FAILURE ANALYSIS OF ADHESIVELY BONDED JOINTS

C. H. Wang and L. R. F. Rose
Aeronautical and Maritime Research Laboratory, Melbourne, Australia.

ABSTRACT

Adhesively bonded joints are presently designed based on the conventional stress or strain based failure criteria, although fracture mechanics approach is emerging as a better alternative. A number of experimental studies have shown that the static strength of adhesively bonded joints decreases with the adhesive thickness, in a trend opposite to that predicted by existing strength type of failure criteria. In this paper, a critical assessment is made of the existing failure criteria by comparing predictions with experimental results. Three failure regimes have been identified for cases where joint strength is limited by failure in the adhesive: gross yielding, elastic-plastic failure, and elastic fracture. A failure criterion is proposed for predicting the failure strength of adhesively bonded joints under static and fatigue loading.

KEYWORDS Bonded joints, fracture, failure criteria.

INTRODUCTION

Despite an extensive literature on the stress-strain analysis of adhesively bonded joints, following the pioneering work by Volkersen (1938) and Goland and Reissner (1944) on single lap joints (see Fig.1), the predictive tools for joint strength and fatigue durability are not well established. Using a similar approach, Cornell (1953), and Hart-Smirth (1973a) analysed double lap joints. In these one-dimensional analyses, the adhesive stresses turn out to be bounded, and there does not exist a stress singularity. In other words, the end of a joint represents a stress concentration rather than a stress singularity, a fact that has been repeatedly and convincingly demonstrated by the good agreement between the analytical (1D) stress-strain distribution and the 2D finite element solutions. Even though there may exist a theoretical singularity due to mismatch that occurs at the bi-material interface, the region of dominance of this elastic singularity is limited to a scale less than or comparable with the thickness of the adhesive, t_a. It can therefore be ignored, particularly in the presence of plastic yielding in the adhesive over a distance greater than t_a. This condition is almost invariably satisfied in practice for structural adhesives, which are required to have adequate toughness if they are to be useful.

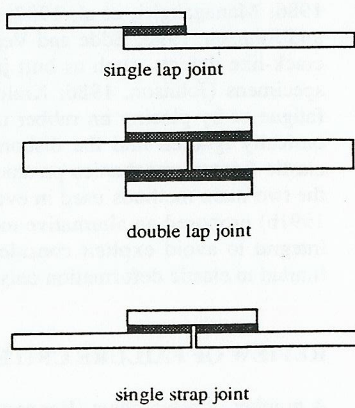

Fig. 1. Configurations of single lap, double lap, and single strap joints

The large number of stress analyses of adhesively bonded joints have revealed that, for a variety of joint configurations, both the shear and peel stresses are inversely proportional to the square root of the adhesive thickness. In other words, the thicker the adhesive, the lower the stresses are. Adhesive failure within a joint is usually assumed to be governed by a critical stress, or a critical strain criterion, sometimes coupled with a characteristic length (Kinloch,1987). Some examples include Hart-Smith (1973a, 1973b), Ikegami and Sugibayashi (1987), Adams (1989,1992), Bigwood and Crocombe (1990), Crocombe et al (1990), Kairouz and Matthews (1993). Strain energy density (Hart-Smith, 1973a; Jones, et al, 1993) and stress over a zone (Clark and Mcgregor, 1993) have also been suggested for predicting joint strength. However, there has been little experimental validation of these suggested approaches, especially for joints with different bondline thickness. This problem is exacerbated by the limited amount of experimental data available in the literature, especially joints with long overlap. Nevertheless, it has been reported that (Kinloch,1987) that there is a large discrepancy between theoretical predictions and experimental data. Using the conventional strain or stress based failure criteria, an increase in joint strength (total failure load) is predicted with an increase in adhesive layer thickness. However, exactly the opposite is often observed in experiments (Bennett, 1972; Crocombe and Moult, 1988; Hylands and Sidwell, 1980; Imanaka, et al, 1989; Harris and Fay, 1992). Furthermore, it has also been reported that fatigue crack growth rates and fatigue endurance (Imanaka et al, 1988, 1989; Harris and Fay, 1992; Krenk *et al*, 1996) also exhibited anomalous behaviour with respect to adhesive thickness. These workers have reported that, when compared on the basis of the maximum (shear or normal) stress in the adhesive, fatigue strength decreases as the bond-line thickness increases. Therefore it is clear that the conventional failure criteria, be it stress, strain, or strain energy density based, are not geometry independent, hence the data obtained from one configuration are not readily transferable to other types of joint, or the same joint with different bondline thickness.

