LMECA2410 – Mechanics of Materials

Fracture Mechanics Project

Work performed by Group 3:

Fasilow Igor

Shimwa Muhire Beni

Termini Alessandro

Vansnick François

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Project Overview

This report focuses on evaluating the fracture toughness of a new adhesive material for aerospace applications. The adhesive is characterized by its toughness, which determines its ability to resist crack propagation under given loading conditions.

1 Analysis of Laboratory Testing Results

An adhesive layer containing an edge crack is subjected to laboratory testing at $T = 25C$. The stress observed at failure is $\sigma_\infty = 40$MPa. The material properties of the adhesive are the following: Young's modulus $E = 2.5$ GPa , Yield strength is $\sigma_{yield} = 30$ MPa and Poissons ratio is $\nu = 0.4$. Let's assume there is no thickness effect.

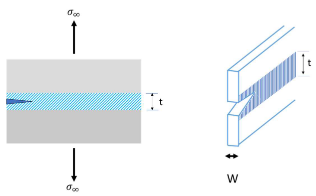

Figure 1: bi metal adhesive joint with adhesive thickness t.

1.1 Critical-crack length and energy release rate at critical stress

We know that for this given thickness we got the stress intesity factor for mode 1 $K_{Ic} = 3.17$ MPA$\sqrt{m}$.

From the equation of the stress intensity factor:

$$K_{Ic} = Y\sigma^\infty\sqrt{\pi a} \tag{1}$$

If we assume a $Y = 1$, and for the critical applied stress σ^∞ we use yield stress $\sigma^\infty = \sigma_{yield} = 30$ MPa and we easily get the critical-crack length as:

$$a = \frac{(\frac{K_{Ic}}{\sigma^\infty Y})^2}{\pi} = 3.55mm$$

Then we calculate the energy release rate at the critical crack length that quantifies the amount of energy per unit area released during crack propagation in a material. In general:

$$G = \frac{K_I^2}{E*} \tag{2}$$

Since we are in a case where the thickness of the plate is very small we can assume that we are in the plane stress case and the stress can be assumed to be in one plane. So this mean that $E^* = E$. Finally we get:

$$G = \frac{(3.17e^6)^2}{2500e^9} = 4019.56[\frac{J}{m^2}]$$

1.2 Stress-intensity factor of a thicker plate

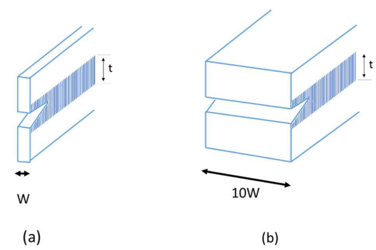

Figure 2: (a) thin plate with out of plan thickness of W, (b) thick plate with out of plane thickness 10W.

As we are in the case of a thicker plate, plane stress assumption no longer holds and therefore we must make the hypothesis that we are in the plane strain case where $E^* = \frac{E}{1-\nu^2}$.

On the other hand, the energy release rate remain the same so the new stress concentration factor can be calculated as:

$$K_{Ic} = \sqrt{GE^*} = \sqrt{G\frac{E}{1-\nu^2}} = 3.46 \text{ MPA}\sqrt{m}$$

We can see that for thick plates the K_{Ic} of the material increases which means that there will be more stress at the crack tip and as a result the crack will tend to propagate more and more which reduce the resistance to crack propagation also increases.

2 Effect of the temperature and resiudual stresses on the fracture energy

To check for the effect of temperature on the fracture energy for the thin plate we measured the effect of the residual stresses at different temperatures. These residual stresses in adhesives are due to "curing" of adhesives and mismatch of thermal expansion. The residual stress has been measured to be compressive ($\sigma_{compressive} = 2$ MPA) at T= 25°C and tensile ($\sigma_{tensile} = 3$ MPA) at T=15°C. For this case we are making the hypothesis that the critical energy release rate is independent of temperature.

2.1 Failure Stress

As we know that failure stress was $\sigma_\infty = 40$ MPA in the our case, we can easily calculate the actual failure stress for the given temperatures to be:

$$\sigma_{fail} = 40 + 2 = 42 \text{ MPA at } 25°\text{C}$$
$$\sigma_{fail} = 40 - 3 = 37 \text{ MPA at } 15°\text{C}$$

The compression residual stress ($\sigma_{compressive}$) is opposed to the forces applied during the test, which tends to increase the actual applied failure stress observed. On the other hand, the tensile residual stress ($\sigma_{tensile}$) is in the same direction as the forces applied during the test which will indeed decreases the actual failure stress.

2.2 Energy release rate at fracture

2.2.1 At 25°C

From equation (1) using the applied stress $\sigma_\infty = 42$ MPA we get:

$$K_{Ic} = 1 * 42\sqrt{\pi 3.55e^{-3}} = 4.43 \text{ MPA}\sqrt{m}$$

Which now allows us to calculate the energy release rate at fracture with equation (2):

$$G = \frac{K_I^2}{E} = 7869.31[\frac{J}{m^2}]$$

2.2.2 At 15°C

From equation(1) using the applied stress $\sigma_\infty = 37$ MPA we get:

$$K_{Ic} = 1 * 37\sqrt{\pi 3.55e^{-3}} = 3.91 \text{ MPA}\sqrt{m}$$

And so the resulting energy release rate at fracture is:

$$G = \frac{K_I^2}{E} = 6107.19[\frac{J}{m^2}]$$

As we can see, residual stresses have a significant impact on the energy release rate. Indeed, compressing the atoms increases this energy and therefore improves the mechanical behavior and prevents fractures.

This also, shows that it is better to have materials under warm conditions rather than cold conditions ; in cold conditions, materials tend to have less energy release rate and can fracture more easily.

3 The Size of plastic Zone

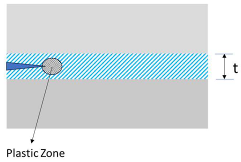

Figure 3: bi metal adhesive joint with adhesive thickness of t.

3.1 Radius of plastic zone

The next task in this project is to determine whether the plastic zone remains entirely within the adhesive joint for two different thicknesses $t_1 = 5$ mm and $t_2 = 8$ mm, assuming that linear elastic fracture mechanics (LEFM) is well satisfied. We calculate the formula for the crack radius using :

$$r_Y^{plane\_stress} = \frac{1}{\pi}(\frac{K_I}{\sigma_0})^2 \tag{3}$$

As we are in the case of a thin plate, we will use the plane stress assumption and we get:

$$r = \frac{1}{\pi}(\frac{3.17}{30})^2 = 3.554mm$$

Consequently, the plastic zone must have at the very least a thickness equals to 7.1 mm, 2 times r_Y. The adhesive thickness of $t_1 = 5$ mm is insufficient to fully contain the plastic zone. However, the adhesive of thichness $t_2 = 8$ mm will indeed make sure the size of the plastic zone is fully defined within it.

3.2 Minimum adhesive thickness to reach maximum fracture toughness

If the thickness of the adhesive is less than the size of the plastic zone, the plastic zone cannot fully expand, decreasing the fracture toughness of the joint. so the minimum thickness is simply:

$$t = 2r_Y = 7.1mm$$

This comes to affirm that only the adhesive of thickness $t_2 = 8$ mm will be the only one to reach maximum fracture toughness.

4 DCB compliance method

For the next task, we evaluated the DCB compliance of 2 different adhesive materials and plotted the results of the test to identify the toughest adhesive. The force displacement curve of the two materials is shown as below.

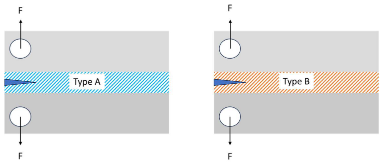

Figure 4: bi metal adhesive joint subjected to DCB test.

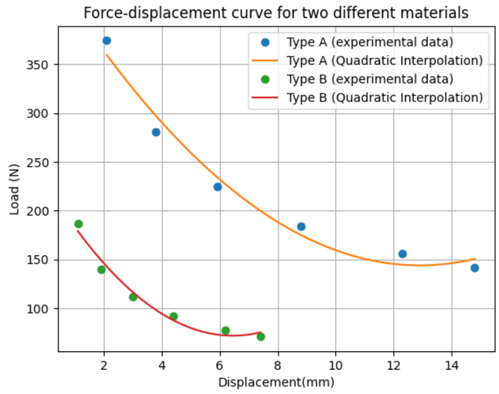

Figure 5: Force-Displacement curve

From the graph above, type A material appears to be tougher than type B because it requires more force to propagate the crack.

4.1 Critical energy release rate

With the compliance method we can calculate the energy release rate using the following formula:

$$G = \frac{-\delta P}{\delta A} = \frac{F^2}{2}\frac{\delta C}{\delta A} = \frac{F}{2B}\frac{\delta u}{\delta a} \tag{4}$$

Using this equation we calculated the mean energy from the experimental results using graphical interpolation as below.

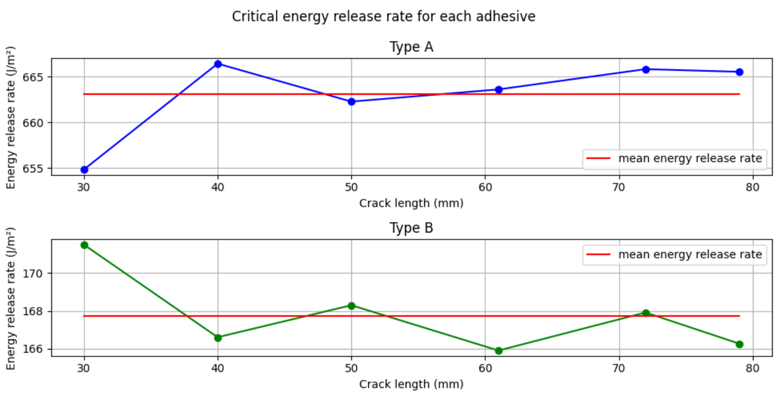

Figure 6: Mean Energy release rate

For type A material, G = 663.085 $[\frac{J}{m^2}]$ and for type B, G = 167.75 $[\frac{J}{m^2}]$. This confirms our initial deduction as type A has a higher Energy release rate and therefore much tougher than type B.

4.2 Bi-adhesive joint

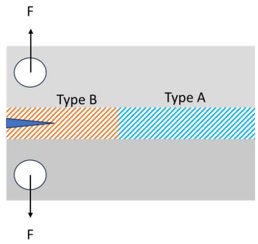

Figure 7: bi metal adhesive joint with combination two different adhesives subjected to DCB test.

Next we tested the effect of using a bi-adhesive joint. This joint is made of the Type B adhesive for the first 40 mm, and then it is replaced by the Type A adhesive for the rest of the joint. The force-displacement curve of the joint is as below. First, load transfer to the second material occurs

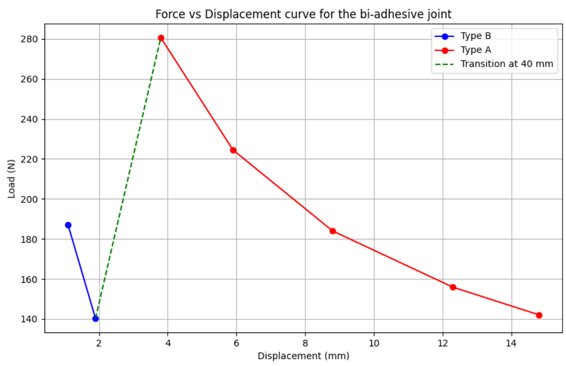

Figure 8: Force displacement curve

when the initial adhesive begins to fail. In this case, the applied load is transferred to the second material. This transition is beneficial because the second material, being more resistant to fractures, will be able to support this additional load, which can improve the robustness of the connection.

Then, adding the second material can help strengthen the overall structure. Indeed, if this second material has greater fracture resistance than the initial adhesive, it can effectively redistribute the load and limit the propagation of cracks. Thus, this transition to a more resistant material can result in an improvement in the resistance of the overall structure.