Study on Effect of Bond Thickness upon Adhesive Strength and Fracture Characteristics of Brittle Epoxy Adhesively Bonded Dissimilar Joint

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Abstract

Adhesive joint is definitely the ideal substitute for any conventional bonding methods (e.g. rivet, welding, diffusion bonding, etc.) in structural engineering applications, particularly in dissimilar materials joining. Nevertheless, adhesive joint inevitably contains flaws or discontinuities at the interfaces. Moreover, even in the perfectly bonded adhesive joint, the existence of stress singularity due to the elastic mismatches which develops at the region of interface corner may initiate failure. As such, adhesive joints often fail unexpectedly and severely under a relatively low mechanical or thermal load in service. Therefore, in order to ensure high reliability and significant strength performance of adhesive joints, the strength and fracture toughness of adhesive joints should first be properly determined. In the literature, numerous works have been devoted on determining the strength and fracture behavior of similar material sandwiched adhesive joint using various types of joint geometries. These include investigations upon effect of joint geometry, crack path propagation and assessment of fracture initiation criteria. It has been reported that the strength and fracture behavior of the rubber modified (i.e. ductile) adhesive joints is greatly dependent on the adhesive bond thickness and existence of cracks or flaws. However, the mechanisms of the dependency for brittle adhesive joints are yet to be elucidated and study on adhesively bonded joints of dissimilar adherends sandwiched joint is very limited thus motivated this work.
Hence, in this dissertation, the strength and fracture toughness of epoxy adhesively bonded joints of dissimilar metallic adherends under a remote uniaxial tensile load were examined on various adhesive bond thicknesses and several scarf angles. The adherends were SUS304 stainless steel and YH75 aluminium alloy. The epoxy adhesive resin used in this study was a relatively brittle commercial epoxy adhesive. The bond thickness, \( t \) between dissimilar adherends was controlled to be ranged between 0.1 mm and 1.2 mm whilst scarf angle, \( \theta = 90^\circ, 75^\circ, 60^\circ, 45^\circ \) and \( 0^\circ \) were employed. Beside the experimental investigations, finite element (FE) stress analyses were also executed by ANSYS 11 code to investigate the stress distributions of adhesive layer in adhesive joints. Since the singularity due to the mismatch of materials at the interface corner of adhesive joint also contributes to interfacial crack growth, fracture toughness of adhesive joints with an interfacial crack was also evaluated by J integral in FE. From both experimental and finite element analysis results, together with macroscopic observations on fracture surfaces, strength and fracture characteristics of adhesive joints of dissimilar adherends will be qualitatively discussed. Finally, the strength prediction and reliability of adhesive joints considered are also treated in detail. It is emphasized that the bond thickness of adhesive joint is a key parameter which must be seriously considered in bonded joint design.
Chapter 1  Introduction

Adhesive joint has many outstanding advantages over other traditional bonding methods (e.g. rivet, bolt and nut, welding, diffusion bonding, etc.), especially in joining dissimilar materials. The main purpose of adhesive joint is to transmit significant loads through the structures in many engineering and industrial applications. Therefore, integrity and reliability of adhesive joints are very crucial. There are many critical factors affecting the structural integrity and reliability of scarf joints. In the literature, the most commonly considered factors are joint geometry, mechanical properties of adhesive and adherend, bonding surface as well as loading condition. These effects of joint geometry and loading condition refer mainly to the bond thickness and scarf angle, respectively, and these two key parameters becomes the main subject of numerous study. In practical, to evaluate the mechanical performance of adhesive joints, both stress analyses and destructive testing are employed. However, most of these investigations considered only adhesive joints bonded with similar adherend, so much so, the study on sandwiched dissimilar adherends joints is hardly available. As has been well known that the adhesive has advantages for attaching two different materials, in-depth investigation upon this matter becomes very important in order to get the full benefit of it. It has been reported that, in terms of mechanical behavior and stress performance, the latter behaves slightly different if compared to the former due to the more complex elastic mismatches incorporated [1-3].

Knowledge of stress and strain distributions in adhesive layer provides insight into better understanding the effect of various critical parameters. Therefore, stress and strain
analyses are very essential in evaluating the adhesive joints. Though theoretical analyses are more cost effective, the numerical approaches such as FE analyses are extensively employed because of its versatility and capability to cope with much more complex problems. Moreover, varying the key parameters not only will inevitably alter the stress and strain distributions but it also affects the failure mechanisms of adhesive layer in adhesive joints: determine the joint strength. Refer to [4] for further references and details.

An understanding of failure mechanisms of adhesive layer is decisively important in interpreting the performance of a particular adhesive joint. Two types of failure are distinctive in adhesive joints; cohesive failure and interface failure. In cohesive failure, the crack propagates through the adhesive layer while when the separation (i.e. delamination) is at the interface of adhesive/adherend, it is referred to as interface failure. It is known that bond strength is greater than the adhesive force. Therefore, strength of adhesive joints which failed cohesively has been reported to be stronger than those which failed at the interface. In addition, the locus of failure is also distinguished in terms of adhesive ductility. Ductile adhesive, for instance, rubber-toughened adhesive joints usually favor cohesive failure. By contrast, the relatively rigid, brittle adhesive joints generally fail preferentially at the interface. The stress concentration near the interface corner region and higher stress triaxiality states inside the brittle adhesive layer are known to be the primary contributor to interface failure.

Another important issue in adhesive joint technology which has received incredible attention recently is the joint strength prediction. In this regards, a number of models have been proposed and is now widely utilized but with a limited degree of success.
Nevertheless, these predictions remain tolerably difficult due to lack of sufficient criteria with sound physical basis [5, 6]. In general, the strength prediction approaches are based on either strength of materials, plastic yield criteria, void nucleation models or fracture mechanic analysis. In actual practice, the fracture mechanics methodology has been proven to be a feasible tool for the assessment of strength and fracture toughness of both brittle and ductile adhesive systems. Particularly, for the problem of adhesive joints with interface crack, interface fracture mechanics has been established. Yuuki has reviewed this topic in detail elsewhere [7]. In the case of adhesive joints bonded with relatively rigid brittle adhesive resin, so far, there is some evidence which supports that the relation between the strength and bond thickness of such joints can be satisfactorily estimated by means of the interface corner toughness parameter, $H_c$. In fact, some investigators have validated experimentally the applicability of $H_c$ as a fracture initiation criterion to the problem of unstable failure which initiates from interface corner [8-11]. Meanwhile, in the case of adhesive joints with an interfacial crack, fracture toughness, $J_c$ from the fracture mechanics concept can be applied as a fracture criterion. However, these studies considered only the adhesive joints bonded with similar adherend. Therefore, it is of great interest to assess the applicability of both fracture criteria in adhesive joints bonded with dissimilar adherends.

Reliability analysis is also crucially required in engineering safety design, especially in the strength prediction of brittle materials; ceramics components, rock, timber, etc. Based on recent interest in the study of reliability of adhesive joint, Weibull statistics based probability approach increasingly receives attention and appears to be the most widely used in practice. More recently, Weibull strength distribution approach has been
proven by some researchers to be the most promising failure criterion and also as an effective reliability indicator for joints bonded with brittle adhesive [12-15].

Indeed, both applications of stress singularity based parameter (i.e. $H_c$ or $J_c$) and Weibull statistical approaches are very promising and should be implemented when predicting the adhesive joints that combine the best strength performance with high reliability. However, to the best of present authors’s knowledge, no work has been undertaken which applied both methods simultaneously to facilitate the design of adhesive joints. Thus, the main objective of this study was to elucidate the effects of joint geometry and loading mode upon the mechanical performance and fracture characteristics of adhesive joints. Therefore, in this study, fracture tests of epoxy adhesively bonded joints of dissimilar adherends were conducted under uniaxial tension load on various adhesive bond thicknesses and several scarf angles. In this dissertation, the author is also concerned with the strength prediction of adhesive joints using structural mechanics and fracture mechanics approaches. In addition, the reliability analysis of strength of these joints based upon the statistical Weibull analysis of strength distribution is also employed. The effects of stress singularity at the interface corner and scale sensitivity upon brittle adhesive joints considered will be discussed.

This dissertation is divided into nine (9) chapters (i.e. including Appendixes). Chapter 1 starts with a brief introduction of the main scope and objectives of the present dissertation. Chapter 2 is the introductory overviews of science and technology of adhesion and adhesive. Adhesive bonding and their methods of evaluation are also reviewed in this chapter. In Chapter 3, the experimental procedures and numerical analysis of this study are
explained. The following Chapters 4 to 6 are concerned with the destructive testing and stress analysis of adhesive joint bonded with dissimilar adherends using brittle epoxy adhesive. Chapter 4 focuses on investigations on butt adhesive joint. Chapter 5 specifically deals with the scarf adhesive joint. Chapter 6 inclusive evaluates the shear adhesive joint. Next, Chapter 7 discusses the prediction and reliability analysis of strength of adhesive joint. Chapter 8 finally concludes the entire study. Appendixes are also intentionally included in addition to the earlier chapters for further reference should these be necessary.
Chapter 2  Adhesive bonding

2.1  Adhesion and adhesives

2.1.1  Theory of adhesion, history and types of adhesive

Adhesive is a substance, such as paste or cement, that provides or promotes adhesion [16]. Meanwhile, adhesion refers to the act or state of adhering itself. In recent years, the adhesion phenomenon has become a very important field of study since it is greatly relevant to many scientific and technological areas. One may find that, the main application of adhesion is in structural bonding by adhesives (i.e. adhesive bonding or adhesive joint). In structural bonding, adhesive has sufficient strength and should be capable of bearing and transmitting loading through the structure without lose of its own integrity within design limits [17]. Another application of adhesion is in nonstructural bonding, e.g. coatings, paints, and varnishes; multilayered sandwiches; composite materials; sealants, electrical insulant, etc.

The theories of adhesion have been reviewed in details by many authors in several excellent books and now are available in references [4, 17-26]. A combination of different mechanisms is most probably responsible for adhesion within a chosen adhesive system. So far, amongst the proposed theories or mechanisms of adhesion, the most widely accepted can be listed as what follows:

1. Physical bonding (often called physical absorption) theory

   1.1  Thermodynamics of wetting (i.e. wettability)
1.2 Attractive interaction of interface and reversible thermodynamics adhesion work

2. Electronic and electrostatic attraction
   2.1 Charge migration
   2.2 Difference in contact potential
   2.3 Electrostatic coupling

3. Diffusion or interdiffusion
   3.1 Entanglements theory

4. Chemical reaction bonding
   4.1 Acid-base (donor concept) theory

5. Weak boundary layer and interphases

6. Mechanical bonding or interlocking

Theories of adhesion can also be distinguished arbitrarily as either specific adhesion or mechanic adhesion. Specific adhesion is being based on the various types of bonds (e.g. electrostatic, secondary, chemical, etc.) that can develop between two solids. As all adhesive bonds involve molecules in intimate contact, physical adsorption must always contribute. In contrast, as polymers are insulators, it seems difficult to apply the electronic and electrostatic attraction theory to adhesives. Diffusion or interdiffusion theory suggests that adhesion is developed through the interdiffusion of molecules in between the adhesive and the adherend. This theory is primarily applicable when both the adhesive and the adherend are polymers with relatively long-chain molecules capable of movement.
According to mechanical bonding or interlocking theory, mechanic adhesion occurs by the penetration of adhesives into pores, cavities, asperities and other surface irregularities on the surface of the substrate. However, it is still debated whether mechanical interlocking is responsible for strong bonds or an increase in the adhesive contact surface enhances other mechanisms. Since adhesion is a surface phenomenon, it is controlled by the condition of the surface of the adherend. Both specific adhesion and mechanic adhesion are important to the understanding of how adhesion is affected by surface preparation.

Once more, six theories mentioned above are both complementary and contradictory to each other. Actually, each of these theories is valid, to some extent, depending on the nature of the solids in contact and the conditions of formation of the bonded system. Nevertheless, physical absorption and mechanical interlocking are more likely to contribute to the strength of all structural adhesive joints and may well be the main mechanism of adhesion of such joints [18]. Here, structural adhesive joints refer to the bonding of metallic adherend to polymer adhesive, which is the subject of this study.

For thousands of years the only adhesives of major importance in human civilization were the animal and vegetable glues. Animal glues were mostly based on mammalian collagen, which is the main protein of skin, bone and sinew, and the vegetable kingdom provided starches and dextrins from corn, wheat, potatoes and rice [22, 23]. However, these kinds of natural origin adhesives were found to have some limitations (e.g. low strength, limited resistance to moisture, etc.), thus had provided the stimulus responsible for the great expansion in the development of new adhesives since the 1930s.
These new adhesives which are based upon synthetic resins and other materials are widely employed then for their outstanding advantages.

Phenol formaldehyde was the first synthetic resin adhesive 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 [22].

Synthetic adhesives can be divided into elastomeric, thermoplastic and thermosetting plastic (polymers) as shown in Table 1. Thermoplastic molecules are essentially combined by the 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 synthetic adhesives [17].

<table>
<thead>
<tr>
<th>Kind</th>
<th>Elastomeric</th>
<th>Thermoplastic</th>
<th>Thermosetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
<td>Based on synthetic or naturally occurring polymers.</td>
<td>Softened and melted by viscous flow at elevated temperature without significant change in their properties.</td>
<td>Not softened and has no fixed temperature. Only decomposition occurs at elevated temperature.</td>
</tr>
<tr>
<td>Example</td>
<td>Natural rubber</td>
<td>Polystyrene (PS)</td>
<td>Phenolics (PF)</td>
</tr>
<tr>
<td></td>
<td>Styrene-butadiene rubber</td>
<td>Polyvinylechloride (PVC)</td>
<td>Melamines (MF)</td>
</tr>
<tr>
<td></td>
<td>Reclaimed rubber</td>
<td>Polyethylene (PE)</td>
<td>Epoxies (EPX)</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>Polypropylene (PP)</td>
<td>Polyesters (UP)</td>
</tr>
<tr>
<td></td>
<td>Polysulfide</td>
<td>Polyamide</td>
<td>Polyimide</td>
</tr>
<tr>
<td></td>
<td>Etc.</td>
<td>Etc.</td>
<td>Etc.</td>
</tr>
</tbody>
</table>

2.1.2 Applications of adhesive: engineering & industrial

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. In fact, in many cases, adhesives have replaced another means of joining. Though paper, packaging, footwear, woodworking still remain as the major outlet for adhesives, the usage has also increased significantly as the key structural components in industrial equipment, building and construction, vehicle manufacturing, and for military and space applications [4, 17, 22].
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 join any surfaces, which are too difficult or nearly impossible to join 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.

2.1.3 Adhesive bonding: advantages/disadvantages

Adhesive bonding offers many advantages but at the same time it has few disadvantages too. Major advantages and disadvantages of adhesive bonding are summarized in Table 2 below.

Table 2 Advantages and disadvantages of adhesive bonding [4, 17, 20-22].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) No stress concentrations due to piercing of adherends, uniform distribution of stress and larger stress-bearing area.</td>
<td>(1) Strength is dependent upon the condition of the adherend surface.</td>
</tr>
<tr>
<td>(2) Improved fatigue and cyclic loads resistance.</td>
<td>(2) Durability in adverse environments affected by surface conditions.</td>
</tr>
<tr>
<td>(3) Lighter weight structures.</td>
<td>(3) Lack of non-destructive quality control and testing methods.</td>
</tr>
<tr>
<td>(4) Ability to join and seal simultaneously</td>
<td>(4) Lack of engineering curricula describing</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>5</td>
<td>Ability to join galvanically problematic metals and minimize or prevent corrosion between dissimilar materials.</td>
</tr>
<tr>
<td>6</td>
<td>Can be less expensive, quicker and cheaper to form than mechanical fasteners.</td>
</tr>
<tr>
<td>7</td>
<td>Ability to join thin sheets or thick materials of complex shapes.</td>
</tr>
<tr>
<td>8</td>
<td>Improved stiffness and improve sound absorption.</td>
</tr>
<tr>
<td>9</td>
<td>Adhesive can add another function.</td>
</tr>
<tr>
<td>10</td>
<td>Ability to join similar and dissimilar materials.</td>
</tr>
<tr>
<td>11</td>
<td>Provide joints with smooth contours.</td>
</tr>
<tr>
<td>12</td>
<td>Insulate against heat transfer and electrical conductance (in some cases adhesives are designed to provide such conductance).</td>
</tr>
<tr>
<td>13</td>
<td>The heat required to set the joint is usually too low to reduce the strength of adhesive bonding.</td>
</tr>
<tr>
<td>5</td>
<td>Can be more expensive than mechanical fasteners.</td>
</tr>
<tr>
<td>6</td>
<td>Adhesives are difficult to rework.</td>
</tr>
<tr>
<td>7</td>
<td>Possibility of slower curing and processing.</td>
</tr>
<tr>
<td>8</td>
<td>Some adhesives have toxic components.</td>
</tr>
<tr>
<td>9</td>
<td>Some adhesives have a limited shelf-life which depends on the environment to which it is exposed.</td>
</tr>
<tr>
<td>10</td>
<td>Some adhesives have poor resistance to crack propagation.</td>
</tr>
<tr>
<td>11</td>
<td>Holding fixtures, presses, ovens and autoclaves may be necessitates.</td>
</tr>
<tr>
<td>12</td>
<td>The upper service temperatures are limited to approximately 177°C in most cases, but special adhesives, usually more expensive, are available for limited use up to 371°C.</td>
</tr>
<tr>
<td>13</td>
<td>Rigid process control, including emphasis on cleanliness, is required for</td>
</tr>
<tr>
<td>the metal parts.</td>
<td>most adhesives.</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>(14) Dampen vibration and absorb shock.</td>
<td>(14) Exposure to solvents used in cleaning or solvent cementing may present health problems.</td>
</tr>
<tr>
<td>(15) Provide an attractive strength/weight ratio.</td>
<td>(15) The strength and toughness of adhesives in tension and shear is relatively low compared to many metals.</td>
</tr>
<tr>
<td>(16) The adherends are not stressed by high temperatures, as in welding and, partly, even in soldering.</td>
<td>(16) Optimum bond strength usually not realized instantaneously as for spot-welding assembly.</td>
</tr>
<tr>
<td>(17) Versatility of adhesive forms and methods of applications permits their adaptation to many production processes.</td>
<td>(17) Careful joint design required to minimise peel and cleavage stresses as well as those due to differential thermal expansions.</td>
</tr>
</tbody>
</table>

### 2.1.4 Epoxy adhesives

Epoxy adhesives are typical representative of thermosetting synthetic products, which derived from the chemical reaction of an epoxide resin and a basic or acidic curing agent (hardener). They are characterized by the presence of the oxirane group. The first commercially useful epoxy resins appeared during World War II and were based on the diglycidyl ether of bisphenol A (DGEBA). Today these resins, in a range of molecular
weights, constitute the majority of all epoxy resins used worldwide. By contrast, however, hardeners come in a variety of shapes and sizes, including amines and amides, mercaptans, anhydrides, and Lewis acids and bases. The selection of hardener depends on the application requirements, and the wide range of hardeners available increases the versatility of adhesives based on epoxy resins. Epoxy adhesives have several advantages over other polymers as adhesive agents as listed here [22, 23]:

(1) High surface properties.
(2) High cohesive strength for cured polymers which often exceed adherend's strength.
(3) Low shrinkage during cure which minimizes stresses.
(4) Permits bonding of large areas and a wide range of substrates.
(5) High creep resistance with better retention of stress under sustained loading than thermoplastic adhesives.
(6) Can be modified by (a) selection of base resin and hardener, (b) addition of another polymer, and (c) addition of filler which permitting a wide range of pot lives, application conditions, and cure properties.
(7) Elimination of galvanic corrosion when bonding dissimilar metals.
(8) Solvent-free liquids with open times similar to pot life.
(9) Minimal clamping requirements.
(10) Stoichiometrically cured epoxies generally inert and physiologically harmless.
However, as with all structural components, there are also some drawbacks inevitable for the epoxy adhesives. Disadvantages of epoxy resin adhesives may be summarized as follows [23]:

1. Two-component systems require mixing in correct ratios, with attendant pot-life problems.
2. Many components toxic or irritants.
3. Relatively poor heat resistance of many cured systems.
4. Inherent brittleness, requiring careful joint design.
5. Poor cure at low temperatures.
6. Careful surface preparation required.
7. Need for skilled applicators.
8. High cost.

