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Fracture toughness in Mode I (G_{IC}) for ductile adhesives

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Abstract. Works carried out in this publication belong to a project that seeks the replacement of welded joints by adhesive joints at stress concentration nodes in bus structures. Fracture toughness in Mode I (G_{IC}) has been measured for two different ductile adhesives, SikaTack Drive and SikaForce 7720. SikaTack Drive is a single-component polyurethane adhesive with high viscoelasticity (more than 100%), whose main use is the car-glass joining and SikaForce 7720 is double-component structural polyurethane adhesive. Experimental works have been carried out from the test called Double Cantilever Beam (DCB), using two steel beams as adherents and an adhesive thickness according to the problem posed in the Project, of 2 and 3 mm for SikaForce 7720 and SikaTack Drive, respectively. Three different methods have been used for measuring the fracture toughness in mode I (G_{IC}) from the values obtained in the experimental DCB procedure for each adhesive: Corrected Beam Theory (CBT), Compliance Calibration Method (CCM) and Compliance Based Beam Method (CBBM). Four DCB specimens have been tested for each adhesive. Dispersion of each G_{IC} calculation method for each adhesive has been studied. Likewise variations between the three different methods have been also studied for each adhesive.

1. Introduction

In recent years, the use of adhesives for structural applications [1] is growing due to the benefits and solutions that this technology is capable of providing to different industries. Among the potential beneficiaries of adhesive technology are Aerospace and Automotive Industries.

Using adhesives enable improving the performance obtained with traditional joints, allowing the joint of dissimilar materials, reducing the structure weight and manufacturing costs, improving the resistance to dynamic and static loads, reaching quasi homogeneous stress distribution and better damage tolerance [2].

Actually, traditional joining techniques (welding, rivets, screws…) continue being used mostly, but problems related to these joints make necessary to develop other joining technologies. It is necessary to know all the characteristics of any material designed for be used in structural applications, so that it is possible to predict its behavior for the raised solicitations. Finite element software are increasingly widespread in adhesive joints, being able to simulate the behavior of the joint. To obtain a correct operation of the program it is necessary to know precisely all the properties of the involved materials in the adhesive joint. Thus, mechanical characterization of adhesive is mandatory prior to its use.

Fracture resistance values of structural adhesives can be calculated with different tests, widely studied in the literature [3,4,5]. In this work, Double Cantilever Beam (DCB) test have been carried out in order to obtain the Fracture Toughness in mode I (G_{IC}) value of two ductile polyurethane adhesives, SikaTack Drive and Sika Force 7720.

Most common methodologies for analysis of G_{IC} are based on linear elastic fracture mechanics (LEFM), including Compliance Calibration Method (CCM) and Corrected Beam Theory (CBT), but recently developed method such Compliance-Based Beam Method (CBBM) is based on the crack equivalent concept, depending only on the specimen`s compliance during the test [6]. DCB test allows obtaining the resistance to crack initiation and propagation, being able to calculate the R-curve (Resistance Curve), plotting G_{IC} versus crack length [7].

1.1. DCB Data Analysis

To avoid the accumulation of data, in this work only the formulas are exposed, being able to find more complete information in [6] and [8]:

-Compliance Calibration Method (CCM):

$$G_{IC} = \frac{P^2}{2b}\frac{dC}{da}$$

P is the load and b the specimen width. The compliance (C) is calculated by $C = \frac{\delta}{P}$ being δ the specimen displacement. $C = f(a)$ curves are adjusted by cubic polynomials ($C = C_3a^3 + C_2a^2 + C_1a + C_0$).

-Corrected Beam Theory (CBT):

$$G_{IC} = \frac{3P\delta}{2b(a + |\Delta|)}$$

Corrected Beam Theory (CBT) is based on elementary beam theory including the effects of crack tip rotation and deflection, being Δ crack length correction for crack tip rotation and deflection. For calculating Δ, a linear regression analysis of $(C)^{1/3}$ versus a data is carried out.

-Compliance-Based Beam Method (CBBM) [8,9]:

$$G_{IC} = \frac{6P^2}{b^2h}\left(\frac{2a_{eq}^2}{h^2E_f} + \frac{1}{5G}\right)$$

This method, based on the crack equivalent concept, depends only on the compliance of the specimen during the test. a_{eq} is the equivalent crack length, estimated from the experimental compliance. $a_{eq} = a + |\Delta| + \Delta a_{FPZ}$, being a real crack length, Δ the root rotation correction for the initial crack length and Δa_{FPZ} the correction because the fracture process zone (FPZ) is considered. h is the specimen height; E_f is a corrected flexural modulus, which takes into account some phenomena that may affect the $P - \delta$ curves, such as the stiffness variability between different specimens; and G is the substrate´s shear modulus.

