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

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Abstract

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 joint, the fracture toughness of adhesive joints should first be determined. It has been reported in the literature that the fracture toughness of an adhesive joint depends on the bond thickness and existence of crack. However, the mechanism 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.
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1. Introduction

1.1 History of adhesives

For thousands of years the only adhesives of major importance in human civilization were the animal and vegetable glues. However, these kinds of natural origin adhesives were found to have some limitations (e.g. low strength, limited resistance to moisture, etc.), thus have provided the stimulus responsible for the great expansion since the 1930s in the development of new adhesives. The new adhesives which are based upon synthetic resins and other materials were widely employed then for their outstanding advantages.

Phenol formaldehyde was the first synthetic resin being mainly used for wood assembly and plywood manufacture. Later on, the modified phenolic resins containing synthetic rubber have been employed for metal bonding in the aircraft industry as to high shear and peel strengths performance. The 1950s saw the introductions of epoxy resin-based adhesives offering equal strength properties and the processing advantages associated with 100% reactive solids systems.

1.2 Applications of adhesive joint

Nowadays, the number of applications for adhesives is large and ranges from the use of small quantities in assembling jobs to considerable amounts in industrial processes. Though paper, packaging, footwear, woodworking remain as the major outlet for adhesives, the usage has also increased significantly as structural components in industrial equipment, building and construction, vehicle manufacture, and for military and space applications.

The last two decades have seen the advent of many new synthetic resins and other components which have made possible the development of stronger, more durable and versatile adhesives that can joint any surfaces which were too difficult or nearly impossible to joint before (e.g. thermosetting plastics and composites). As a result, adhesive bonding is now of considerable importance for joining metals together and other materials in structural applications and for a wide variety of other purposes.

1.3 Adhesive types

Adhesives can be divided into thermoplastic and thermosetting plastic (polymers)
as shown in Table 1. Thermoplastic molecules are essentially combined by weak so-called van de Waals bonding and with increasing temperature this bonding force becomes weaker. Thus, these types of adhesives are fusible, soluble, soften when heated and are subject to creep under stress.

On the other hand, for thermosetting adhesives the molecules grow not only in the molecular length direction, but also connect with each other (cross link) through chemical reaction with covalent or ionic bonding. Unlike the thermoplastic adhesives, thermosetting adhesives never soften or melt before final decomposition if heated. Thermosetting adhesives display good creep resistance and provide high-load applications and exposure to severe environmental conditions (e.g. heat, cold, radiation, humidity atmosphere etc.).

### Table 1 Classification of adhesives

<table>
<thead>
<tr>
<th>Kind</th>
<th>Thermoplastic</th>
<th>Thermosetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
<td>S oftened and melted by viscous flow at elevated temperature. Only decomposition occurs at elevated temperature.</td>
<td>Not softened and has no fixed temperature.</td>
</tr>
<tr>
<td>Example</td>
<td>Polystylene (PS), Phenolics (PF)</td>
<td>Melamines (MF), Polyvinyle chloride (PVC), Epoxies (EPX)</td>
</tr>
</tbody>
</table>

#### 1.4 Epoxy adhesives

Epoxy adhesives are typical representative of thermosetting synthetic products which derived from the chemical reaction of an epoxy resin and a basic or acidic curing agent (hardener). Epoxy adhesives have several advantages over other polymers as adhesive agents as listed here:

1. High surface properties,
2. High cohesive strength for cured polymers which often exceed adherent strength,
3. Low shrinkage and permits bonding of large areas,
4. High creep resistance with better retention of stress under sustained loading than thermoplastic adhesives,
5. Can be modified by (1) selection of base resin and hardener, (2) addition of another polymer, (3) addition of filler.
Two decades of developments have shown that the best performance in shear and peel strength can be obtained from blended compositions in which the modifier (rubber or thermoplastic) reacts chemically with the epoxy resin. Reactive liquid rubbers with the certain terminal function groups (amine, thiol, phenolic, and especially carboxyl) are able to interact with the resin to produce ‘toughened’ (fracture resistant) epoxide systems that effectively combat the crack propagation responsible for catastrophic failure of structural joints. Under mechanical stress, these physically discrete particles of size 2-5μm which are chemically linked to the resin distort and thus dissipate the fracture energy in the cured composite. Thereby, the composite resistance to crack propagation and impact strength are greatly improved.
2. Fracture mechanics