Epoxy resin adhesives are used mainly in niche applications rather than as general-purpose adhesives, such as [23]:

1. Building and construction
2. Metal bonding
3. Road making
4. Wood bonding
5. Engineering applications (e.g. automotive, aeronautical and space, marine)
6. Electrical applications
7. Repair and maintenance
2.2 Mechanics and failure of adhesive joint

2.2.1 Destructive testing

Nowadays, adhesive joint is employed in some of the most critical areas in engineering structures and industrial applications. Therefore, destructive testing is very required to assess the performance of an adhesive joint. Destructive testing of adhesive joint is performed for a variety of reasons. Perhaps the most common reasons are [17, 20, 24, 25]:

(1) As a qualitative comparison of properties of two or more adhesives that are being considered for a given application. (e.g. tensile, shear, peel, flexural, impact and cleavage strength, durability, fatigue, environmental resistance, conductivity, etc.).

(2) Quality checks for a ‘batch’ of adhesives to determine whether the adhesives are still up to standard.

(3) To check the effectiveness of surface treatments, coupling agents, anodizing and/or other preparations.

(4) To determine parameters or ‘properties’ useful in designing and/or predicting the performance of a particular joint to be used in a structure (i.e. cure conditions, drying conditions, bond-line thickness, etc.).
Many different adhesive joint configurations are used extensively in engineering and industrial applications. Therefore, adhesive joints similar to those used in actual applications are developed and standardized by International Standards Organization (ISO), American Society for Testing and Materials (ASTM), British Standards Institution (BS) and few other organizations [4, 20, 23]. The most common types of adhesive joints are shown schematically in Fig. 1. Though these adhesive joint geometries exhibit features in common with the others, the stress/strain state within these geometries is rather complex.

(a) Butt adhesive joint

(b) Lap adhesive joint

(c) Scarf adhesive joint

Fig. 1 Butt adhesive joint, lap (often called lap shear) adhesive joint and scarf adhesive joint. Adapted from Ebnesajjad [17].
2.2.2 Strength and fracture toughness

In practical purposes, the magnitude of adhesion is generally determined by bond strength. In fact, the most essential demand of adhesive is also bond strength. However, theoretical approach of bond strength is extremely difficult and many related phenomena are remained unsolved. The major reasons are as follows [26]:

1. Surface of material (i.e. adherend) and bonding interface between adhesive and adherend are greatly complex.

2. There is no particular method that can independently measure the bonding force of interface (adhesive force).

3. Science of fracture and strength is not well established.

There are many factors affecting the bond strength of adhesive joint. For instance, Fig. 2 shows the major factors governing the bonding strength [26]. Moreover, strength and failure behavior of an adhesive joint depend upon the stress distribution within the joint. This stress distribution is influenced primarily by [17, 27-29]:

1. Joint geometry (bond thickness, adherend thickness, spew fillet).

2. Mechanical properties of the adherend and the adhesive.

3. The degree of true interfacial contact, surface topology and preparation.

4. Location and size of the flaws, and the crack path through the joint.

5. Residual internal stresses.
In addition, it is well known that there are some contradicting phenomena exist within bond strength [4, 26]. Fig. 3 shows the relationship of bond strength against elastic modulus of adhesive and bond thickness. It has been reported that shear strength increases with increasing elastic modulus. Meanwhile, peel strength is optimum at an ideal elastic modulus of adhesive and increasing the stiffness of adhesive will only reduce the peel strength of joint. For influence of bond thickness, shear strength and peel strength have opposite mechanism wherein the increase of bond thickness will result in a reduction of shear strength and an increment of peel strength. Moreover, shear strength has a maximum value at an optimum bond thickness, but with relatively small bond thickness less than optimum bond thickness, shear strength is further decreased.
<table>
<thead>
<tr>
<th>Mechanical strength</th>
<th>(1) Mechanical behavior of adhesive &amp; adherend</th>
</tr>
</thead>
<tbody>
<tr>
<td>= resistance to fracture by external loading</td>
<td>(2) Failure condition</td>
</tr>
<tr>
<td></td>
<td>(a) Measurement method</td>
</tr>
<tr>
<td></td>
<td>- (type of bond strength)</td>
</tr>
<tr>
<td></td>
<td>(b) Temp-Speed-Geometry</td>
</tr>
<tr>
<td></td>
<td>(3) Adhesive force</td>
</tr>
<tr>
<td></td>
<td>(a) Macro anchor effect</td>
</tr>
<tr>
<td></td>
<td>(b) Micro (molecule level)</td>
</tr>
<tr>
<td></td>
<td>- 1st order bonding</td>
</tr>
<tr>
<td></td>
<td>- 2nd order bonding</td>
</tr>
<tr>
<td></td>
<td>- Adhesion work (thermodynamics)</td>
</tr>
<tr>
<td></td>
<td>- Interdiffusion, electrostatic, etc.</td>
</tr>
<tr>
<td></td>
<td>(4) Weak Boundary Layer (WBL)</td>
</tr>
</tbody>
</table>

Fig. 2 Major factors governing the bonding strength.
Fig. 3 Relation of bond strength against (a) elastic modulus of adhesive and (b) bond thickness [4, 26].
In single lap joints, another key design is the overlap length. Fig. 4 shows the fracture load and stress of single lap joint as a function of overlap length. It is evident that fracture load at joint fracture increases significantly as overlap length is increased until it reach a plateau of an approximately constant value. Hence, single lap joint with very long overlap length will almost fracture at same fracture load. In contrast, average applied fracture stress decreases as overlap length decreases. This feature is related to the shear stress concentrations at the interface corner of the overlaps, i.e. the longer the overlap length, the more shear stress will concentrate at the interface corner.

Fig. 4 Fracture load and stress of single lap joint as a function of overlap length [4, 30].
Stress intensity factors and fracture energy for mode I and mode II of various adhesives in bonded joints are summarized in Table 3. These data are selected amongst recently published results by several researchers. The purpose is to demonstrate that different type of adhesives and adherends are employed. However, the methods of evaluation are generally of those already specified by ASTM or ISO standard. It can be noticed that the stress intensity factor or fracture energy of adhesive joint in mode II is always higher than those of mode I. Moreover, these values are also higher when specimen tested was bonded using thick adhesive layer.

Fracture toughness against bond thickness of various bonded joints has been reported as shown in Fig. 5. The correlation between fracture toughness and bond thickness are recently understood. For example, a very simple model has been proposed as illustrated in Fig. 6 [4, 31]. In both Type A and Type B, the fracture toughness increases almost proportionally to the increase of bond thickness. Fracture toughness eventually reaches a plateau at relatively large bond thickness. However, it is interesting to point out that in Type A, there exists an optimum bond thickness where the maximum fracture toughness is obtained. This feature has been elucidated by Kinloch and Shaw [4] as a role of plastic zone in which the fracture energy is maximized when the bond thickness equals the diameter of the plastic zone formed ahead of the crack tip. Type A is usually observed in ductile adhesive joints whilst Type B is observed in brittle adhesive joints, i.e. it is widely accepted that fracture toughness of brittle adhesive is less affected by bond thickness.
Table 3 Stress intensity factors and fracture energy for mode I and mode II of various adhesives in bonded joints.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Adherend</th>
<th>t (mm)</th>
<th>$K_{IC}$ (MPa.m$^{1/2}$)</th>
<th>$K_{IIC}$ (MPa.m$^{1/2}$)</th>
<th>$G_{IC}$ (N/m)</th>
<th>$G_{IIC}$ (N/m)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM®300-2</td>
<td>Al</td>
<td>0.2</td>
<td>0.609</td>
<td>1.03</td>
<td>67.8</td>
<td>195</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>0.41</td>
<td>0.763</td>
<td>1.235</td>
<td>210.7</td>
<td>552.1</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>0.2</td>
<td>0.334</td>
<td>0.585</td>
<td>19.9</td>
<td>61</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>0.41</td>
<td>0.471</td>
<td>0.878</td>
<td>80.4</td>
<td>279.1</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td>CF/PEI</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>96.5</td>
<td>135.2</td>
<td>[32]</td>
</tr>
<tr>
<td></td>
<td>CF/PEI</td>
<td>0.41</td>
<td>0.651</td>
<td>0.806</td>
<td>153.2</td>
<td>235.3</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td>CF/PEI</td>
<td>0.41</td>
<td>2.658</td>
<td>5.174</td>
<td>788</td>
<td>1160</td>
<td>[34]</td>
</tr>
<tr>
<td>Duralco 4525</td>
<td>Mild Steel</td>
<td>0.15</td>
<td>0.75</td>
<td>1.7</td>
<td>152</td>
<td>739</td>
<td>[5]</td>
</tr>
<tr>
<td>AV138/HV998</td>
<td>Steel</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>346</td>
<td>4910</td>
<td>[35, 36]</td>
</tr>
<tr>
<td>2015</td>
<td>Steel</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>526</td>
<td>11900</td>
<td>[35, 36]</td>
</tr>
<tr>
<td>Ciba Geiby*</td>
<td>Al</td>
<td>0.1</td>
<td>0.59</td>
<td>0.56</td>
<td>-</td>
<td>-</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>-</td>
<td>0.482</td>
<td>0.529</td>
<td>-</td>
<td>-</td>
<td>[38]</td>
</tr>
<tr>
<td>Epibond**</td>
<td>Composite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>997</td>
<td>1162</td>
<td>[39]</td>
</tr>
<tr>
<td>Epibond***</td>
<td>Composite</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1254</td>
<td>1998</td>
<td>[39]</td>
</tr>
</tbody>
</table>

*(AW106/HV953U)  
**Epibond 1590 A/B  
***Epibond 1590 A/B + 7.5% XNBR
Fig. 5 Fracture toughness against bond thickness of various bonded joints.

Fig. 6 Models of relationship between fracture toughness and bond thickness [4, 31].
2.2.3 Types of failure

Bond strength can be defined as the resistance of an adhesion system (bonded components) when submitted to the fracture. Thus, adhesion and fracture are opposite process. Fracture occurs at the weakest location as shown in Fig. 7. According to the ASTM D5573 standard, locations of fracture can be categorized as follows:

(1) Adhesive layer (cohesive failure); in this case, adhesive is weak. (i.e. A and B)

(2) Interface (interfacial failure); in this case, adhesive bonding is bad. (i.e. C)

(3) Mixed failure, (1) + (2). (i.e. D and E)

(4) Adherends or its surface layer (adherend failure). (i.e. F)

For cohesive failure, it is obvious 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. Hence, when investigating the bond strength, first, confirmation of fracture location is very much needed.
In adhesive joint design, adhesive technologist and engineers must consider a lot of features and do and don't. Basically, the general requirements for attaining the good adhesive joint are [17]:

1. Proper choice of adhesive.
2. Good joint design.
3. Cleanliness of surfaces.
4. Wetting of surfaces that are to be bonded together.
5. Proper adhesive bonding process (solidification and cure).

Fig. 7 Failure locations of adhesive joint [40].
If all of aforementioned requirements are fulfilled, the adherend of an adhesive joint may yield or fracture before the adhesive fails. In other words, an adhesive joint that has been properly designed will exhibit cohesive failure in the adherend.

2.3 Stress analysis of adhesive joint

Other than destructive testing, stress analysis can also be used to evaluate the bond strength. Stress analysis permits us to deduce the nature and magnitude of stresses and strains in an adhesive joint. There are two means of stress analyses which have been commonly employed, i.e. closed-form analytical solutions and numerical methods [4, 41, 42]. The former are based on defining the mathematical differential equations by using stress function or other techniques, whereas the latter are mainly that of finite element method or finite difference method. Analytical approach is reported to have been used as early as 1938 in the simple shear lag model of Volkersen [4]. Many works have been done later on which offer the improved solutions of stress distribution in adhesively bonded single or double lap joints. An extensive literature review and comparative study on existing analytical models for both single and double lap joints are available in [43, 44]. For example, Fig. 8 shows Goland and Reissner’s adhesive shear and peel stress distributions of single lap joint [45]. However, yet in most cases which involving complex geometries and elaborate materials model, the closed-form solution is not always exist. In contrast, with the help of current sophisticated and powerful computational tools, FEM is far more versatile and will always yield a result. Fig. 9 shows a representative of peel and shear stresses in single lap joints obtained in FEM analysis [46]. Clearly, FEM analyses also can give a joint
designer the stress distribution of adhesive joint in detail. Therefore, nowadays, the earlier analytical approaches have been replaced by FEM stress analysis. Knowledge of stress distribution and appropriate failure criterion leads to accurate bond strength prediction.

Fig. 8 Goland and Reissner’s adhesive shear and peel stress distributions of single lap joint [45].

Fig. 9 Peel and shear stresses in single lap joints obtained in FEM analysis [46].
Chapter 3  Experimental procedures and numerical analysis

3.1  Specimen preparation and experimental method

3.1.1  Material and bonding process

The brittle adhesive used in this study was High-super 30 produced by Cemedine Co., Japan as shown in Fig. 10. This is a commercial two-part epoxy adhesive which can be cured at room temperature (hereafter abbreviated as R.T.) approximately within 30 minutes. The general information regarding the material properties of this adhesive are tabulated in Table 4. The adhesive was prepared prior to bonding by mixing thoroughly the epoxy resin and hardener inside a 12 ml ointment container in 1:1 ratio (i.e. 3.5 gram each) using the centrifugal conditioning mixer (see Fig. 11). The schedule of diffusion and de-foaming were 1 min and 3 min, respectively.

Fig. 12 (a) and (b) show the bonding fixtures which were used in bonding the adherends together with the adhesive to manufacture butt or scarf joint and shear joint, respectively. Only three specimens can be manufactured at the same time. For butt and scarf joints specimen, the adhesive bond thickness, $t$ inside the joint was controlled by using the two micrometers attached to the bonding fixture and varied from 0.1 mm to 1.2 mm. However, for shear joints specimen, $t$ was attained by using the spacers having 5 different thicknesses. All specimens were allowed to cure at least for 24 hours duration at
R.T. for the complete curing. After that, the excessive adhesive was carefully removed by a portable grinder and a sharp carving knife (see Fig. 13).

Fig. 10 Two-part adhesive (Cemedine High-super 30, 80 gram set).

Fig. 11 Centrifugal conditioning mixer (Thinky AR-100).
Table 4 Material properties of adhesive used in this study.

<table>
<thead>
<tr>
<th>Property</th>
<th>High-Super30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (Pa.s/23°C)</td>
<td>Epoxy 70</td>
</tr>
<tr>
<td></td>
<td>Hardener 160</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>Epoxy 1.17</td>
</tr>
<tr>
<td></td>
<td>Hardener 1.14</td>
</tr>
<tr>
<td>Curing time</td>
<td>30 min.</td>
</tr>
<tr>
<td>Mature bonding time</td>
<td>1 h</td>
</tr>
<tr>
<td>Tensile shear strength (N/mm²) *</td>
<td>17.5</td>
</tr>
<tr>
<td>T-peel strength (N/mm) **</td>
<td>0.47</td>
</tr>
<tr>
<td>Hardness (Shore-D)</td>
<td>82</td>
</tr>
<tr>
<td>Linear expansion coefficient (x10⁻⁵)</td>
<td>67</td>
</tr>
<tr>
<td>Glass transition temperature (°C)</td>
<td>43</td>
</tr>
<tr>
<td>Volume resistivity (Ω.cm)</td>
<td>3.8 x 10¹¹</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>2.3</td>
</tr>
</tbody>
</table>

¶ Manufacturer’s catalogue

* JIS K6850

** JIS K6854
(a) Bonding fixture for butt and scarf joints specimen

(b) Bonding fixture for shear joints specimen

Fig. 12 The developed bonding fixtures.
3.1.2 Experimental apparatus and setup

Tensile fracture tests of adhesive joints specimens were carried out with a universal testing machine (INSTRON 4206). Fig. 14 shows the overview of experimental apparatus used in tensile fracture testing. All tests were conducted at R.T. with the crosshead speed held constant at 0.5 mm/min. Load range was set to 10% of the load cell capacity which was at 100 kN and position full scale was 2 mm.

The loading fixture which has two pinholes of 16 mm in diameter is shown in Fig. 15 (a). To ensure that the specimen was in equilibrium, two 34 mm by 40 mm aluminium shims (see Fig. 15 (b)) were fixed between the specimen and loading fixture. Then, the specimen was attached to the loading fixture using two 15 mm diameter steel pin as shown in Fig. 15 (c).
Fig. 14 Overviews of experimental apparatus used in tensile fracture testing.
(a) 16 mm diameter pinhole loading fixture

(b) 5 mm thick aluminium shims (34 mm x 40 mm)
3.1.3 Measurements

Stroke displacement and load outputs from the control console of universal testing machine were connected to the notebook PC through a data logger. Fig. 16(a) - (e) show the load cell, control console unit, data logger, notebook PC and strain gage, respectively. During the experiments, the stroke displacement, load and strain were monitored and recorded using the pre-installed data plotter software (NEC DC31-701 ver. 9) in a notebook PC.
Before the tensile fracture testing, the bond thickness, $t$, of specimen was measured. Immediately after the test, fracture surface was also observed. Fig. 17 shows the photo of digital microscope used in measurement of $t$ and fracture surface observations.

(a) 100 kN Load cell (INSTRON 2518-100)

(b) Control console (INSTRON Model 4206)
(c) Data logger remote scanner jr. (NEC DC3100) and Universal scanner unit

(NEC DC31-203A)

(d) Notebook PC (DELL Inspiron I8100) and data software (NEC DC31-701 ver. 9)
(e) Strain gage (KFEL-5-120-C1L1M2R from Kyowa Electronic Instruments Co., Ltd.)

Fig. 16 Data measurement controller and devices.

Fig. 17 Digital microscope (Keyence VH-8000).

3.2 Finite element analysis

3.2.1 Modeling

2D non-linear elastic finite element (FE) analysis was performed using ANSYS 11 code. The 8 nodes isoparametric elements were used to construct the FE mesh. Only plane stress condition has been considered. The SUS304 stainless steel and YH75 aluminium alloy adherends were modeled as isotropic, linear elastic materials. The adherends were
assumed to remain elastic materials and the data of mechanical properties were taken from Table 5. The adherends were assumed to remain elastic materials. For the adhesive layer, the true stress-strain curve as shown in Fig. 18 was extrapolated from the actual uniaxial tensile test data to constitute the adhesive layer in the FE model [47].

The present author employed internal multipoint constraint (abbreviated as MPC hereafter) approach to define the contact assembly in FE model of adhesive joint. These MPC elements ignore any friction and the interaction between adhesive and adherend is always bonded (i.e. no separation at the interface). With this feature, the stress of each interface nodes can be obtained from its closest integration point.

FE simulations were performed with several bond thicknesses and interfacial crack lengths. The FE model was stress controlled such that all nodes at the end of the upper and lower adherends having a prescribed uniform tensile stress in the opposite direction. These FE simulations were carried out to investigate the triaxial stresses (i.e stress-y, -x and –xy) distributions along the joint interfaces, near the interface corner region and centerline of adhesive layer, and also to evaluate the fracture toughness, $J_c$ of FE model with an interfacial crack.
Table 5 Mechanical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>E  (GPa)</th>
<th>σ_y (MPa)</th>
<th>υ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy adhesive</td>
<td>3.4</td>
<td>36.5</td>
<td>0.396</td>
</tr>
<tr>
<td>SUS304*</td>
<td>206</td>
<td>307.8</td>
<td>0.3</td>
</tr>
<tr>
<td>YH75 (Al-alloy)*</td>
<td>71</td>
<td>559.0</td>
<td>0.33</td>
</tr>
</tbody>
</table>

*Data taken from manufacturer’s catalogue

3.2.2 J -integral

Fracture toughness can be evaluated by J integral calculation in FE analysis. For a nonlinear elastic body containing a crack in 2D problem as shown in Fig. 19, the J integral is given by [48]:

![Fig. 18 Extrapolated true stress-strain curve of epoxy adhesive used in FE analysis.](image)
\[ J = \int \left( W \, dy - T \frac{\partial u}{\partial x} \, ds \right) \]  

(1)

where \( u \) is the displacement vector components and \( ds \) is the length increment along an arbitrary counterclockwise contour \( \Gamma \) around the crack-tip. The strain energy density is defined by

\[ W = W(\varepsilon) = \int_{0}^{\varepsilon} \sigma_{ij} \, d\varepsilon_{ij} \]  

(2)

where \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are the stress and strain tensors, respectively. The components of traction vector are given by

\[ T_i = \sigma_{ij} n_j \]  

(3)

where \( n_j \) is the components of the unit vector normal to \( \Gamma \).

