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Research Paper

The Effect of Adherend Thickness and Width on Fracture Behavior in Adhesively bonded Double Cantilever Beam Joints

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Abstract

In recent years, bonding joints are the most effective way to successfully and safely combine different materials in sectors such as automotive, aircraft and aerospace industries. In particular, the combination of composite materials, such as rivets, welds, non-conformity of traditional methods have been made use of bonding joints. The fracture behavior of the adhesive is important in adhesively bonded. In the present study, the fracture behavior of the adhesive was investigated experimentally under Mode-I loading of Double Cantilever Beam (DCB) joints obtained by using materials of different width and thickness. AA2024-T3 aluminum is used as the adherend and two component Araldite 2015 tough adhesive is used as adhesive. The fracture progression during the experiment was measured with a high-speed camera and the displacement was measured by a video extensometer. As a result; when the fracture energies of the experimentally obtained adhesive are examined, the fracture energy of the joint changes when the width and thickness of the adherend changes. In addition, the fracture energies of the joint obtained with the Corrected Beam Theory (CBT) and the Standard Test Method (SBT) are compared, and the fracture energy obtained with CBT is more accurate considering the elastic rotation in the adherend.

Keywords: Adhesive joints, Fracture, Double cantilever beam test, Corrected beam theory, Standard test method.

1. INTRODUCTION

In recent years, bonding joints are the most effective way to successfully and safely combine different materials in sectors such as automotive, aircraft and aerospace industries. In particular, the combination of composite materials, such as rivets, welds, non-conformity of traditional methods have been made use of bonding joints. A large part of the work on adhesively bonded joints is to increase the load carrying capacity of these joints. The connection strength, adhesive and material type, overlap length, connection geometry, material thickness and width etc, affected by many factors [1-6].

During the loading of adhesively bonded joints, it requires geometrically nonlinear analysis to accurately calculate stresses due to the plasticity of the material, ie the rotation of the end parts of the adherend by the effect of the peel stresses. An approach that has been widely used in the nonlinear finite element analysis of adhesively bonded joints until the last few years; considering the stress-strain behavior obtained from the tensile test of bulk samples, the elastic - plastic stress and deformation values of the materials are used. However, the stress singularity of the free ends of the connection and the dependence of the stresses on the number of mesh used make this approach problematic [7].

In recent years, the use of Cohezive Zone Model is increasing day by day in numerical analysis of adhesive bonded joints. This model; by simulating the onset, progression of the crack and the occurrence of damage, it is used not only to estimate damage, but also to estimate damage progress. To make finite element analysis with cohesive zone model in the adhesively bonded, it is necessary to know some parameters. Tests for elasticity and shear modulus parameters of bulk samples and fracture energy parameters are calculated by testing of double cantilever beams or tapered cantilever beam samples in Mode-I. The standard D 3433 (Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints), recommended by ASTM, is used to determine the fracture energy in Mode-I [8].

Various theories are used to calculate the fracture energy of

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the adhesive by DCB test. Mohammadreza et al. [9] used the modified beam theory (MBT), compliance calibration method (CCM) to calculate the fracture energy of the adhesive and compared it to the two-dimensional and three-dimensional numerical analysis. According to the results of this study, it was found that three-dimensional analysis was more compatible.

Lopes et al. [10], DCB testing was performed for three different adhesives and fracture energy of each adhesive was obtained by using three different energy methods (Compliance Calibration Method, Corrected Beam Theory and Compliance-Based Beam Method). According to the results of this study, while the DCB test is suitable for soft and normal hard adhesives, it is seen that Tapered Double-Cantilever Beam (TDCB) test is more suitable for very hard adhesives.

In the present study, the fracture behavior of the adhesive was investigated experimentally under Mode-I loading of Double Cantilever Beam (DCB) joints obtained by using materials of different width and thickness. AA2024-T3 aluminum is used as the adherend and two component Araldite 2015 tough adhesive is used as adhesive. The fracture progression during the experiment was measured with a high-speed camera and the displacement was measured by a video extensometer. G_{IC} (critical pull energy) values of DCB joints were obtained according to two different standards such as Corrected Beam Theory (CBT) and Standard Test Method (SBT) and these two standards were compared.

2. EXPERIMENTAL WORK

In this study, AA2024-T3 aluminum alloy,– due to its good mechanical and physical properties – was used as an adherend. For bonding, Araldite 2015 toughened adhesive type (produced by Huntsman, Basel, Switzerland) was used as adhesive. Mechanical properties for the adhesives used in experimental studies are given in Table 1. Curing conditions and composition rates of the adhesive is given in Table 2.

