DETERMINATION OF THE ENVELOPES FOR MODE-MIXITY EVALUATION OF ADHESIVELY BONDED STEEL

Filipe J.P.Chaves [1] , L.F.M. da Silva [2], M.F.S.F. de Moura[2], D. Dillard[3]

[1] IDMEC- Pólo FEUP
[2] DEMec
Faculdade de Engenharia da Universidade do Porto,
Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
E-mail: chaves.filipe@fe.up.pt

[3] Virginia Tech, 120-E Patton Hall, Mail Code 0219, Blacksburg, VA 24061

ABSTRACT

This study is about the effect of the adhesive thickness and adhesive ductility on the mixed mode loading of Double Cantilever Beam joints.
The project is divided into three main tasks. The first task is about the development of a finite element model using a cohesive zone model to design an experimental device based on the standard ASTM D6671D.
The second task is concerned with the generation of experimental results in mixed mode varying the type of adhesive and the adhesive thickness. In the third task, the experimental results will be used to develop an adhesive toughness model as a function of the mode mixity.
A dual actuator load frame from Virginia Tech's Engineering Science & Mechanics Dept. was used to obtain the envelopes for mode mixity for three different adhesives and thicknesses.
A proposal for a data reduction scheme for the determination of the strain energy release rate is presented and validated in this paper without the need of the experimental measure of the crack length.

KEY WORDS: adhesive failure, structural adhesive, double cantilever beam specimen, double actuator load frame

1. INTRODUCTION

A data reduction scheme was developed to obtain the stress energy release rate of adhesive joints loaded under mixed mode in a dual actuator load frame. This data reduction scheme does not require the observation of the crack propagation because it takes into account the fracture process zone effect with an equivalent crack length obtained by the compliance-based beam model data reduction scheme [1].

The numerical validation is presented with an envelope obtained with finite element simulations done with ABAQUS using a cohesive element subroutine.

This analysis is applied to the asymmetrical loading of Double Cantilever Beam (DCB) specimens done in a dual-actuator load frame developed by Virginia Tech.

The development of a dual-actuator load frame [2] has facilitated tests evaluating the mixed-mode fracture behavior of adhesively bonded joints. The experiments focused on evaluating the critical strain energy release rate that characterizes mode I, mode II and mixed-mode I/II fracture of different material systems. The dual-actuator load frame allows the use of standard DCB specimens over the full range of mode mixities (Figure 1).

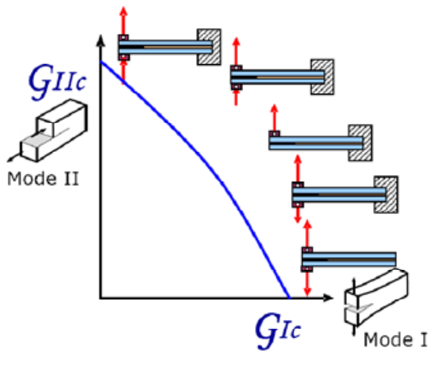


Figure 1. Mode mixity covered with asymmetric loading of symmetric DCB specimens.

The precracked ends of the specimen are connected to the grips of the two actuators and the other end of the specimen was clamped at the base. By simultaneously applying different displacement rates with the two independently controlled actuators, different levels of mode-mixity were obtained at the locus of failure, as seen in Figure 2. Presently, the determination of the strain energy release rate is done using the crack length which is often very difficult to localize and misleading because it does not take into account the fracture process zone (FPZ).

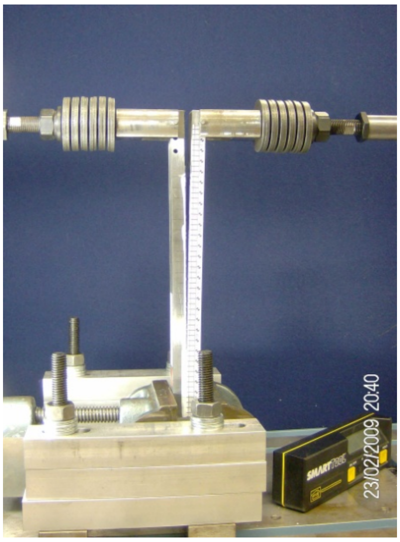


Figure 2. DCB specimen being tested.