Fracture mechanics concepts have also been introduced for characterising bonded joints (Mall, et al, 1982; Johnson and Mall, 1985; Flashner et al, 1985; Mangalgiri and Johnson, 1986; Managakgiri, et al, 1987; Schmueser and Johnson, 1990; Schmueser, 1991; Russell and Johnson, 1990; Edde and Verreman, 1992; Krenk *et al*, 1996), but mainly to joints with crack-like defects, such as butt joints, edge cracked cantilever beam and cracked-lap-shear specimens (Johnson, 1986; Kinloch, 1987). Frequently a pre-crack is introduced either by fatigue or by placing an rubber insert to create a disbond. The thickness of the adhesive is basically ignored and the disbond is treated as a crack, thus permitting the use of linear elastic fracture mechanics parameters. Finite element analysis and compliance approach are the two main methods used in evaluating the energy release rate. Fernlund and Spelt (1991a; 1991b) proposed an alternative method of calculating the strain energy release rate via the J-integral to avoid explicit consideration of the adhesive layer stresses, but their analysis is limited to elastic deformation only.

REVIEW OF FAILURE CRITERIA AND EXPERIMENTAL DATA

A number of researchers (Bennett, 1977; Crocombe and Moult, 1988; Harris and Fay, 1992) have reported that the failure load of single lap joints decreased with the glue-line thickness. In most of these studies, short overlap lengths were adopted to ensure failure to occur within the adhesive. As expected, strain or stress based failure criteria will clearly predict thicker joints to be stronger than thinner joints. A comparison between experimental results and analytical predictions is shown in Fig.2. Since adhesive thickness is the only variable in these experiments, experimental data are plotted in terms of the normalised failure load and normalised bondline thickness. Here the normalisation is carried out with respect to that of the thinnest joint in each case. Clearly, as the bondline thickness is increased, the failure load decreased by up to 40 percent. Also shown in the figure are the analytical prediction based on maximum stress criterion. For single lap (Goland and Reissner, 1944), double lap and single strap joints (Wang, 1996), the maximum shear and peel stresses in the adhesive can be expressed as

$$\sigma_{\max} = -\frac{ME_a}{2t_a D\lambda^2} \qquad (1)$$

$$\tau_{\max} = \left[\frac{P}{Et} - \frac{6M}{Et^2}\right]\frac{G_a}{t_a\beta} \qquad (2)$$

where M is the bending moment at the edge of the joint induced by eccentricity of load, E_a and t_a are the adhesive Young's modulus and thickness, D is the bending stiffness of the plate $(=(1-\nu^2)Et^3/12)$ which carries the load P. For the same applied load, the bending moment is dependent on the adhesive thickness. Parameters $\lambda^4 = E_a(1/D_1 + 1/D_2)/(4t_a)$ and $\beta^2 = \frac{4G_a}{t_a}(\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2})$. Therefore, it is easy to see from equations (1) and (2) that both the shear and peel stresses are inversely proportional to the square root of adhesive thickness, i.e., $\sigma_{\max} = \frac{A_1 P}{\sqrt{t_a}}$ and $\tau_{\max} = \frac{A_2 P}{\sqrt{t_a}}$, where A_1 and A_2 are two constants. If the failure of joint is assumed to occur when either the peel or shear stress attains a critical value, then the predicted failure load would be proportional to the square root of bondline thickness:

$$\frac{P_f}{P_f(t_{a,0})} = \sqrt{\frac{t_a}{t_{a,0}}} \qquad (3)$$

where $P_f(t_{a,0})$ is the failure load for a joint with an adhesive thickness equal to $t_{a,0}$. As shown in Fig.2, the prediction is extremely non-conservative if the failure load of thin joints is used to derive the relevant material constants. An example of the influence of adhesive thickness on fatigue endurance is shown in Fig.3, where the experimental data were taken from Imanaka *et al* (1989). Clearly at a give local stress level, thicker joints exhibited lower endurances than thin joints.