Table1. Material properties of the adhesives.

		Araldite 2015	AA2024-T3
E (MPa)		1832 $^{\pm 57}$	71400 $^{\pm 240}$
n		0.33	0.33
s_t (MPa)		21.2 $^{\pm 1.17}$	487 $^{\pm 15}$
e_t (%)		4.6	17

E: Young's modulus; ν: Poisson's ratio; s_t : Ultimate tensile strength; e_t : Ultimate tensile strain

Table 2. Curing conditions and composition rates of the structural adhesives

Adhesive	Compound Rate (Epoxy:A / Hardener:B)	Curing temperature/time
Araldite 2015	A:B=2:1	70°C/120 minutes

The geometry and dimensions of the DCB joint samples are shown in Fig. 1. The geometry and dimensions of the DCB common samples are standardized [8, 11].

Surface bonding methods (AA2024-T3 aluminum alloy) are applied to the bonded material prior to the bonding process to ensure high performance of the bonded joints. Samples were first scrubbed with 600-degree SiC sandpaper to remove burrs due to cutting of the samples to the desired size and the oil and dirt on the sample, and then a smooth surface was obtained with 1000-degree SiC sandpaper. After the friction procedure, the samples were washed under running water and left in acetone for 20 minutes [12].

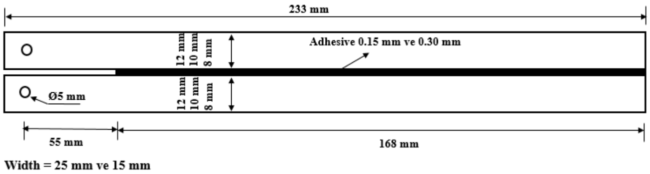

Fig. 1. Double cantilever beam joint geometry.

Because the performance of the bonded connections is dependent on the surface preparation process, surface preparation of the materials to be bonded is required. Therefore, the oil, grease, dirt and dust on the test samples were cleaned with 600 grade sandpaper. Then the fine lines on the samples were removed with 1000 grade sandpaper. Samples were washed with powder detergent in the tap counter and placed in acetone. Samples extracted from the acetone bath were completely evaporated by evaporating the acetone in an oven at a temperature of 60°C before surface bonding.

The mold shown in Fig. 2a was used to maintain the position of the bonding materials, to adjust the thickness of the adhesive and to apply uniform pressure to the connection samples. Adhesives were applied to the overlapping regions of the samples by a gauge and the metal shims having this thickness were placed at the free ends of the samples so that the adhesive thickness was 0.15 and 0.30 mm. Moreover, a hot press shown in Fig. 2b was used to provide the curing conditions for the structural adhesives shown in Table 2 [12].

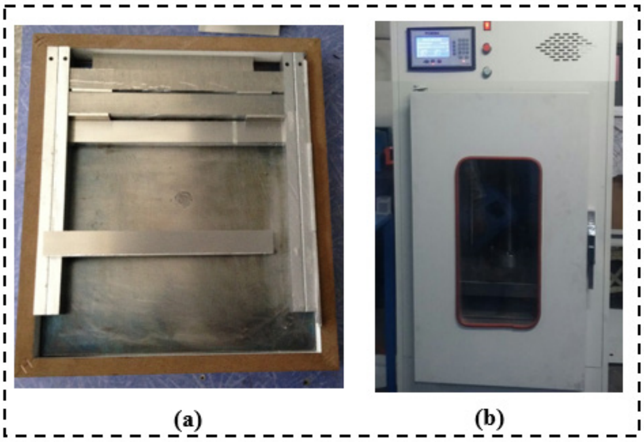

Fig. 2. a. Joint production mold, b. Hot-press

The connection samples were cleaned over the excess adhesive samples that were removed during curing (Fig 3a). A thin film layer was then formed with spray paint on the surface of the sample to better detect crack propagation (Fig 3b). To determine the progression of the crack, the tape was bonded onto the surface of the sample (Fig 3c) [12].

Fig.3. a. DCB joint sample, **b.** spraying paint on the surface, **c.** bonding tape onto the surface of the sample. [13].

Samples were divided into five main groups and the experimental parameters of these samples were given in Table 3. Three samples were generated for each parameter given in Table 3 and these samples were averaged.

Table 3. Experimental parameters used in the experimental investigation.