2.1 Fracture criterion

Fracture is a significant problem in the industrialized world and there is a necessity of theoretical and practical basis for design against fracture. Thus, in the 1950’s fracture mechanics was initiated in the United States to solve the problem. Fracture mechanics can be approached from a number of points of view, including energy to cause failure, stress analysis, micro-mechanisms of fracture, applications of fracture, computational approaches and so on.

For example at the atomic level, fracture can be viewed as the separation of atomic planes. At the scale of the microstructure of the material, the grains in a polycrystalline material, or the fibers in a composite, the fracture of the material around these features can be studied to determine the physical nature of failure. From the engineering point of view, the material is treated as a continuum and the analysis of stress, strain and energy is of major interest.

In general, fracture can be identified either as brittle or ductile depends on their behaviors. As to the brittle fracture no apparent plastic deformation takes place and it absorbs relatively little energy before fracture. On the other hand, in ductile fracture, high degree of plastic deformation takes place before fracture and considerable energy is involved. Nevertheless, there is no absolute standard upon this classification. Therefore, the distinction between brittle and ductile fracture can not be determined directly from material characteristics and should be deals as unstable problems of mechanics. Hence, the evaluation of strength properties of notched material is become necessary. Here, the so-called fracture toughness is a parameter that refers to the material resistance of failure and that can be used as material constants and design measures.

2.2 Crack-tip deformation

According to linear elastic fracture mechanics (LEFM), a crack is considered as a free surface inside a solid. If a force is acting on a crack plane, stress concentration will be occurred near the crack-tip, thus allowing deformation. There are three basic modes of crack-tip deformation, the opening (Mode I), the in-plane shear (Mode II), and the out-of-plane shear (Mode III) as depicted in Fig.1.
2.3 Crack-tip stress field

The stress components and (r, θ) polar coordinate system are shown in Fig. 2.

For the notation shown in Fig. 2, Sneddon has shown that the crack-tip stresses and displacements are found to be
\[
\sigma_x = \frac{K_0}{\sqrt{2\pi}} \cos \frac{\theta}{2} (1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}) \\
\sigma_y = \frac{K_0}{\sqrt{2\pi}} \sin \frac{\theta}{2} (1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2}) \\
\tau_{xy} = \frac{K_0}{\sqrt{2\pi}} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \\
\sigma_z = \nu(\sigma_x + \sigma_y), \quad \tau_{xz} = \tau_{yz} = 0 \quad (2-1)
\]

\[
u = \frac{K_0}{G} \sqrt{\frac{r}{2\pi}} \cos \frac{\theta}{2} (1 - 2\nu + \sin^2 \frac{\theta}{2}) \\
\tau = \frac{K_0}{G} \sqrt{\frac{r}{2\pi}} \sin \frac{\theta}{2} (2 - 2\nu + \cos^2 \frac{\theta}{2}) \\
w = 0
\]

where, \(u, v, w\) are the displacements in the x-, y-, z-directions respectively. Equation (2-1) is valid for case of sufficiently thick plate (plane strain condition). Thus, \(K\) is given by:

\[
K = \sigma_0 \sqrt{\pi a F} \quad (2-2)
\]

\(K\) defines the magnitude of the crack tip stress field singularity, and is termed the stress intensity factor. The stress intensity factor \(K\) incorporates both geometrical terms (the crack length appears explicitly, while the crack-tip radius is assumed to be very sharp) and the applied stress level.