To evaluate J integral of FE model, series of ANSYS commands for J contour integration formulation were saved in a macro file. After FE analysis solution was converged, a set of circular contours around the crack-tip was defined. The radius of contours was defined as \( 0.25a, 0.5a, 0.75a \) and \( a \), where \( a \) is the crack length. The macro file was then executed at each pre-determined circular contour and the corresponding J value has been recorded. Thus, J was taken as an average value from a set of J values obtained at each execution.
Fig. 19 J integral contour around a crack-tip.
Chapter 4  Strength and fracture characteristics of butt adhesive joint

Abstract

In this chapter, fracture characteristics of epoxy adhesively bonded butt-joint of dissimilar metals, namely SUS304 stainless steel and YH75 aluminium alloy were examined on various adhesive bond thicknesses in associations with artificial interface crack subjected to pure mode I loading. The bond thickness, $t$ between dissimilar adherends is controlled to be ranged between 0.1 mm and 1.2 mm. Finite element analysis was also executed to investigate the stresses distribution in adhesive layer and also evaluating fracture toughness of adhesive joints by ANSYS 11 code. The results show that the strength of adhesive joints without crack decreases with increasing bond thickness. Interfacial crack in adhesive joints propagates in two directions, that is, along the interface (i.e. interface failure) or deviated into adhesive layer (i.e. cohesive failure). Next, the evaluated fracture toughness, $J_c$ of adhesive joints with interfacial crack was independent of bond thickness when failure was associated with crack deviated into adhesive layer. Nevertheless, $J_c$ for adhesive joints with interfacial crack was dependent on bond thickness when the failure was apparently interfacial. However, if the interfacial crack is analogous to the center crack in adhesive layer constrained between two rigid substrates, $K_c$ parameter can be used to assess the fracture toughness of adhesive joints with interfacial failure.
4.1 Introduction

Adhesive joint is definitely the ideal substitute for any conventional bonding methods (e.g. rivet, welding, diffusion bonding, etc.) in structural engineering and industrial applications. To extend the exploitation of adhesive joints the evaluation of strength and failure mechanisms becomes very crucial. However, strength and failure behavior of adhesive joints are not only complex and but also depend extremely on the mechanical properties of the adhesive layer and the state of stresses inside it as imposed by the constraint effect of stiff adherends [4, 49, 50]. Therefore, in the literature, many works have been devoted on elucidating the critical factors affecting the reliability and integrity of sandwiched adhesive joints. These include investigations upon the effect of joint geometry (i.e. bond thickness, rigid or flexible substrate, scarf angle, spew fillet and etc.), loading rate and temperature.

The effect of bond thickness upon the strength of adhesive joint has been investigated extensively by numerous researchers for many years. Zhu and Kedward [51] analyzed the effect of bond thickness and fillet upon the titanium single and double lap joints using finite element method and closed-form solutions. Their parametric studies revealed that the maximal strength of lap joints of ductile adhesive increased with decreasing bond thickness. Taib et al. [52] studied the effect of bond thickness on L-section joints of composite adherends using two components structural paste adhesive Hysol EA 9359.3. They attributed the decreased failure load to the increasing bond thickness in terms of the stress state (i.e. plane stress or plane strain) prevailing inside the adhesive layer: the thin bond thickness favors plane stress while thick bond thickness
favors plane strain state. More recently, Davies et al. [53] examined the physico-chemical and mechanical behavior of aluminium substrates bonded with commercial epoxy adhesive joints of several thicknesses. They noted a small reduction in the mechanical properties of adhesive layer as the bond thickness was increased. They also explained this feature by a change in the stress state as the modified Arcan fixtures of thick adhesive layer were tested within their numerical analysis results.

In general, the strength of adhesive joints increases as the bond thickness decreases [1]. However, this is not necessarily true. Park et al. [30] tested thick aluminium lap joint specimens with four different adhesive bond thicknesses and predicted the strength based on modified damage zone ratio method. According to their experimental results, failure load of adhesive joints without defects increase as bond thickness increases from 0.15 to 0.45 mm and then decrease when the bond thickness reaches 0.9 mm. Moreover, according to the innumerous published results, the fracture mechanics approach has also been proved to be a very useful tool to gain insight this correlation. Lee et al. [54], for example, investigated experimentally the bond thickness-effect on the fracture toughness of compact tension (CT) adhesive/aluminium alloy joint specimens with five different bond thicknesses: 0.1, 0.3, 0.7, 1.5 and 2.1 mm. Similar to [54], based on linear elastic fracture mechanics (LEFM), Yan et al. [55] have reported that the fracture toughness of double-cantilever-beams (DCB) specimens was affected by bond thickness. So far, the bond thickness-effect can be best attributed based upon the constraint effect induced by the adherends, the statistical probability of imperfections or defects and the change of the energy dissipating mechanisms of the adhesive layer [4, 53].
In this study, failure test of epoxy adhesively-bonded butt joints of dissimilar adherends was conducted under a remote tensile load on various adhesive bond thicknesses. The effect of joint geometry (i.e. bond thickness) upon the effective mechanical properties and failure criteria of butt joints will be qualitatively discussed.

4.2 Experimental procedures

To investigate the strength and fracture toughness of epoxy adhesively bonded joint of dissimilar adherends, butt adhesive joint specimens were fabricated. The geometry and dimensions of the specimen are shown in Fig. 20. The adherends were consisted of SUS304 stainless steel and YH75 aluminium alloy. YH75 is the trade name of aluminium alloy which is identical to A7075P-T651 aluminium alloy in terms of mechanical properties according to JIS H 4000:2006 specification [56]. Epoxy adhesive used and its preparation was already explained in Chapter 3, refer to Sec. 3.1.1. The mechanical properties of the bulk epoxy adhesive have been reported in the previous study [57] using the dog-bone specimen in uniaxial tension wherein the cure state was at R.T. for over 24 hours. Fig. 21 below shows the stress-strain responses of bulk epoxy adhesive specimens with its geometry and dimensions. It is noted from this figure that the bulk epoxy adhesive used in this study shows relatively linear stress-strain behavior and the fracture was also brittle in manner. The pertinent results are tabulated in Table 6 where, $E$, $\sigma_y$ and $\nu$ are Young's modulus, 0.2% proof stress and Poisson's ratio, respectively.
Bonding surfaces were uniformly polished with #2000 waterproof abrasive paper and afterward degreased with acetone. Adhesive bond thickness, $t$, inside an adhesive joint was controlled by using a developed bonding fixture (see Fig. 23) and varied from 0.1 mm to 1.2 mm. Also, for specimens with interfacial crack, an interfacial crack which originated from an interface corner was inserted to represent a flaw at adhesive joints interface. This pre-crack was introduced by pasting a strip of 0.05 mm thick Teflon tape on the edge of adherend surface prior to bonding. The pre-crack length, $a$, is controlled to study their effects on each test. Here, the ratio $a/W$ is given as 1/8, 1/4 and 3/8, where $W$ is the specimen width. All specimens were cured at R. T. over than 24 hours.

After specimens were totally cured, the excessive adhesive was removed by a portable grinder and a sharp knife. The actual bond thickness, $t$, was then measured by a digital microscope.

Tensile fracture tests of butt adhesive joint specimens were carried out with a universal tensile test machine (INSTRON 4206), as shown in Fig. 23. All tests were conducted at R. T. with the crosshead displacement speed held constant at 0.5 mm/min.

![Fig. 20 Geometry and dimensions of butt adhesive joint specimen.](image-url)
Fig. 21 Stress-strain curves of bulk epoxy adhesive specimens.

Table 6 Mechanical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
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<td>206</td>
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<td>0.3</td>
</tr>
<tr>
<td>YH75 (Al-alloy)*</td>
<td>71</td>
<td>559.0 [7.82]</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* data taken from manufacturer’s catalogue.

[ ] denotes the value of standard deviation.
Fig. 22 Butt adhesive joint specimen is fabricated by using a developed bonding fixture.

Fig. 23 Butt adhesive joint specimen under tensile fracture testing.
4.3 Numerical modelling

Fig. 24 shows the typical model for the stress analysis of a butt adhesive joint. Eight nodes isoparametric elements are used in the analysis. Taking into account the symmetry of the joint to the axis $x = 20$, only half of the joint is analyzed. The boundary constraints and loading conditions imposed are also shown in this figure. The tensile stress of $1 \text{ MPa}$ is applied in the $y$-direction on all nodal points at both ends of adherends. The prescribed boundary conditions are as follows: all nodal points at $x = 20$ are fixed in the $x$-direction.

Fig. 24 FE model meshes of butt adhesive joint and detail view of the elements near to interface corner.
The number of nodes and elements employed for each model incorporating different bond thickness are summarized in Table 7. Since the stress singularity occurs near the interface corners, the elements near this region are divided into finer meshes (i.e. using nearly square shaped elements) such that this effect can be accurately modeled. The finest mesh size is also listed in Table 7. The analysis is performed within elastic deformation.

Table 7 Description of FE model used for stress analysis of butt adhesive joint.

<table>
<thead>
<tr>
<th>Bond thickness, (t) (mm)</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
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<td>6496</td>
<td>0.1</td>
</tr>
<tr>
<td>0.5</td>
<td>Half</td>
<td>20578</td>
<td>7349</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td>Half</td>
<td>23368</td>
<td>8281</td>
<td>0.1</td>
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</table>

Fig. 25 shows the typical model for the stress analysis of a butt adhesive joint with an interfacial crack. The whole model of the joint is analyzed. Eight nodes isoparametric elements are used in the analysis. The boundary constraints and loading conditions imposed are also shown in Fig. 25. The pilot nodal points at right edge of the upper and lower adherends are fixed in the x-direction. The tensile stress of 1 MPa is applied in the y-direction on all nodal points at both ends of adherends in opposite direction. The number of nodes and elements employed for each model incorporating different bond thickness and crack length are summarized in Table 8. Since the stress singularity occurs near the interface corners and interfacial crack-tip, the elements near these regions are divided into
finer meshes (i.e. using nearly square shaped elements) such that this effect can be accurately modeled. The finest mesh size is listed in Table 8. The analysis is performed within elastic deformation.

Fig. 25 FE model meshes of butt joint with interface crack and detail view of the elements near to interface crack.
Table 8 Description of FE model used for stress analysis of butt adhesive joint with an interfacial crack, \( a = 5, 10, 15 \) mm.

<table>
<thead>
<tr>
<th>Bond thickness, ( t ) (mm)</th>
<th>Crack length, ( a ) (mm)</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
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4.4 Results and discussion

4.4.1 Non-crack butt adhesive joint

4.4.1.1 Numerical results

First, the stress distributions in butt adhesive joint with SUS304/ALYH75 dissimilar adherends which are analyzed in FE will be discussed. Fig. 26 shows the stress-x, -y and -xy distributions in butt adhesive joint bonded with dissimilar adherends at both interface
lines and adhesive center. It can be noticed that at both SUS304/epoxy interface and ALYH75/epoxy interface, when $r$ approaches zero, stress-$y$ elevates to infinity. Also, stress-$y$ at SUS304/epoxy interface has the highest magnitude if compared to other stresses. Stress-$y$ approaches to the applied stress (i.e. 1 MPa) when $r$ is greater than 2.5 mm. Besides, stresses are less concentrated at the center of adhesive layer. Therefore, for the purpose of strength evaluation, the stress of practical interest is solely stress-$y$. Henceforward, the stress-$y$ will be considered.

A comparison of stress-$y$ distributions at interface corner of similar and dissimilar adherends bonded adhesive joints are shown in Fig. 27. Here, SS, AA and SA denote adhesive joint bonded with similar SUS304 adherend, similar ALYH75 adherend and SUS304/ALYH75 dissimilar adherends, respectively. As seen, stress-$y$ at interface corner of adhesive joint bonded with identical adherend is slightly different from those of adhesive joint of dissimilar adherends. The adhesive joint bonded with dissimilar adherend shows the highest and lowest stress-$y$ at SUS304/epoxy and ALYH75/epoxy interface corner, respectively. Also, the interface corner that has higher stress-$y$ in order is SUS304/epoxy of dissimilar joint, SUS304/epoxy of similar joint, ALYH75/epoxy of similar joint and ALYH75/epoxy of dissimilar joint. This is in good agreement with the results obtained by Kyogoku et al. [58]. They have examined experimentally and analytically the strength of butt scarf adhesive joints of dissimilar adherends bonded with epoxy adhesive. They reported that the deformation state and fracture process of these joints were remarkably different from those joints of identical adherends.
Fig. 26 Stress-\(x\),-\(y\),-\(xy\) distributions in butt adhesive joint bonded with dissimilar adherends.
Fig. 27 Comparison of stress-y between butt adhesive joint bonded with similar and dissimilar adherends.

The effect of bond thickness on stress-y distributions in butt adhesive joint is also important to evaluate. Stress -y distributions in butt adhesive joint of dissimilar adherends with different bond thickness, t are shown in Fig. 28. Obviously, as t becomes thicker, the concentration of stress-y near edge of SUS304/epoxy interface corner significantly increases. Oppositely, the stress-y at the middle of adhesive layer is less constraint in butt adhesive joint with thick bond.
4.4.1.2 Experimental results

In tensile test of butt adhesive joints, load and crosshead displacement were recorded. Fig. 29 (a) and (b) show the typical load against crosshead displacement obtained for butt adhesive joints of dissimilar adherends having 0.1 mm bond thickness and 1.0 mm bond thickness. It is noted that at the beginning of tensile loading (i.e. crosshead displacement is less than 0.1 mm), load is quadratically increased. This is due to the initial alignment of specimen. Beyond 0.1 mm displacement, load increases proportionally up to maximum load (hereafter failure load) where a sudden failure occurs. This dynamic failure is accompanied by a ‘ping’ sound. Despite some scatter in data, butt adhesive joint having 0.1 mm bond thickness has better load performance than those having 1.0 mm bond
thickness. In FE analyses, it is obvious that as $t$ becomes thicker, the concentration of stress $y$ near the edge of interface corner significantly increases. Therefore, one may anticipate that adhesive joint having thick bond thickness will probably fail at low failure load due to this critical stress concentration. Besides, the constraint effect opposed by the upper and lower adherends in adhesive joint with thick bond thickness is lesser than those in thin adhesive layer. Moreover, from statistical mechanics standpoint, butt adhesive joint having 1.0 mm bond thickness is more sensitive to any defects.

![Graphs showing load vs. crosshead displacement for different bond thicknesses](image)

(a) 0.1 mm bond thickness  
(b) 1.0 mm bond thickness

Fig. 29 Load vs. crosshead displacement of butt adhesive joint.
As seen in fracture surfaces examinations, the failure types of butt adhesive joints fell mainly into two categories: interfacial failure (i.e. type A) or cohesive failure (i.e. type B), as illustrated in Fig. 30. For type A, the failure initiates at an interface corner and propagates entirely through the boundary of adhesive/adherend. However, for type B, failure is initiates at the interface corner except it propagates along the interface line for up to 0.5-2 mm before immediately deflecting into adhesive layer. It is observed that type A is more likely to occur at ALYH75/epoxy interface whereas B occurs at SUS304/epoxy interface. Hereafter, B is defined as cohesive failure due to the overall appearance. A representative of failure surface for type A is shown in Fig. 31. Meanwhile, Fig. 32 shows the failure surface of each specimen with type B.

Fig. 30 Schematic illustration of failure growth paths in butt adhesive joint specimen.

Fig. 31 Representative of failure surface for type A (i.e. specimen no. is i1c).
<table>
<thead>
<tr>
<th>Failure path</th>
<th>Type B (specimen no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond thickness, t (mm)</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>(g1a)</td>
</tr>
<tr>
<td></td>
<td>(g1c)</td>
</tr>
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<td>(g1e)</td>
</tr>
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<td>(g3a)</td>
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<td></td>
<td>(g3c)</td>
</tr>
<tr>
<td></td>
<td>(g3e)</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
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<td>(g6a)</td>
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<tr>
<td>-----</td>
<td>-------</td>
</tr>
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<td>(g7a)</td>
</tr>
<tr>
<td></td>
<td>(g7c)</td>
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<td></td>
<td>(g8c)</td>
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<td></td>
<td>(g8e)</td>
</tr>
<tr>
<td>1.0</td>
<td>(g10b)</td>
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<tr>
<td></td>
<td></td>
</tr>
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</table>

Fig. 32 Failure surface of each butt adhesive joint specimen (i.e. failure type B).
The failure stress of adhesive joints is now plotted against bond thickness, \( t \) in Fig. 33 (a). For both failure types A and B, it is found that the failure stress gradually decreases when the bond thickness, \( t \) increases. However, the magnitude of failure stress for butt adhesive joints of type B is much higher than type A for \( t < 0.3 \) mm. A is ordinary since the bonding strength of the interfaces is weaker than the strength of adhesive or adherends. Moreover, poor wetting of ALYH75 adherend may also plays the role. In contrast, if the surfaces preparations of the adherends are sufficient, particularly in the systems considered here, failure may deviate away from interface corner and propagates inside the adhesive layer: cohesive failure as observed in type B is in favor.

For the purpose of comparison, tensile test of butt adhesive joint bonded with similar adherend is also conducted. The failure stress against the bond thickness is plotted in Fig. 33 (b). Here, SS and AA denote butt adhesive joint bonded with similar SUS304 adherend and similar ALYH75 adherend, respectively. Note that in butt adhesive joint bonded with identical adherend (i.e. SS and AA), the failure path is always type B. Comparison between butt adhesive joints bonded with dissimilar adherends and those of identical adherend is shown in Fig. 34. From Fig. 34, one may realize that the failure stress of similar butt adhesive joint is also dependent on bond thickness: as the bond thickness increases, the failure stress will decrease. In addition, the failure stress of SS is in fair agreement with the SA of type B.
Bond thickness, $t$ (mm)  

<table>
<thead>
<tr>
<th>Failure Stress (MPa)</th>
<th>A</th>
<th>B</th>
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<th>AA</th>
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<td></td>
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<tr>
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</tbody>
</table>

(a) Dissimilar butt adhesive joint  
(b) Similar butt adhesive joints  

Fig. 33 Failure stress against bond thickness.  

Fig. 34 Failure stress against bond thickness. Comparison between butt adhesive joints bonded with dissimilar adherends and those of identical adherend.
4.4.2 Butt adhesive joint with an interfacial crack

4.4.2.1 \(J_c\) calibration

The present author considered two systems of adhesive joints with interfacial crack (i.e. produced by Teflon tape) originated from the upper left interface corner, as shown in Fig. 35 (a) and (b). Hereafter, SEA and AES are referred to the adhesive joints with interfacial crack originated at SUS304/epoxy interface corner and ALYH75/epoxy interface corner, respectively.

To evaluate the fracture toughness of butt adhesive joint with an interface crack, \(J\) integral calculation in FE is applied. However, since the actual bond thickness in a specimen might be varied from the targeted value, a calibration of \(J\) value is needed beforehand. Fig. 36 shows the results of \(J\) calibration obtained from FE analysis. It is noted that this FE analysis was conducted with the applied stress of 1 MPa.
Fig. 35 Schematics of butt adhesive joints of dissimilar adherends with an interfacial crack originated from (a) SUS304/epoxy interface (SEA) and (b) ALYH75/epoxy interface (AES). Interface crack length, $a = 5, 10, 15$ mm.
Fig. 36 J calibration of butt adhesive joint with interfacial crack in FE analysis.
4.4.2.2 Experimental results

From observations of fracture surfaces, it was revealed, as similar to failure types in joints without crack, that the interfacial crack has propagated either type A or type B, as illustrated in Fig. 37. Fig. 38 shows the fracture surface of specimens. In fact, the present author has also determined the deviation angle of crack in type B [47] and the results correlated well with the prediction by maximum hoop stress criterion. Hence, it is here necessary to reanalyze the fracture toughness of each specimen with further consideration on their types of failure.

![Fracture propagation paths](image-url)

**Fig. 37 Fracture propagation paths.**
<table>
<thead>
<tr>
<th>Side Crack length, $a$ (mm)</th>
<th>SEA (specimen no.)</th>
<th>AES (specimen no.)</th>
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(a) Bond thickness, $t = 0.1\text{mm}$
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<th>AES (specimen no.)</th>
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(b) Interface crack length, $a = 10\text{mm}$

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Fig. 38 Fracture surface of butt adhesive joint with interface crack.

