Three-Point Bending Fracture Test of Epoxy Adhesive-bonded Dissimilar Materials

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The objective of this study is to investigate the strength of epoxy adhesively bonded dissimilar materials at different bond thickness with interfacial pre-crack. From three-point bending (3PB) fracture test of adhesive joints, it is observed that the fracture strength decreases as the bond thickness increases. Nevertheless, fracture strength of 3PB adhesive joints with interfacial pre-crack is independent on bond thickness. The interfacial crack-tip inside the adhesive joints of dissimilar material has also experienced Mode II manner when it is subjected to Mode I loading. In addition, for 3PB adhesive joints with aluminium/adhesive interfacial crack, it is found that J_c is dependent on pre-crack length, thus there is a change in fracture behavior. Moreover, such behavior is also observed from numerical analysis.

1. Introduction
Adhesive joint is the best candidate to replace 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 determined. It has been reported in the literature that the fracture toughness of an adhesive joints depends on the bond thickness and existence of crack. However, the mechanisms of the dependency are yet to be elucidated.

In this study, three-point bending strength characteristics of epoxy adhesive-bonded butt joints of dissimilar metals were examined on several adhesive's bond thicknesses. 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 two component epoxy adhesive resin and can be cured at room temperature within 30 minutes. To investigate the mechanical properties of the bulk adhesive, (a) typical tensile and (b) single edge notched tensile (SENT) specimens were fabricated as shown in Fig. 1(a) and (b). The adhesive and hardener were mixed in conditioning mixer for 1 min: 3min schedule of diffusion and de-foaming, respectively. The pre-crack in SENT was initiated by inserting a sharp razor blade at an edge of the plate prior to the molding.

Adhesively bonded three-point bending test specimens (3PB), Fig. 1(c) were prepared to determine the strength and fracture toughness of adhesive joints. The adherents were two rectangular bars of SUS304 stainless steel and YH75 aluminium alloys. The dimensions of 3PB test specimens are shown in Fig.1(c). Adhesive bond thickness, t was controlled by using a developed fixture. Bond thickness was varied from 0.1mm to 1.6mm. For 3PB test specimens with interfacial crack, the pre-crack was introduced by pasting a strip of 0.05mm thickness Teflon tape on the adherent surface before the bonding.

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

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

4. Results and discussion
The tensile stress-strain responses of bulk adhesive are shown in Fig.3. As seen in Fig. 3, bulk adhesive used in this study demonstrated almost linear-elastic and brittle failure similar to the typical un-modified thermosetting resin behaviors. It is also known that the strength of bulk adhesive was significantly improved if prepared by conditioning mixer. Figure 4 shows the Mode I fracture toughness, K_{IC} of SENT specimens against normalized pre-crack length, a/W. K_{IC} was determined according to ASTM E-399 standard. From Fig. 4, the K_{IC} values of bulk adhesive gradually increased from 0.94 to 1.87 MPam^{1/2}.

The failure load of 3PB adhesive joints versus bond thickness is plotted in Fig. 5. It was observed that strength of 3PB adhesive joints in Mode I loading decreased when the bond thickness is increased. However, Mode I fracture toughness, J_c of 3PB adhesive joints with interfacial crack exhibits independence of bond thickness (see Fig. 6). Therefore, it is necessary to measure the fracture toughness of these specimens with further consideration of mode loading conditions.

In order to determine Mode I and II fracture toughness (i.e. K_{Ic} and K_{IIc}) from FE simulation, the stress and crack-tip opening displacement (CTOD)-based extrapolation method was applied. Simulation result for 3PB adhesive joints with 6mm aluminium/adhesive interfacial crack length is illustrated in Fig. 7. From Fig. 7, the ratio of K_{Ic}/K_{IIc} can be obtained as shown in Fig. 8. Obviously, as seen in this figure, two trends can be noted.

Firstly, in steel/adhesive interfacial crack, Mode II loading is always larger than aluminium/adhesive interfacial crack regardless of bond thickness. This is due to the mismatch of elasticity and constraint effect of adherents. Because the elastic modulus of aluminium adherent is closer to the elastic modulus of adhesive (i.e. E_{alu}=20Eadh), as compared to the elastic modulus of stainless steel (i.e. E_{ssu}=60Eadh), the aluminium adherent has better containing capability.

Secondly, in aluminium/adhesive interfacial crack, Mode II loading slightly decreased when the bond thickness has exceeded 0.5mm. After exceeding 0.5mm bond thickness, steel adherent at the opposite side is no longer can constrain the adhesive layer, resulting in smaller Mode II loading. With smaller Mode II loading in *b, the smaller J_c was obtained. This explains the interfacial fracture in *b as Mode I loading dominance (see Fig. 9). On the
other hand, higher Mode II loading was revealed in *a as cohesive fracture (see Fig. 9).

5. Conclusions
1) The strength of bulk adhesive can be improved by using conditioning mixer. $K_{IC}$ values of bulk adhesive ranges from 0.94 to 1.87 MPa.m$^{1/2}$.
2) The strength of 3PB adhesive joints in Mode I loading decreased with the increasing bond thickness.
3) In 3PB joints with interfacial crack, $J_c$ was governed by both constraint effect of adherent and mode mixity at the interfacial crack-tip. Interfacial crack is weaker in Mode I than in Mode II loading condition.

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Fig. 1 Geometry of 3PB adhesive joints specimen

Fig. 2 Finite element mesh of 3PB adhesive joints model

Fig. 3 Tensile stress-strain response of bulk adhesive

Fig. 4 $K_{IC}$ of SENT against normalized crack length, $a/W$

Fig. 5 Failure load vs. bond thickness, $t$ of 3PB adhesive joints

Fig. 6 $J_c$ vs. bond thickness, $t$ for 3PB adhesive joints with aluminium/adhesive interfacial crack

Fig. 7 Result of stress and CTOD-based extrapolation method

Fig. 8 Ratio of $K_{II}/K_{I}$ vs. bond thickness, $t$ for 3PB adhesive joints with 6mm interfacial crack length

Fig. 9 Fracture surface of *a and *b