2.4 J Integral

\(K\) can be evaluated for the case of a small scale plastic zone at a crack-tip (small scale yielding); the plastic zone is relatively small compared to the crack length. However, when the plastic zone size is considerably large and/or plastic deformation takes place in the vicinity of a crack in an actual structure, \(K\) can no longer be used. Rice proposed the line integral (i.e. J Integral), based on plasticity theory to define the fracture conditions in a materials experiencing both elastic and plastic deformation. For a nonlinear elastic body containing a crack in two-dimensional problem as shown in Fig.3,
the J Integral can be defined as

$$ J = \int_{\Gamma} (Wdy - T_i \frac{\partial u_i}{\partial x} ds) $$

where \( W = W(\varepsilon_{ij}) = \int_0^\infty \sigma_{ij} d\varepsilon_{ij} \) is the strain energy density, \( T_i = \sigma_{ij} n_j \) is the traction vector, \( \Gamma \) is an arbitrary contour around the tip of the crack, \( n \) is the unit vector normal to \( \Gamma \); \( \varepsilon, \sigma, \) and \( u \) are the stress, strain, and displacement field, respectively.

Rice also showed that the J Integral is a path-independent line integral and it represents the strain energy release rate of nonlinear elastic materials:

$$ J = - \frac{d\Pi}{dA} $$

where \( \Pi = U - W \) is the potential energy, the strain energy \( U \) stored in the body minus the work \( W \) done by external forces and \( A \) is the crack area. Thus, the dimension of \( J \) is

$$ \text{Dim}[J] = \frac{F}{L^2} \text{L} = \frac{\text{Energy}}{\text{Area}} $$

For linear elastic materials, the J Integral \( J \) is in fact the strain energy release rate, \( G \) and both are related to the stress intensity factor \( K \) in the following fashion:

$$ J = G = \left\{ \begin{array}{cl} \frac{K^2}{E} & \\ \frac{K^2}{E} (1 - \nu^2) & \end{array} \right. $$
2.5 Adhesive mechanics

2.5.1 Theory of adhesion

An adhesive is a compound that adheres or bonds two substrates together. In general, adhesion mechanisms can be classified into three areas:
1) Mechanical interlocking; anchor effect by penetrating into holes of the substrate.
2) Physical interaction; intermolecular force (van der Waals’ force)
3) Chemical interaction; covalent bond or hydrogen bond

Even there have been many studies conducted toward describing the adhesion phenomena but still an adequate theory is yet to be proposed. It is known that, in actual the adhesion phenomena are a mixture of mechanisms which stated above. However, in the area of metal to polymer adhesive which is the subject of this study, 1) and 2) have been reported to be the most related adhesion mechanisms.

2.5.2 Fracture of adhesive joint

When intermolecular contact between the adhesive and substrate is sufficiently achieved, according to calculation the minimum of adhesive force is expected to be more than 200Mpa. Besides, survey shows that the actual bond strength is limited to 50Mpa. In the present paper, adhesive force and bond strength are distinguished as follows. "Adhesive force" is the theoretical bonding force between adhesive and adherent’s boundary. Thus, it is almost impossible to measure. On the other hand, "bond strength" is a measurable quantity that can be obtained from the fracture test (i.e. the stress that is needed to break the adhesive joint).

When adhesive joint is subjected to loading, failure may occur at different locations as shown in Fig.4. There are seven classes of failure modes exist, as identified according to the standard ASTM D5573. Here, only the 1st three classes stated are relevant to the current study, and are listed below.
- Cohesive failure, rupture of the adhesively bonded joint, such that the separation is within the adhesive.
- Thin-layer cohesive failure (TLCF), failure similar to cohesive failure, except that the failure is very close to the adherent interface, characterized by a ‘light dusting’ of adhesive on one adherent surface and a thick layer of adhesive left of the other (sometimes referred to as inter-phase failure).
- Adhesive failure, rupture of the adhesively bonded joint, such that the separation
appears to be at the adhesive-adherent interface (here referred to as interfacial failure).

For cohesive failure, it is obviously that adhesive force > bond strength such that the strength of adhesive joint can be improved by strengthening the adhesive itself. Though, in the case of interfacial failure, adhesive force is not equals to bond strength. In both cases, adhesive force > bond strength prevails. Hence, for the latter it can be considered that there exist some factors which decrease the strength between the adhesive and adherent boundaries.