EXPERIMENTS AND RESULTS

A series of experiments have been performed using single strap joints (see Fig.1c), representative of one-sided bonded repairs. A schematic drawing of the specimen is shown in Fig.4 Two aluminium alloy plates were bonded together with a steel splice plate. Detailed information regarding the mechanical properties of FM73 can be found in Ref. (Chalkley and Chiu, 1993). Specimens were surface treated and then bonded with FM73 file adhesive. A special jig was fabricated to achieve a precise control of the adhesive thickness when specimens were cured in an autoclave. Specimens were cured for about one hour in an autoclave at a temperature of 180^{0}C.

Experiments were conducted under displacement control at ambient temperature. A constant crosshead speed of 0.1 mm/minute was used. Load and displacement were recorded using a computer data acquisition system. Fig.5 shows some typical load-deflection curves recorded

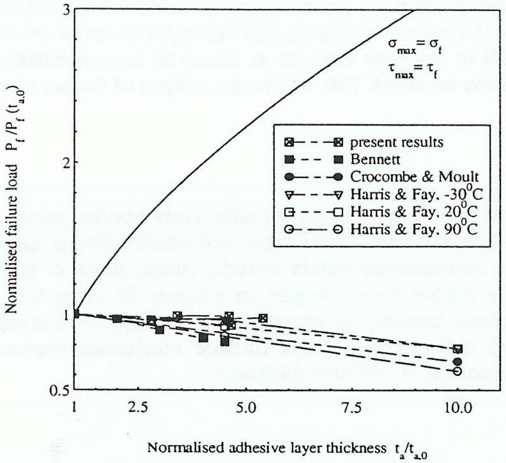

Fig.2 Comparison between experimental results and prediction.

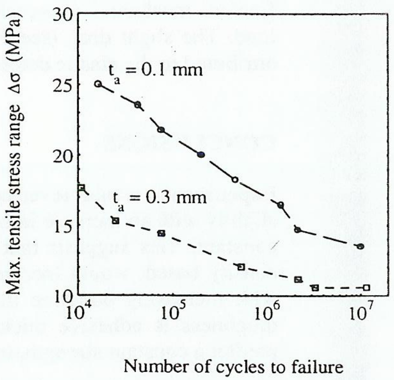

Fig.3 Influence of bondline thickness on fatigue endurance

for three different adhesive thickness: 0.25, 0.45 and 0.71 mm, respectively. It is evident the load-deflection curve is non-linear, which is mainly due to the plastic deformation of the adhesive, although the strap joint's geometrical nonlinearity caused by secondary bending also plays a part. It is worth noting most of the joints did not fail in a brittle manner, in the sense that there is still considerable post-failure plastic deformation or crack growth.

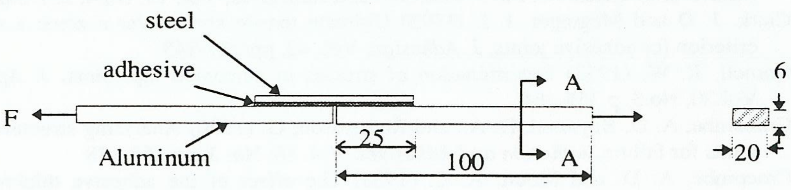

Fig.4 Drawing of single strap joint specimen (dimensions in mm)

Since all the joint dimensions are exactly the same except the bondline thickness, which is the only variable affecting the joint strength, the maximum failure load is plotted against the adhesive thickness in Fig.6. It is seen that the joint strength exhibits a slight decrease with bondline thickness, in agreement with the reported experimental results discussed in the previous section. It is interesting to note that the average failure load of 12 kN is much lower

than the plastic collapse load or gross yielding load, 16.5 kN, at which the entire joint overlap attains the shear yield stress. In other words, the hypothesis that joint strength is carried by yield stress (sections under yielding) will considerably over-predict joint strength.