Fig. 39 (a) shows the results of fracture toughness, $J_c$ versus percentage of interface fracture (abbreviated as IF hereafter) for the tensile dissimilar joint having interfacial crack length of 5, 10 and 15 mm. Note that the IF is the area of interface fracture over the entire bonding area. In the case of SEA, as shown in Fig. 39 (a), $J_c$ values fall within 10-30 (N/m) when IF is less than 60%. Meanwhile, for AES case, the $J_c$ value is apparently constant for IF ranges between 40-90%, as can be seen in Fig. 39 (b). In contrast to the SEA case, most joints of AES fractured entirely at the joint interface. Furthermore, it was also observed that from all specimens, there was no established dependency of $J_c$ upon interfacial crack length. Thus, the following discussion will be restricted only to the effect of bond thickness on the $J_c$ of dissimilar joints with an interfacial crack.
Fig. 39 Fracture toughness, $J_c$ against fraction of interface fracture.
Now, the fracture toughness, $J_c$ which corresponds to butt adhesive joints that fractured cohesively (abbreviated as CF hereafter) is considered. $J_c$ is plotted as a function of bond thickness, $t$, as shown in Fig. 40 (a). Clearly, when scatter is neglected, $J_c$ is indeed a material property that depends on the specific material combinations under consideration. In other work by the same author, when adhesive joints with interfacial crack were fractured, fracture toughness, $J_c$ exhibited independent of bond thickness, $t$ [47, 57]. Oppositely, if $J_c$ for adhesive joints with interfacial failure is examined, it is found that $J_c$ depends slightly on bond thickness, see Fig. 40 (b). This is due to the state of interfacial crack-tip sharpness. For adhesive joints with thin bond thickness, the ratio of bond thickness to inserted crack thickness is relatively small. This means that the crack-tip is dull and this leads to lower stress concentration at crack neighborhood as can be seen, for example, from Fig. 41. This figure shows the contour plots of equivalent stress in FE model of 0.1 mm thick adhesive joints with interfacial crack. From these contour plots, one can see that the highest equivalent stress in the adhesive joints, about 8.931 MPa, is located at the ideally sharp crack-tip, i.e. case (a). However, it can be observed that the equivalent stress falls at the Teflon tape crack-tip, i.e. case (b), to approximately 5.8 MPa since the presence of wide crack-tip opening allows the reduction of stress concentration. This is also found to be true for another adhesive thickness but reduces slightly with increasing bond thickness. As a result, higher fracture toughness is measured, especially for joints with $t < 0.4$ mm. Hence, $J_c$ is inapplicable for fracture toughness assessment in this case and consequently, another fracture criterion is needed.
Bond thickness, \( t \) (mm)

Fracture toughness, \( J_c \) (N/m)

(a) Cohesive failure

(b) Interface failure

Fig. 40 Fracture toughness, \( J_c \) against bond thickness.
Fig. 41 Contour plots of equivalent stress in FE model of 0.1 mm thick adhesive joints with interfacial crack. ($a = 5$ mm, $\sigma_0 = 1$ MPa).
For that purpose, the present author assumed that the interfacial crack behaves similarly to the center crack in adhesive layer constrained between two rigid substrates. By doing so, the interfacial toughness, $K_c$ can be in the simplest way expressed as follows:

$$K_c \approx \sigma_c \sqrt{\pi a} \cdot F \left( \frac{a}{W} \right) \approx \sigma_c \sqrt{\frac{a}{2}}$$  \hspace{1cm} (4)

Interfacial toughness, $K_c$ against bond thickness, $t$, is shown in Fig. 42. Obviously, as seen in this plots, $K_c$ values are almost constant and vary only slightly through the range of bond thickness considered. Thus, it can be concluded that, at least in the adhesive joints configuration considered in this study, $K_c$ is preferable in assessing the fracture toughness of adhesive joints which fractured adhesively.

![Fig. 42 Interface toughness, $K_c$ against bond thickness.](image-url)
4.5 Conclusions

The effect of bond thickness upon the strength and fracture toughness of epoxy adhesively bonded butt joint of dissimilar adherends was investigated. The stress distributions at the interface corner of butt adhesive joint were analyzed by FE analysis.

1) From FE analysis results, it is found that the interface corner of butt adhesive joint which has higher stress-\( y \) in order is SUS304/epoxy of dissimilar joint, SUS304/epoxy of similar joint, ALYH75/epoxy of similar joint and ALYH75/epoxy of dissimilar joint.

2) Experimental results show that the strength of butt adhesive joint without crack decreased with increasing bond thickness.

3) In the present experiments, interfacial crack in butt adhesive joint propagates in either two directions, that is, along the interface (i.e. interfacial failure) or deviated into adhesive layer (i.e. cohesive failure).

4) For adhesive joints with interfacial crack, in the case of cohesive failure, the evaluated fracture toughness, \( J_{ic} \) is independent of bond thickness. In contrast, in the case of interfacial failure, \( J_{ic} \) of both adhesive joints with interfacial crack shows some dependency upon bond thickness.

5) However, when the interfacial crack is assumed to behave similar to the center crack in adhesive layer constrained between two rigid substrates, \( K_{ic} \) parameter can be used to assess the fracture toughness of adhesive joints with interface failure.
Chapter 5  Strength and fracture characteristics of scarf adhesive joint

Abstract

In this chapter, strength of epoxy adhesively bonded scarf joints of dissimilar metallic adherends, namely SUS304 stainless steel and YH75 aluminium alloy is examined on several scarf angles and various bond thicknesses under uniaxial tensile loading. Scarf angle, $\theta = 45^\circ$, $60^\circ$ and $75^\circ$ are employed. The bond thickness, $t$ between dissimilar adherends is controlled to be ranged between 0.1 mm and 1.2 mm. Finite element (FE) analysis is also executed to investigate the stress distributions in the adhesive layer of scarf joints by ANSYS 11 code. As the results, the apparent Young's modulus of adhesive layer in scarf joints is found to be 1.5 ~ 5 times higher than those of bulk epoxy adhesive, which has been obtained from tensile tests. Though the measured stress multiaxiality of scarf joints proportionally increases as the scarf angle increases, the results do not agree with the theoretical values. From analytical solutions, stress singularity exists most pronouncedly at the SUS304/epoxy interface corner of joints having $45^\circ$ to $75^\circ$ scarf angle. The failure surface observations confirm that the failure has always initiated at this apex. This is also in agreement with stress-$y$ distribution obtained within FE analysis. The strength of scarf joints increases as the bond thickness decreases. Besides, for scarf joints with an interfacial crack, the fracture toughness, $J_c$ values are independent of bond thickness and less sensitive to adherends. Moreover, $J_c$ increases as mode mixity increases.
5.1 Introduction

Mechanical behavior, strength and fracture toughness of adhesive joints depend extremely on stress states and fracture resistance properties of the adhesive layer. Since adhesive exhibits stronger load-bearing performance in shear rather than in tensile, scarf joint is more preferable to butt joint. Indeed, scarf joint is somewhere between butt and lap joint. The combination ratio of tensile and shear loading in scarf joint can be varied with the inclination of the scarf angle. At optimal scarf angle of 52.47°, singular stress at interface corners vanishes so that a completely uniform stress distribution in adhesive layer can be obtained [59]. In scarf joint, the loading is kept in line with the joint and their design is simple so that it requires no extensive machining. Moreover, scarf joint has higher static strength and efficiency in comparison to other generic joint types (e.g. step lap joint, double lap joint and single lap joint). Unfortunately, until present, there is no standard test method designated for specifically testing scarf joints.

In a noteworthy study, Adams and Coppendale [60] reported that in the case of ductile epoxy adhesive, the stress triaxiality state causes not only to an increase in apparent adhesive layer modulus but also an increase in the strength of butt joint. On the other hand, the existence of stress concentration reduces the failure stress of butt joint bonded with brittle epoxy adhesive. Hence, two important factors which become crucial in evaluating the joints strength are the multiaxial stress conditions in the adhesive layer and the stress concentration at the vicinity of interface corner. Because of these two factors, strength and failure criteria of bulk adhesive can not be applied directly to estimate the failure stress of
adhesive joints. Therefore, many researchers have investigated these features by adopting scarf joints with various scarf angles [50, 61, 62].

Investigations on tensile and fatigue strength of scarf joints have been conducted and the matter is reasonably well understood. Most of these studies employed either similar engineering alloys or composites as adherends. Qian and Akisanya [11] examined the effects of cure temperature on the tensile strength of scarf joints between aluminium adherend and epoxy resins. They reported from their study that the bond thickness, cure temperature and scarf angle has strong influence upon the measured tensile strengths. Imanaka et al. [50] studied the fracture and yield behaviour of scarf joint comprised of SS400 low carbon steel with three kinds of epoxy-based adhesives. Kumar et al. [63] have investigated the strength and failure for adhesively bonded scarf joints of aerospace CFRP composite with small scarf angles (i.e. scarf angle ranges from 0° to 5°) in uniaxial tension both experimentally and numerically. An investigation by Wang [64] on two kinds of adhesives reported the influence of stress distribution on fatigue strength of 2024-T3 aluminium-alloy scarf joints. It is worth noting that some researchers have studied the tensile strength of scarf joints consisting of a combination of metals and composites [65, 66]. However, there is only limited work can be found which related to scarf joint of dissimilar metallic adherends.

Recently, He et al. have analyzed the 2D and 3D stress analysis of scarf joints with identical and dissimilar adherends subjected to static tensile loadings [2, 67]. From the FEM calculations, they reported the effects of scarf angle, adhesive Young’s modulus and bond thickness on the interface stress distributions. They mentioned that the singular stress
at the interface corner decreases as the adhesive Young’s modulus increases and as the adhesive thickness decreases. In both reports they also estimated numerically the strength of scarf joints by using the maximum principal strain criteria. The estimated joint strengths were in fairly good agreement with the experimental results and the rupture stress was maximal when the scarf angle was around 60º in their scarf joints.

Wheeler [68] has established a more viable and practical method to test scarf joints. He used the Fracture Mechanics Analysis (FMA) methodologies, in particular the Energy Release Rate (ERR) in FE analysis to predict the effects of bond thickness, scarf angle and material discontinuities (i.e. introduced crack) upon the joint strength. The calculated ERR values also provide an effective means to predict the location of crack initiation or propagation. From the experiment, the joint strength is typically increases as bond thickness decreases and when the scarf angle increases from 0º to 90º. Bascom [5, 61, 69] and Wang [5] are amongst others who also adopted FM approaches to study mixed mode loading condition related to scarf joints.

The objectives of this study are twofold. First is to determine the relationship between the bond thickness and in situ mechanical properties of brittle epoxy adhesive in the scarf joints since there are very limited sources in the literature regarding this relationship. Second is to predict the strength of scarf joint with an appropriate failure criterion regardless of their scarf angle. Thus, in this study, failure test of epoxy adhesively-bonded scarf joints of dissimilar adherends was conducted under a remote tension load on several scarf angles and various adhesive bond thicknesses. The effect of joint geometry (i.e. bond thickness and scarf angle) upon the effective mechanical properties and strength
of scarf joints will be presented and qualitatively discussed. In addition, the applicability of conventional failure criteria to the prediction of scarf joint strength is also addressed.

5.2 Experimental procedures

To examine the strength and fracture toughness of epoxy adhesively bonded joint of dissimilar adherends under mixed mode loading, scarf adhesive joint specimens were fabricated. The scarf angle, \( \theta \) of 45°, 60° and 75° were chosen. The geometry and dimensions of the specimen are shown in Fig. 43. The adherends were consisted of SUS304 stainless steel and YH75 aluminium alloy. YH75 is the trade name of aluminium alloy which is identical to A7075P-T651 aluminium alloy in terms of mechanical properties according to JIS H 4000:2006 specification [56]. Epoxy adhesive used and its preparation was already explained in Chapter 3, refer to Sec. 3.1.1. The mechanical properties of materials are tabulated in Table 9 where, \( E \), \( \sigma_y \) and \( \nu \) are Young's modulus, 0.2% proof stress and Poisson's ratio, respectively.

Bonding surfaces were uniformly polished with # 2000 waterproof abrasive paper and afterward degreased with acetone. Adhesive and its preparation was already explained in Chapter 3, refer to Sec. 3.1.1. Adhesive bond thickness, \( t \) inside an adhesive joint was controlled by using a developed bonding fixture (see Fig. 44) and varied from 0.1 mm to 1.2 mm. Also, for specimens with interfacial crack, an interfacial crack which originated from an interface corner was inserted to represent a flaw at adhesive joints interface. This pre-crack was introduced by pasting a strip of 0.05 mm thick Teflon tape on the edge of adherend surface prior to bonding. The \( a/W \) was fixed to 1/8, where \( a \) and \( W \) were the pre-
crack length and the width of the specimen, respectively. All specimens were cured at R. T. over than 24 hours.

After specimens were totally cured, the excessive adhesive was removed by a portable grinder and a sharp knife. Fig. 45 shows examples of photos of ground specimen edges. Obviously, fairly sharp edges were realized as can be seen from this figure. The actual bond thickness, $t$, was then measured by a digital microscope. After that, four strain gages of 5 mm gage length (KFEL-5-120-C1L1M2R from Kyowa Electronic Instruments Co., Ltd.) were mounted on bonding line; two were perpendicular to the bonding line (i.e. front and back sides of specimen) and the other two in the longitudinal direction (i.e. left and right sides of specimen).

Tensile fracture tests of scarf adhesive joint specimens were carried out with a universal tensile test machine (INSTRON 4206), as shown in Fig. 46. All tests were conducted at R. T. with the crosshead displacement speed held constant at 0.5 mm/min.

Fig. 43 Geometry and dimensions of tensile scarf adhesive joint specimen
Table 9 Mechanical properties of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy adhesive</td>
<td>3.4</td>
<td>34.76 [1.67]</td>
<td>0.396</td>
</tr>
<tr>
<td>SUS304*</td>
<td>206</td>
<td>307.8 [6.02]</td>
<td>0.3</td>
</tr>
<tr>
<td>YH75 (Al-alloy)*</td>
<td>71</td>
<td>559.0 [7.82]</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* data taken from manufacturer’s catalogue.

[ ] denotes the value of standard deviation.

Fig. 44 Scarf adhesive joint specimen is fabricated by using a developed bonding fixture.
Fig. 45 Grounded scarf adhesive joint specimens.

Fig. 46 Scarf adhesive joint specimen under tensile fracture testing.
5.3 Numerical modelling

Fig. 47 shows the typical model for the stress analysis of a scarf adhesive joint. Eight nodes isoparametric elements are used in the analysis. The whole model of the joint is analyzed with the length is 80 mm and width is 40 mm. The bond thickness is 1.0 mm. The boundary constraints and loading conditions imposed are also shown in this figure. The tensile stress of 1 MPa is applied in the y-direction on all nodal points at both ends of adherends. As for the prescribed boundary conditions, the nodal points at $x = 0$ and $y = \pm 40$ are fixed in the x-direction. The number of nodes and elements employed for each model incorporating different scarf angle are summarized in Table 10. Since the stress singularity occurs near the interface corners, the elements near this region are divided into finer meshes (i.e. using nearly square shaped elements) such that this effect can be accurately modeled. The finest mesh size is listed in Table 10. The analysis is performed within elastic deformation.

Table 10 Description of FE model used for stress analysis of scarf adhesive joint.

<table>
<thead>
<tr>
<th>Bond thickness, $t$ (mm)</th>
<th>Scarf angle, $\theta$</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>45º</td>
<td>Full</td>
<td>5553</td>
<td>2016</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td>60º</td>
<td>Full</td>
<td>4170</td>
<td>1519</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td>75º</td>
<td>Full</td>
<td>3711</td>
<td>1356</td>
<td>0.1</td>
</tr>
</tbody>
</table>
(a) 45°

(b) 60°
Fig. 47 FE model meshes for scarf adhesive joint.

Fig. 48 shows the typical model for the stress analysis of a scarf adhesive joint with an interfacial crack. Eight nodes isoparametric elements are used in the analysis. The whole model of the joint is analyzed with the length is 80 mm and width is 40 mm. The length of interfacial crack is 5 mm. The boundary constraints and loading conditions imposed are also shown in this figure. The tensile stress of 1 MPa is applied in the y-direction on all nodal points at both ends of adherends. The prescribed boundary conditions are as follows: the nodal points at x = 0 and y = ±40 are fixed in the x-direction. The number of nodes and elements employed for each model incorporating different bond thickness and scarf angle are summarized in Table 11. Since the stress singularity occurs near the interface corners, the elements near this region are divided into finer meshes (i.e. using nearly square shaped...
elements) such that this effect can be accurately modeled. The finest mesh size is listed in Table 11. The analysis is performed within elastic deformation.

Table 11 Description of FE model used for stress analysis of scarf adhesive joint with an interfacial crack.

<table>
<thead>
<tr>
<th>Bond thickness, t (mm)</th>
<th>Scarf angle, θ</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>45º</td>
<td>Full</td>
<td>4448</td>
<td>1623</td>
<td>0.1</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>Full</td>
<td>6799</td>
<td>2402</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>Full</td>
<td>9179</td>
<td>3190</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>60º</td>
<td>Full</td>
<td>3862</td>
<td>1397</td>
<td>0.1</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>Full</td>
<td>5142</td>
<td>1821</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>Full</td>
<td>6426</td>
<td>2247</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>75º</td>
<td>Full</td>
<td>3231</td>
<td>1179</td>
<td>0.1</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>Full</td>
<td>4386</td>
<td>1560</td>
<td>0.1</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>Full</td>
<td>5576</td>
<td>1956</td>
<td>0.1</td>
</tr>
</tbody>
</table>
(a) 45°

(b) 60°
5.4 Results and discussion

5.4.1 Non-crack scarf adhesive joint

5.4.1.1 Numerical results

The stress distributions in scarf adhesive joint with SUS304/ALYH75 dissimilar adherends are analyzed in FE. For simplicity, only the result of scarf adhesive joint of 1.0 mm bond thickness is given in Fig. 49. It can be noticed that at SUS304/epoxy interface, when \( r \) approaches zero, stress-\( y \) elevates to infinity. Vice versa, at ALYH75/epoxy interface, stress-\( y \) elevates to infinity when \( r \) approaches 40 mm. However, stress-\( y \) at SUS304/epoxy interface has the highest magnitude if compared to other stresses.
Nevertheless, stress-y approaches to the applied stress (i.e. 1 MPa) when \( t \) is far from edge which is greater than 2.5 mm. Besides, stresses are less concentrates at the center of adhesive layer. Therefore, for the purpose of strength evaluation, the stress of practical interest is solely stress-y. Henceforward, the stress-y will be considered.

Stress-y distributions in scarf adhesive joint of dissimilar adherends with three different scarf angles are shown in Fig. 50. As seen, stress-y distributions at interface corners of scarf adhesive joint changes significantly with increasing scarf angle. The scarf adhesive joint having 75° scarf angle shows the highest stress-y at right SUS304/epoxy and left ALYH75/epoxy interface corners.
Fig. 49 Stress-x,-y,-xy distributions in 45° scarf adhesive joint bonded with dissimilar adherends (at interface lines, adhesive center).
Fig. 50 Comparison of stress-\(y\) between various scarf adhesive joints bonded with dissimilar adherends.
5.4.1.2 Experimental results

If scarf joints are submitted to the axial tensile load, stresses and strains inside the adhesive layer of scarf joints are relatively uniform except for the small region at the vicinity of interface corner. In this subsection, the discussion will be restricted only to the stresses and strains in the central region of adhesive layer in scarf joints. Fig. 51 shows the coordinate system which is typically used to evaluate stresses and strains in the central region of adhesive layer in scarf joints [50]. Theoretically, for scarf joints loaded axially with average stress, $\sigma_0$, normal and shear stresses are given by:

$$\sigma_n = \sigma_0 \sin^2 \theta$$  \hspace{1cm} (5)

and

$$\tau_{sn} = \sigma_0 \sin \theta \cos \theta$$  \hspace{1cm} (6)

, respectively. Other stresses acting in s- and z-direction are identical:

$$\sigma_z = \sigma_z = v_s \sigma_n / (1 - v_s)$$  \hspace{1cm} (7)

According to these stresses, maximum and minimum principal stresses can be derived as:

$$\sigma_{1,3} = \left[ \sigma_z + \sigma_n \pm \sqrt{[\sigma_z - \sigma_n]^2 + 4 \tau_{sn}^2} \right] / 2$$   \hspace{1cm} (8)

and median principal stress is obtained as follows:

$$\sigma_2 = \sigma_3 = \sigma_z = v_s \sigma_n / (1 - v_s)$$  \hspace{1cm} (9)

In addition, Mises equivalent stress is given by:

$$\sigma_{eq} = \sqrt{(\sigma_1 + \sigma_2)(\nu^2 - \nu + 1) - 3\sigma_1 \sigma_2}$$  \hspace{1cm} (10)

and hydrostatic stress is given by:

$$\sigma_{hyd} = (\sigma_1 + \sigma_2 + \sigma_3) / 3$$  \hspace{1cm} (11)
Fig. 51 Coordinate system of scarf joint

The representatives of load-displacement plots from tensile test of scarf joints are shown in Fig. 52 (a) and (b). The load-displacement curves exhibit linear behavior until they reach the maximum load. After the maximum load, the failure occurred suddenly. These features are comparable to the brittle nature of the adhesive itself. It is also clearly seen that the maximum load of scarf joints increases with the decreasing scarf angle and bond thickness. Fig. 53 (a) below shows an example of stress-strain data obtained from 45° scarf joint specimen in our experiment. As can be seen in this figure, there is difference between the two values. However, the difference between the two values always exist since the specimen is loaded by pins where a slight misalignment in the attachment of specimen to the pin will results in the eccentricity of loading. Nevertheless, the stress-strain relation of each gage is almost linear except for some cases where a small flexural was recorded at the early stage of loading. Therefore, if average of two values of opposite gages is taken, the data can be corrected then one may assume that the results can be considered acceptable. Fig. 53 (b) shows an example of stress-strain relation obtained after averaging the two values of opposite gages. It can be seen in this figure that a linear stress-strain relation is
obtained for each averaged data of each specimen. This is also true for all specimens tested.