2. Data reduction scheme description

The DCB specimens that were used in the tests were obtained with two high strength steel beams. The substrates were sandblasted before the application of the adhesive. Three adhesives of increasing ductility were used: two epoxies (Araldite AV138M and Araldite 2015 from Huntsman) and a polyurethane (Sikaflex-255 from Sika). The values for the energy release rate (G_{Ic}) for each adhesive resulting from the DCB experimental testing are shown in Table 1 [3].

Table1. Energy release rate values for the three adhesives [3].

		Average	Deviation
Araldite AV138M with HV998 hardener	G_{Ic} [N/m]	**345.9**	47.8
Araldite 2015	G_{Ic} [N/m]	**525.7**	80.8
Sikaflex-255 FX	G_{Ic} [N/m]	**2901.1**	121.9

Three different adhesives were studied: 0.2, 0.5 and 1 mm. The thickness layer was controlled with the insertion of spacers at the two ends of the sample.

The tests were conducted with symmetric DCB specimens and asymmetric displacement rates. Applied displacements result in a combination of pure mode I and pure mode II loading. The forces exerted on the two beams were measured by load cells attached to each actuator and the fracture components are calculated with the following:

$$F_I = (F_R + F_L)/2 \tag{1}$$

$$F_{II} = (F_R - F_L)/2 \tag{2}$$

where F_R and F_L are the forces measured by the two load cell. The two values of the strain energy release rate were calculated with the following equations.

$$J_I = \frac{F_I^2 a^2}{EIb} \tag{3}$$

$$J_{II} = \frac{3F_{II}^2 a^2}{4EIb} \tag{4}$$

where b is the width of the bond, I and E are the moment of inertia and the elastic modulus of the adherends respectively, and a is the crack length. F_I and F_{II} refer to the imposed force in mode I and II. The global mode mixity is then indicated with the angle Ψ.

$$\Psi = ArcTan\left(\sqrt{\frac{G_{II}}{G_I}}\right) \tag{5}$$

The tests were conducted imposing two displacement rates with the actuators, in order to cover different mode mixity levels. During the tests the values of the imposed displacements, the forces at the actuators and the crack length were monitored and recorded. An interesting observation is that for almost all the tests, excluding those in pure modes, the value of Ψ increases as the test progresses and the crack grows. This trend is expected from the analytical evaluation of the failure process. The value of Ψ is not uniquely set by the displacement rates imposed at the beams, but is affected by crack length and increases for a growing crack length.

The analysis described with the previous method requires the observation of the crack propagation which is not easy nor entirely accurate because it does not takes into account the FPZ. A compliance based beam method was developed trying to overcome these handicaps and improving the results obtained. Based upon the work of Oliveira et al. [1] two equations were obtained for J_I and J_{II}:

$$J_I = \frac{12P_I^2 a_{eq,I}^2}{b^2 E h^3} + \frac{6P_I^2}{5b^2 hG} = \frac{6P_I^2}{b^2 h}\left(\frac{2a_{eq,I}^2}{h^2 E} + \frac{1}{5G}\right) \tag{6}$$

$$J_{II} = \frac{9P_{II}^2 a_{eq,II}^2}{b^2 E h^3} \tag{7}$$

where:

$$P_I = \frac{P_2 - P_I}{2} \tag{8}$$

and

$$P_{II} = \frac{P_2 + P_I}{2} \tag{9}$$

During propagation equivalent cracks lengths should be considered in order to account for the FPZ effects. For beam I:

$$a_{eq,I} = a + h|\Delta_I| + \Delta a_{\mathrm{FPZ}} \tag{10}$$

$$a_{eq,I} = \frac{1}{6\alpha}\forall - 2\frac{\beta}{\forall} \tag{11}$$

where

$$\alpha = \frac{8}{Bh^3 E_{\mathrm{fI}}} \qquad \beta = \frac{12}{5Bh\ \ G} \qquad \gamma = -C_I$$

$$\forall = \left(\left(-108\gamma + 12\sqrt{3\left(\frac{4\beta^3 + 27\gamma^2\alpha}{\alpha}\right)}\right)\alpha^2\right)^{\frac{1}{3}} \tag{12}$$

