INDENTATION METHOD TO EVALUATE METAL-TO-METAL ADHESIVE BOND RESIDUAL STRENGTH

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ABSTRACT

The interface strength in an adhesive joint plays a major role in load transfer across bonded joints. However, the presence of defects hinders or deflects the load transmission. In this study, an attempt has been made using the cohesive zone method to study the effect of interfacial strength (or residual strength) on the interfacial crack propagation under indentation contact. Stable and unstable crack growth behaviour have been investigated and the effect of the presence of defects along one of the interfaces has been analysed. It has been concluded that higher interfacial strengths favour unstable crack propagation. The presence of defects does not affect the crack initiation but affects the crack initiation load because of the reduction in the apparent interface length.

Keywords: *adhesive joints; interface defects; finite element (FE); cohesive zone model (CZM); indentation*

1. Introduction

Adhesive joints are being widely implemented in a variety of applications such as aircraft structures, wind turbines and automotive body parts, etc. The failure prediction of adhesive joints has been studied and failure criteria have been established for various geometries and loading conditions. The previous research in this field is mostly based on analytical closed form solutions of stress and displacement fields in the adhesive and hence predict the failure based on stress or strain based criteria. However, these studies can only be used under the assumption that the interface between the adhesive layer and adherends is perfectly bonded and that there exist no defect within the adhesive layer. In the real world manufacturing of the adhesive joints, there exists a possibility of inclusion of defects in the form of air bubbles and foreign materials within the adhesive and improper bonding (Kissing bonds), the presence of oxide layers or the presence of interfacial defects because of improper surface cleaning methodologies. Investigation of the effect of these defects on the strength of the adhesive joint can be carried out either through experimentation or through numerical calculations based on finite element (FE) method. It is apparent that the interface between adhesive and adherends plays an important role in the load transmission through the adhesive joint. However, the isolation of the interface in terms of strength and fracture toughness is a difficult task as the crack propagation along the interface is always accompanied by plastic deformation either in the adhesive or the adherends.

The formation of a cohesive zone ahead of the crack tip and the size of this zone determines the steady state fracture toughness and the adhesive strength of the interface. The estimation of the interface toughness can be carried out through the calculation of the work of adhesion of the adhesive on the adherend material which is estimated to be around 0.1 J/m^2 [1] using the surface free energy of the adhesive and the contact angle of an adhesive droplet on the adherend surface. This estimate assumes a perfect interface without defects and 0° contact angle. However, in the presence of defects or improper adhesion because of oxide layer formation on the metal surface this value can be lower than the estimated value. In the present study the different interfacial strengths have been represented by a cohesive zone model (CZM) embedded into an outer FE model of the adhesive and the adherends. The CZM models the interface as a series of springs whose stiffness is a function of the normal and tangential displacements. The principal advantage of the CZM is that the stress state at any node is independent of its distance from the crack tip. Moreover, the use of linear elastic fracture mechanics (LEFM) is limited to small-scale yielding conditions where the dissipation of work in the cohesive zone in front of the crack tip is negligible. LEFM breaks down where large scale yield conditions exist as in adhesive joints in front of an interfacial crack [2]. The importance of different CZM parameters has

been studied numerous times. The initial opening stiffness does not have a significant effect on the behaviour of the model. Increasing the critical traction (σ_c^m) increases the crack propagation load and increasing the steady-state toughness increases the overall load carrying capacity of the bonded joint.

In the present investigation, the toughness of the interface (i.e. area of the traction-separation curve) has been maintained constant and the critical traction (σ_c^m) has been varied as fractions of the adhesive material yield strength 'σ_y' (e.g. at $0.25\sigma_y$, $0.5\sigma_y$, $0.75\sigma_y$, σ_y). In addition, interfacial defects were assumed to be along the lower interface. Three crack radii were considered (R = 200 µm, 400 µm, 600 µm) in addition to a joint with a perfectly bonded interface. The crack propagation with respect to indentation depth and the effect of varying the critical strength have been studied. It has been observed that the crack initiation load and depth varied with adhesive thickness and interfacial strength. Also, at lower adhesive thickness and lower interfacial strengths, cracks appeared at both the interfaces.