Type	Adherend Width	Adherend Thickness	Adhesive Thickness
Type-I	25 mm	12 mm	0.30 mm
Type-II	25 mm	12 mm	0.15 mm
Type-III	15 mm	12 mm	0.15 mm
Type-IV	15 mm	10 mm	0.15 mm
Type-V	15 mm	8 mm	0.15 mm

In the study, Mod-I was applied as the crack mode to the DCB joints produced in the study and the boundary conditions are seen in Fig. 5a. All experiments were carried out in a computer controlled Shimadzu AG-IS 100 universal tester with a load cell of 5 kN at 23°C and 34% humidity at a tensile speed of 5 mm / min.

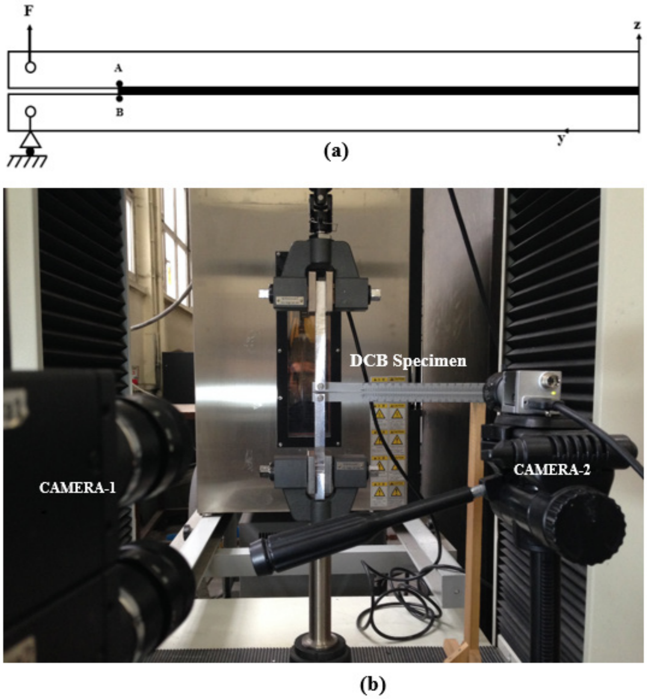

Fig. 5. a. Mode-I test boundary conditions, **b.** Cameras used in the experiments.

Two cameras were used to test the DCB connection samples (Fig.5b). Camera-1 (video extensometer) measures displacement between points A and B shown in Fig. 5a, while camera-2 measures crack propagation. In addition, the displacement of the force was obtained from the stroke of the device [10]..

G_{IC} (critical tensile energy) values of DCB connections were obtained according to two different standards.

First, the BS 7991 standard Corrected Beam Theory (CBT) - [11],

$$G_{IC} = \frac{3P\delta}{2B(a+\Delta)} \tag{1}$$

Secondly ASTM 3433-99 - Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints (STM) - [8],

$$G_{IC} = \frac{(4P^2\,\max)(3a^2+h^2)}{(EB^2h^3)} \tag{2}$$

4. RESULTS AND DISCUSSIONS

The fracture energy-crack length curves obtained for all joint types (Type-I, Type-II, Type-III, Type-IV and Type-V) are obtained by taking the average of three sample test results. It is between about 1% and 1.5% of the standard deviation between the three samples. Afterwards, the loads (P)–displacements (δ) and crack progression data for the DCB joint samples were measured. The fracture energy-crack length curves of the bonded DCB joints are given in Fig. 6. These curves were obtained according to equations 1 and 2.

The fracture energy obtained from STM is 21% higher compared to the fracture energy data obtained from CBT and STM in Fig. 6a and b. This is because the STM does not take into account the minimum elastic recovery resulting from the thickness and width of the material (thickness 12 mm and width 25 mm). However, during the test, the amount of elastic recovery in the materials affects the displacement (δ) between the two materials. The CBT considers this elastic recovery (**Δ** = crack length correction for crack tip rotation and deflection). Furthermore, in the graphs given in Figs. 6c, d, and e, the decrease of material thickness and width reduces the difference between CBT and STM by about 5%.

Table 4. Mechanical properties of joints produced with Aradite 2015 adhesive

Type	P_{max} (N)	δ (mm)	G_{IC} -N/mm² (CBT)	G_{IC} -N/mm² (STM)
Type-I	927	1.453	0.48	0.61
Type-II	841	1.346	0.38	0.48
Type-III	470	0.893	0.39	0.41
Type-IV	332	0.946	0.37	0.39
Type-V	228	1.413	0.31	0.33

P max (N) : maximum load, δ= displacement at maximum load, G_{IC}-N/mm (CBT) : The fracture energy obtained according to the Corrected Beam Theorem, G_{IC}-N/mm (STM): The fracture energy obtained according to Standard Test Method