2.6 Interfacial fracture mechanics of adhesive joint

At the interface of adhesive joints, there may be exists a large number of voids and the well known region of high intrinsic stresses. These factors can weakened the adhesive force and thus resulting failure of adhesive joints at the interface. Yukki, et al. proposed the stress intensity factor of an interfacial crack in the dissimilar materials joint. Based on stress extrapolation method, the individual $K$ at the crack-tip can be expresses as
\[
K_1 = \lim_{r \to 0} \frac{\sqrt{2\pi}}{r} \left( \sigma_y \cos \theta + \tau_{xy} \sin \theta \right) \quad (2-7)
\]
\[
K_{II} = \lim_{r \to 0} \frac{\sqrt{2\pi}}{r} \left( \tau_{xy} \cos \theta - \sigma_y \sin \theta \right) \quad (2-8)
\]

where,
\[
Q = \varepsilon \ln\left(\frac{r}{2a}\right), \quad \varepsilon = \frac{1}{2\pi} \ln\left(\frac{\kappa_1 / G_1 + 1/G_2}{\kappa_2 / G_2 + 1/G_1}\right), \quad \kappa_i = \begin{cases} 
3 - \nu_i & \text{(for plane stress)} \\
\frac{3 - 4\nu_i}{1 + \nu_i} & \text{(for plane strain)}
\end{cases}
\]

\(G\) is the elastic modulus, \(i = 1, 2\), the subscripts 1 and 2 refer to materials across the interface.

Alternatively, \(K\) also can be determined from the crack-tip opening displacement based extrapolation method
\[
K_1 = C \lim_{r \to 0} \frac{\Delta w \cdot A + \Delta v \cdot B}{\sqrt{r/2\pi}} \quad (2-9)
\]
\[
K_{II} = C \lim_{r \to 0} \frac{\Delta v \cdot A - \Delta w \cdot B}{\sqrt{r/2\pi}} \quad (2-10)
\]

where, \(A, B,\) and \(C\) are materials constant that can be obtained, respectively, by
\[
A = \cos Q + 2\varepsilon \sin Q
\]
\[
B = \sin Q - 2\varepsilon \cos Q
\]
\[
C = \frac{1}{2(1/\mu_1 + 1/\mu_2)}
\]

According to Smelser and Gurtin, \(J\) is related to the both \(K_1\) and \(K_{II}\) as follows
\[
J = \frac{\pi}{16} (\lambda_a + \lambda_b)(K_1^2 + K_{II}^2) \quad (2-11)
\]
\[
\lambda_a = \begin{cases} 
4(1-\nu_a) & \text{(for plane stress)} \\
\frac{\mu_a}{4} & \text{(for plane strain)} \\
\mu_a(1+\nu_a) & \text{ } \text{ (for plane strain)}
\end{cases}
\]

where, \(\mu_a, \nu_a\) are the elastic modulus and Poisson’s ratio, respectively.
3. Experimental procedures

3.1 Preparation of bulk adhesive specimens

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 (Thinky AR-100) for 1 min: 3min schedule of diffusion and de-foaming, respectively. The mold was made of Teflon plate as shown in Fig. 6. The pre-crack in SENT was initiated by inserting a sharp razor blade at an edge of the plate prior to the molding.

3.2 Preparation of three-point bending adhesive butt joint

Adhesively bonded three-point bending test specimens (3PB), as shown in 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.7. The contact surfaces of cross-section of specimens were uniformly polished with 2000 grit sandpapers under running water and finally ungreased with acetone liquid. 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.

3.3 Fracture tests

The 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 (see Fig. 8). Both fracture tests were conducted at room temperature with the crosshead speed of 1.0mm/min. After the fracture test, the fracture surface of each specimen was observed by using optical microscope.
Fig. 5 Dimensions of a) typical tensile, b) SENT bulk adhesive specimen

Fig. 6 Mold of a) typical tensile, b) SENT bulk adhesive specimen
Fig. 7 Geometry and dimensions of 3PB adhesive joints specimen

Fig. 8 Fracture test apparatus a) tensile test, b) 3PB test
4. FE analysis

4.1 FE model of SENT bulk epoxy adhesive

Two dimensional elastic-plastic finite element analysis was performed using ANSYS 10 code. The true stress-true strain curve of adhesive used in this simulation is shown in Fig. 9. The finite element mesh consisted of eight nodes plane stress isoparametric with quadrilateral elements type (i.e. PLANE183) as shown in Fig. 10. Due to the symmetry of the plate, only top half of the model was analyzed. The plate was constrained at the bottom in both x and y-direction and a distributed load was subjected at the top of the plate. The crack was generated by releasing the constrain at the bottom left of the plate according to the desired crack length (i.e. 2, 4, 6mm).