2. Indentation Simulations

The adherends (aluminium, *Al*) and adhesive have been modelled using an elastic-plastic bi-linear model in ANSYS APDL using PLANE 182 elements. The interfaces have been modelled using CONTACT 172 and TARGET 169 elements. The element size has been maintained at 5 µm in the adhesive to increase the accuracy of the model. A plane strain element formulation has been used along with a two-dimensional (2D) model. The simulation was displacement controlled with a 150 µm vertically downward displacement applied as boundary condition on the indenter (Rockwell B scale of 1.558 mm diameter). The material properties and geometry is shown in Fig. 1. The crack propagation has been analysed at various displacement levels. The lower edge of the lower adherend has been constrained in the Y-direction and the axis of symmetry is as shown in the above figure. The location of the crack along the lower interface is also shown in the Fig. 1.
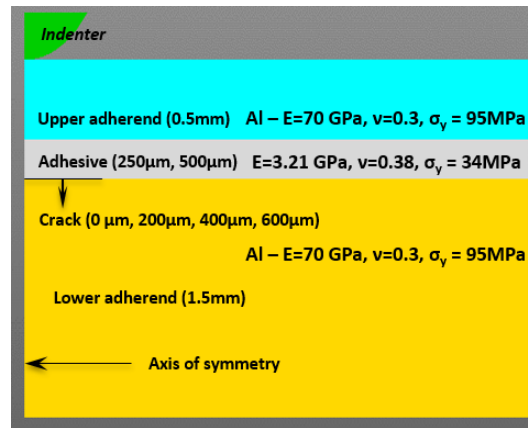

Figure 1: Representation of the model employed

2.1. Cohesive zone model (CZM) formulation

The CZM is governed by a traction-displacement law as shown in Fig. 2. The behaviour follows a triangular law (the area under which gives the steady-state fracture toughness). The behaviour is reversible below the critical stress and the elements retain the stiffness in this zone. After the critical stress is exceeded the behaviour is as indicated by the dotted line (shown in Fig. 2). Once the critical displacement (δ_c^m) has been exceeded, the surfaces become de-bonded and assume frictional contact. The mixed-mode displacement is calculated as a root-square value of the normal and tangential displacements. The initiation of a crack or delamination is tracked using a damage parameter and the stiffness is expressed as a function of this parameter so as to incorporate irreversible damage to the contact pair after the stress exceeds the corresponding critical value.
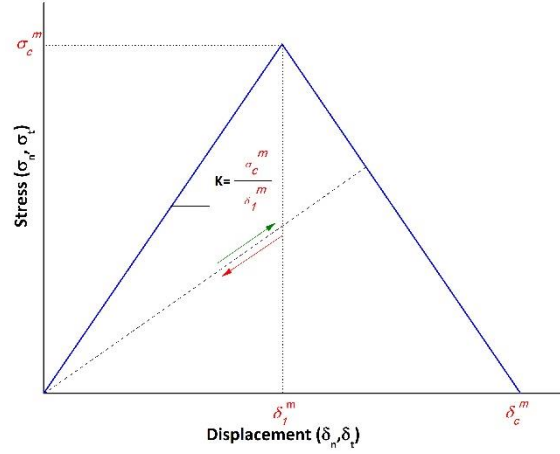
Figure 2: Traction-separation law of the CZM

The mixed-mode stress is given by Equation (1):

$$P_m = K_m U_m (1-d_m) \qquad (1)$$

and the fracture criterion is given by Equation (2):

$$\frac{G_n}{G_{nc}} + \frac{G_t}{G_{tc}} = 1 \qquad (2)$$

where 'd_m' is the damage parameter and varies between 0 and 1 between δ_1^m and δ_c^m respectively, 'K_m' is the initial stiffness of the interface, 'U_m' is the mixed mode displacement 'G_n', 'G_t' are the normal and tangential energy release rates and 'G_{nc}' and 'G_{tc}' are the critical values. As can be seen, the traction-displacement relation is represented by a triangle, the area of which is the steady-state toughness of the interface the value of which depends on the mode-mixity and the loading nature. Parameter δ_c^m represents the critical mixed-mode displacement beyond which the crack opens. Parameter σ_c^m represents the critical stress. The above parameters are for a mixed-mode cohesive law and are suitable for mixed-mode loading conditions. The Table 1 shows the CZM parameters employed for simulations.