When the fracture energy data obtained from CBT are analyzed, the reduction of the adhesive layer thickness decreased the fracture energy of the joint by 21% (Table 4). In addition, width of the bonded adherend is reduced from 25 mm (Type-II) to 15 mm (Type-III) and does not cause a change in the fracture energy of the joint. Because the parameters given in equation (1) for CBT are examined, this is an expec-

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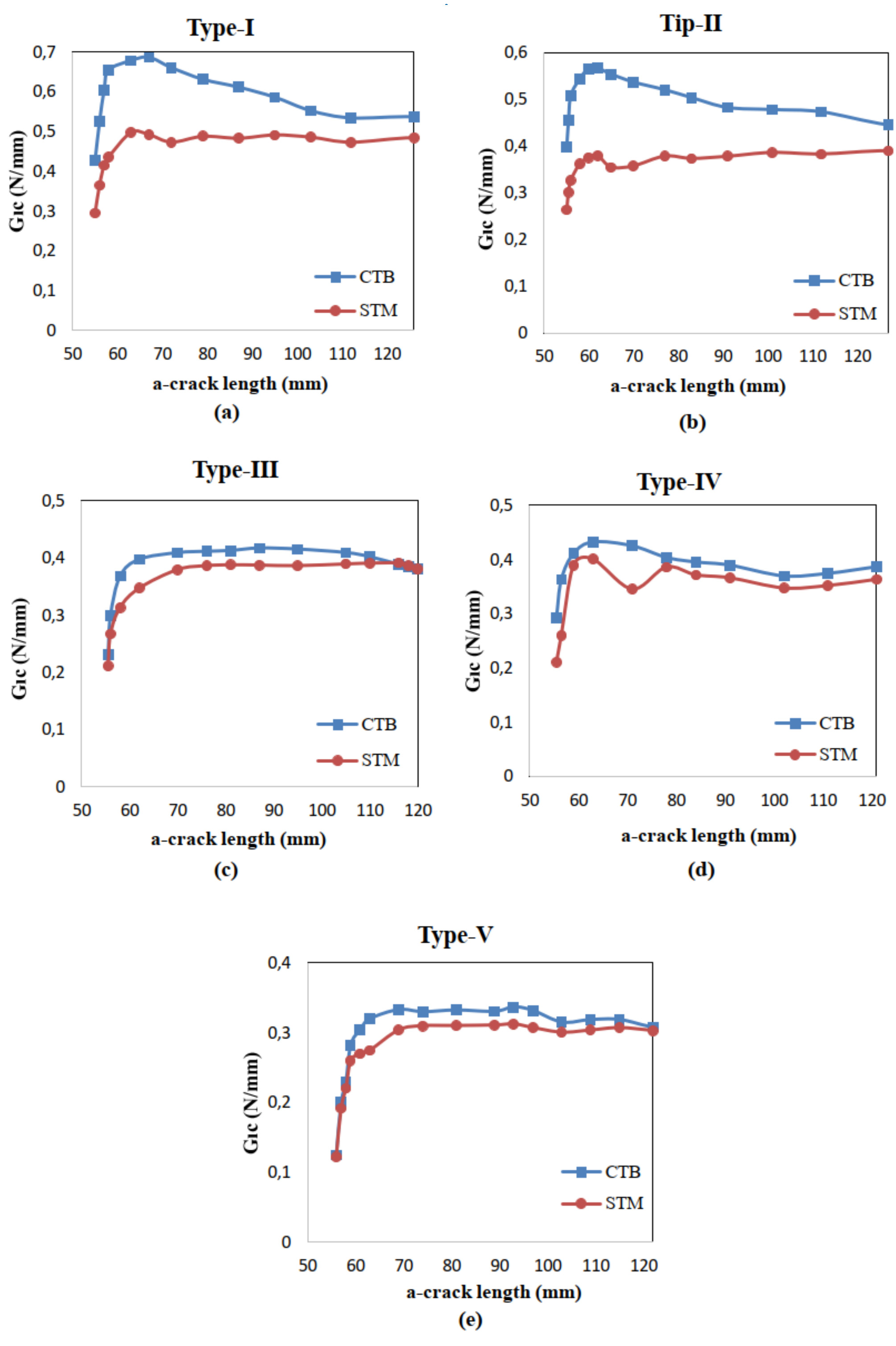

Fig. 6. Fracture energy–crack length curves of DCB joints bonded with the Araldite 2015 adhesive **a)** Type-I, **b)** Type-II, **c)** Type-III, **d)** Type-IV, **e)** Type-V.

ted result. However, decreasing the bonded adherend thickness from 12 mm (Type-III) to 10 mm (Type-IV) and 8 mm (Type-V) decreases the fracture energy of the joint by about 5% and 20%, respectively (Table 4). This can be explained by reducing the thickness of the bonded adherend by affecting the elastic recovery that CBT considers (Δ = crack length correction for crack tip rotation and deflection).