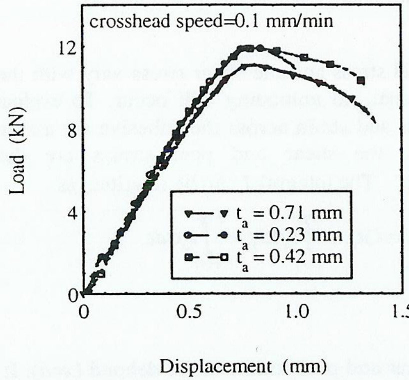

Fig.5 Load deflection curve for single strap joints.

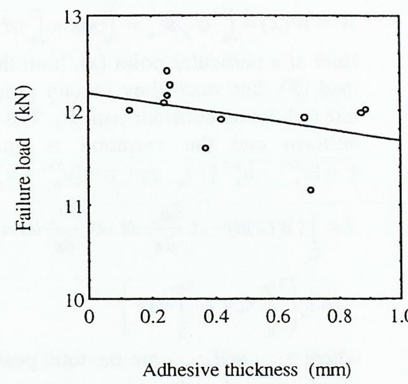

Fig.6 Failure loads for various adhesive layer thickness.

ELASTIC-PLASTIC FAILURE CRITERIA

Let us consider a region near the end of a disbond between two adherends, as shown in Fig.7, which is a representative of adhesively bonded joints. The two main stress components for the adhesive are the shear stress and the transverse peel stress. When the applied load exceeds a certain level, adhesive yielding will occur, hence inducing plastic deformation. In this case, the plastic zone is constrained within the adhesive and spreads only along the bondline, due to the constraint imparted by the stronger adherends surrounding the adhesive. The configuration shown in Fig.7(a) clearly resembles more like a notch than a crack, since the

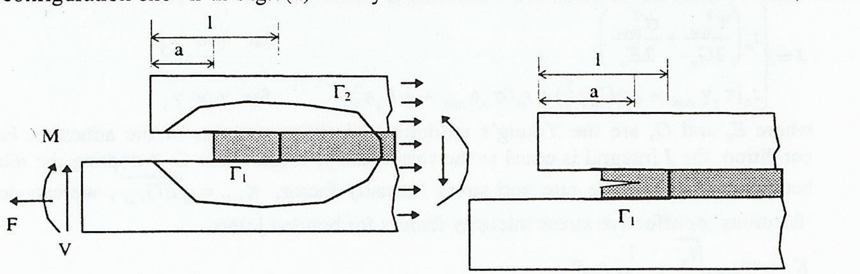

Fig.7 Contours for J-integral

elastic stress and strain are bounded and the distribution does not obey a inverse square root relationship, but an exponential decay with respect to the distance from the end of the joint. For the sake of simplicity, here we will ignore any plastic deformation of the adherends, assuming the adhesive will fail before the stresses in the adherend reach yielding. Consequently the plastic deformation is contained in the adhesive only. We also assume that the disbond growth is stable, in other words, the stress-strain field ahead of the disbond simply shifts forward after advancing a small distance. The energy consumed during the disbond growth is thus equal to the nonlinear energy release rate, namely the J-integral calculated along a path circulating the notch root. The J-integral theory can be applied to an adhesively bonded joint, providing the strain-energy-density W is defined by

$$W = W(x) = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij} = \int_0^{\varepsilon} \sigma d\varepsilon + \int_0^{\gamma} \tau d\gamma \,. \tag{4}$$