And for beam II :

$$a_{eq,II} = a + h|\Delta_{II}| + \Delta a_{\mathrm{FPZ}} \tag{13}$$

$$a_{eq,I} = \frac{1}{6\alpha}\forall - 2\frac{\beta}{\forall} \tag{14}$$

where

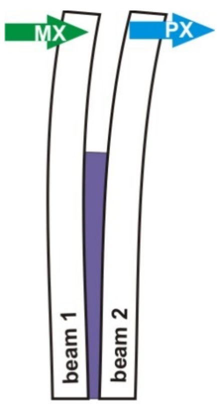
$$\alpha = \frac{8}{Bh^3 E_{\mathrm{fI}}} \qquad \beta = \frac{12}{5Bh\ \ G} \qquad \gamma = -C_{II}$$

$$\forall = \left(\left(-108\gamma + 12\sqrt{3\left(\frac{4\beta^3 + 27\gamma^2\alpha}{\alpha}\right)}\right)\alpha^2\right)^{\frac{1}{3}} \tag{15}$$

3. RESULTS

Based on this formulation, finite element simulations were conducted with different displacements as seen in Table 2 and analyzed to obtain the fracture envelope seen in Figure 3. Crack growth was simulated by the linear fracture energetic criterion $\frac{J_I}{J_{Ic}} + \frac{J_{II}}{J_{IIc}} = 1$ whith $J_{Ic} = 0.6$ [N/mm] and $J_{IIc} = 1.2$ [N/mm].

Table2. Imposed displacements for each simulation



	imposed displacem.	
Simul.	beam 1	beam 2
1	10	-9
2	10	-8
3	10	-7
4	10	-5
5	10	-3
6	10	-1
7	10	0
8	10	1
9	10	3
10	10	5
11	10	7
12	10	7.5
13	10	8
14	10	8.5
15	10	9

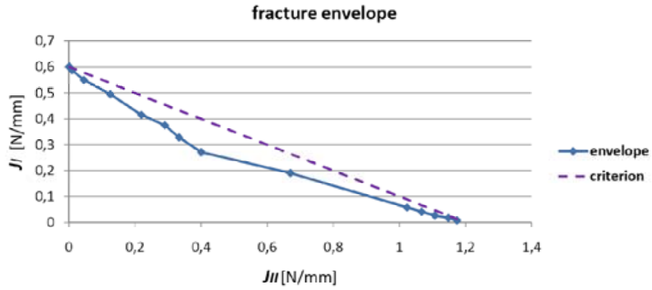


Figure 3. Fracture envelope obtained from numerical results.

Figure 4 shows the result for simulation number 3 with J_I, J_{II} and the FPZ. It shows a stable plateau from 75 mm until 200 mm, for the FPZ and the value of J_I. This emphasizes the accordance between the FPZ and the energy released with the crack growth. As observed in Figure 4, this loading case is mostly mode I . The value for J_I tends to the imposed value of J_{IC}.

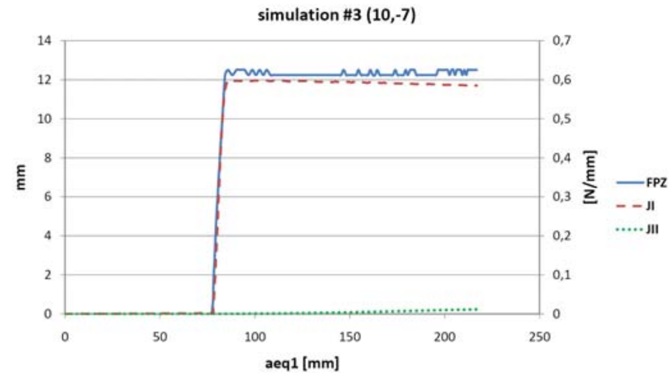


Figure 4. Number 3 simulation results plot for FPZ, J_I and J_{II}.

For simulation number 3, Figure 5 shows the deformed shape and Von Mises stress plot result from the finite element model done with a cohesive element subroutine with ABAQUS.

