CRACK TIP STRESS FIELDS AND FRACTURE TOUGHNESS IN ADHESIVE JOINTS

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SUMMARY: To study the fracture behaviour of an adhesive joint, a thorough understanding of the crack tip stress field is essential. In this study, large deformation finite element analysis has been carried out for compact tension (CT) specimen with different bond thickness. Numerical results indicate a higher opening stress is observed in the joint with a smaller bond thickness (h) when loaded to the same applied J-integral value. Beyond the crack tip region, a self-similar stress field can be described by the normalized loading parameter $J/h\sigma_o$. The relationship between J and crack tip opening displacement is dependent on the bond thickness. For small bond thickness, toughness is linearly proportional to bond thickness caused by the high constraint. Beyond a critical bond thickness, the toughness decreases due to the rapid opening (blunting) of the crack tip with loading.

KEYWORDS: adhesive joint, bond thickness, finite element analysis, constraint, fracture toughness.

INTRODUCTION

Rubber-toughened epoxies have been widely used to improve the toughness of adhesive joints. An important parameter in adhesive joint design is the bond thickness. Some investigations showed that there was an optimum thickness at which a maximum fracture toughness was obtained [1-2]. Kinloch and Shaw [2] explained this behaviour in terms of the size of plastic zone imposed by the adherends. A higher toughness is associated with a larger plastic zone. However, Chai [3] showed that the fracture characteristic and energy dissipation mechanisms are not directly related to the size of the crack tip plastic zone but instead to the fracture surface morphology. Recently, finite element analysis has been performed by Ikeda et al [4] on edge-crack and tapered double-cantilever-beam (TDCB) adhesive joints. Their results also showed that the area of plastic zone bears no relation to the fracture toughness. Further study is therefore necessary to discover the true effect of bond thickness on the fracture behaviour in an adhesive joint.

In this work, attention was focused on the elastic-plastic analysis of a crack in compact tension (CT) specimen with different bond thickness (h). The effects of constraint imposed by the adherends on the crack tip stress fields were analyzed. The relationship between J-integral and crack tip opening displacement (CTOD) was investigated. A simple model has been proposed to predict the variation of fracture toughness with bond thickness.

NUMERICAL PROCEDURE

Material Specification

To investigate the effect of bond thickness on the mode I fracture toughness in a toughened adhesive joint, a typical rubber-modified epoxy adhesive was chosen, which was a diglycidyl ether of bisphenol A (DGEBA) epoxy resin (Araldite® GY 260, Ciba-Geigy, Australia) modified by 15% liquid rubber (CTBN, 1300X13, BF Goodrich). The curing agent was piperidine. The mechanical properties of the adhesive in tension were measured in [5]. The elastic properties are: Young's modulus E=2.1 GPa and Possion's ratio ν=0.35. The adherends are assumed elastic with a Young's modulus E_s=71 GPa and Possion's ratio ν_s= 0.3.

Finite Element Modelling

Large deformation finite element analysis was carried out with finite element code ABAQUS (Version 5.7). Plane strain condition was assumed. The dimensions of the CT specimen are shown in Fig. 1.

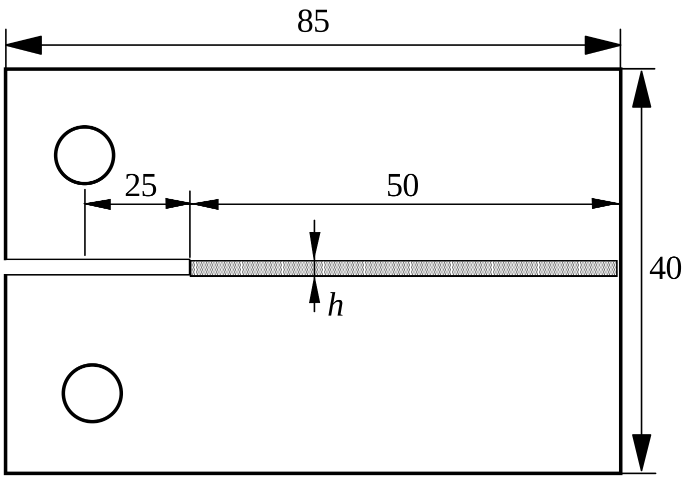


Fig. 1 Compact tension (CT) specimen (all dimensions in mm).