Here at a particular point (x), both the peel stress and the shear stress vary with the applied load (F), but since they remain proportional, no unloading will occur. To evaluate the J-integral, let us consider path Γ_1. The stress and strain across the adhesive are assumed to be uniform and the variation is ignored, the shear and peel strains are defined as $\gamma = [u_x^{(+)} - u_x^{(-)}]/t_a$ and $\varepsilon = [u_y^{(+)} - u_y^{(-)}]/t_a$. The integral J can be rewritten as

$$\begin{aligned} J &= \int_{\Gamma_1} (W(x)dy - \tau \frac{\partial u_x}{\partial x} ds - \sigma \frac{\partial u_y}{\partial x} ds = W(x=\ell)t_a + \int_{\gamma(\ell)}^{\gamma_{max}} t_a \tau d\gamma + \int_{\varepsilon(\ell)}^{\varepsilon_{max}} t_a \sigma d\varepsilon \\ &= t_a \left(\int_0^{\gamma_{max}} \tau d\gamma + \int_0^{\varepsilon_{max}} \sigma d\varepsilon \right) \end{aligned} \tag{5}$$

where γ_{max} and ε_{max} are the total peak shear and peel strains at the debond ($x=a$). It is worth pointing out that the above integral is independent of the exact stress-strain relation. It also confirms that the J integral is independent of paths, in this case, length ℓ. Thereafter it can be evaluated by collapsing the integral path on to the direct path along a path transversing the adhesive.

Since the stresses along path Γ_1 for the two cases shown in Fig.6 are virtually the same, the J integral given by equation (5) is also the same, viz $J_A = J_B = J_C$, provided the applied load is the same. Thus J-integral provides a universal parameter for bonded joints, which is insensitive to the local disbond profile, be it a flat end or a sharp crack. Therefore in the following analysis, the exact shape of the debond front is not distinguished.

The J-integral appropriate to a nonhardening adhesive is

$$J = \begin{cases} t_a \left(\dfrac{\tau_{max}^2}{2G_a} + \dfrac{\sigma_{max}^2}{2E_a} \right) & \text{for } \gamma < \gamma_y \\ t_a[\tau_y \gamma_{max} - \tfrac{1}{2}\eta G_a \gamma_y^2] + t_a[\sigma_y \varepsilon_{max} - \tfrac{1}{2} E_a \varepsilon_y^2] & \text{for } \gamma > \gamma_y \end{cases} \tag{6}$$

where E_a and G_a are the Young's modulus and shear modulus of the adhesive. For elastic condition, the J integral is equal to the strain energy release rate G. Adopting the relationship between energy release rate and stress intensity factor, $K_{I,II} = \sqrt{EG_{I,II}}$, we can define two 'fictitious' or effective stress intensity factors for bonded joints,

$$K_I = \sigma_{max} \sqrt{\frac{t_a}{2}} = \frac{1}{\sqrt{2}} A_1 P \tag{7}$$

and

$$K_{II} = \tau_{max} \sqrt{\frac{t_a}{2} \frac{E_a}{G_a}} = \sqrt{\frac{E_a}{2G_a}} A_2 P \tag{8}$$

It should be pointed that these parameters are valid only for elastic fracture, in other words, for brittle adhesives. It is interesting to note that the above results suggest that a bonded joint

with an adhesive layer of thickness of t_a behaves like a homogeneous solid with an intrinsic crack of a half length equal to $t_a/2\pi$ for mode I and/or $E_a t_a/(2\pi G_a)$ for mode II, provided the local stresses σ and τ are bounded. It is interesting to note that the stress intensity factors for the 'fictitious crack' are independent of the bondline thickness. This means that the fracture mechanics approach will predict a constant joint strength in terms of the applied load. The slight drop (see Fig.2) in the joint strength as observed experimentally could be attributed to the plastic deformation involved. This will be the subject of further work.

CONCLUSIONS

Experimental results revealed that the static strength of adhesively bonded joints decreased slightly with an increase in bondline thickness, and fatigue endurance remains approximately constant. This suggests that the conventional failure criteria, stress, strain or strain energy density based, would incorrectly predict joint strength: an increase in strength is predicted with increasing bondline thickness, contrary to experimental findings. Assuming fracture toughness is adhesive thickness independent, elastic fracture mechanics approach would predict a constant strength, independent of adhesive thickness.

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