See Fig. 43 for the positioning of strain gages.

![Graphs showing load-displacement plots of scarf joint specimens](image)

Fig. 52 Load-displacement plots of scarf joint specimens having (a) 0.1 mm bond thickness and (b) 1.0 mm bond thickness.
Fig. 53 Stress-strain relations of 45° scarf joint specimen having 0.1 mm and 1.0 mm bond thicknesses. (a) Strain outputs measured from four gages, (b) After averaging the measurements of the opposite sides of the specimen.

The apparent Young’s modulus of adhesive layer, \( E_{\text{adh}} \), can be measured by dividing the normal stress, \( \sigma_n \) of scarf joints by the apparent strain of adhesive layer, \( \varepsilon_{\text{adh}}' \). Here, a correction is needed to deduce \( \varepsilon_{\text{adh}}' \) from the strain output obtained by strain gage, \( \varepsilon_g \). This can be fulfilled by calculating:

\[
\varepsilon_{\text{adh}}' = \frac{E_t \varepsilon_g}{L} \left[ \frac{1}{2} (L-t) \frac{\sigma}{E_t} - \frac{1}{2} (L-t) \frac{\sigma}{E_y} \right]
\]

where, \( L \) is the length of strain gage and subscripts 1 and 2 are referred to the SUS304 and YH75, respectively. It has been established for relatively brittle adhesive, that \( E_{\text{adh}} \) is related to the Young’s modulus of bulk epoxy adhesive, \( E_{\text{adh}} \) by [4]

\[
E_{\text{adh}}' = \left[ \frac{1 - v_{\text{adh}}}{(1 + v_{\text{adh}})(1 - 2v_{\text{adh}})} \right] E_{\text{adh}}
\]
Thus, the effect of bond thickness on apparent Young’s modulus of adhesive layer, $E_{\text{adh}}$ is shown in Fig. 54. It is noted, by substituting Poisson’s ratio of bulk epoxy adhesive, $\nu_{\text{adh}}$ into Eq. (13), that $E_{\text{adh}}$ is approximately 2 times higher than $E_{\text{adh}}$ and this is also plotted in Fig. 54, together with the $E_{\text{adh}}$. Clearly, $E_{\text{adh}}$ is higher than $E_{\text{adh}}$ and is found to be affected by the bond thickness of scarf joints wherein $E_{\text{adh}}$ is gradually increased when the bond thickness decreases. The apparent Young’s modulus of adhesive layer in scarf joints is found to be 1.5 ~ 5 times higher than those of bulk epoxy adhesive, which has been obtained from tensile tests. This also suggests that the apparent Poisson’s ratio of adhesive layer, $\nu'_{\text{adh}}$ is not always equals to $\nu_{\text{adh}}$ and changes with the bond thickness. By substituting $\nu_{\text{adh}}$ in Eq. (13) with $\nu'_{\text{adh}}$, the effect of bond thickness on apparent Poisson’s ratio of adhesive layer, $\nu'_{\text{adh}}$ can be obtained as shown in Fig. 55. This figure confirms that for thick adhesive bond (i.e. $t > 0.4$ mm), $\nu'_{\text{adh}}$ is lower than $\nu_{\text{adh}}$ and for thin adhesive bond (i.e. $t < 0.4$ mm), $\nu'_{\text{adh}}$ is greater than $\nu_{\text{adh}}$: $\nu'_{\text{adh}}$ varies across the bond thickness.
Fig. 54 Effect of bond thickness on apparent Young's modulus of adhesive layer.

Fig. 55 Effect of bond thickness on apparent Poisson's ratio of adhesive layer.
Amongst others, the maximum principal stress and Mises equivalent stress are the most widely accepted as the appropriate failure criteria for scarf joints [2, 51, 60]. The former is for scarf joints of 45° to 90° while the latter is used for scarf joints with 0° to 45°. Fig. 56 shows the effect of scarf angle on the failure criteria of scarf joints. Clearly, for scarf joints with the scarf angle, $\theta$ larger than 45°, maximum principal stress is the dominant failure criterion. Though, for scarf joints with the scarf angle, $\theta$ smaller than 45°, Mises equivalent stress becomes the dominant failure criterion. However, the bond thickness effect upon these failure criteria is still need to be elucidated.

![Fig. 56 Effect of scarf angle on failure criteria.](image)

The comparison between maximum principal stress and Mises equivalent stress obtained from experimental results is shown in Fig. 57. Here, the ratio of each criterion to the failure stress, $\sigma_c$ is given. Obviously, the scatter of data obtained by Mises equivalent

103
stress is greater than the maximum principal stress. Therefore, maximum principal stress is preferable than Mises equivalent stress and could be used to determine the failure of scarf joints with various bond thickness. However, attention should be paid when applying the maximum principal stress criteria because there is yet a tendency where $\sigma_1$ reduces with the increasing bond thickness as shown in Fig. 58 (a). Fig. 58 (b) again supports the inapplicability of Mises equivalent stress criterion where the scatter is comparatively worst.

Fig. 57 Comparison between two failure criteria.
Recently, Imanaka et al. [50] have evaluated the yield and failure criteria of scarf joints with 0.3 mm thickness adhesive layer based on stress multiaxiality parameter. In their study, they successfully estimated the endurance limits of various scarf joints with three different types of adhesive: unmodified, Thiokol-modified and rubber-modified adhesive. Since they only considered a constant adhesive thickness, the straightforward applicability of this approach to the present investigation is still in doubt. Hereafter, the author will apply this approach and towards the end, verify its validity.

Principal stresses acting inside the adhesive layer of scarf joints can be measured experimentally from the strain gages. For this purpose, the author employed the Rosette analysis to the measured strain values from the output of four strain gages. It is noted that, since strain in s-direction is negligible, only strains in n- and y-directions are taken into
account. The average of two strain gages of opposite sides was taken. From strain values acting on both n- and y-directions, one can obtain the maximum and minimum principal strains as:

\[ \varepsilon_{i,3} = \frac{1}{2} \varepsilon_i + \varepsilon_y \pm \sqrt{\varepsilon_y^2 + (\varepsilon_y - 2\varepsilon_i)^2} \]

Thus, from Eq. (14), the principal stresses can be derived, respectively as what follows:

Maximum principal stress

\[ \sigma_1 = \frac{E'}{1 - \nu^2} (\varepsilon_i + \nu' \varepsilon_y) \quad (15) \]

Median principal stress

\[ \sigma_2 = \sigma_1 = \frac{\nu' E'}{1 - \nu^2} \varepsilon_y \quad (16) \]

Minimum principal stress

\[ \sigma_3 = \frac{E'}{1 - \nu^2} (\varepsilon_i + \nu' \varepsilon_y) \quad (17) \]

where, for plane strain condition, \( E' \) and \( \nu' \) are given, respectively by:

\[ E' = \frac{E'_{\text{adh}}}{1 - \nu^2_{\text{adh}}} \quad (18) \]

\[ \nu' = \frac{\nu'_{\text{adh}}}{1 - \nu_{\text{adh}}} \quad (19) \]

Now, the stress multiaxiality failure criterion will be verified. In this regard, stress multiaxiality can be expressed by one parameter, that is the ratio of the principal stresses; either \( \sigma_3/\sigma_1 \) or \( \sigma_2/\sigma_1 \). Fig. 59 shows the relation between \( \sigma_3/\sigma_1 \) and bond thickness, \( t \). In this figure, one can confirm that the \( \sigma_3/\sigma_1 \) is almost constant irrespective of the scarf angle. This
suggests the $\sigma_3/\sigma_1$ criterion satisfies one of the material constant regulations which must be independent of bond thickness. Nevertheless, the experimental results should also be compared with the theoretical prediction to verify the applicability of this criterion.

The stress multiaxiality in the central region of adhesive layer in scarf joints of various angles is shown in Fig. 60. Here, the dash-dash lines are referred to the theoretical values obtained from Eq. (8) to Eq. (9). Obviously, for scarf joints considered (i.e. $\theta = 45^\circ$, $60^\circ$ and $75^\circ$) in this study, the stress states inside the adhesive layer are remarkably triaxial and the magnitude of tension principal stresses increases with the inclining scarf angle. However, it can be seen that the experimental results do not match with the theoretical values especially for $\theta = 45^\circ$ and $60^\circ$ scarf joints tested. Hence, $\sigma_3/\sigma_1$ criterion also is not applicable to the results of the present study. The reason for this discrepancy will be explained in the subsequent section in terms of the failure behavior.

![Fig. 59 Stress multiaxiality parameter against bond thickness.](image-url)
Fig. 60 Stress multiaxiality of epoxy adhesive layer in scarf joints.

From failure surface examinations, the brittle failure was observed in all scarf joints specimens tested as shown in Fig. 61. Noteworthy, the bulk epoxy adhesive employed in this study also shows a very brittle manner when failed [57]. From Fig. 61, one can distinguish the failure path of adhesive layer in scarf joints as two types, as schematically shown in Fig. 62. It is seen that, in all cases, the failure initiates at the left SUS304/epoxy interface corner and propagates through the upper interface boundary up to some distance. After that, the crack deviates into the adhesive layer and immediately reaches the adjacent ALYH75/epoxy interface. The difference between path A and B is that for path A, the distance of initial interface boundary propagation is shorter than those in path B. Type of path for each specimen is summarized in Table 12. Moreover, it is noted that, path A is typically observed in the scarf joints of 45° while for scarf joints of 75° is path B.
<table>
<thead>
<tr>
<th>Scarf angle, $\theta$</th>
<th>$t = 0.1 \text{ mm} \sim 0.5 \text{ mm}$ (upper to lower)</th>
<th>$t = 0.6 \text{ mm} \sim 1.0 \text{ mm}$ (upper to lower)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>60°</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>75°</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Note: SUS304 plate is placed on top of AL YH75 plate.

Fig. 61 Failure surface of adhesive layer in scarf joints.
Fig. 62 Schematic of failure paths of adhesive layer in scarf joints.
Table 12 Types of failure path.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Target bond thickness, ( d ) (mm)</th>
<th>( 45^\circ )</th>
<th>( 60^\circ )</th>
<th>( 75^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>A</td>
<td>A</td>
<td>A</td>
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<tr>
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<td>0.2</td>
<td>A</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>A</td>
<td>A</td>
<td>B</td>
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<tr>
<td>4</td>
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<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
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<td>B</td>
<td>A</td>
<td>A</td>
</tr>
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<td>6</td>
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<td>B</td>
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<td>A</td>
<td>B</td>
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<td>8</td>
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<td>B</td>
<td>B</td>
<td>B</td>
</tr>
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<td>0.9</td>
<td>A</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>
These observations can be explained with the help of FE stress analysis. For instance, the stress-y contour for scarf joint having 45° scarf angle is shown in Fig. 63. From this FE stress-y contour, it is revealed that the highest stress-y exists at the left interface corner of SUS304/epoxy. It is also noticed that, at a distance ahead of the SUS304/epoxy interface line, the stress concentration is gradually vanished while at the ALYH75/epoxy interface it is proportionally increased, thus the failure path deviates from SUS304/epoxy interface to the opposite ALYH75/epoxy interface as observed in failure path. Nevertheless, there is no significant change in the failure load recorded between scarf joints failed with path A and path B. Thus, the difference between path A and path B is maybe related to the adhesive force and/or surface property which are up to now is still difficult to evaluate and less understood.

The most important finding in these failure surfaces and path trajectories examination as well as stress-y distribution in the FE results is that the failure has great potential to be initiated at an identical spot which is the interface corner of SUS304/epoxy. This is probably why neither the maximum principal stress criterion nor \( \sigma_3/\sigma_1 \) criterion can precisely estimate the strength and failure behavior of scarf joints; these failure criteria will be applicable only if failure occurs within the adhesive layer (i.e. cohesive failure). Thus, one need another criterion which best estimates the relationship between bond thickness and failure stress of scarf joints bonded with brittle epoxy adhesive.
Fig. 63 Stress-y contour in scarf joints having 45° scarf angle.
5.4.2 Scarf adhesive joint with an interfacial crack

5.4.2.1 Jc calibration

To evaluate the fracture toughness of scarf adhesive joint with an interface crack, J integral calculation in FE is applied. However, since the actual bond thickness in a specimen might be varied from the targeted value, a calibration of J value is needed beforehand. Fig. 64 shows the results of J calibration obtained from FE analysis. It is noted that this FE analysis was conducted with the applied stress of 1 MPa.
Fig. 64 J calibration of scarf adhesive joint in FE analysis.
5.4.2.2 Experimental results

The fracture toughness of scarf joints with an interfacial crack is now discussed. Fracture toughness, $J_c$ of scarf joints with an interfacial crack corresponding to fracture load was evaluated by a path-independent integral, $J$ integral calculation in FE analysis. The stress-strain curve as shown in Fig. 18 was extrapolated from the actual uniaxial tensile test data to constitute the adhesive layer. The adherends were assumed to remain elastic materials and the mechanical properties data were taken from Table 6.

Fig. 65 shows the fracture surface of scarf adhesive joints. Fig. 66 (a) shows the results of fracture toughness, $J_c$ versus percentage of interface fracture (abbreviated as IF hereafter) for the scarf dissimilar joint having interfacial crack length of 5 mm. Note that the IF is the area of interface fracture over the entire bonding area. In the case of SEA, as shown in Fig. 66 (a), for 45º scarf joint, $J_c$ increases when IF is decreased. Meanwhile, for AES case, the $J_c$ value is apparently constant for IF ranges between 40-90% which is between 8 ~ 22 (N/m), as can be seen in Fig. 66 (b). Obviously, $J_c$ for 45º scarf joint is higher than others. In contrast to the SEA case, most joints of AES fractured entirely at the joint interface. It can be concluded that from all specimens, $J_c$ depends upon fracture morphology.
<table>
<thead>
<tr>
<th>Degree</th>
<th>$t = 0.2\text{mm} \sim 1.0\text{mm}$ (Series 1)</th>
<th>$t = 0.2\text{mm} \sim 1.0\text{mm}$ (Series 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>60°</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>75°</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Note: SUS304 plate is placed on top of AL YH75 plate.

Fig. 65 Fracture surface of scarf adhesive joint with an interface crack.
Fig. 66 Fracture toughness, $J_c$ against fraction of interface fracture.
The relationship between fracture toughness, $J_c$ and bond thickness, $t$ is shown in Fig. 67 (a) and (b). Here, SEA and AES represent the scarf joint specimens with an interfacial crack at the SUS304/epoxy interface and ALYH75/epoxy interface, respectively. From Fig. 67 (a) and (b), despite small variance in data, $J_c$ values for scarf joints having scarf angle of 45°, 60° and 75° are independent of bond thickness. This suggests that interface crack-tip inside scarf joints of identical scarf angle experiences the same level of plastic deformation irrespective of the bond thickness. Since interface crack is obviously longer than bond thickness, no constraint effect can be observed. Therefore, testing of scarf joints with short interface crack (i.e. $a < t$) may be needed to clarify this feature, but it is realized that this will be a difficult task.

It is interesting to note that $J_c$ values of SEA and AES scarf joints at certain scarf angle are almost identical: i.e. $J_c$ values are less sensitive to adherend material. This is consistent with the experimental results obtained by Yan et al. [9] using double-cantilever beam (DCB) joints with 7075 aluminium and steel adherends. This indicates that the surface preparation of adherends was adequate. Nonetheless, Choupani [10] mentioned that whenever adhesive joints failed at the interface, the surface preparation of adherends should be considered inadequate. According to his findings using modified Arcan joints bonded with a high strength rubber modified film adhesive, fracture surfaces examination of aluminium adherend specimens revealed that crack growth was clearly occurred within the adhesive, resulting in relatively high toughness values compared to the steel systems. In the present study, all of AES scarf joints failed at the interface. However, two of SEA specimens having 45° and 60° scarf angle failed cohesively and the corresponding $J_c$
values are relatively high. It should be inferred that the quality of the bonding surface might influence the adhesive joint toughness.

It is also noticed from Fig. 67 (a) and (b), that $J_c$ values increase when mode mixity increases. That is, $J_c$ values of 45° scarf joints are higher than 60° and 75° scarf joints about a factor of two. With increasing scarf angle, the amount of mode II loading (i.e. shear loading) in scarf joints also increases. The consequence is an increment in the total toughness, $J_c$ (viz. $J_c = J_I + J_{II}$). Wang [11] reported a same trend from a series of investigations by some researchers using brittle epoxy adhesive joint. In fact, the mode II component has been also reported to be 2~10 times higher than the mode I component. Further evaluation of present data in terms of $J_I$ and $J_{II}$ is needed.

Fig. 67 Fracture toughness against bond thickness. (a) SEA and (b) AES.
5.5 Conclusions

In the present work, the author has investigated both experimentally and analytically as well as numerically the effects of bond thickness and scarf angle upon the strength of scarf joints of dissimilar adherends bonded with a brittle epoxy adhesive. The following conclusions can be drawn:

(1) The in situ mechanical properties of epoxy adhesive layer in scarf joints are found to be different from those of bulk epoxy adhesive. It is found that the apparent Young's modulus and apparent Poisson's ratio of epoxy adhesive layer are affected by the bond thickness.

(2) Three existing failure criteria (i.e. the maximum principal stress, Mises equivalent stress and stress multiaxiality) have been employed to predict the relationship between bond thickness and joint strength. However, the results are not very satisfactory.

(3) From analytical solutions, stress singularity, $\lambda$ exists most pronouncedly at SUS304/epoxy interface corner of joint having 45° to 75° scarf angle and this is in accordance with the FE analysis results and is also confirmed by failure surface observations wherein the failure has always initiated at this point.

(4) The strength prediction of brittle epoxy adhesively bonded scarf joints based on the interface corner toughness, $H_c$ parameter is in good agreement with the experimentally measured data.
Chapter 6  Strength and fracture characteristics of shear adhesive joint

Abstract

In this chapter, the effect of bond thickness upon the shear strength of epoxy adhesively bonded joints with dissimilar adherends is addressed. The bond thickness, \( t \) between the adherends is controlled to be ranged from 0.1 mm to 1.2 mm. Finite element analyses are also executed by ANSYS 11 code to investigate the stress distributions in adhesive layer of adhesive joints. As a result, shear strength of adhesive joint reduces with increasing bond thickness. The strength of shear adhesive joint is also dependent on elastic modulus of adherend. Moreover, the failure of dissimilar adherends bonded shear joint has been initiated at a location with critical stress-\( y \) which is the interface corner of ALYH75/epoxy. It is interesting to note that in the case of shear adhesive joint with an interface crack, the fracture occurred also at ALYH75/epoxy interface even in SEA specimens. Fracture toughness, \( J_c \) of AES is close to those of SES and demonstrates strong dependency upon bond thickness. Furthermore, the interface crack in SEA specimen has relatively large fracture resistance if compared to those in AES specimen. Finally, \( K_c \) fracture criterion is found to be appropriate for shear adhesive joints which fracture adhesively.
6.1 Introduction

The single lap joint (SLJ) is one of the most common type of joint in practice because of its simple geometry and ease of manufacture. Due to its resemblance to many “real-world” joint designs, the mechanical testing of SLJ has been exhaustively conducted. Therefore, the SLJ loaded in tension has been well studied in the literature, both experimentally and theoretically. But this does not necessarily mean that it is easy to analyze the stresses present in that joint because one should consider the existence of eccentricity of loading path, which means that there is bending deformation and stress concentrations arise from the differential straining of the adherends. Thus, the adhesive will experience tensile stresses (peel) at the end of the joint as well as shear. The standard mechanical test of SLJ which is fully documented in ASTM D 1002-72 will give the data of 'apparent' shear strength. This standard also proposes a very simple design rule to guarantee that the adherends do not yield. While this standard joint test is quite popular, it does not enable the mechanical properties of the adhesive itself to be deduced because the adhesive is subjected to a complicated state of stress. Therefore, another test configuration should be considered when determining the shear properties of adhesive.