4.2 FE model of 3PB adhesive joint

Mechanical properties of materials used in this analysis are given in Table 2. The same adhesive as described in section 4.1 was employed. As can be seen in Fig. 11, the beam was constrained in the y-direction at the bottom with span length of 64mm. The load was subjected at the top center of the beam. The mesh for adhesive layer was refined sufficiently whilst the contact pairs defined to constraint the adhesive layer to adherents. The contact pairs were based on internal multipoint constraint (MPC) approach with bonded always option on the contact elements. The crack was created by releasing the constraint of the contact and target elements at the local crack faces according to the desired crack length (i.e. 2, 4, 6mm).
Fig. 9 True stress-true strain curve of bulk epoxy adhesive

Table 2 Mechanical properties of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>E (kgf/mm²)</th>
<th>y (kgf/mm²)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304 Stainless steel</td>
<td>21000</td>
<td>30.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Aluminium YH75</td>
<td>7200</td>
<td>40.7</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Fig. 10 Mesh of SENT bulk epoxy adhesive model

Fig. 11 Finite element mesh of 3PB adhesive joint model
5. Results and discussion

5.1 Characteristics of bulk epoxy adhesive

The tensile stress-strain responses of bulk epoxy adhesive are shown in Fig. 12. As seen in this figure, bulk epoxy adhesive employed in this study demonstrated almost linear-elastic and brittle failure that is similar to the behaviors of typical un-modified thermosetting resin adhesive. It is also known that the strength of bulk adhesive was significantly improved if prepared by conditioning mixer.

![Fig. 12 Tensile stress-strain response of bulk adhesive](image)

5.2 Fracture toughness of SENT bulk epoxy adhesive

The fracture toughness of bulk epoxy adhesive can be defined in terms of the stress intensity factor, $K_c$ at a critical stress state. According to the ASTM E-399 standard, in the case of the tensile test, $K_c$ value of single edge notched plate can be obtained from:
\[ K_c = \sigma \sqrt{\pi a F(\alpha)} \frac{a}{W} \]

\[ F(\alpha) = 1.12 - 0.23 \kappa + 10.55a^2 - 21.72a^3 + 30.39a^4 \]

where \( F(\alpha) \) is a dimensionless parameter that depends on both the specimen and crack geometry in Fig. 13, \( \sigma \) is an applied stress, \( a \) is crack length and \( W \) is specimen width.

Figure 13 Specimen geometry in evaluation of stress intensity factor

Figure 14 shows \( K_c \) values of SENT bulk epoxy adhesive obtained from the tensile test. As seen, the \( K_c \) values of bulk epoxy adhesive is gradually increased from 0.94 to 1.87 MPam\(^{1/2}\) as the normalized crack length, \( a/W \) increased.

Fracture toughness, \( J \) can be evaluated directly with FE analysis from several circular paths integration. To determine \( J_c \) of SENT bulk epoxy adhesive, FE model as explained in section 4.1 is considered. The radius of path was defined as 0.1\( a \), 0.2\( a \), 0.3\( a \), 0.4\( a \), 0.5\( a \) and 0.6\( a \), where \( a \) is crack length. Only plane stress condition is considered for its simplicity. Figure 15 shows circular paths for the \( J \) Integral evaluation. From several paths integration, \( J_c \) values can be obtained as shown in Fig. 16. \( J_c \) values obtained in this simulation were then plotted against normalized crack length, \( a/W \) as can be seen in Fig. 17. Here, \( J_c^* \) values of SENT bulk epoxy adhesive determined from the theoretical solution (i.e. equation (2-6)) were also plotted for comparison. It can be found that the \( J_c \) is approximately equal to \( J_c^* \). Thus, it can be concluded that FE model and \( J \) Integral evaluation employed in this study is valid and reproducible.
Fig. 14 Kc of SENT bulk epoxy adhesive against normalized crack length, a/W