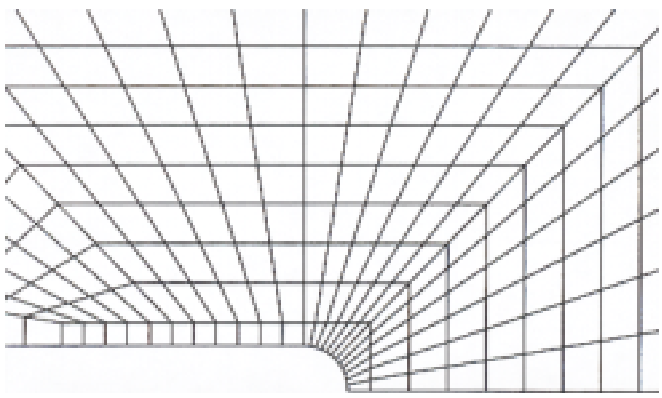


Fig. 2 Finite element mesh for the crack tip.

The bond thickness (h) was 0.1, 0.4, 1.0, 2.0 and 3.0 mm, respectively. Only one-half of the specimen was modelled because of symmetry. The details of the mesh at the crack tip are shown in Fig. 2. Rate-independent plasticity and associated flow rule were used for the material constitutive model. The J-integral was evaluated according to the domain integral method. The crack tip opening displacement (CTOD) was measured from the separation between the intercept of two 45^o-lines drawn from the crack tip with the deformed crack profile.

RESULTS AND DISCUSSION

Opening Stress Distribution ahead of Crack Tip

Fig. 3 shows the variation of opening stress (σ_{22}) with loading in the CT specimen (h=3 mm). X is the distance to crack tip and σ_o is yield stress. It can be seen that the opening stress increases with loading (J). A similar trend can be found for other specimens with different bond thickness. The stress fields in a metal foil between two elastic blocks have been investigated by Varias et al [6]. They found that the peak opening stress increases with loading at a distance several bond thickness ahead of the tip. More recently, the effects of constraint on crack tip stress fields in strength mismatched welded joints have been studied by Burstow et al [7] using finite element method. Their results showed that the opening stress increases with applied loading if the crack is located in the material with lower yield strength (under-matched joint).

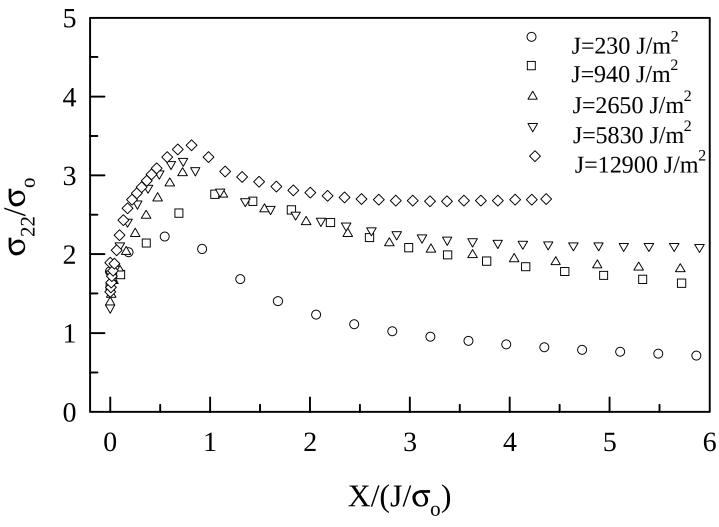


Fig. 3 Distribution of opening stress (σ_{22}) ahead of crack tip.