2. Experimental Procedure

2.1. *Double Cantilever Beam Test (DCB)*

Different materials can be used as substrate for developing DCB Test, normally metals such as Steel and Aluminum, but it is possible find other works carried out with substrates made of unidirectional fiber-composite materials [10]. Two steel substrates have been used in this work for manufacturing each specimen. So that each pair of substrates are bonded together with the adhesive. A cohesive failure is essential to calculate correctly the fracture toughness of the studied adhesives.

Tests are carried out at room conditions on a universal testing machine through an opening process by pin loading at the beam-ends, with 1mm/min of test velocity. Tensile testing machine reproduces for each test the curves of applied load versus displacement (P-δ curves). The crack propagation is measured over the length of the adhesive with a calibrated ruler using a digital photography system, taking photos every five seconds until the process is finalized (Figure 1).

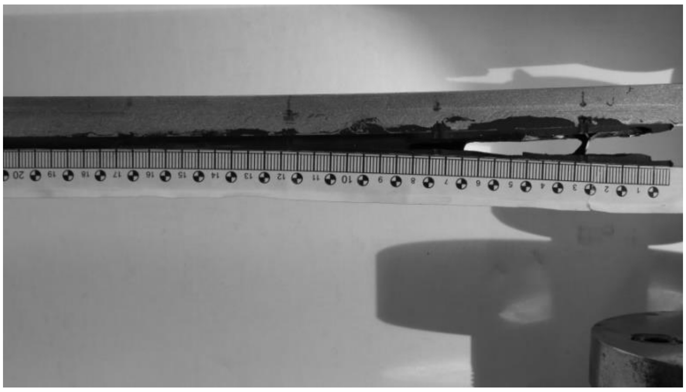

Figure 1. Crack propagation measured over the adhesive length.

2.2. *Test Geometry*

The test specimen sketch is shown in Figure 2, being F_c the applied force, whose values are obtained from the collected data during the test developed by the tensile testing machine. d= substrate thickness, being a constant value of 12.5mm. a=crack length, result of the sum of initial crack length and measured length values. w_{med}=substrate width, being a constant value of 25mm. The thickness of the adhesive layer is different on both adhesives, being 3 mm for Sikatack Drive and 2 mm for SikaForce 7720.

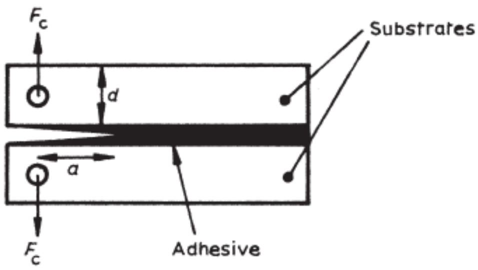

Figure 2. Measurements of DCB Specimen used [3].

2.3. Materials

Two different polyurethane structural adhesives supplied by Sika ® are used for the development of this work. One single-component adhesive with high viscoelasticity (more than 100%) whose trade name is SikaTack Drive. And other double-component ductile adhesive, called SikaForce 7720.

3. Results

From the DCB tests, $P - \delta$ curves were obtained for both adhesives. Representative curves of the studied adhesives are shown in Figure 3. As shown in the figure, the double-component adhesive (SikaForce 7720) presents less elongation at break due to its lower elastoplasticity. In the case of SikaTack, a greater elongation for higher values of rupture is obtained. In terms of elastic-plastic bahavior, it is important to remark that the most ductile adhesive, SikaTack Drive, is able to continue deforming for a longer time before reaching the minimum breaking value.

Figures 4 and 5 show representative curves of Resistance (R-Curve) of both adhesives. G_{IC} values are obtained from these graphs. The horizontal part of the curves represents G_{IC} values, so that, after a first peak of maximum G_{IC} value, this value stabilizes. This stabilization zone shows a set of similar values, where the sought value is obtained. G_{IC} values for both adhesives are shown in Table 1.

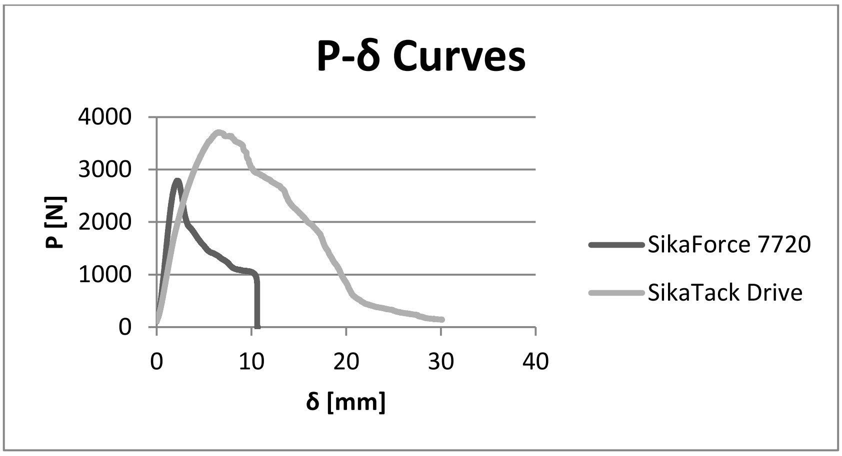

Figure 3. P-δ curves for SikaForce 7720 and SikaTack Drive. As the graph shows, SikaTack Drive is more ductile than SikaForce 7720, being also greater the maximum breaking value.