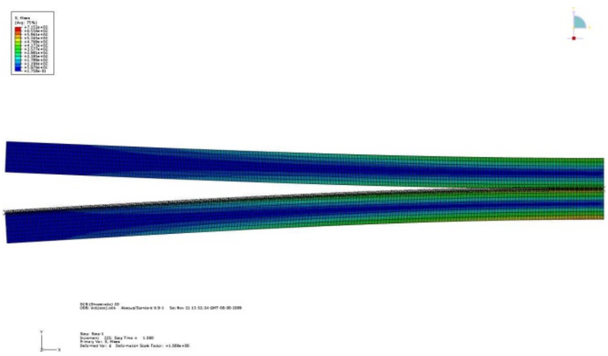


Figure 5. Von Mises stress plot for number 3 simulation.

It is also interesting to observe the results for simulation number 11 shown in Figure 6 with a small plateau near 210 mm, showing a stable crack propagation.

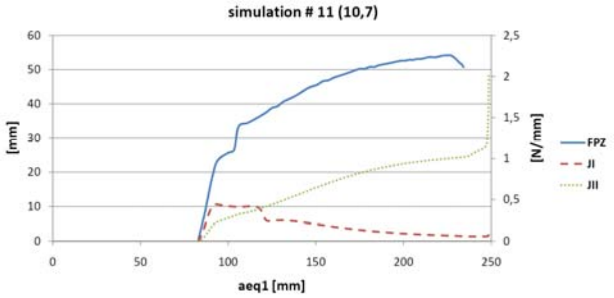


Figure 6. Number 11 simulation results plot for FPZ, J_I and J_{II}.

Figure 7 shows the Von Mises stress plot result for this same imposed displacement. The deformed shape confirms the imposed displacement in the same direction for the two beams of the DCB specimen.

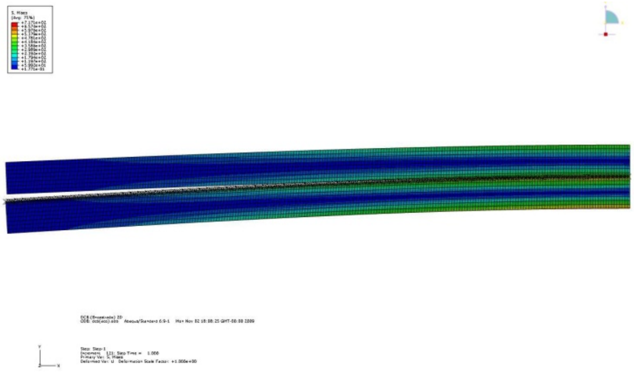


Figure 7. Von Mises stress plot for number 11 simulation.

4. Conclusions

The Asymmetric Compliance-Based Beam Method (ACBBM) data reduction scheme presented here for the determination of J for specimens tested in a dual actuator load frame were validated through a numerical model. This data reduction scheme does not require the crack length and takes into account the FPZ. This data reduction scheme will be used to determine the fracture envelope based on the experimental loading curves.

Acknowledgments

The authors would like to thank the contribution of Edoardo Nicoli, for his testing work at Virginia Tech. The authors also acknowledge the financial support of Fundação Luso Americana para o Desenvolvimento (FLAD) through project 314/06, 2007 and IDMEC.

References

[1] Oliveira, J.M.Q., de Moura, M.F.S.F., Silva, M.A.L., Morais, J.J.L., Numerical analysis of the MMB test for mixed-mode I/II wood fracture, Composites Science and Technology Vol.67 (9), 2007, pp. 1764-1771

[2] Hitendra K. Singh, Soojae Park, DonOhanehi and David A. Dillard, “A Design Space for a Novel Dual-Actuator Mixed-Mode Test Frame”,Proceedings of the 29th Annual Adhesion Society Meeting, Jacksonville,FL, 2006.

[3] Lucas. F.M. da Silva, R.J.C. Carbas , G.W. Critchlow, M.A.V. Figueiredo , K. Brown, Effect of material, geometry, surface treatment and environment on the shear strength of single lap joints, International Journal of Adhesion & Adhesives 29 (2009) 621–632.