Fig. 15 Circular paths for J Integral calculation
Fig. 16 Jc value obtained from several paths integration

Fig. 17 Jc against normalized crack length, a/W
5.3 Study on strength of epoxy adhesively-bonded dissimilar materials

5.3.1 3PB fracture test of adhesive joints

The failure load of 3PB adhesive joints versus bond thickness is plotted in Fig. 18. It can be observed that strength of 3PB adhesive joints in Mode I loading decreases when the bond thickness increases. In addition, adhesive joint with aluminium-aluminium adherents is higher than that with steel-steel adherents. Particularly, for adhesive joints with steel-aluminium adherents, failure load is seems to be scattered in between the above-mentioned band.

![Graph showing failure load vs. bond thickness of 3PB adhesive joints](image)

Fig. 18 Failure load vs. bond thickness, t of 3PB adhesive joints

Fig. 19 shows the fracture surfaces of 3PB adhesive joints at different bond thickness. It can be observed that the fracture surfaces change from relatively flat to extremely rough as the bond thickness increases: the cohesive fracture is in controlled in the thick bond layer. Moreover, from the detailed observation with optical microscope, the fracture in thin bond layer is found to be initiated by interfacial fracture at steel surface.
a) 0.1mm bond thickness

b) 0.3mm bond thickness

c) 0.5mm bond thickness
5.3.2 FE Analysis of 3PB adhesive joints

5.3.2.1 Effect of elastic modulus of adhesive

To investigate the effect of elastic modulus of adhesive on the stress distribution at
the adhesive-adherent interfaces, 2D elastic finite element analysis was carried out. The elastic modulus, \( E \) of adhesive is chosen as 100, 200, 300, 400 and 500 kgf/mm\(^2\). Dimensions and material properties of adherents of 3PB adhesive joint considered in this study are described in section 4.2. The applied load is 100 kgf.

---

**a) Stress-y distribution at steel/adhesive interface**

---

**b) Stress-y distribution at aluminium/adhesive interface**
c) Stress-\(y\) distribution at adhesive center

Fig. 20 Effect of elastic modulus of adhesive on the stress-\(y\) distribution

Fig. 20 illustrates the influence of \(E\) on the stress-\(y\) distribution at the interface corners and center of 3PB adhesive joint FE model. Only half left of specimen is considered since failure is predicted to occur in this region. It is found that with the increment of \(E\), the peak value of stress-\(y\) at each location is gradually increased. However, with further increment of \(E\) (i.e. from 400 to 500\(\text{kgf/mm}^2\)), there is only relatively small change. In addition, the location that has higher opening stress is steel-adhesive boundary, aluminium-adhesive and adhesive center in order. That is, higher opening stress is associated to higher \(E\).

5.3.2.2 Effect of bond thickness

In this study, it is assumed that adhesive is behaved as an elastic-plastic solid. Therefore, the characteristics of adhesive as depicted in Fig. 9 are applied. Firstly, investigation on effect of bond thickness, \(t\) on load-displacement of 3PB adhesive joints was performed. Here, bond thickness, \(t\) is 0.1, 0.3, 0.5, 0.7, 1.0 and 1.5 mm. The result is shown in Fig. 21. From this figure, it can be noted that the slope of curves at elastic deformation region decreases as the bond thickness increases. This means, the
apparent elastic modulus of adhesive joints is decreased when the bond thickness increases. According to the experimental results as discussed in section 5.2.1, failure load was recorded to be approximately limited at 60kgf. Thus, in comparison to simulation result, failure of 3PB adhesive joints is considerably occurred within the elastic deformation region. Though, there is still probability that in some location, plastic deformation has also occurred due to the constraint’s effect of adherents.