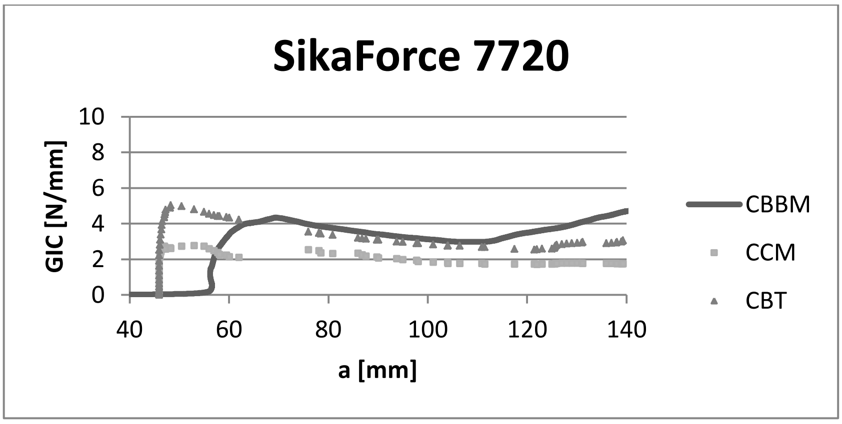

Figure 4. Representative Resistance Curve (R-Curve) for SikaForce 7720.

As Figure 4 shown (SikaForce 7720), CBBM and CBT curves are similar, being the curve for CCM similar but with lower G_{IC} values. Figure 5 (SikaTack Drive) shows similar curves for CBBM and CCM models, being different the CBT curve. CBBM model depends only on the compliance of the specimen during the test, with G_{IC} not being affected by errors due to the crack propagation measuring over the length of the adhesive with a calibrated ruler.

The CBT model includes a crack length correction for crack tip rotation and deflection (Δ). So better behavior is obtained in CBT model for Sikaforce 7720 than for SikaTack Drive. In the case of CCM model, the opposite happens. Better elastic-plastic behavior of SikaTack Drive allows better adjustment of $C = f(a)$ curves by cubic polynomials ($C = C_3a^3 + C_2a^2 + C_1a + C_0$).

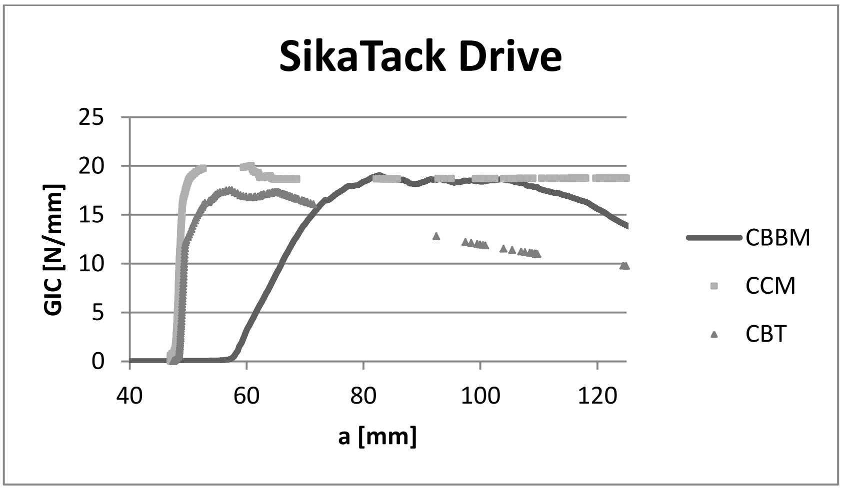

Figure 5. Representative Resistance Curve (R-Curve) for SikaTack Drive.

Table 1. G_{IC} values (in N/mm) for both studied adhesives with the three employed models.

	SikaTack Drive	SikaForce 7720
CBBM (N/mm)	20.63±1.56	3.83±0.72
CCM (N/mm)	18.35±1.40	2.18±0.28
CBT (N/mm)	17.45±2.77	3.24±0.86

4. Conclusions

Recent works have demonstrated the validity of using CBBM model in adhesives, being probably the most reliable method to obtain G_{IC}. This is due to the difficulty of measuring experimentally crack growth with an optical system, which is aggravated by high elastic-plastic behavior of both studied adhesives. The CBBM is only based on the crack equivalent concept, depending only on the compliance of the specimen during the test.

The CBT model shows better results for SikaForce 7720 and CCM model shows better results for SikaTack Drive. This is due to the different properties of each adhesive, together with the different adjustment of each model.

5. References

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