As mentioned in the **INTRODUCTION**, fracture toughness is dependent on the bond thickness for the toughened adhesive joint. It is therefore necessary to compare the stress field ahead of crack tip in the joint with different bond thickness. Fig. 4 gives a comparison of the opening stress for the CT specimens with different bond thickness at the same J. The opening stress is elevated with reduction of the bond thickness. In an adhesive joint, the constraint on the crack tip fields is mainly attributed to the restriction of plastic zone in the adhesive layer by the adherends. At the same applied load, the plastic zone is highly restricted by the adherends for the joints with a smaller bond thickness.

For homogeneous material in plane strain, the size of plastic zone (r_p) can be evaluated approximately by

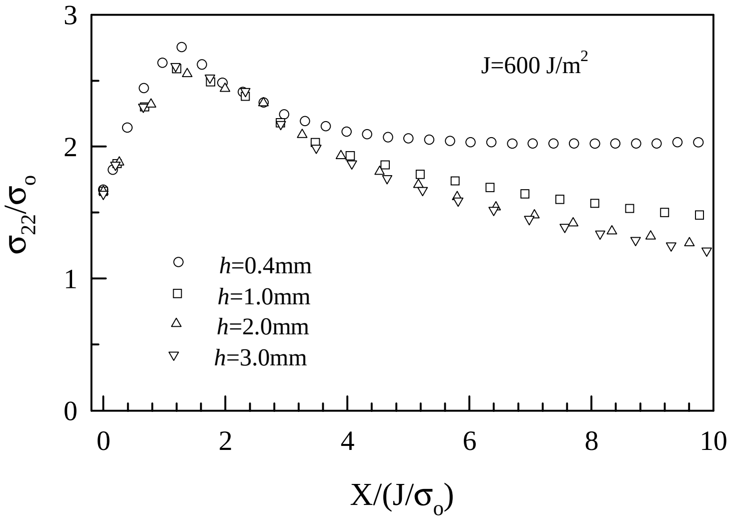
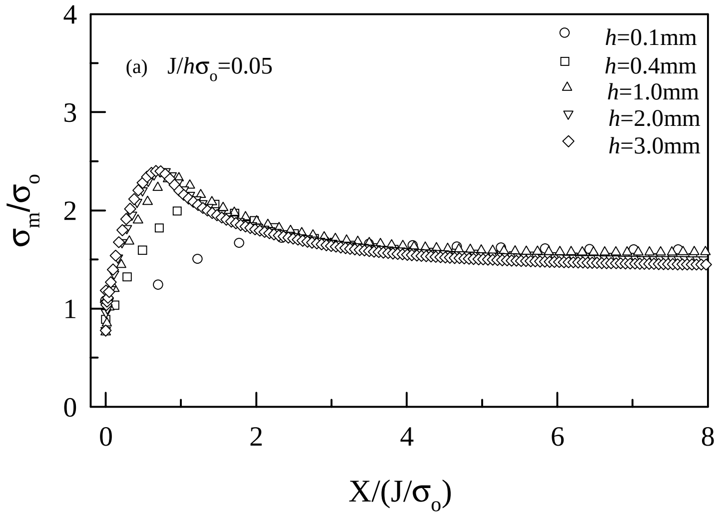


Fig. 4 Distributions of opening stress (σ_{22}) in CT specimen with different bond thickness.

$$r_p = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_o}\right)^2 = \frac{J}{\sigma_o}\left[\frac{1}{6\pi}\frac{E}{(1-\nu^2)\sigma_o}\right] \tag{1}$$

where *K* is stress intensity factor. It is clear that the size of plastic zone is approximately scaled by J/σ_o. The relative size of plastic zone in an adhesive layer with a thickness *h* is scaled by $J/h\sigma_o$. Therefore, $J/h\sigma_o$ is a potential parameter to indicate the constraint level imposed by the adherends. Fig. 5 gives the distributions of mean stress (σ_m=1/3(σ_{11}+σ_{22}+σ_{33})) for the CT specimens with different bond thickness, but loaded to the same value of $J/h\sigma_o$.