There are few principal torsional shear tests and tensile shear tests available which yield both data for shear strength of joint and mechanical properties of adhesive. The former includes tests on bulk specimens, butt joints and the napkin ring test (ASTM E 229-70). The latter are the thick adherend shear test (TAST) and the butterfly test. In practice, the TAST (ASTM D 3983-91) is more popular due to its merits and has been widely used. However, the standard method recommends the use of a special extensometer attached to
the specimen that requires a very experienced technician and high costs of production. Another shortcoming is the extensometer measures both the displacements of the adhesive and adherend. Therefore, it is necessary to apply a correction for deformations in the adherends from the measured deformations to deduce the deformation of the adhesive only. da Silva et al. [70] have proposed an alternative methods to measure the thin adhesive shear displacement in the TAST. They reported that a conventional clip gauge can be used provided a correction factor obtained from finite element analysis (FEA) is applied.

A number of parameters have been considered in experimental investigations by various researchers to study their influence upon the strength and the durability of shear joint. These include the bond thickness, the type of surface treatment, overlap length and width, the yielding of the adherend, the plasticity of the adhesive, and added pressure. The optimum condition determined for experimental factors can improve the bonding technique and design of high strength joint. Also, these data provide bonding structure with appropriate design criterion and contribute to raise the productivity and reducing cost. However, all of these studies involve only single lap joints that have similar adherends. Other researchers have tried to analyze the single lap joint with dissimilar adherends. A paper by Fongsamootr and Dechwayukul [71] has illustrate a way for analyzing the stress distribution in generalized single lap joints of dissimilar adherends by using FEA-TALA (Thin Adhesive Layer Analysis) method. They analyzed this joint under variation of Young’s modulus ratio and the adherend thickness ratio between the upper and lower adherends to understand their effect on the interface stress distribution. Nevertheless, to the
best of present author's knowledge, no work has been reported in regard of experimental study of strength of single lap joint of dissimilar adherends.

Stresses distributions of SLJ can be analyzed by two approaches: closed form analyses (i.e. a simplified algebraic analytical solutions) or numerical analyses [41]. Classical closed form approaches are usually based on a continuum mechanics (shear lag) model or a beam on elastic foundation theory model. Besides, there are three major numerical analyses used for solving partial differential equations are boundary element method (BEM), finite element method (FEM) and finite difference method (FDM). The advantage of closed form analyses is that they are very suitable for preliminary joint design assessment. However, complex joint geometries are extremely difficult to simulate and very little has been done to incorporate failure criteria into these closed form analyses [44]. These are currently being done in numerical analyses especially in FE modelling. Such FE modeling has been shown to be capable of including also the effects of material discontinuities and plasticity (i.e. non-linearity). Chapter 5 in [41] describes many studies that deal with adhesive joints of complex geometry using the FE method. Prediction of strength and failure of single lap joint in context of FE method is comprehensively reviewed by Adams and Davies [25]. It is obvious that a suitable failure criterion for predicting the joint strength either by means of strength of material, fracture mechanics or continuum damage mechanics based approaches is often difficult to determine, therefore it still remains as a challenging issue.
6.2 Experimental procedures

To investigate the strength and fracture toughness of epoxy adhesively bonded joint of dissimilar adherends under shear loading, shear adhesive joint specimens were fabricated. The geometry and dimensions of the specimen are shown in Fig. 68. The adherends were consisted of SUS304 stainless steel and YH75 aluminium alloy. YH75 is the trade name of aluminium alloy which is identical to A7075P-T651 aluminium alloy in terms of mechanical properties according to JIS H 4000:2006 specification [56]. Epoxy adhesive used and its preparation have already been explained in Chapter 3, i.e. refer to Sec. 3.1.1. The mechanical properties of materials are tabulated in Table 13 where, $E$, $\sigma_y$ and $\nu$ are Young's modulus, 0.2% proof stress and Poisson's ratio, respectively.

Bonding surfaces were uniformly polished with # 2000 waterproof abrasive paper and afterward degreased with acetone. Adhesive bond thickness, $t$ inside an adhesive joint was controlled by using a developed bonding fixture (see Fig. 69) and varied from 0.1 mm to 1.2 mm. Also, for specimens with interfacial crack, an interfacial crack which originated from an interface corner was inserted to represent a flaw at adhesive joints interface. This pre-crack was introduced by pasting a strip of 0.05 mm thick Teflon tape on the edge of adherend surface prior to bonding. The $a/W$ was fixed to $1/8$, where $a$ and $W$ were the pre-crack length and the width of the specimen, respectively. All specimens were cured at R. T. over than 24 hours.

After specimens were totally cured, the excessive adhesive was removed by a portable grinder and a sharp knife. The actual bond thickness, $t$ was then measured by a digital microscope. Tensile shear fracture tests of shear adhesive joint specimens were
carried out with a universal tensile test machine (INSTRON 4206), as shown in Fig. 70. All
tests were conducted at R. T. with the crosshead displacement speed held constant at 0.5
mm/min.

Fig. 68 Geometry and dimensions of shear adhesive joint specimen.

Table 13 Mechanical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy adhesive</td>
<td>3.4</td>
<td>34.76 [1.67]</td>
<td>0.396</td>
</tr>
<tr>
<td>SUS304*</td>
<td>206</td>
<td>307.8 [6.02]</td>
<td>0.3</td>
</tr>
<tr>
<td>YH75 (Al-alloy)*</td>
<td>71</td>
<td>559.0 [7.82]</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* data taken from manufacturer’s catalogue.

[ ] denotes the value of standard deviation.
Fig. 69 Shear adhesive joint specimen is fabricated by using a developed bonding fixture.

Fig. 70 Shear adhesive joint specimen under tensile shear fracture testing.
6.3 Numerical modelling

The typical model for the stress analysis of a shear adhesive joint is shown in Fig. 71. The whole model of the joint is analyzed. The boundary constraints and loading conditions imposed are also shown in this figure. All nodes at the left end of the left adherend are fully constraint, which means that all degrees of freedoms are constrained at this end. The model is stress controlled which means that all nodes on the right end of the right adherend have a prescribed stress of 1 MPa in the x-direction. The number of nodes and elements employed for each model incorporating different bond thickness are summarized in Table 14. Since the stress singularity occurs near the interface corners, the elements near this region are divided into finer meshes (i.e. using nearly square shaped elements) such that this effect can be accurately modeled. The finest mesh size is listed in Table 14. The analysis is performed within elastic deformation.

Table 14 Description of FE model used for stress analysis of shear adhesive joint.

<table>
<thead>
<tr>
<th>Bond thickness, t (mm)</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Full</td>
<td>20843</td>
<td>8178</td>
<td>0.025</td>
</tr>
<tr>
<td>0.5</td>
<td>Full</td>
<td>18954</td>
<td>6915</td>
<td>0.05</td>
</tr>
<tr>
<td>1.0</td>
<td>Full</td>
<td>28096</td>
<td>9967</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Fig. 71 FE model meshes used for shear adhesive joint.

Fig. 72 shows the typical model for the stress analysis of a shear adhesive joint with an interfacial crack. Eight nodes isoparametric elements are used in the analysis. The whole model of the joint is analyzed. The length of interfacial crack is 5 mm. The boundary constraints and loading conditions imposed are also shown in this figure. The shear joint model is fully constrained at the left end and loaded (applied tensile stress) in the longitudinal x-direction. The number of nodes and elements employed for each model incorporating different bond thickness and scarf angle are summarized in Table 15. Since
the stress singularity occurs near the interface corners, the elements near this region are divided into finer meshes (i.e. using nearly square shaped elements) such that this effect can be accurately modeled. The finest mesh size is listed in Table 15. The analysis is performed within elastic deformation.

Table 15 Description of FE model used for stress analysis of shear adhesive joint with an interfacial crack.

<table>
<thead>
<tr>
<th>Bond thickness, t (mm)</th>
<th>Model type</th>
<th>Nodes</th>
<th>Elements</th>
<th>Finest mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Full</td>
<td>14952</td>
<td>5385</td>
<td>0.05</td>
</tr>
<tr>
<td>0.5</td>
<td>Full</td>
<td>21962</td>
<td>7715</td>
<td>0.05</td>
</tr>
<tr>
<td>1.0</td>
<td>Full</td>
<td>29331</td>
<td>10176</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Fig. 72 FE model meshes used for shear adhesive joint with an interfacial crack.
6.4 Results and discussion

6.4.1 Non-crack shear adhesive joint

6.4.1.1 Numerical results

Fig. 73 shows the stress-y, -x and -xy distributions which was obtained in FEM analysis of disimilar adherend bonded shear adhesive joint model. This distribution confirms that at ALYH75/epoxy interface corner, the stress-y is highly concentrates. Besides, it is also noted that in the centerline of adhesive in shear joint, the stresses are less concentrated. The comparison of stress-y distribution at the region of interface corner in dissimilar adherends bonded shear joint having three bond thicknesses is shown in Fig. 74. Clearly, as t becomes thicker, the concentration of stress-y near the edge of ALYH75/epoxy interface corner significantly increases. Oppositely, the stress-y at the middle of adhesive layer is less constraint in shear joint with thick bond.
Fig. 73 Stress-x, -y and –xy distributions in shear adhesive joint
Fig. 74 Comparison of stress-y in shear adhesive joint having various bond thicknesses.
6.4.1.2 Experimental results

In tensile test of shear adhesive joints, load and crosshead displacement are recorded. Fig. 75 (a) and (b) show the typical load against crosshead displacement obtained for shear adhesive joints of dissimilar adherends having 0.1 mm bond thickness and 1.0 mm bond thickness, respectively. It is noted that at the beginning of tensile loading (i.e. crosshead displacement is less than 0.1 mm), load is quadratically increased. This is due to the initial alignment of specimen. Beyond 0.1 mm displacement, load increases proportionally up to maximum load (hereafter failure load) where a sudden failure occurs. This dynamic failure is accompanied by a ‘ping’ sound. Despite some scatter in data, shear adhesive joint having 0.1 mm bond thickness has better load performance than those having 1.0 mm bond thickness. Shear adhesive joint having 0.1 mm bond thickness is sensitive to any defects.
It is essential to determine the critical shear stress of adhesive joints. The relation between shear stress and bond thickness which has been obtained from our experimental study is shown in Fig. 76. It is obvious from this figure that the shear stress reduces gradually with increasing bond thickness in all types of specimen. This indicates a typical influence of bond thickness upon the strength of brittle adhesive joints and has also been reported elsewhere [8, 72].

In recent study, Azuma [73] has reported the relation between strength and bond thickness of shear adhesive joint bonded with similar adherend. The results are plotted in Fig. 77. It is noted that shear stress of S-S specimens is greater than those of A-A specimens. Meanwhile, the shear stress of S-A specimens is only slightly higher than those of A-A specimens. One may attribute the high shear stress recorded in S-S specimens as the
contribution of high elastic modulus, $E$ of SUS304 adherend. Low shear stress in A-A specimens, however, involves both effect of elastic modulus and stress singularity.

Fig. 78 shows failure surface in shear adhesive joint specimens. From failure morphology investigation, the failure initiation site was observed. It is evident that in all specimens, the failure initiates at ALYH75/epoxy interface. The final separation is always 100% interface failure. Fig. 79 shows a schematic illustration of failure growth path in shear adhesive joint specimen. This feature can be explained as high stress concentration develops at ALYH75/epoxy interface when shear adhesive joint is loaded. Stress-$y$ distribution is then analyzed in FE analysis. Fig. 80 shows the stress-$y$ contour plots in FE model of shear adhesive joint having 1.0 mm bond thickness. It can be seen obviously that at B, stress-$y$ is highly concentrates. Therefore, the failure is likely to initiate from this apex. Since the ALYH75 interface is comparatively poor in wettability, the failure propagates along this boundary until 100% separation.
Fig. 76 Critical shear stress of shear adhesive joint against target bond thickness.

Fig. 77 Critical shear stress against measured bond thickness. Note that the data of S-S and A-A are reported elsewhere [73].
<table>
<thead>
<tr>
<th>Bond thickness, $t$ (mm)</th>
<th>Series A (specimen no.)</th>
<th>Series B (specimen no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>(h1a)</td>
<td>(h1b)</td>
</tr>
<tr>
<td>0.2</td>
<td>(h2a)</td>
<td>(h2b)</td>
</tr>
<tr>
<td>0.3</td>
<td>(h3a)</td>
<td>(h3b)</td>
</tr>
<tr>
<td>0.5</td>
<td>(h5a)</td>
<td>(h5b)</td>
</tr>
<tr>
<td>0.7</td>
<td>(h7a)</td>
<td>(h7b)</td>
</tr>
<tr>
<td>1.0</td>
<td>(h10a)</td>
<td>(h10b)</td>
</tr>
</tbody>
</table>

Fig. 78 Failure surface in shear adhesive joint specimens.

Fig. 79 Schematic illustration of failure growth path in shear adhesive joint specimen.
6.4.2 Shear adhesive joint with an interfacial crack

6.4.2.1 $J_c$ calibration

To evaluate the fracture toughness of shear adhesive joint with an interface crack, $J$ integral calculation in FE is applied. However, since the actual bond thickness in a specimen might be varied from the targeted value, a calibration of $J$ value is needed beforehand. Fig. 81 shows the results of $J$ calibration obtained from FE analysis. It is noted that this FE analysis was conducted with the applied stress of 1 MPa.
6.4.2.2 Experimental results

Fig. 82 shows the fracture surface of shear adhesive joint specimens. It is observed for both SEA and AES specimens that the fracture has occurred at ALYH75/epoxy interface. Interface failure at ALYH75/epoxy in SEA may be caused by the poor wettability and intrinsic surface property of ALYH75 surface. Therefore, for the evaluation of fracture toughness, $J_c$ only AES system is considered.
<table>
<thead>
<tr>
<th>Bond thickness, t (mm)</th>
<th>SEA (specimen no.)</th>
<th>AES (specimen no.)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>(h1a)</td>
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</tr>
<tr>
<td>0.2</td>
<td>(h2a)</td>
<td>(h2b)</td>
</tr>
<tr>
<td>0.3</td>
<td>(h3a)</td>
<td>(h3b)</td>
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<tr>
<td>0.5</td>
<td>(h5a)</td>
<td>(h5b)</td>
</tr>
<tr>
<td>0.7</td>
<td>(h7a)</td>
<td>(h7b)</td>
</tr>
<tr>
<td>1.0</td>
<td>(h10a)</td>
<td>(h10b)</td>
</tr>
</tbody>
</table>

Fig. 82 Fracture surface in shear joint specimens.
Fracture toughness, $J_c$ of shear adhesive joint against bond thickness is plotted in Fig. 83. Note that the results for shear adhesive joint bonded with similar adherend is adapted after Azuma [73]. From this figure, it can be noticed that $J_c$ of AES is close to those of SES and demonstrates strong dependency upon bond thickness. Meanwhile, $J_c$ for AEA is likely the lower threshold. This gives an explanation why SEA system failed at ALYH75/epoxy interface. The interface crack in SEA specimen has relatively large fracture resistance compared to those in AES specimen.

![Fracture toughness, $J_c$ against bond thickness, $t$.](image_url)
In the previous Sec. 4.4.2.2, it has been verified that the interfacial toughness, $K_c$ can be used as fracture criterion for butt adhesive joints which failed as 100% interface failure. Therefore, there is possibility that the same fracture criterion is appropriate to the present adhesive joint configuration. Interface toughness, $K_c$ against bond thickness for shear adhesive joint with a crack at ALYH75/epoxy interface is shown in Fig. 84. It is obvious again that $K_c$ values are almost constant, thus solidifying the suitability of $K_c$ fracture criterion to the adhesive joints which fracture adhesively.

Fig. 84 Interface toughness, $K_c$ against bond thickness.
6.5 Conclusions

The strength and fracture toughness of shear adhesive joints of brittle epoxy bonding two dissimilar adherends have been investigated. The following conclusions can be drawn from this chapter:

(1) The strength of shear adhesive joint reduces with increasing bond thickness. In addition, the strength of shear adhesive joint also depends on elastic modulus of adherend.

(2) The failure initiated at a location with the critical stress-y concentration which was the ALYH75/epoxy interface corner.

(3) In the case of shear adhesive joint with an interface crack, the fracture occurred also at ALYH75/epoxy interface even in SEA specimens.

(4) Fracture toughness, $J_c$ of AES is close to those of SES and demonstrates strong dependency upon bond thickness. Hence, the interface crack in SEA specimen has relatively large fracture resistance if compared to those in AES specimen.

(5) Finally, $K_c$ fracture criterion is found to be appropriate for shear adhesive joints which fracture adhesively.
Chapter 7  Strength prediction and reliability of adhesive joint

Abstract

This chapter deals with the strength and failure prediction as well as the reliability issues of adhesive joints of brittle epoxy bonding two dissimilar adherends. The effects of bond thickness and scarf angle upon the strength of such joints are also addressed. Three kinds of adhesive joints, i.e., butt, scarf and shear joints which have been reported in previous chapters are considered. It is found that the strength prediction of various adhesive joints under consideration can be done by establishing the interface corner toughness, $H_c$ parameter. For adhesive joints with an interfacial crack, $J_c$ can be used as a fracture criterion. Weibull modulus is suitable to define the reliability of adhesive joints. The scarf joint of $45^\circ$ is identified to be preferable since it satisfies both outstanding load-bearing performance and tolerable reliability. Hence, both applications of stress singularity based parameter (i.e. $H_c$ or $J_c$) and Weibull statistical method allow the strength and failure predictions of adhesive joints with fairly improved reliability.

7.1  Introduction

Integrity and reliability of adhesive joints are very crucial in structural engineering and industrial applications. Therefore, destructive testing and stress analyses are essential in predicting the performance of adhesive joints. In general, strength and failure predictions of
adhesive joints are either based on strength of materials or fracture mechanics approach [4]. Nevertheless, these predictions remain tolerably difficult due to lack of sufficient criteria with sound physical basis [5, 6]. In the case of adhesive joints bonded with relatively rigid brittle adhesive resin, so far, there is some evidence that presents the relation between strength and bond thickness of such joints can be satisfactorily estimated by means of the stress singularity based fracture parameters, i.e. interface corner toughness, $H_C$ or critical fracture energy, $J_C$.

Some investigators validated experimentally the $H_C$ stress intensity factor parameter. For instance, Reedy and Guess [8] accurately predicted the dependence of cylindrical butt joints strength upon the bond thickness by using $H_C$ approach. They also reported the difference of measured strength between joints with steel-steel and aluminium-aluminium adherends. This “adherend’s stiffness effect” has been correlated with the difference in the order of stress singularity at the interface corner. Further, Reedy [9] examined the connection between interface corner and interface fracture mechanics approaches with asymptotic and finite element solutions. The applicability of both techniques to the problem of unstable failure which initiates from interface corner has been validated.

In another study, Akisanya and Meng [10] used their experimental results to support the application of $H_C$ as a fracture initiation criterion at the interface corner of bonded joints. Using elastic-plastic finite element analysis, they concluded that in order for $H_C$ to be applicable, the region over which the singularity dominates the stress field should be fully embedded within the failure process zone (i.e. or plastic zone). Qian and Akisanya [11] reported the tensile strength prediction of scarf joints subjected to a combination of
mechanical and thermal loading by $H_c$ criterion with a good accuracy. This study led to a better understanding of the failure mechanisms and the influences of joint geometry and cure temperature.

With the progress of fracture mechanics methodology, many researchers have analyzed the strain energy release rate (ERR) or stress intensity factor (SIF) to predict the strength and growth of cracked adhesive joint. This approach is actually a complementary approach to that of stress magnitude and distribution analysis. However, the stress intensity factor of adhesive joint is not easily determinable when the crack grows at or near to an interface because the crack propagates in mixed mode behavior. Thus, many studies dealing with adhesive joints use the ERR instead of SIF [74]. There are many techniques available that can be used to determine the ERR in FE analysis, e.g. J-integral, virtual crack closure, virtual crack extension and stiffness derivative. Rice’s J-integral which is the most popular has been widely used to predict the strength of adhesive joint with crack with fairly good results [48, 74]. It was reported that the $J_c$ (i.e. the critical energy release rate) can be employed as a mixed mode fracture criterion [42].