Fig. 21 Load vs. displacement of 3PB adhesive joint model

Fig. 22 shows stress distribution of 3PB adhesive joint model at two different bond thicknesses. The applied load is 100kgf. From Fig. 22 a), it can be observed that at t/2 distance from free edge, peak of stress-y at the center of adhesive layer exceeded the yield strength of bulk adhesive. This indicates that cohesive failure is instantly governed at t/2 distance from free edge. Thus, fracture is found to be initiated at an interface corner then shifted direction into the adhesive layer: interface failure is shifted to cohesive failure as the crack propagates. Especially, this is appeared to be true in the thin layer failure (see Fig. 19 a), b) and c)).
a) Stress-y distribution at different bond thickness

b) Stress-x distribution at different bond thickness

Fig. 22 Stress distribution of 3PB adhesive joint FE model
Failure of 3PB adhesive joints can also be explained based on Tresca yield criteria as follows. Generally, when 3PB adhesive joint is subjected to Mode I loading, at the interface corner of tensile region the opening stress, $\sigma_y$, develops to infinity. When $\sigma_y$ exceeds the adhesive force, $\sigma_{int}$, the interfacial failure will initiate at the corner edge. On the other hand, according to Tresca yield criteria the yield condition inside the adhesive layer is given as

$$|\sigma_y - \sigma_x| > \sigma_{adh}$$

(5-1)

where $\sigma_{adh}$ is the adhesive yield strength.

As can be seen in Fig. 22 b), with increment in the bond thickness $\sigma_x$ is become negligibly smaller compared to $\sigma_y$. Thus, (5-1) is then

$$\sigma_y > \sigma_{adh}$$

(5-2)

Since $\sigma_{int} > \sigma_{adh}$, for thick adhesive layer, cohesive failure takes place before interfacial failure. This can be observed in Fig. 19 c), d) and e).

5.3.2.3 Stress concentration factor

Stress concentration factor, $\kappa$, can be derived as

$$\kappa = \frac{\sigma_{max}}{\sigma_{surface}}$$

(5-3)

(see Fig. 23).

![Fig. 23 Determination of stress concentration factor, $\kappa$](image-url)
Fig. 24 shows stress concentration factor, $\kappa$, at interface corners of 3PB adhesive joint FE model. It can be observed that $\kappa$ for steel-adhesive interface is always higher than those for aluminium-adhesive interface. Thus, the probability of interfacial failure is higher at steel-adhesive interface than those aluminium-adhesive interface. The observation of fracture surfaces revealed that in the case of interfacial failure, it has probably initiated at steel-adhesive interface (see Fig. 19 a), b), and c)).

![Fig. 24 Stress concentration factor at interface corners](image_url)
5.4 Study on fracture toughness of 3PB adhesive joint with interfacial crack

5.4.1 Effect of bond thickness on fracture toughness, $J_c$

3PB fracture tests were conducted with two systems of specimens with an interfacial crack, i.e. steel-adhesive system and aluminium-adhesive system. The interfacial crack length, $a$ is 2, 4, 6 mm. The bond thickness, $t$ is 0.2, 0.3, 0.5, 0.7 and 0.8mm. The critical failure load, $P_{\text{max}}$ obtained from 3PB fracture test is used to evaluate the Mode I fracture toughness, $J_c$ in numerical FE analysis. Fig. 25 shows the Mode I fracture toughness, $J_c$ versus bond thickness of 3PB adhesive joints with interfacial crack. As can be seen, $J_c$ values of 3PB adhesive joints with interfacial crack exhibit somewhat independence of bond thickness. Therefore, it is necessary to determine the fracture toughness of these specimens with further consideration on mode loading conditions.

5.4.2 Determination of $K_I$ and $K_{II}$

In order to determine Mode I and II fracture toughness (i.e. $K_I$ and $K_{II}$) from FE simulation, the stress and crack-tip opening displacement (CTOD)-based extrapolation method was employed. For example, simulation results for 3PB adhesive joints with 6mm crack length are illustrated in Fig. 26. From Fig. 26, the ratio of $K_{II}/K_I$ ratio can be obtained as shown in Fig. 27. Obviously, as seen in this figure, two identical trends can be noted.