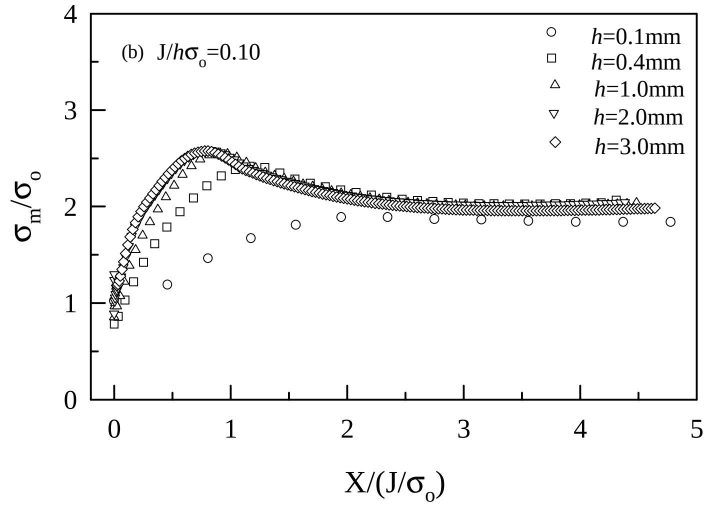


Fig. 5 Distributions of mean stress (σ_m) ahead of crack tip in the CT specimen when parameterized by $J/h\sigma_o$: (a) $J/h\sigma_o$=0.05, and (b) $J/h\sigma_o$=0.1.

It can been seen that beyond the crack tip, i.e., X/(J/σ_o)>2.0, the stress distributions are similar irrespective of the bond thickness. The same trend can be found for the opening stress distributions. A similar phenomenon has been observed by Burstow et al [7] for the plastic mis-matched weld joints. Fig. 6 shows the variation of σ_m/σ_o with $J/h\sigma_o$ at different locations X/(J/σ_o) ahead of the crack tip. It is clear that σ_m/σ_o increases almost linearly with $J/h\sigma_o$.

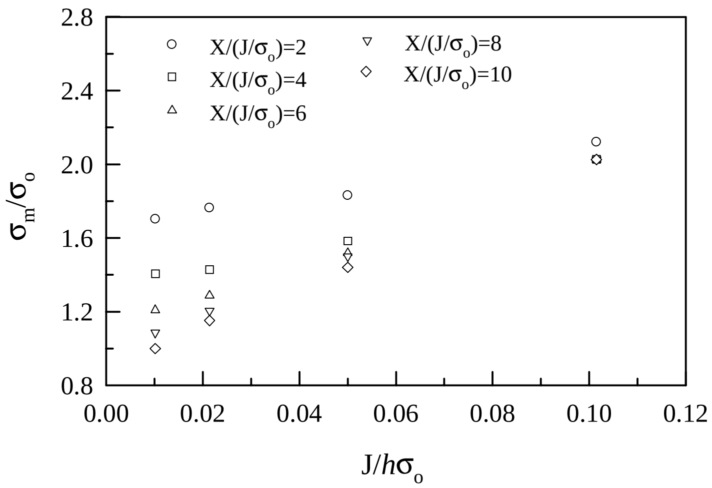


Fig. 6 Variation of σ_m/σ_o with load ($J/h\sigma_o$) at different X/(J/σ_o).

Relationship between J-integral and CTOD

In the early work of Shih [8] the relationship between *J*-integral and the crack tip opening displacement can be expressed by

$$J = m\sigma_o\delta \tag{2}$$

where δ is crack tip opening displacement. Fig. 7 shows the variation of m with the bond thickness h in the CT specimen. Clearly, m increases with decreasing bond thickness. Therefore, a large m is associated with a high constraint condition. This is similar to the calculation of Daghyani, Ye and Mai [9].

