MODE I COHESIVE LAW CHARACTERIZATION PROCEDURE IN ADHESIVE JOINTS

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Keywords: Interlaminar failure, Cohesive zone, DCB test, Mode I

Abstract
A method is proposed for the experimental characterization of damage propagation in adhesive joints. The Double Cantilever Beam test configuration is used to propagate damage stably while load, load point displacement and load point rotation are recorded.

These measurements are used to compute the fracture toughness and crack opening displacement from which a cohesive law is determined.

The procedure is validated by finite element analysis including cohesive zone modeling and results of the proposed method are compared to those obtained with the Direct Method, where the crack opening displacement is directly determined.

The proposed method provides a simple way to obtain the mode I cohesive law using only the load, the load point displacement and the load point rotation data, without any external crack opening displacement measurement technique and without any assumption of the form of the cohesive law.

1. Introduction

The cohesive law plays an important role in the simulation of the fracture behavior of materials [1]. Thus, methods to determine the cohesive law of adhesive layers have been developed by several authors [2-6].

In order to determine relative displacements at the crack tip, those methods require the use of external equipment as Digital Image Correlation (DIC) or Linear voltage differential transformer (LVDT) [3,4,6]. Experimental difficulties associated with the existing measurement methods have been reported, related to inaccurate results in the measurement of very small crack tip separations [4].

In the present study, a new method to determine the cohesive law in Mode I has been developed.

2. Analytical Approach

The path independent *J*-integral, presented by Rice [7] can be used to calculate the fracture resistance *J* during the crack growth.

$$J = \int_C \left(W dy - T \frac{\partial u}{\partial x} \, dC \right) \tag{1}$$

Where *c* is the counter clockwise integration path, *W* is the strain energy density, ***T*** the traction vector and ***u*** the displacement vector. By choosing *c* close to the crack tip, ***T*** is null [2, 7,8] and Eq. (1) becomes in:

$$J = \int_C W dy = \int_0^{\Delta_n} \sigma \, d\Delta_n + \int_0^{\Delta_t} \tau \, d\Delta_t \tag{2}$$

where σ, τ, Δ_n and Δ_t are the cohesive normal stress, shear stress, opening and shear displacement at the crack tip, respectively.

According to Eq. (2) if the relationship among G, Δ_n and Δ_t is known, assuming that G is an exact differential, the cohesive laws can be obtained as

$$\sigma(\Delta_n, \Delta_t) = \frac{\partial J}{\partial \Delta_n} \qquad \tau(\Delta_n, \Delta_t) = \frac{\partial J}{\partial \Delta_t} \tag{3}$$

For a symmetric specimen, symmetrically loaded with a crack advancing along the mid-plane, the crack opening displacement is normal to the crack plane and the crack shear displacement is zero. Then, the cohesive normal stress σ depends only on the normal opening Δ_n [9,10], being:

$$\sigma(\Delta_n) = \frac{\partial J}{\partial \Delta_n} \tag{4}$$

The double cantilever beam (DCB) test shown in Fig. 1 is the most popular method used to calculate delamination toughness in mode I [11]. In order to achieve pure mode I, a pre-cracked specimen is loaded at one edge by means of bonded blocks or piano hinges. The *J-integral* is computed by means of the expression proposed by Andersson et al [6] as:

$$J = \frac{2P}{w}\theta \tag{5}$$

where w is the specimen width, P is the applied load and θ is the rotation angle at the load introduction point.

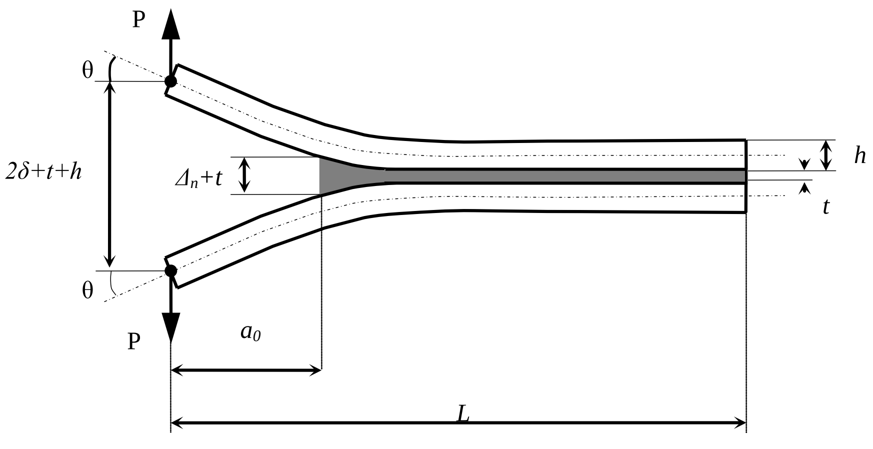


Figure 1. DCB-specimen with measured quantities P, 2δ and θ.

According to beam theory and assuming that the adherent behavior is linear elastic, the crack tip opening displacement can be determined by the following equation:

$$\Delta_n = 2\delta - 2\left(\theta - \frac{Pa_0^2}{2E_f I}\right)a_0 - 2\left(\frac{Pa_0^3}{3E_f I} + \frac{6}{5}\frac{Pa_0}{G_{13}A}\right) \tag{6}$$

Where Δ_n is the crack opening displacement; 2δ is the load line displacement; P is the applied load; θ is the rotation angle at the load introduction point; a_0 is the initial crack length; $E_f I$ is the adherent bending stiffness; and $G_{13}A$ the adherent shear stiffness.

3. Numerical verification of the proposed method

A finite element analysis of the DCB specimen was used to assess the accuracy of the proposed method. In the considered DCB configuration the specimen length is L= 100 mm; the initial crack length a_0=35mm; the width is w= 20 mm; and the arm thickness is h = 1.5 mm. The elastic properties corresponding to the adherents are shown in Table 1.

Table 1. The material mechanical properties

E_{11} (GPa)	$E_{22}=E_{33}$ (GPa)	$G_{12}=G_{13}$ (GPa)	G_{23} (GPa)	$\nu_{12}=\nu_{13}$	ν_{23}
144.0	10.6	5.36	3.95	0.34	0.4

The model was developed in ABAQUS [12] using four-node 2D plane strain incompatible elements (CPE4I) (Fig. 2). A row of t = 0,2mm thickness four-node cohesive elements (COH2D4) was placed ahead of the notch tip to model the adhesive. The input cohesive law is shown in Fig. 2.

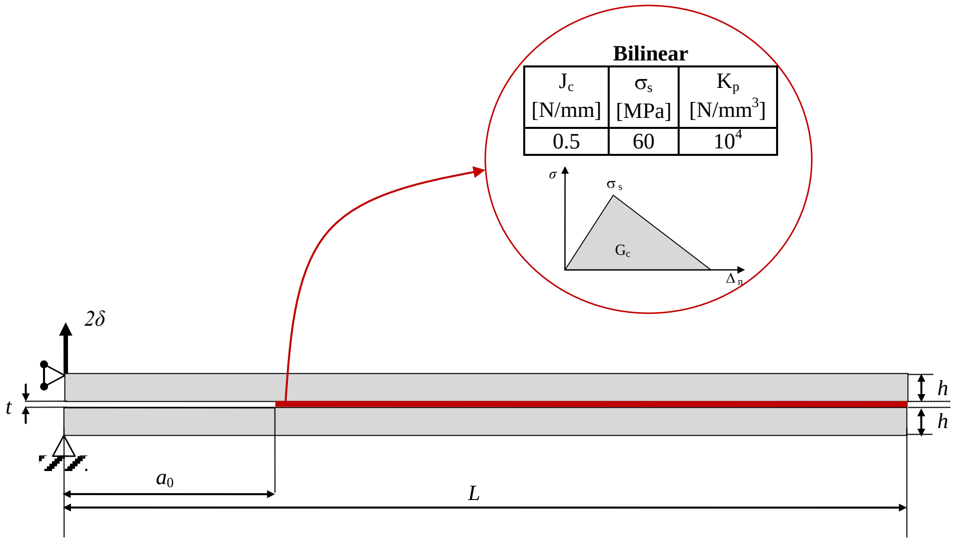


Figure 2. Finite Element model (dimensions and boundary conditions)

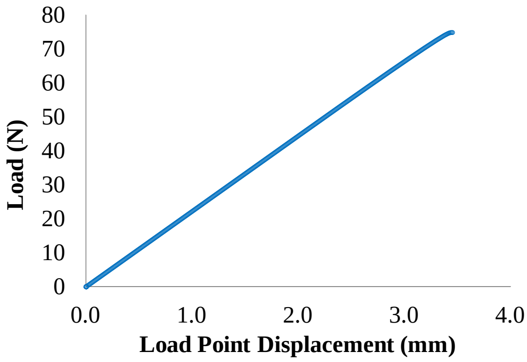
The aim of this numerical validation is to check if the cohesive law used in the model input can be determined based on the data reduction method proposed in the present work. Two different procedures are used in order to get the input cohesive law:

1) **Direct method:** J is computed replacing the load and the rotation at the load application point in Eq. (5). The relative opening displacement is determined by FEM at the initial crack tip. The cohesive law is obtained by numerical differentiation.

2) **Present approach**: J is computed also by Eq. (5) and the relative opening displacement is determined replacing the load, the load point displacement and the rotation at the load application point in Eq. (6). Finally, the cohesive law is obtained by numerical differentiation.

4. Results and Discussion

The load, the load point displacement and the load point rotations are obtained from numerical simulation. Related curves are shown in Fig.3.



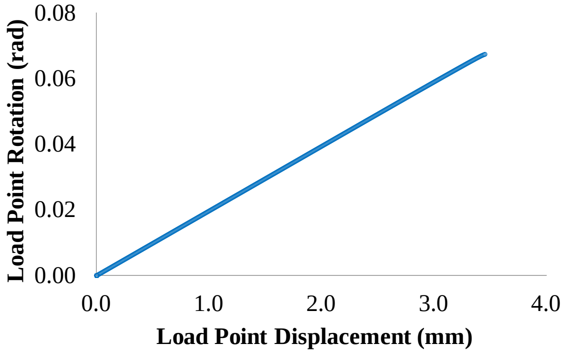


Figure 3. a) Load – Load point displacement curve and b) Load point rotation – Load point displacement curve

Δ_n related to the Direct Method, and Δ_n obtained by the present approach corresponding to the bilinear cohesive law are plotted in Fig. 4.

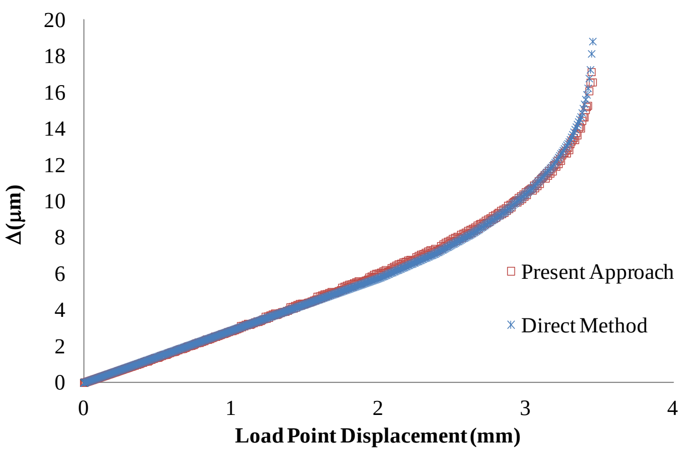


Figure 4. Crack tip opening displacement - Load Point Displacement for the bilinear Cohesive Law.

Fig. 5 shows the fracture toughness versus crack tip opening displacement curves corresponding to the bilinear cohesive law. The J-Δ_n curves according to the Direct Method in blue, G-Δ_n curves according to the present approach in red.

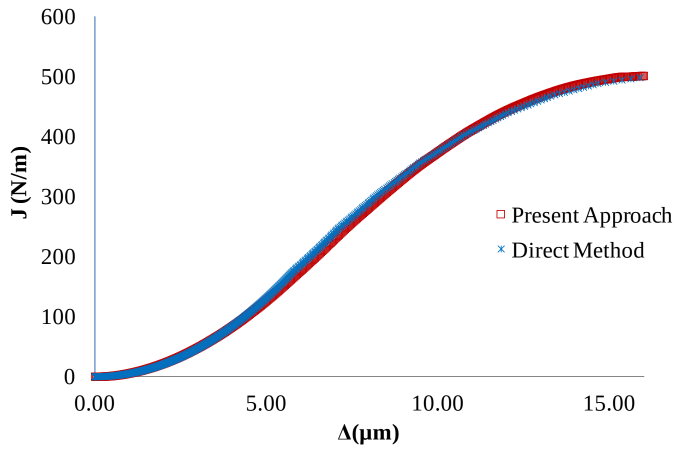


Figure 5. Interlaminar Toughness **-** Crack tip opening displacement for the bilinear Cohesive Law.

Fig. 6 shows a comparison among the input cohesive law and those obtained by numerical differentiation of the curves shown in Fig. 5 with respect to Δ_n.

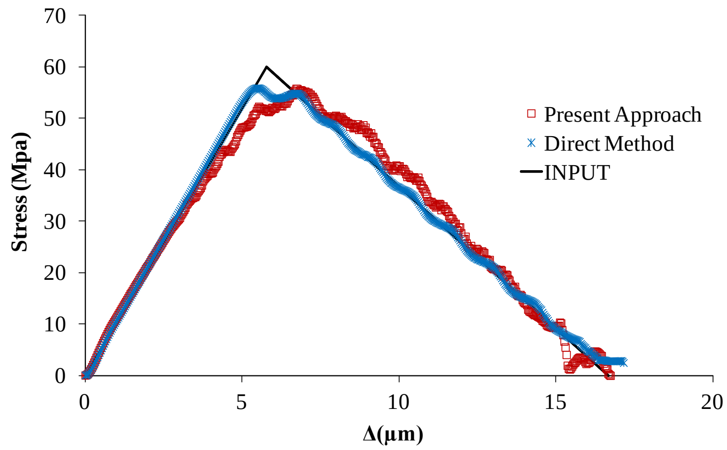


Figure 6. Bilinear Cohesive Law: σ_s=60MPa; J=0.5N/mm; K_p=10^4 N/mm^3

5. Conclusions

This new method provides a simple way to obtain the mode I cohesive law using load, displacement and rotation data, without any external crack opening displacement measurement technique and without any assumption of the form of the cohesive law.

Acknowledgments

The financial support of the University of the Basque Country (UPV/EHU) in the Research Group GIU 16/51 “Mechanics of Materials” is gratefully acknowledged.

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