Reliability analysis is crucially required in engineering safety design, especially in the strength prediction of brittle materials; ceramics components, rock, timber, etc. Based on recent interest in this similar study, Weibull statistics based probability approach increasingly receives attention and appears to be the most widely used in practical. More recently, Weibull strength distribution approach has been proven by some researchers to be the most promising failure criterion and also as an effective reliability indicator for joints
bonded with brittle adhesive [12-14]. Even so, rather less work has been undertaken to facilitate the design of adhesive joints. Some investigations are briefly reviewed below.

Seo and Lim [12] have investigated the distributions of tensile, four-point bending and shear strength of butt adhesive joints. They reported the effects of the adhesive sectional area and compared the aforementioned test methods in terms of standard deviation and Weibull modulus. In their study, tensile and flexural strengths decrease with increasing volume of specimens. They concluded that the four-point bending specimen has the best strength probability and shear specimen is the least affected by the sectional area.

Arenas et al. [13] proposed the use of a statistical analysis based on Weibull distribution to define the optimum bond thickness that combines the best mechanical performance (i.e. shear tensile strength) with high reliability. In their experimental study, they applied acrylic adhesive to manufacture the single lap joint with 6160 aluminium alloy adherend. As a result, the optimum bond thickness for their single lap joint was reported as 0.5 mm.

Vallée et al. [14] have developed a probabilistic method based on Weibull statistical distribution for the strength prediction of balanced adhesively bonded double lap joints composed of pultruded GFRP adherends. They also presented a short review regarding the size effects on strength of materials and FRP composites.

Hadj-Ahmed et al. [6] proposed a strength probability law to predict the shear strength of double lap adhesive joints. They related the influence of bond thickness and overlap length upon joint strength to the Weibull modulus, $m$. Through analytical and numerical investigations, they pointed out that the optimal bond thickness becomes
pronounced when \( m = 4 \) in low dispersion (i.e. relatively ductile) model. The existence of an optimal bond thickness can be attributed to the competition between the “number of defects” effect and stress concentration effect.

Burrow et al. [15] used Weibull analysis to determine the reliability of data from bond strengths to dentin measurements as well as tensile tests on resin-based dental restorative materials. With the help of Weibull analysis, they have: (i) determined whether or not the test method has a significant effect on bond test results, (ii) obtained the information related to the overall performance of an adhesive material, and (iii) theoretically modeled the behavior of materials systems in dental restorations.

In this paper, the author is concerned with the prediction of mechanical performance and failure characteristics of adhesive joints of dissimilar adherends bonded with relatively brittle adhesive. The author also employed the reliability analysis of strength of these joints based upon the statistical Weibull analysis of strength distribution. The effects of stress singularity at the interface corner and scale sensitivity upon brittle adhesive joints are discussed.

7.2 Stress singularity based strength prediction

7.2.1 \( H_c \) parameter

Most recently, much attention has been paid to the validation of interface corner failure criterion. Consider an adhesive joint body within linear elasticity context behavior. When the body is subjected to a remote uniaxial load, the asymptotic stress field develops at the vicinity of interface corners and exhibits singularity behavior in the form of [25]:

\[ \sigma(\theta) = \frac{K}{r^{1/m}}. \]
\[ \sigma \approx H r^{-\lambda} \]  

(20)

where \( \sigma \) is the stress, \( r \) is distance from the interface corner, \( H \) is intensity of stress singularity and \( \lambda \) is order of stress singularity. The \( H \) failure criterion has been originally proposed by Groth [75] and is analogous to the linear elastic fracture mechanics (LEFM) concept, where it is associated with the discontinuity at the interface corner instead of crack. Failure is assumed to initiate at the interface corner when \( H \) exceeds the critical value, \( H_c \).

In order for \( H_c \) to be a valid failure criterion, any plasticity (i.e. plastic deformation) must be confined to a small region at the interface corner: conditions referred to as small scale yielding in LEFM. There is already some experimental evidence, which emphasized that \( H_c \) and \( \lambda \) parameters can be effectively used to successfully predict the onset of failure and eventually evaluate the relationship between bond thickness and adherend stiffness, and the strength of certain adhesively-bonded butt and scarf joints [8, 62, 76]. Hence, the evaluation of \( \lambda \) in such adhesive joints is of technical important, and this can be fulfilled via adopting the calculation method as performed by Bogy [77]. In this study, the calculation of \( \lambda \) at an interface corner of bi-material joint was carried out analytically by using Fortran PowerStation 4.0 software (i.e. see Appendixes A.3). The results will be discussed in the following section.

### 7.2.2 \( J_c \) parameter

\( H_c \) parameter which has been explained in the previous section is suitable to the problem of adhesive joint without defect. In this section, the application of fracture toughness, \( J_c \) parameter as a fracture criterion for adhesive joint with intrinsic or artificial
interfacial crack will be discussed. When a crack in adhesive joint propagates at only one of the interface corners, the fracture toughness of this system has about the same maximum value as in the case of cohesive crack. Therefore, $J_c$ parameter is seemed to be appropriate to this problem. This fracture criterion parameter has the non-dimensional form of a combination of parameters as follows [78, 79]:

$$\phi^2 \left[ \frac{a}{t} \right] = \frac{E_{\text{adh}} J_c}{\sigma_c^2 t}$$

(21)

where $\Phi$ is a function to be determined, $a$ is the crack length, $t$ is bond thickness and $E_{\text{adh}} = E_{\text{adh}} / (1 - \nu_c^2)$ is the plane strain Young’s modulus of adhesive layer. Therefore, if one knows by experimental the fracture toughness of a particular adhesive joint which is independent of $t$, one may predict the critical stress of that adhesive joint. The critical stress of adhesive joint with defect can be derived as:

$$\sigma_c = \sqrt{\frac{E_{\text{adh}} J_c}{\phi^2 t}}$$

(22)

7.3 Weibull statistical strength distribution

When the failure of material is sensitive to the nature and distribution of flaws and defects within the specimens, this material strength will exhibit a scale sensitivity or size effect. This size effect is indeed based on weakest link theory and thus the severity level of defect will determine the variability of failure load. The larger the specimen is, the higher the severity level is and the lower the strength of corresponding sample will be. The size
effect on material strength is adequately explained by statistical probability theories such as Weibull strength distribution theory. Two types of Weibull statistical distribution are available: two-parameter and three-paramater. Due to its simplicity, in this study, the author has chosen two-parameter Weibull distribution (i.e. shape and scale parameters) to represent the strength probabilities of adhesive joint. As originally proposed by Weibull [80], the cumulative probability of failure, \( P_f \) in the simplified form can be expressed by:

\[
P_f = 1 - \exp \left[ -\left( \frac{\sigma}{\sigma_0} \right)^m \right]
\]

(23)

where, \( m \) and \( \sigma_0 \) are shape and scale parameters, respectively. \( m \) is conveniently referred to as the Weibull modulus. These two parameters can be determined by several means; however, the linear regression method is more straightforward. Furthermore, if one takes double natural logarithms for Eq. (23), one may obtain another empirical equation:

\[
Y = \ln \ln \left[ \frac{1}{1-P_f} \right] = m \ln \sigma - m \ln \sigma_0
\]

(24)

Thus, \( m \) can be readily obtained directly from the slope of plot \( Y \) against \( \ln \sigma \). The \( P_f \) can be calculated by experimentally testing a number (\( n \)) of specimens, and then ranking the measured strengths in ascending order, [12]. In the literature, \( P_f \) is often defined by using several estimators [81] and the most established to be used is the following equation [12, 15, 82]:

\[
P_{f-1} = \frac{i}{n+1}
\]

(25)

in which \( i \) is the ranking of the failure stress and \( n \) is the total number of tested specimens.
7.4 Results and discussion

7.4.1 Strength and failure prediction

7.4.1.1 Non-crack adhesive joint

Fig. 85 shows the load versus crosshead displacement of various adhesive joints tested under tension or shear force in this study. This figure shows only the representative results obtained from adhesive joint specimens having (a) 0.1 mm, and (b) 1.0 mm bond thickness, respectively. It is noted that the failure load of scarf joint specimen decreases with increasing scarf angle. Shear joint specimen shows the lowest failure load. In all specimens, load increases gradually with displacement until sudden failure occurs. Very similar trends have also been found on other specimens having bond thickness between 0.1 mm and 1.2 mm.
Failure paths of adhesive joints are illustrated schematically in Fig. 86. For butt joints, failure has been initiated at the SUS304/epoxy interface corner, A, and then immediately deviates into the adhesive layer and propagates inside it until complete separation. Thus, the final appearance of surface was almost cohesive failure. Meanwhile, for scarf joints, even the failure still onset at an identical spot (i.e. A), the distance where it starts deviating into the adhesive layer is slightly different for different scarf angle. The failure ends at the opposite ALYH75/epoxy interface corner, A’. However, there are no obvious discrepancies between path A and path B. Intrinsic properties of adhesion might play a major role to this phenomenon [4, 17]. In the case of shear joints, the failure begins at the ALYH75/epoxy interface corner, B. The separation occurs completely at the ALYH75 interface. In scarf joints and shear joints tested it was found that the interface failure was dominant.

The aforementioned observations can be best explained in terms of stress singularity order, $\lambda$ at the interface corners of adhesive joint. There are four interface corners where stress singularity exists, i.e. A, A’, B and B’, as illustrated diagrammatically in Fig. 86. Following the same procedure as Bogy as mentioned above, assuming the plane strain condition, the author has measured the $\lambda$ of adhesive joints under present consideration. The results for butt and scarf adhesive joints are first plotted in Fig. 87. As can be seen, $\lambda$ at an interface corner varies with the scarf angle and vanishes at a certain scarf angle. From these results, at a glance, one can anticipate at which interface corner the scarf joint will fail. For example, at 45° scarf angle, $\lambda$ exists at SUS304/epoxy interface corner but not at ALYH75/epoxy interface corner. So, in this case, it can be predicted that the failure will
always initiate at SUS304/epoxy interface corner. There is a case where \( \lambda \) exists at both interface corners, let say in 75° scarf joints. In this case, \( \lambda \) at the SUS304/epoxy interface corner A and ALYH75/epoxy interface corner B was measured as 0.3648 and 0.3069, respectively. Since the order of stress singularity at the former is higher than the latter, the failure is predicted to initiate at the former. In fact, it has been confirmed from the failure surface observations that failure initiates at this point in almost all specimens tested as already mentioned above. However, in the case of dissimilar adherends bonded shear adhesive joint, it appears that, \( \lambda \) is highest at ALYH75/epoxy interface corner, B with the value of 0.3623. Since, the failure initiation is likely to occur at the site with the highest order of singularity, the failure will onset at the ALYH75/epoxy interface corner.

Stress singularity at interface corners of adhesive joints (i.e. A, B, A’ and B’) which has been obtained from our analytical calculations are now summarized in Table 16 below. From this table, one may notice that the order of singularity at the SUS304/epoxy interface corner, A is always higher if compared to other interface corners in butt and scarf joints. However, the highest order of singularity in shear joints is at the ALYH75/epoxy interface corner, B. Obviously, this feature provides a fairly good explanation why the failure in butt and scarf joints does initiate from this location.
Fig. 86 Schematics of the observed failure paths

Table 16 Order of singularity at interface corners

<table>
<thead>
<tr>
<th>Degree</th>
<th>Position</th>
<th>( \lambda_A )</th>
<th>( \lambda_B )</th>
<th>( \lambda_{A'} )</th>
<th>( \lambda_{B'} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td></td>
<td>0.3289</td>
<td>0.2963</td>
<td>0.2963</td>
<td>0.3289</td>
</tr>
<tr>
<td>75°</td>
<td></td>
<td>0.3648</td>
<td>0.3069</td>
<td>0.2369</td>
<td>0.2545</td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td>0.3619</td>
<td>0.2532</td>
<td>0.1179</td>
<td>0.1242</td>
</tr>
<tr>
<td>45°</td>
<td></td>
<td>0.2796</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0°(shear)</td>
<td></td>
<td>0.2963</td>
<td>0.3623</td>
<td>0.3289</td>
<td>0.3534</td>
</tr>
</tbody>
</table>
It is essential to determine the critical failure stress of adhesive joints. The relation between the critical failure stresses and bond thickness which has been obtained from our experimental study is depicted in Fig. 88. It is obvious from this figure that the critical stresses reduce gradually with increasing bond thickness in all types of specimen. This indicates a typical influence of bond thickness upon the strength of brittle adhesive joints and has been reported elsewhere [4, 8, 10, 13].

To predict the strength of adhesive joints and its relation to bond thickness, the interface corner toughness, $H_c$ can be applied. According to Akisanya and Meng [5], $H_c$ is defined by:

$$H_c = \sigma_c t^4 Q(\alpha, \beta)$$

(26)

where $Q$ is a non-dimensional constant function of the material elastic parameters (i.e. Dunder’s parameters). For simplicity, the value of $Q$ is taken as 0.5. For shear joint, $\sigma_c$ in
Eq. (26) is readily substituted with critical shear stress, $\tau_c$. The values of $\lambda_{\text{max}}$ and average values of $H_c$ (i.e. $H_{\text{ave}}$) as well as standard deviation for scarf joints having scarf angle of 45°, 60° and 75° are summarized in Table 17. It is noted that the ratio of standard deviation to $H_{\text{ave}}$ is moderate, i.e. less than 30 %. This suggests that $H_c$ is indeed a material property which is independent of bond thickness. Using the value of $H_{\text{ave}}$ in conjunction with Eq. (26), inversely, the strength for each adhesive joint can be predicted. Prediction lines for strength of adhesive joints having 0°, 45°, 60°, 75° and 90° are represented by long dash line, short dash line, dash-dot line and dot-dot line, respectively, as shown in Fig. 88. Obviously, to some extent, the prediction is in good agreement with the measured data. Hence, it is concluded that the application of $H_c$ approach is appropriate to the estimation of the strength of brittle epoxy adhesively bonded joints with several bond thicknesses.

![Fig. 88 Critical failure stress against bond thickness.](image)
Table 17 $H_c$ and standard deviation.

<table>
<thead>
<tr>
<th>Degree</th>
<th>$\lambda_{\text{max}}$</th>
<th>$H_{cave}$</th>
<th>Std Dev*</th>
<th>Std Dev/$H_{cave}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>0.3289</td>
<td>4.1549</td>
<td>0.8759</td>
<td>21.08</td>
</tr>
<tr>
<td>75°</td>
<td>0.3648</td>
<td>4.8183</td>
<td>0.8323</td>
<td>24.23</td>
</tr>
<tr>
<td>60°</td>
<td>0.3619</td>
<td>5.4821</td>
<td>1.3285</td>
<td>17.27</td>
</tr>
<tr>
<td>45°</td>
<td>0.2796</td>
<td>8.1371</td>
<td>2.1306</td>
<td>26.18</td>
</tr>
<tr>
<td>0°(shear)</td>
<td>0.3623</td>
<td>1.7116</td>
<td>0.4329</td>
<td>25.29</td>
</tr>
</tbody>
</table>

*Std Dev is standard deviation

7.4.1.2 Adhesive joint with an interfacial crack

In the case of adhesive joints which failed cohesively, fracture toughness is almost constant. Here, the joint strength prediction based on $J_c$ parameter is verified. In order to achieve this, Eqs. (21) and (22) above are employed. Fig. 89 shows the fracture stress against bond thickness for butt adhesive joint with an interfacial crack. For both SEA and AES systems, the prediction lines fit well with the corresponding experimental data. Almost same validation and tendency can be appreciated from the results of scarf adhesive joints with an interfacial crack as shown in Fig. 90 (a) and (b). If $J_c$ for an adhesive joint is constant, the fracture strength of this system will be depend on bond thickness; fracture stress decreases when the bond thickness increases.
Fig. 89 Prediction of fracture stress against bond thickness for butt adhesive joint with an interfacial crack based on $J_c$ parameter.

Fig. 90 Prediction of fracture stress against bond thickness for scarf adhesive joint with an interfacial crack, (a) SEA and (b) AES.
In some cases, adhesive joint failed at entire ALYH75/epoxy interface. In these specimens, another fracture criterion will be invoked. As in the case of $J_c$ parameter, in order to be a valid fracture criterion, $K_c$ parameter needs to be a constant. Fig. 91 and Fig. 92 show the prediction of fracture stress against bond thickness based on $K_c$ parameter in butt adhesive joint and shear adhesive joint, respectively. It is seen that in both cases, the prediction lines are in good correlation with the experimental results, henceforth verified the applicability of $K_c$ parameter as fracture criterion for adhesive joints which failed 100% at interface.

![Graph showing predicted and experimental fracture stress against bond thickness in butt adhesive joint with an interfacial crack based on $K_c$ parameter.](image_url)

Fig. 91 Prediction of fracture stress against bond thickness in butt adhesive joint with an interfacial crack based on $K_c$ parameter.
7.4.2 Reliability

First, the Weibull strength analysis of shear adhesive joint with four different bond thickness was conducted. For each condition, 10 specimens were tested. Fig. 93 shows the results which have been obtained. It is obvious from Fig. 93 (a) that there is considerably large scatter in the measured failure shear stress. Fig. 93 (b) shows Weibull plots of shear adhesive joints. It is noted that in this investigation, Eq. (25) was used to evaluate the probability of failure, $P_f$. In actual practice, 10 specimens may be insufficient to draw a solid conclusion [15, 83]. However, with only 10 specimens for each configuration, a good linear regression line as can be appreciated from Fig. 93 (b). This suggests that the present result has some useful validity. Fig. 93 (c) gives a direct comparison on the correlation between Weibull modulus, $m$ as well as average failure stress against bond thickness. It is
noted that both $m$ and average failure stress decrease with increasing bond thickness, i.e. shear adhesive joint with thick adhesive layer has low strength performance and low reliability. Hence, for reliability analysis of butt and scarf joints, another 10 specimens having only 0.1 mm bond thickness were additionally evaluated (i.e. Series B).

Fig. 94 shows the logarithmic Weibull plots of various adhesive joint specimens for Series A and B. Note that the Series A data include all specimens having bond thickness ranged from 0.1 mm to 1.0 mm (i.e. data adapted from Chapter 4, 5 and 6). These results are now summarized in Fig. 95. In Fig. 95, it appears that both Series A and Series B show a similar pattern except values in Series A are lower than those in Series B. With increasing scarf angle, $m$ is gradually reduced, but then, increases again before eventually declines further. As a conclusion, shear joints have the highest strength reliability than others. From the results of Series B, the higher probability in ascending order is butt joint (i.e. 90°), 60° scarf joints, 45° scarf joints, 75° scarf joints and shear joints.
Fig. 93 Weibull strength analysis of shear adhesive joint.

(a) Failure stress against bond thickness

(b) Weibull plots

(c) Weibull modulus and average failure stress against bond thickness
Fig. 94 Logarithmic Weibull plots of adhesive joint specimens.

Fig. 95 Weibull modulus against various scarf angles.
The reason why the value of $m$ decreases with the increase in scarf angle, $\theta$ is likely to be associated with changes in the failure surface morphology. For $\theta = 0$ (i.e. shear joint), only the interface failure was observed, but when $\theta$ increases the ratio of cohesive fracture also increases, especially for $\theta = 45^\circ$, $60^\circ$ and $90^\circ$. In the scarf joint (i.e. $\theta = 45^\circ$ and $60^\circ$), cohesive failure can be clearly seen because of failure meanders from an interface to the opposite interface. Moreover, in butt joint (i.e. $\theta = 90^\circ$), cohesive failure is dominant and the interface fracture occurs only in a small area at the interface corner neighborhood. On the other hand, it is also noted that the cohesive failure ratio also increases with increasing thickness of the adhesive. Therefore, this is the best explanation of why the value of $m$ for the Series A is lower than those in Series B. Based upon the present experimental results, it appears that $45^\circ$ scarf joints have the best failure stress performance with tolerably good $m$ value. Therefore, it can be concluded that $45^\circ$ scarf joints should be considered when designing adhesive joints with the same adhesive as used in this study. It should be noted that, in contrast to $H_c$ parameter which is a material property, $m$ is a specimen property. Hence, the application of both parameters is highly recommended for better prediction of strength and failure of brittle adhesive joints.

7.5 Conclusions

The strength and failure prediction as well as the reliability issues of adhesive joints of brittle epoxy bonding two dissimilar adherends have been addressed. From the presented results, the following conclusions have been obtained:
(1) The strength of adhesive joint reduces with increasing bond thickness and scarf angle.

(2) The failure has been initiated at a location with the critical stress singularity order which is the interface corner of SUS304/epoxy of butt and scarf joints. However, the failure initiation site of shear joints is at the ALYH75/epoxy interface.

