivet, welding, diffusion bonding, etc.) in structural engineering applications. In order to have high reliability and significant strength performance of adhesive joints, the fracture toughness of adhesive joints should first be properly determined. It has been reported in the literature that the fracture toughness of an adhesive joint is greatly dependent on the adhesive bond thickness and existence of cracks or flaws. However, the mechanisms of the dependency are not yet clarified.

In this study, fracture characteristics of the epoxy adhesive-bonded butt joints of dissimilar metals were examined on various adhesive bond thicknesses in associations with artificial interface-crack lengths subjected to pure mode I loading. Finite element analysis was also performed to investigate the fracture mechanism of the adhesive joints.

2. Experimental procedures

The epoxy adhesive resin used in this study was Hi-Super 30 produced by Cemedine Co., Japan. This is a commercial brittle epoxy adhesive that can be cured at room temperature approximately in 30 minutes. The adhesive was prepared prior to bonding by mixing the epoxy resin and hardener with the conditioning mixer for 1 min: 3min schedule of diffusion and de-foaming, respectively. The mechanical properties of the bulk epoxy adhesive have been reported in the previous study[1], and the pertinent results are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>σ&lt;sub&gt;y&lt;/sub&gt; (MPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>0.34</td>
<td>36.5</td>
<td>0.3</td>
</tr>
<tr>
<td>SUS304</td>
<td>20.6</td>
<td>295</td>
<td>0.3</td>
</tr>
<tr>
<td>YH75 (Al-alloy)</td>
<td>7.1</td>
<td>399</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Tensile and three-point bending test specimens (3PB) were prepared to obtain the strength and fracture toughness of adhesive joints. The dimensions of tensile and 3PB test specimens are shown in Fig. 1(a) and (b), respectively. The adherents were consisted of SUS304 stainless steel and YH75 aluminum alloys. Adhesive bond thickness, t inside an adhesive joint was controlled by using a developed fixture and was varied from 0.2mm to 1.2mm. For specimens with interfacial crack, the pre-crack was introduced by pasting a strip of 0.05mm thickness Teflon tape on the adherent surface prior to bonding. The pre-crack length, a was controlled to study their effects on each test. Thus, a/W is given as 1/8, 1/4 and 3/8, where W was the specimens width.

Tensile and 3PB fracture tests of adhesive joints were carried out with a universal tensile test machine (INSTRON) and a three-point bending test machine (Little Senstar), respectively. Both fracture tests were conducted at room temperature with the crosshead speed of 1.0 mm/min.

3. FE analysis

2D elastic-plastic finite element (FE) analysis was performed using ANSYS 10 code. The FE mesh consisted of eight nodes plane stress isoparametric with quadrilateral elements (i.e. PLANE183). The mesh for adhesive layer was refined sufficiently whilst the contact element was properly defined to constraint the adhesive layer to adherents. 2D FE simulations were carried out to:

1) investigate the stress-y distribution at the free-edge and interfacial crack-tip region.
2) evaluate the fracture toughness, Jc of model with interfacial crack.

4. Results and discussion

Failure load of tensile adhesive joints of SUS304/YH75 against bond thickness, t is plotted in Fig. 2. It is obtained that the failure load significantly decreased when the bond thickness, t increased. While tensile adhesive joints with interfacial crack was fractured, mode I fracture toughness, Jc exhibit somewhat independence of bond thickness, t(see Fig. 3). Moreover, from observations of fracture surfaces, it can be found that the interfacial crack has propagated through the boundary of adhesive/adherent (A) and in particular cases deviated into the adhesive layer (B), as illustrated in Fig. 4. These results agree with the 3PB tests reported in the previous study. Hence, it is necessary to evaluate the Jc of each specimen with further consideration on their mode loading condition and locus of failure.
In order to determine mode I and II fracture toughness (i.e. $K_I$ and $K_{II}$) of adhesive joints, we employed FE analysis by means of stress and CTOD-based extrapolation method as proposed by Kikuchi[2]. Fig. 5 shows $K_{II}/K_I$ against bond thickness, $t$ of tensile adhesive joints with SUS304-side interfacial crack (SEA). Solid lines represent results obtained from FE analyses. At 5mm crack length, no significant trend can be noted as both interfacial and cohesive failure appeared simultaneously. At 10mm crack length, cohesive failure starts to reveal above 0.6mm bond thickness. Meanwhile, for tensile adhesive joints with YH75-side interfacial crack (AES) as can be seen in Fig. 6, at 5mm crack length, all failures occurred as interfacial failure regardless of the bond thickness, $t$. However, at 10mm crack length, cohesive failure appeared at bond thickness, $t$ over 0.4mm. In conclusion, $K_{II}$ governs the crack growing direction.

Next, relationship between the mode loading and deviation angle of crack in each specimen associated with cohesive failure is of practical interest. Fig. 7 shows the correlation between $K_{II}/K_I$ and $\theta_{max}$. Here, $\theta_{max}$ is referred to the clockwise angle from crack-front line. The theoretical curve can be deduced at $\sin \theta_{max}$ in equation below. As is seen, in 3PB tests, the crack was considerably deviated into adhesive layer and in close agreement with the prediction curve. Such a trend is also observed in tensile tests save for small in numbers. Thus, further investigation is much needed to gain a better understanding regarding this point.

5. Conclusions

The strength of adhesive joints without crack decreased with the increasing bond thickness. Nevertheless, fracture strength of adhesive joints with interfacial crack is independent on bond thickness. The interfacial crack-tip inside the adhesive joints of dissimilar material has also experienced the mode II manner even when it is subjected to pure mode I loading.

6. References