When the maximum load (P_{max}) and displacement (**δ**) data given in Table 4 are examined, the reduction of the thickness of the bonded adherend decreases the maximum load that the joint can carry, while increasing the displacement. This is due to the decreased rigidity of the bonded adherend.

5. CONCLUSIONS

In this work, mechanical behavior of five different types of DCB connection types were investigated experimentally and the following results were obtained.

- In all connection types, the mechanical properties were obtained with the average results of the three samples, and the standard deviation of the three specimens was between about 1-1.5%.
- The elastic rotation in the bonded adherend during the

experiment affects the displacement value (δ) between the two adherend. Considering that the displacement of the fracture energy obtained by STM is not taken into account, the fracture energy obtained by CTB is more accurate.

- When the fracture energies obtained by both methods are compared, Type-III, Type-IV and Type-V fracture energies are very close.
- As the thickness of the bonded adherend decreases, the fracture energy value decreases.
- At the same time, as the width of the bonded adherend decreases, the fracture energy value decreases. But this decrease is not proportional.
- Adhesive thickness significantly affects the fracture energy.

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5. REFERENCES

[1] Li, G., Pang, S.S., Woldesenbet, E., Stubblefield, M.A., Mensah, P.F. and Ibekwe, S.I. (2001). Investigation of prepreg bonded composite single lap joint. Composites Part B, 32:651-58, DOI: 10.1016/S1359-8368(01)00045-2.

[2] Liao, L., Huang, C. and Sawa, T. (2013). Effect of adhesive thickness, adhesive type and scarf angle on the mechanical properties of scarf adhesive joints. Int. J. Solids Struct., 50:4333-40, DOI: 10.1016/j.ijsolstr.2013.09.005.

[3] Adin, H. (2013). The investigation of effect of adherend thickness on scarf lap joints. Mat.-wiss. u.Werkstofftech., 44: 839-846, DOI: 10.1002/mawe.201300123.

[4] da Silva, L.F.M., Carbas, R.J.C., Critchlow, G.W., Figueiredo, M.A.V. and Brown, K. (2009). Effect of material, geometry, surface treatment and environment on the shear strength of single lap joints. Int J Adhes Adhes., 29:621-32, DOI: 10.1016/j.ijadhadh.2009.02.012.

[5] Adin, H., Temiz, Ş. (2014). Experimental and Numerical Strength Analysis of Double Lap Joints Subjected to Tensile Loads. Materials Testing., 56:160-168, DOI: 10.3139/120.110521.

[6] Gultekin, K., Akpinar, S. and Ozel A. (2014). The effect of the adherend width on the strength of adhesively bonded single-lap joint: Experimental and numerical analysis. Composites Part B, 60:736-45, DOI: 10.1016/j.compositesb.2014.01.022.

[7] Kanar, B. (2018). Investigation of Fracture Behavior of Nanostructure Added Under Ambient Temperature and Thermal Cycling, Erzurum Technical University, Master Thesis.

[8] ASTM 3433-99: (2012). Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints. West Conshohocken, PA: ASTM International.

[9] Mohammadreza, K. and Farhad, A.M. (2012). Fracture analysis in adhesive composite material/aluminum joints under mode-I loading; experimental and numerical approaches. Int J Adhes. Adhes, 39: 8-14, DOI: 10.1016/j.ijadhadh.2012.06.005.

[10] Lopes, R.M., Campilho, R.D.S.G., da Silva, F.J.G. and Faneco, T.M.S. (2016). Comparative evaluation of the Double-Cantilever Beam and Tapered Double-Cantilever Beam tests for estimation of the tensile fracture toughness of adhesive joints. Int J Adhes. Adhes., 67: 103-111, DOI: 10.1016/j.ijadhadh.2015.12.032.

[11] BS 7991:2001 standard. Determination of the mode I adhesive fracture energy, GIC, of structural adhesives using the double cantilever beam (DCB) and the tapered double cantilever beam (TDCB) specimens.2001.

[12] Kanar, B., Akpinar, S., Akpinar, I. A., Akbulut, H. and Ozel, A. (2018). The fracture behaviour of nanostructure added adhesives under ambient temperature and thermal cyclic conditions. Theoretical and Applied Fracture Mechanics, 97: 120-130, DOI: 10.1016/j.tafmec.2018.08.006.