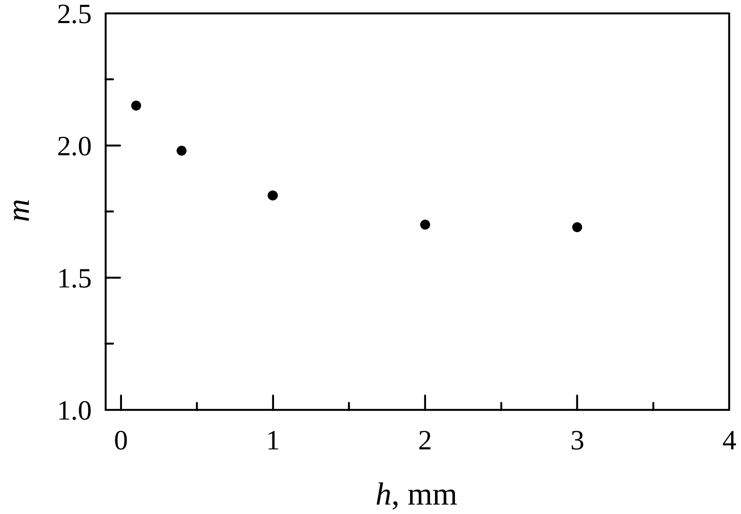


Fig. 7 Variation of m with bond thickness (h).

Effect of Bond Thickness on Fracture Toughness

For the CT specimen (Fig. 1), the fracture loads were measured at different bond thickness [10]. The J-integral values corresponding to the fracture load (J_c) were obtained from the finite element analysis and could be regarded as the fracture toughness. The variation of J_c versus bond thickness is also shown in Fig. 8. A maximum J_c was obtained at 1.00 mm bond thickness.

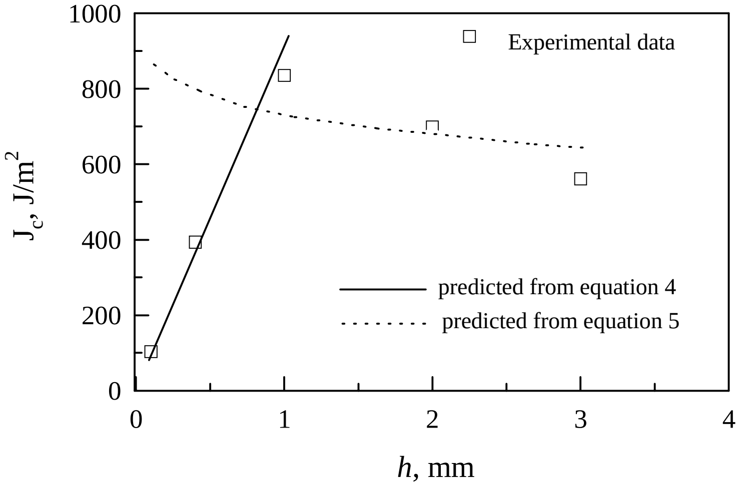


Fig. 8 Fracture toughness (J_c) at different bond thickness (h).

For metallic materials, Varias et al [6] showed that two competing fracture mechanisms existed for a constrained layer. For an adhesive joint, the effect of bond thickness on the fracture surface morphology was investigated by Chai [3]. The fracture surface morphology changed with bond thickness, which indicates different fracture mechanisms corresponding to different bond thickness. Recently, the mode I fracture behaviour of rubber-toughened adhesive joint was investigated experimentally by Daghyani *et al* [11] using the same material and specimen geometry (CT) as used in this work. They found that brittle fracture mechanism was associated with thin bond thickness (h<0.5 mm) but ductile fracture mechanism was predominant for thick bond thickness (h>1.0 mm). Hence, there was a transition of fracture mechanisms with increasing bond thickness. Generally, brittle fracture is mainly controlled by critical triaxiality or critical opening stress [12]. On the other hand, critical strain criterion has been widely adopted for ductile fracture. For an under-matched welded joint, Smith [13] used a critical crack tip opening displacement to evaluate the variation of J-integral with crack size and weld thickness. Therefore, based on the above observations by these previous investigators, it is reasonable to assume that fracture is controlled by a critical stress and a critical crack tip opening displacement for the adhesive joint with thin and thick bond thickness, respectively. In Fig. 6, the mean stress σ_m/σ_o increases almost linearly with the load ($J/h\sigma_o$). Hence, we have