Table 1: CZM parameters employed in the simulations

Parameter set no.	Mode-I critical stress (σ_n)	Mode-II critical stress (σ_t)	Mode-I critical displacement (δ_n)	Mode-II critical displacement (δ_t)
1	34	0.0005	34	0.0005
2	17	0.001	17	0.001
3	25.5	0.00067	25.5	0.00067
4	8.5	0.002	8.5	0.002

3. Results and Discussion

The variation of the crack initiation load with various interfacial strengths for an adhesive joint with no defect has been shown in Fig. 3(a). This critical initiation load increases with increasing interfacial strength and for the interface with no defect and interface with 200 μm long defect the critical initiation loads are very similar. However, for the interfaces with 400 μm and 600 μm long defects, the critical initiation loads are lower. This might be because of two reasons: (a) due to the appearance of crack tip stress concentration leading to premature failure, and/or (b) due to the reduction in overall interfacial load carrying capability because of the reduced interfacial bond length. In the present case the latter seems to be more applicable as there does not seem to be any stress concentration at the tip of the defect. This is because of the existence of the crack within the highly compressed zone underneath the indenter and so the initiation of the crack does not happen near the tip of the defect. The decrease in the critical load with the decreasing interfacial strength is also expected. The Fig. 3(b) shows the variation of the normalised (with respect to load-displacement data from joint with no interfacial bonding 'P_o') load with the normalised (with respect to total interface length 'L') crack length. The Fig. 3(b) shows that

the crack propagation behaviour changes from stable to unstable growth as the interface strength increases. As can be seen, the joint with interface strength of σ_y (yield strength of the adhesive) exhibits an unstable crack growth after a particular crack length where the load drops suddenly. Moreover, the crack initiation load is similar for interfaces with interfacial strengths $0.5\sigma_y$ and $0.75\sigma_y$. However, after the crack initiation, the crack extension in the latter case ($0.75\sigma_y$) takes place under an almost constant load where as for the former ($0.5\sigma_y$) the load increases. This observed behaviour at higher interface strengths is because of the accumulation of the energy within the adhesive layer and the interface with increasing indentation load and the sudden release of this energy beyond a critical load leading to crack extension under constant load. The area under the load-displacement curve can be used as a measure of the indentation energy. Also, the slope of the load-displacement curve (Fig. 3) after the crack initiation gives a fair idea of the crack propagation scheme. It has also been found that the joints with lower interfacial strengths exhibit a gentler slope of the load curve after crack initiation.
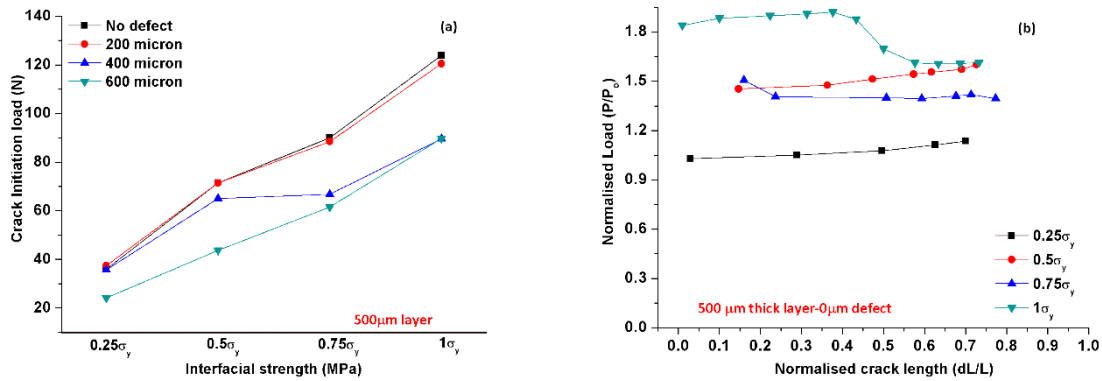
Figure 3: (a) Variation of crack initiation load with various interfacial strengths, and (b) various defects and variation of normalised load with normalised crack length

4. Conclusions and Future Work

a. Indentation based contact mechanics can be used as a testing method to evaluate the strengths (or residual strengths) of adhesively bonded joints of various adhesive layer thicknesses. The crack initiation load decreases with decreasing interfacial strength.

b. The effect of the presence defects (at the adhesive bond interface) on the load carrying capability can be seen as a reduction in the overall interfacial load carrying capability. This does not affect the crack initiation or propagation behaviour because of the presence of the crack within the high compressive stress zone (at indentation sub-surface zone). The effect of cracks situated away from this zone will be part of ongoing investigations.

c. The adhesive bond interfaces with higher bond strengths exhibit unstable crack growth behaviour and those with lower bond strengths exhibit stable crack growth. This is because of the higher crack length initiation loads at higher interfacial strengths leading to accumulation of strain energy in the bulk of the adhesive and adherends thus increasing the energy available for crack propagation.

References

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