Firstly, an interfacial crack of 3PB adhesive joints is experienced both Mode I and II loading even when subjected to pure Mode I external loading. This is due to the mismatch of elasticity of adherent-adhesive at interface and the constraint effect of adherents. It is found for steel-adhesive with 2 and 6mm interfacial crack, Mode II loading is always larger than those in aluminium-adhesive interfacial crack regardless of bond thickness. Because the elastic modulus of aluminium adherent is closer to the elastic modulus of adhesive (i.e. $E_{\text{alu}}=20E_{\text{adh}}$), as compared to the elastic modulus of steel adherent (i.e. $E_{\text{sus}}=60E_{\text{adh}}$), the aluminium adherent has better constraint capability.

Secondly, $K_{II}/K_I$ ratio increases with an increase in interfacial crack length. As can be seen in Fig. 26, Mode II loading contribution as correspond to $K_{II}/K_I$ ratio increases with longer interfacial crack length and certainly is constant at any bond thickness.
a) 3PB adhesive joint with steel-adhesive interfacial crack

b) 3PB adhesive joint with aluminium-adhesive interfacial crack

Fig. 25 Fracture toughness, Jc vs. bond thickness, t
a) Steel-adhesive interfacial crack (a = 6mm)

b) Aluminium-adhesive interfacial crack (a = 6mm)

Fig. 26 Result of stress and CTOD-based extrapolation method for 3PB adhesive joint with interfacial crack
Interfacial Crack 2mm

\[ t \text{ (mm)} \]

\[ \frac{K_{II}}{K_I} \]

\[ S_t/\text{Adh} \]

\[ \text{Al/Adh} \]

a) \( a = 2\text{mm} \)

Interfacial Crack 4mm

\[ t \text{ (mm)} \]

\[ \frac{K_{II}}{K_I} \]

\[ S_t/\text{Adh} \]

\[ \text{Al/Adh} \]

b) \( a = 4\text{mm} \)
c) $a = 6mm$

Fig. 27 $K_{II}/K_I$ ratio vs. bond thickness, $t$
5.4.3 Fracture types of 3PB adhesive joints with interfacial crack

Fig. 28 shows the relation between bond thickness and $\theta$ as corresponding $\sigma_{\theta_{\text{max}}}$.

Here, $\theta$ is referred to the counterclockwise angle from crack-front line. As is seen, at thick bond thickness, the crack is considerably propagated through adhesive layer. This is also observed in fracture surfaces. Fig. 29 shows fracture surfaces of 3PB adhesive joints with interfacial crack. From the observation of the fracture surfaces of specimens bonded with thick adhesive layer, it is revealed that the fracture initiated within the adhesive (i.e. cohesive failure). Meanwhile, the fracture surfaces of specimens bonded with thin adhesive layer indicated that fracture is always initiated at interface. Therefore, it can be concluded that cohesive failure is associated with thick adhesive layer.

![Fig. 28 Bond thickness, t vs. $\theta_{\text{max}}$](image)
a) Steel-adhesive interfacial crack (a = 6mm, t = 0.2mm)

b) Steel-adhesive interfacial crack (a = 6mm, t = 0.68mm)

c) Steel-adhesive interfacial crack (a = 6mm, t = 0.78mm)
d) Aluminium-adhesive interfacial crack (a = 4mm, t = 0.2mm)

e) Aluminium-adhesive interfacial crack (a = 4mm, t = 0.7mm)

f) Aluminium-adhesive interfacial crack (a = 4mm, t = 0.86mm)

Fig. 29 Fracture surfaces of 3PB adhesive joints with interfacial crack
6. Conclusions

In this study, an attempt was made to investigate the Mode I fracture behavior of bulk epoxy adhesive and 3PB adhesive joints bonded with dissimilar materials. Through the experimental and numerical analysis, the following conclusions have been reached.

1) The strength of bulk epoxy 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. Stress concentration factor, $\kappa$ at steel-adhesive interface was higher than those at aluminium-adhesive interface.

3) In 3PB joints with interfacial crack, $J_c$ was independent on bond thickness. $K_{II}/K_{I}$ can be determined by stress and CTOD-based extrapolation method. $K_{II}/K_{I}$ ratio increased as the crack length increased.

4) The examination of fracture surface of 3PB adhesive joints with interfacial crack revealed that interfacial fracture occurred in thin adhesive bond.
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8. Bibliography