$$\frac{J}{\sigma_m h} = C_m \tag{3}$$

where C_m is a proportional constant. Assuming the critical mean stress equals $C_n\sigma_o$, the fracture toughness can be expressed as

$$J_c = C_n C_m \sigma_o h \tag{4}$$

where C_n is a constant. It is clear in Eq. 4 that the fracture toughness J_c is proportional to the bond thickness. Tvergaard and Hutchinson [14] used a cohesive model to investigate the toughness of adhesive joint with different bond thickness. They found that the toughness increased initially with the bond thickness and then remained at a constant value, which is independent of the bond thickness. On the other hand, it can be seen in Fig. 6 that although a linear relationship between σ_m/σ_o and $J/h\sigma_o$ can be observed, the slope is different at various locations ($X/J/\sigma_o$) ahead of the crack tip. It means that the proportional parameter C_m is dependent on the locations where the initiation may occur. Assuming a fixed initiation distance ($X/J/\sigma_o$) can be applied for the specimen with different bond thickness, C_nC_m can be calibrated from the fracture toughness corresponding to a certain bond thickness (h). Then, this constant can be applied to Eq. 4 to predict the toughness of other bond thickness. Fig. 8 also gives a comparison between predicted values according to Eq. 4 (solid line) and J_c values corresponding to the respective bond thickness. The agreement is very good for h less than 1 mm, i.e., thin bond thickness.

With increasing bond thickness, fracture is more likely to be controlled by the critical crack tip opening displacement (δ_c). By rearranging Eq. 2, we have

$$\delta_c = \frac{J}{m\sigma_o} \tag{5}$$

Obviously, fracture toughness depends on both δ_c and m. For a given material, the toughness is mainly controlled by m. In Fig. 7, m decreases with increasing bond thickness (h). Thus, to achieve a critical crack tip opening displacement (δ_c) a small J is needed for the joint with thick bond thickness. δ_c can also be calibrated from a joint with a large bond thickness. Then, the variation of fracture toughness J_c with bond thickness can be predicted from δ_c and m. As shown in Fig. 8, the prediction in the CT specimen (dash line) gives the same trend as the calculated J_c when h>1mm.

Therefore, the variation of toughness in adhesive joint is likely to be a result of the competition between two different fracture mechanisms, i.e., brittle fracture due to high stress and ductile fracture by crack tip blunting. For small bond thickness, fracture toughness is linearly proportional with thickness. After reaching a critical bond thickness, fracture toughness decreases with further increase of bond thickness due to the rapid opening (blunting) of crack tip with applied loading. The critical bond thickness, at which fracture mechanisms changes, is dependent on the specimen geometry and the mechanical properties of both the adhesive and adherends, as shown in Fig. 8. Although the simplified model proposed in this study appears to work reasonably well in comparison with experimental data, it is entirely a mechanistic approach but offers no interpretation of physical processes operative at the crack tip. Further work is therefore needed to show the complex but physically different fracture mechanisms, as postulated above, corresponding to both thin and thick bond thickness of the adhesive joint.

CONCLUSIONS

Based on large deformation finite element analyses performed on CT specimens with different bond thickness, the following conclusions can be drawn:

1. At the same J level, a higher opening stress is observed in the joint with a smaller bond thickness. The peak stress increases steadily with applied load
2. Beyond the crack tip region, a self-similar stress field can be described by the normalized loading parameter $J/h\sigma_o$. The relationship between J and crack tip opening displacement is dependent on the bond thickness.
3. A simple model has been proposed to predict the variation of toughness with bond thickness. For small bond thickness, toughness is linearly proportional to bond thickness due to the high constraint imposed. After reaching a critical bond thickness, the toughness decreases with further increase of bond thickness due to the rapid opening (blunting) of the crack tip with loading.

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