(3) Strength prediction of various adhesive joints can be done by interface corner toughness, $H_c$ parameter. Moreover, shear joint specimens have higher reliability than butt and scarf joints, although the stress singularity order at interface corner is maximal.

(4) Even though scarf joint of 45° has relatively lower stress singularity, its Weibull modulus value is moderate. Hence, it can be concluded that the scarf joint of 45° is preferable since it satisfies both outstanding load-bearing performance and tolerable reliability.

(5) With both applications of $H_c$ parameter and Weibull statistical method, the strength and failure predictions of adhesive joints with greatly improved accuracy and reliability can be obtained.
Chapter 8 Concluding remarks

In this dissertation, the effect of bond thickness upon the adhesive strength and fracture characteristics of brittle epoxy adhesively bonded dissimilar joint has been investigated. Three types of joint configurations which represent the most common joint in real applications have been evaluated separately; i.e. butt, scarf and shear adhesive joints. A series of elastic analyses using finite element analysis (FEA) have been also conducted on these configurations. The FEA was used to establish the effect of bond thickness and different adherends upon stress distributions within the adhesive layer and interfaces of such joints.

As a result, the failure stress of adhesive joint was found to be greatly related to the bond thickness and loading mode. As the bond thickness increased, the strength of adhesive joint significantly decreased. However, strength of scarf adhesive joint increases with decreasing scarf angle. For adhesive joints with interfacial crack, in the case of cohesive failure, the evaluated fracture toughness, $J_c$ is independent of bond thickness. In contrast, in the case of interfacial failure, $J_c$ of both adhesive joints with interfacial crack shows some dependency upon bond thickness. However, when the interfacial crack is assumed to behave similar to the center crack in adhesive layer constrained between two rigid substrates, $K_c$ parameter can be used to assess the fracture toughness of adhesive joints with interface failure.

As indicated by the post-failure analyses results, failure in butt adhesive joint specimens was cohesive in manner when loaded under mode I condition whereas failure in
scarf adhesive joint specimens tended to be more and more interfacial as the mode II fracture component increased. Likely, the failure surface in shear adhesive joints was 100% interfacial since the loading was in full mode II condition. Most of test specimens, generally failed at the location where maximum stress-y was identified in FE analysis. This supports the concept that maximum stress-y at interface corner of brittle adhesive joint has a far more dominant influence on the failure initiation site than the practical in-layer failure. Bogy’s analytical solutions of stress singularity order provided further support for the contribution of the concentration of interfacial stress on the failure path selection of brittle adhesive joint.

The strength and failure prediction as well as the reliability issues of adhesive joints of brittle epoxy bonding two dissimilar adherends have been addressed. Strength prediction of various adhesive joints without defect can be done by employing stress singularity order, \( \lambda \) and interface corner toughness, \( H_\text{c} \) parameter. Moreover, shear joint specimens have higher reliability than butt and scarf joints, although the stress singularity order at interface corner is maximal. Besides, scarf joint of 45° has relatively lower stress singularity and Weibull modulus is moderate. Hence, it can be concluded that the scarf joint of 45° is preferable since it satisfies both outstanding load-bearing performance and tolerably good reliability. Finally, with both applications of suitable fracture criterion parameter (i.e. \( H_\text{c} \), \( J_\text{c} \) or \( K_\text{c} \)) and Weibull statistical method, the strength and failure predictions of adhesive joints with greatly improved accuracy and reliability can be obtained.

After completing this work, the author realizes that several issues are still remained which need further clarification. For example, in the FE analysis of this study, the bonding
was assumed to be perfect and the materials were assumed to be flawless, and elsewhere only an interface crack was present in an adhesive joint. This idealization greatly simplified the mathematical model and the analyses, but several cracks and flaws are usually encountered in adhesive joint. Their interactions with each other not only will influence the failure behavior but also greatly reduce the joint strength performance. Therefore, further investigations of adhesive joint with the present of multiple cracks and different crack lengths are seemed to be essential and necessary.

In this research, the author only considered the bond thickness ranging between 0.1 mm and 1.0 mm. It would be advisable also for future research to consider thick adhesive layer than this to gain a better insights into the correlation between strength and bond thickness of adhesive joint.

Unresolved issues which require additional investigations also include:

(1) effect of surface treatment
(2) effect of time and aging
(3) changing humidity and temperature of testing environment
(4) dynamic testing

Finally, the present findings demonstrate that a typical fracture parameter is only suitable for predicting a particular type of failure. Hence, there is still an immediate need for a development of robust failure criterion that can be universally applied to all bonded structures.
References


[56] Information on http://www.jisc.go.jp/.


[73] Azuma K. University of Tsukuba; 2011.


Appendixes

A.1 Macro of FE model in ANSYS 11

(Typical input file source code of shear adhesive joint having 1.0 mm bond thickness)

/PREP7
et,1,183
keyopt,1,3,3        ! plane stress w/thick
type,1              ! activate element type 1
R, 1, 5             ! thickness 0.005
real,1
mp,ex,1,206000
mp,prxy,1,0.3
mp,ex,2,3400
mp,prxy,2,0.396
mp,ex,3,71000
mp,prxy,3,0.33

K,1,0,-0.5          !create keypoints
K,2,5,-0.5
K,3,5,0.5
K,4,0,0.5
K,5,10,-0.5
K,6,10,0.5
K,7,15,-0.5
K,8,15,0.5
K,9,34,-0.5
K,10,34,0.5
K,11,35,-0.5
K,12,35,0.5
K,13,40,-0.5
K,14,40,0.5
K,15,0,-1.5
K,16,5,-1.5
K,17,10,-1.5
K,18,15,-1.5
K,19,34,-1.5
K,20,35,-1.5
K,21,40,-1.5
K,22,50,-1.5
K,23,50,-0.5
K,24,55,-0.5
K,25,60,-0.5
K,26,60,4.5
K,27,0,-20.5
K,28,50,-20.5
K,29,60,-20.5
K,30,120,-20.5
K,31,120,19.5
K,32,60,19.5
K,33,40,1.5
K,34,35,1.5
K,35,34,1.5
K,36,15,1.5
K,37,10,1.5
K,38,5,1.5
K,39,0,1.5
K,40,-10,1.5
K,41,-10,0.5
K,42,-15,0.5
K,43,-20,0.5
K,44,-20,-4.5
K,45,40,20.5
K,46,-10,20.5
K,47,-20,20.5
K,48,-80,20.5
K,49,-80,-19.5
K,50,-20,-19.5
K,51,0,-0.5
K,52,5,-0.5
K,53,5,0.5
K,54,0,0.5
K,55,10,-0.5
K,56,10,0.5
K,57,15,-0.5
K,58,15,0.5
K,59,34,-0.5
K,60,34,0.5
K,61,35,-0.5
K,62,35,0.5
K,63,40,-0.5
K,64,40,0.5

LSTR,1,4 !create lines
LSTR,1,2
LSTR,2,3
LSTR,3,4
LSTR,2,5
LSTR,5,6
LSTR,3,6
LSTR,5,7
LSTR,7,8
LSTR,6,8
LSTR,7,9
LSTR,9,10
LSTR,8,10
LSTR,9,11
LSTR,11,12
LSTR,10,12
LSTR,11,13
LSTR,13,14
LSTR,12,14
LSTR,15,51
LSTR,15,16
LSTR,16,52
LSTR,51,52
LSTR,16,17
LSTR,17,55
LSTR,52,55
LSTR,17,18
LSTR,18,57
LSTR,55,57
LSTR,18,19
LSTR,19,59
LSTR,57,59
LSTR,19,20
LSTR,20,61
LSTR,59,61
LSTR,20,21
LSTR,21,63
LSTR,61,63
LSTR,21,22
LSTR,22,23
LSTR,23,63
LSTR,15,27
LSTR,27,28
LSTR,22,28
LSTR,28,29
LSTR,25,29
LSTR,23,24
LSTR,24,25
LSTR,24,26
LSTR,25,26
LSTR,26,32
LSTR,29,30
LSTR,30,31
LSTR,31,32
LSTR,33,64
LSTR,33,34
LSTR,34,62
LSTR,62,64
LSTR,34,35
LSTR,35,60
LSTR,60,62
LSTR,35,36
LSTR,36,58
LSTR,58,60
LSTR,36,37
LSTR,37,56
LSTR,56,58
LSTR,37,38
LSTR,38,53
LSTR,53,56
LSTR,38,39
LSTR,39,54
LSTR,53,54
LSTR,39,40
LSTR,40,41
LSTR,41,54
LSTR,33,45
LSTR,45,46
LSTR,40,46
LSTR,46,47
LSTR,43,47
LSTR,41,42
LSTR,42,43
LSTR,42,44
LSTR,43,44
LSTR,44,50
LSTR,47,48
LSTR,48,49
LSTR,49,50

AL,1,2,3,4 !assemble lines
AL,3,5,6,7
AL,6,8,9,10
AL,9,11,12,13
AL,12,14,15,16
AL,15,17,18,19
AL,20,21,22,23
AL,22,24,25,26
AL,25,27,28,29
AL,28,30,31,32
AL,31,33,34,35
AL,34,36,37,38
AL,37,39,40,41
AL,21,24,27,30,33,36,39,42,43,44
AL,40,44,45,46,47,48
AL,48,49,50
AL,46,50,51,52,53,54
AL,55,56,57,58
AL,57,59,60,61
AL,60,62,63,64
AL,63,65,66,67
AL,66,68,69,70
AL,69,71,72,73
AL,72,74,75,76
AL,56,59,62,65,68,71,74,77,78,79
AL,75,79,80,81,82,83
AL,83,84,85
AL,81,85,86,87,88,89

CYL4,-15,-4.5,5
CYL4,55,4,5,5
ASBA,16,30
ASBA,27,29

AESIZE,1,0.05
AESIZE,2,0.1
AESIZE,3,0.5
AESIZE,4,0.5
AESIZE,5,0.1
AESIZE,6,0.05
AESIZE,7,0.1
AESIZE,8,0.5
AESIZE,9,0.5
AESIZE,10,0.5
AESIZE,11,0.5
AESIZE,12,0.1
AESIZE,13,0.5
AESIZE,14,5
AESIZE,15,5
AESIZE,16,1
AESIZE,17,5
AESIZE,18,0.1
AESIZE,19,0.5
AESIZE,20,0.5
AESIZE,21,0.5
AESIZE,22,0.5
AESIZE,23,0.1
AESIZE,24,0.5
AESIZE,25,5
AESIZE,26,5
AESIZE,28,5
AESIZE,31,1

mat,2 !epoxy !meshing areas
amesh,1
amesh,2
amesh,3
amesh,4
amesh,5
amesh,6

mat,1 !SUS304
amesh,7
amesh,8
amesh,9
amesh,10
amesh,11
amesh,12
amesh,13
amesh,14
amesh,15
amesh,31
amesh,17

mat,3 !ALYH75
amesh,18
amesh,19
amesh,20
amesh,21
amesh,22  
amesh,23  
amesh,24  
amesh,25  
amesh,26  
amesh,28  
amesh,16  
et,2,conta172  
et,3,targe169  
r,2  
keyopt,2,4,2  
keyopt,2,3,3  
keyopt,2,2,2  
keyopt,2,12,5  
keyopt,2,8,2  
lsel,s,line,,2  
lsel,a,line,,5  
lsel,a,line,,8  
lsel,a,line,,11  
lsel,a,line,,14  
lsel,a,line,,17  
nsll,s,1  
type,2  
esurf  
allsel  
lsel,s,line,,23  
lsel,a,line,,26  
lsel,a,line,,29  
lsel,a,line,,32  
lsel,a,line,,35  
lsel,a,line,,38  
nsll,s,1  
type,3  
esurf  
allsel  
lsel,s,line,,4  
lsel,a,line,,7  
lsel,a,line,,10  
lsel,a,line,,13  
lsel,a,line,,16

188
lsel,a,line,,19
nsll,s,1
type,2
esurf
allsel
lsel,s,line,,73
lsel,a,line,,70
lsel,a,line,,67
lsel,a,line,,64
lsel,a,line,,61
lsel,a,line,,58
nsll,s,1
type,3
esurf
allsel

/solu
dl,88,15,all
sfl,53,pres,-1

solve
finish

/post1
plnsol,s,xy
A.2 Macro of J integral calculation in ANSYS 11

ETABLE, SENE, SENE
ETABLE, VOLU, VOLU
SEXP, W, SENE, VOLU, 1,-1 ! CALCULATE STRAIN ENERGY DENSITY
!LPATH, n1, n2, ..., nn ! DEFINE PATH POINTS BY NODE
PDEF, W, ETAB, W ! PUT STRAIN ENERGY DENSITY ON THE PATH
PCALC, INTG, J1, W, YG ! INTEGRATE ENERGY W.R.T. GLOBAL Y
*GET, JA, PATH,, LAST, J1 ! GET FINAL VALUE OF INTEGRAL FOR 1ST TERM OF J
PDEF, CLEAR ! CLEAR OLD PATH VARIABLES
PVECT, NORM, NX, NY, NZ ! DEFINE THE PATH UNIT NORMAL VECTOR
PDEF, INTR, SX, SX ! PUT STRESS SX ON THE PATH
PDEF, INTR, SY, SY ! PUT STRESS SY ON THE PATH
PDEF, INTR, SXY, SXY ! PUT STRESS SXY ON THE PATH
PCALC, MULT, TX, SX, NX ! CALCULATE TRACTION TX
PCALC, MULT, C1, SXY, NY ! TX = SX*NX + SXY*NY
PCALC, ADD, TX, TX, C1
PCALC, MULT, TY, SXY, NX ! CALCULATE TRACTION TY
PCALC, MULT, C1, SY, NY ! TY = SXY*NX + SY*NY
PCALC, ADD, TY, TY, C1
*GET, DX, PATH,, LAST, S ! DEFINE PATH SHIFT AS 1% OF PATH LENGTH
DX=DX/100
PCALC, ADD, XG, XG, ..., DX/2 ! SHIFT PATH FROM X TO X-DX/2 (GLOBAL X DIR.)
PDEF, INTR, UX1, UX ! DEFINE UX AT X-DX
PDEF, INTR, UY1, UY ! DEFINE UY AT X-DX
PCALC, ADD, XG, XG, ..., DX ! SHIFT PATH FROM X-DX/2 TO X+DX/2
PDEF, INTR, UX2, UX ! DEFINE UX AT X+DX
PDEF, INTR, UY2, UY ! DEFINE UY AT X+DX
PCALC, ADD, XG, XG, ..., DX/2 ! SHIFT PATH BACK TO ORIGINAL POSITION
C=(1/DX)
PCALC, ADD, C1, UX2, UX1, C,-C ! CALCULATE DERIVATIVE DUX/DX
PCALC, ADD, C2, UY2, UY1, C,-C ! CALCULATE DERIVATIVE DUY/DX
PCALC, MULT, C1, TX, C1 ! DEFINE INTEGRAND
PCALC, MULT, C2, TY, C2 ! = TX*DUX/DX + TY*DUY/DX
PCALC, ADD, C1, C1, C2
PCALC, INTG, J2, C1, S ! FORM SECOND INTEGRAL (W.R.T. PATH LENGTH S)
*GET, JB, PATH,, LAST, J2 ! GET FINAL VALUE OF INTEGRAL FOR 2ND TERM OF J
PCALC, ADD, J3, J1, J2, -1
*GET, J11 , PATH,, LAST, J3
!J11=JA-JB ! FOR FULL MODELS
!*PDEF, CLEAR ! CLEAR PATH VARIABLES
!*END
A.3 Bogy's singularity evaluation in Fortran PowerStation 4.0

C......SINGULAR.FOR
    IMPLICIT REAL*8(A-H,O-Z)
    ESUS=206000
    EAL=71000
    EADH=3400
    PNUSUS=0.3
    PNUAL=0.33
    PNUADH=0.396
    EPS=1.D-5
C.... GS=0.5*ESUS/(1.0+PNUSUS)
C.... GA=0.5*EAL/(1.0+PNUAL)
C.... GAD=0.5*EADH/(1.0+PNUADH)
    WRITE(6,*) 'PLANE STRESS=0, PLANE STRAIN=1..'
    READ(5,*) IPP
    WRITE(6,*) 'SUS=0, AL=1..'
    READ(5,*) IYOUNG
    IF(IYOUNG.EQ.0) THEN
        E1=ESUS
        PNU1=PNUSUS
    ELSE
        E1=EAL
        PNU1=PNUAL
    ENDIF
C.................
    E2=EADH
    PNU2=PNUADH
    CALL PLANE(IPP,E1,PNU1,RK1,G1)
    CALL PLANE(IPP,E2,PNU2,RK2,G2)
    BUNBO=G1*(RK2+1.0)+G2*(RK1+1.0)
    ALF=(G1*(RK2+1.0)-G2*(RK1+1.0))/BUNBO
    BET=(G1*(RK2-1.0)-G2*(RK1-1.0))/BUNBO
    WRITE(6,*)'ALF,BET...',ALF,BET
C.................
    PI=3.141592653589793
    T1= PI/2
    T2= PI/2
C    TMINUS=T1-T2
    TPLUS=T1+T2
    DP=0.1D0
    P0=0.000001D0
C P0=0.0D0
C
P1=P0
P2=P0+DP
5 CALL K(P1,T1,TK1)
   CALL K(P1,T2,TK2)
   CALL K(P1,TMINUS,TK3)
   CALL K(P1,TPLUS,TK4)
   CALL F(P1,TK1,TK2,TK3,TK4,T1,T2,F1,ALF,BET)
C
CALL K(P2,T1,TK1)
CALL K(P2,T2,TK2)
CALL K(P2,TMINUS,TK3)
CALL K(P2,TPLUS,TK4)
CALL F(P2,TK1,TK2,TK3,TK4,T1,T2,F2,ALF,BET)
IF(F1*F2) 20,20,30
20 P3=0.5D0*(P1+P2)
   CALL K(P3,T1,TK1)
   CALL K(P3,T2,TK2)
   CALL K(P3,T1-T2,TK3)
   CALL K(P3,T1+T2,TK4)
   CALL F(P3,TK1,TK2,TK3,TK4,T1,T2,F3,ALF,BET)
IF(F1*F3.LE.0.0) THEN
   P2=P3
   F2=F3
ELSE
   P1=P3
   F1=F3
ENDIF
C
PS=2.D0*(P2-P1)/(P1+P2)
C
WRITE(6,*)'P1,P2,PS=',P1,P2,PS
C IF(PS.LE.EPS) STOP
C
WRITE(6,*)'EPS,P3,F3=',EPS,P3,F3
C STOP
IF(ABS(PS).GT.EPS) GOTO 20
PP=0.5D0*(P1+P2)
GOTO 40
30 P1=P1+DP
P2=P2+DP
IF(P2.GT.1.D0)THEN
C WRITE(6,*)'NO ANSWER!!'
STOP
ENDIF
GOTO 5
40 WRITE(6,*)'P=', PP
STOP
END

C.............................
SUBROUTINE PLANE(IPP,E,PNU,RK,G)
IMPLICIT REAL*8(A-H,O-Z)
IF(IPP.EQ.0) THEN
   RK=(3.0-PNU)/(1.0+PNU)
ELSE
   RK=3.0-4.0*PNU
ENDIF
G=0.5*E/(1.0+PNU)
RETURN
END

C.............................
SUBROUTINE K(P,T,TK)
IMPLICIT REAL*8(A-H,O-Z)
S1=SIN(P*T)
S2=SIN(T)
TK=S1*S1-P*P*S2*S2
RETURN
END

C.............................
SUBROUTINE F(P,TK1,TK2,TK3,TK4,T1,T2,FX,ALF,BET)
IMPLICIT REAL*8(A-H,O-Z)
A=4.0*TK1*TK2
B=2.0*P*P*(SIN(T1)*SIN(T1)*TK2+SIN(T2)*SIN(T2)*TK1)
C1=SIN(T1)*SIN(T2)
C=4.0*P*P*(P*P-1.0)*C1*C1+TK3
D1=SIN(T1)*SIN(T2)
D2=SIN(T2)*SIN(T1)
D=2.0*P*P*(D1*D1-D2*D2)
E=D+TK2-TK1
FF=TK4
FX=A*Bet*Bet+2.0*B*ALF*Bet+C*ALF*ALF-2.0*D*Bet-2.0*E*ALF+FF
RETURN
END
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List of publications

Original Papers


Refereed International Conference Paper

Submitted Original Papers


International Conference Papers


National Conference Papers


LIST OF AWARDS

Scholarships:
1. Public Service Department of Malaysia 1999-2006.

Best presentation awards: