Determinaton of Decisive Parameters in the Crack Propagation Analysis of an Adhesive Joint

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Abstract
Validation of an adhesive joint strength is by and large done through crack propagation analysis influenced by the loading modalities leading to different testing methodologies. The DCB test method is extensively used under more-1 loading to study the fracture and delamination toughness of adhesive joints. The significance and suitability of using the test when the hardener-resin proportion of the adhesive is varied needs to be scrutinized. Three mild steel DCB specimens were analysed incorporating the proportion-variation. The analysis revealed the need of using the Cohesive Zone Model (CZM) to study the crack propagation in all the specimens as a pattern of inconsistent proportionality emerged between the resin proportion and the crack propagation. The graphs converged to a particular degree between the experimental and the analytical realms which further instigated the need of modeling of the entire specimen inclusive of the adhesive layer through Finite Element Analysis. The obtained results provided insights on stress distribution inside the adhesive layer when crack propagation takes place in the specimens. The proportion variation done in a systematic manner is seen as a key factor in improvisation techniques for analysis when efforts are undertaken to introduce modalities in crack propagation direction control.

Keywords: Adherent Material, Cohesive Zone Model, Double Cantilever Beam, Fracture Toughness, Hardener-Resin Proportion, Resistance Curves

1. Introduction
Adhesive joints are identified for their effective load and stress distribution over the total bonding region of the joint. They are considered over other conventional joints due to their abilities including fatigue elimination, crack stoppage, galvanic removal, vibration reduction, and enhanced sealing quality. The justification of adhesive joints is done by studying the crack propagation during loading which needs the consideration of parameters including dissimilar adherent materials, adhesive composition, etc. The study of crack propagation in an adhesive joint depends on the type of loading conditions in which the mode-1 loading is more prevalent. Hence an investigation is done to analyse the nature of crack propagation under mode-1 loading conditions using a Double Cantilever Beam (DCB) test. Composition variation is introduced in the specimens and the results are compiled.

2. Function of DCB Tests under Mode-1 Loading
The DCB test is used to study the fracture response of adhesive joints under mode-1 loading. The main objective of the test is the calculation of the Strain Energy Release Rate (SERR) under mode-1 loading conditions. Fan¹ made use of this test to measure the fracture toughness of an adhesive joint between FRP adherents under mode-1 loading. Anderson T² also used a DCB test involving the analysis of the Cohesive nature of an Adhesive joint. Freed Y³ applied the DCB test to study the crack formation of an Adhesive joint formed between laminated composite adherents. The

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fracture analysis of Adhesive joints was done by using both DCB and Tapered DCB specimens by Marzi S.3

3. Numerical Analysis

Cohesive Zone Models (CZM) are used in numerical analysis in the mode-1 loading of adhesively joints. Due to the effective nature of flexibility during the adhesive compression, the model is used. The CZM was initially used by Barenblatt established on its relativity with the Griffith's fracture model. The model was used to analyse the crack propagation in delicate materials. Subsequently, Dugdale projected a CZM which formulated a cohesive region on the crack tip which was ideal for plastic adherents. Li S et al. in his research suggests that the validation of adhesive joints is done using two CZM based methods which are energy and strength based. Hong Peng Sung8 used a CZM based on a bilinear traction separation which was used in an analysis involving a tapered DCB specimen. The methods are based on the Traction-Separation Law (TSL) given by Khoramishad9 as shown in Figure 1.

4. Equations Used

The fracture toughness (Gc) or SERR under the mode-1 loading is the purpose of the DCB test. This is calculated as a result of observing the functional load and the Crack Tip Opening Displacement (CTOD) simultaneously during the test. After this, a critical SERR in terms of the crack length is recorded which gives the separation resistance curve which is given in the ASTM standard D 5528-02. The Gc calculation from the DCB test is done based on the compliance calibration method.

\[
G_{c} = \frac{3P\delta}{2B(a+|\Delta|)}
\]

(1)

\[
G_{c} = \frac{1}{2B} \frac{p^2}{da}
\]

(2)

\[
G_{c} = \frac{12}{E_s B^2 h^3} p^2 a^2
\]

(3)

5. Experimental Information

Tests were done using mild steel adherents bonded by Araldite 2015. Three DCB specimens were prepared by varying the resin-hardener proportion. Aluminium adherents were initially preferred to test but the existence of a large plastic region which will be favourable for the analysis is more present in mild steel according to the work of Azari. Also during the test, adhesive penetrates more into the plastic zone when mild steel adherents were used as explained in the works of Pardoen. The material properties of the mild steel adherent materials are given in Table 1. The DCB specimen geometry is based on ASTM D5528-01.

The mild steel adherent materials are joined using the adhesive which is a combination of an epoxy resin Araldite LY556 and an anhydride hardener HY906. The
adhesive is preferred based on its capacity to join under higher temperatures and provide excellent fatigue resistance. Several research works inclusive of the work done by Kottner. R$^{13}$ and Nishioka T$^{14}$ used the above mentioned type of Adhesive whose properties are given in Table 2.

The bonding surfaces of the steel adherents are thoroughly rubbed with sand paper followed by washing with acetone which is done to remove contamination. This also creates a uniform load transfer and prevents separation of adherents.

The DCB specimens having the hardener-resin proportion variation as given in Table 3 were primarily kept under dead weight for 9 to 11 hours. After this, they were clamped in a machine vice for 24 hours and dried thoroughly before going for the experiment. The thickness of the adhesive in all the three specimens was equivalently kept at 1mm with the help of a protusion made of teflon material. The pre-crack length was assumed as 25 mm. A uniquely designed spring loaded clamp as shown in Figure 5 is used to clamp the DCB specimen for load administering. The UTM had a load capacity upto 5 tons along with special attachments like digital pattern encoding, speed variational facility, digital readouts for plotting P-δ curves, etc. The cross-head speed was fixed as 1 mm/min.

6. Results and Discussion

The P-δ curves separately obtained from the digital readouts from the tensile testing device for the three DCB specimens as given below.

At the start, the three load displacement curves are taken separately from the digital read-out of the tensile testing device as shown in the Figures 6, 7 and 8. The analytical and experimental results were compiled and correlated for the three specimens shown in Figure 9. After this, the SERR vs. the crack length was plotted for the

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**Table 1.** Mild steel properties

| Sl No | Material property  | Corresponding value |
|-------|--------------------|---------------------|
| 1     | Young's modulus(E) | $2.1 \times 10^5$ MPa |
| 2     | Poisson's ratio ($\mu$) | 0.3 |
| 3     | Density($\rho$)    | 7850 kg/m$^3$ |

**Table 2.** Araldite properties$^{12}$

| Sl.no | Adhesive property | Value (Mpa) | Standard |
|-------|------------------|-------------|----------|
| 1     | Tensile strength  | 55          | ISO 527  |
| 2     | Flexural modulus | 3000        | ISO 178  |
| 3     | Shear strength   | 70          | ASTM D 2344 |

**Table 3.** %- of hardener-resin proportion variation

| Specimen | % of Hardener -Resin used in bonding | Hardener (ml) | Resin (ml) |
|----------|--------------------------------------|---------------|------------|
| A        | 50%-50%                              | 5             | 50         |
| B        | 60%-40%                              | 2.5           | 37.5       |
| C        | 70%-30%                              | 2.5           | 58.3       |
three specimens as shown in Figure 10. The analysis was further justified in the form of a plot drawn between the crack length against the crack tip opening displacement (a-δ curves) in Figure 11.

### 6.1 Significant Observations

The observations revealed that the increase in the resin proportion on the load applied had an impact on the crack length in the 3 specimens. During the test, the observations showed a specially formed cohesive region near the tip of the crack. This region was found to confirm with the TSLs outlined in the CZM analysis. The spread of the region was extensive up to the maximum level where separation took place. After this level, the region collapsed. The crack propagated in a non-uniform manner up to a length of 15 mm after which some degree of linear behavior was observed. Finally, the remaining crack propagation led to total removal of the steel adherents.

### 6.2 Plot Significance

The P-δ curves obtained for the three specimens show correlation and slight departure to some extent. The R curves (Figure 10.) and the a-δ curves (Figure 11.) also divulge the same characteristics which prove the influence of the hardener-resin proportion variation in the adhesive layer. In Figure 9, the curves for the three specimens show a correlation in the initial sloping region between the numerical and experimental values. After this, a sudden drop is seen due to non-uniformity in crack propagation. The reason for this is due to crack driving force dominating the fracture resistance or toughness for the three specimens.

The R curve (Figure 10.) shows a drastic elastic slope followed by a leveling out for the three specimens. The a-δ curves (Figure 11.) divulge very small variations when compared with the P-δ curves (Figure 9.) and the R curves (Figure 10). They also show insights on the minor variations in the performance of the adhesives used in the three specimens. The CTOD and crack lengths observed for drawing the graphs reveal relatively small deviations. The effort to study the crack propagation is justified by drawing these graphs as they reasonably coincided to a suitable level with the graphs got from the digital readout of the UTM.

### 6.3 FEA

An estimate of stress distribution inside the adhesive layer is obtained from FEA for comparative analysis on crack
propagation. ANSYS 14.5 was selected as the tool for this purpose.

Transverse Isotropic quality under normal strain conditions were assumed for the element selection used for modeling the DCB specimens tested under mode-1 loading. According 8 noded iso-parametric quadrilateral elements were selected for this purpose. The adhesive coating was modeled using the cohesive edge elements (2D linear inter 202 type element). The length of the element was taken as 1.1 mm. The entire meshed diagram showing the specimen along with the adhesive layer is given in the Figure 12.

7. Conclusion

The outcome of the DCB tests done on the three specimens revealed the impact of the variation of hardener-resin proportion on the crack propagation. The uniqueness of crack propagation, in both the experimental and analytical realms was studied. The correlation of the results from the experiments, the analytical methods and the FEA was found to coincide to a particular level.

8. References

1. Fan C, Ben JPY, Roger CJJ. Cohesive zone with continuum damage properties for simulation of delamination development in fibre composites and failure of adhesive joints. Engineering Fracture Mechanics. 2008; 75(13):3866–80.
2. Anderson T, Biel A. On the effective constitutive properties of a thin adhesive layer loaded in peel. International Journal of Fracture. 2013; 141(1):227–46.
3. Freed Y, Sills LB. A new cohesive zone model for mixed mode interface fracture in biomaterials. Engineering Fracture Mechanics. 2008; 75(15):4583–93.
4. Marzi S, Biel A, Stigl U. On experimental methods to investigate the effect of layer thickness on the fracture behavior of adhesively bonded joints. International Journal of Adhesion and Adhesives. 2011; 31(8):840–50.
5. Barenblatt G. The mathematical theory of equilibrium cracks in brittle fracture. Applied Mechanics. 1962; 7(1):55–129.
6. Dugdale DS. Yielding of steel sheets containing slits. Journal of the Mechanics and Physics of Solids. 1960; 8(2):100–10.
7. Li S, Thouless MD, Waas AM, Schroeder JA, Zavattieri PD. Mixed-mode cohesive-zone models for fracture of an adhesively bonded polymer–matrix composite. Engineering Fracture Mechanics. 2006; 73(1):64–78.
8. Sun HP, Cho JU. A study on static and fatigue fractures on tapered double cantilever beam specimen with aluminum foam through simulation and experiment. Indian Journal of Science and Technology. 2015; 8(26):1–6.
9. Khoramishad H, Crocombe AD, Katnam KB, Ashcroft IA. Predicting fatigue damage in adhesively bonded joints using a cohesive zone model. International Journal of Fatigue. 2010; 32(1):1146–58.
10. ASTM. D-5528-02. Standard investigation method for mode I loading of uni-directional specimens. Yearly Book of ASTM Standards. 2002; 15(3):254–63.

11. Azari S, Datla V, Ameli A, Spelt KJ, Papini M. Effect of substrate modulus on the fatigue behaviour of adhesively bonded joints. Material Engineering and Science. 2012; 53(1):594–602.

12. Pardoen T, Ferracin T, Landis CM, Delannay F. Constraint effects in adhesive joint fracture. Journal of the Mechanics and Physics of Solids. 2005; 53(1):1951–83.

13. Kottner R, Hynek T, Kroupa. Identification of parameters of cohesive elements for modeling of adhesively bonded joints of epoxy composites. Applied and Computational Mechanics. 2013; 7(1):137–44.

14. Nishioka T, Atluri SN. Finite element simulation of fast fracture in steel DCB specimens. Engineering Fracture Mechanics. 1982; 16(2):157–75.