INFLUENCE OF THE SPECIMEN WIDTH ON THE EXPERIMENTAL MEASUREMENT OF THE COHESIVE LAW USING THE J-INTEGRAL APPROACH

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Abstract

The joining of composite materials has a special interest for modern industry and adhesives certainly offer numerous advantages over other mechanical joining methods like welding or bolt fasteners. To model adhesive bonded joints are commonly used cohesive laws and one of the most used procedure to obtain the cohesive law is the J-Integral approach. In general, the experimental procedure used to apply the J-integral approach, determines the crack tip opening displacement at the front-face of the specimen through a visual technique. Nevertheless, it is well known that the width of the crack front along the adhesive layer is not straight due to the elastic properties of the adhesive such as the Poissons ratio. In present work, the influence of the specimen width in the procedures to obtain cohesive laws by J-integral method using an advanced analytical DCB model with a coupled cohesive damage is studied. The analysis takes into account the change of the cross plane stress state at the crack tip to a triaxial stress state inside the adhesive layer in a DCB test. An experimental campaign of DCB test has been also performed in order to fit a cohesive law for a composite adhesive joint.

1. Introduction

Composite materials are of special interest in modern industry due to the advantages for lightweight structures. The joints of composite material are a challenge for engineers and the adhesives provide numerous advantages over other conventional techniques for this purpose [1]. Different methodologies have been developed for the design of adhesive joints, but certainly finite element methods are the most commonly used. In recent years, the models using cohesive elements have taken more relevance due to the advantages of considering the influence of the adhesive damage process zone in the behaviour of the joint. In numerous works (e.g. [2–8]) have made efforts to improve the cohesive laws and procedures to obtain them. Cohesive elements are commonly considered as zero thickness elements and are used for composite delamination modelling with good results. Nevertheless, for adhesive layer simulations, specially if flexible adhesive are used, the influence of the elasticity of the adhesive on the failure process must be taken into account. For this purpose, Sarrado et al. [8] have proposed a cohesive element model with coupled elastic behaviour of the adhesive with better predictions of a adhesive joint simulation.

The cohesive elements models assume different approaches regarding the stress-strain state present in the adhesive layer. A traversal plane strain is the most common approach used, where for example, in [3] the correction factor ξ for J-integral, $J = J^{ext}\,\xi$, in a DCB test is obtained as,

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$$\xi = 1 - \nu^2 \tag{1}$$

The J^{ext} is the J-integral obtained by external face of the DCB specimen, normally obtained through image processing. The equation (1) assume plane strain and and gives accurate values when large width/thickness (B/t_a) ratios are present in the adhesive layer. This condition is commonly present when rigid adhesives are used, however there is currently a trend to use flexible adhesives due to different advantages as hight resistance for dynamic loads. For flexible adhesives the plane strain condition cannot be always guaranteed. In present work, a new correction function for obtaining the J-integral approach is proposed in order to have a better fit for a cohesive law when joints of composites materials with flexible adhesives are designed.

2. New correction of a linear cohesive law with coupled elastic behaviour regarding the stress state on the adhesive layer

In [8], it was proposed an finite-thickness cohesive elements for modeling thick adhesives, where it was coupled the elastic behaviour of the adhesive, and the cohesive properties. Subsequently, in [9] by means of an analytical procedure, it was demonstrate that is possible use a zero thickness cohesive law with equivalent cohesive displacement jump at failure. The cohesive law is the same of that on finite element method, but using as penalty stiffness an equivalent cohesive displacement jump at failure. Using a linear cohesive law and lineal elastic behaviour on the adhesive as suggests Figure 1, the normal stress distribution can be obtained,

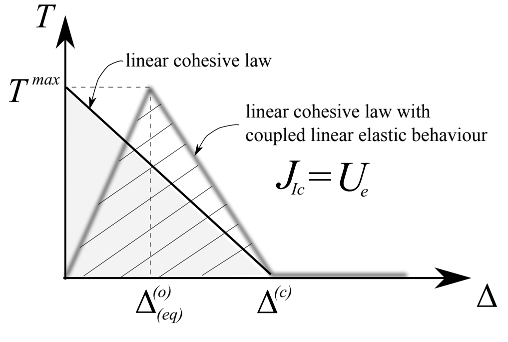

Figure 1. Equivalent linear cohesive law with coupled elastic behaviour.

$$T = \frac{T^{max}}{\Delta^{(o)}_{eq}}(1 - D)\,\Delta \tag{2}$$

where τ_n^{max} is the maximum cohesive traction and $\Delta^{(o)}_{eq}$ the normal equivalent cohesive displacement jump corresponding to the maximum normal traction. Δ is the interface displacement and D the damage expressed as,

$$D = \begin{cases} 0 & : \Delta \leqslant \Delta^{(o)}_{eq} \\ \left(\dfrac{\Delta - \Delta^{(o)}_{eq}}{\Delta}\right)\left(\dfrac{\Delta^{(c)}}{\Delta^{(c)} - \Delta^{(o)}_{eq}}\right) & : \Delta^{(o)}_{eq} < \Delta < \Delta^{(c)} \\ 1 & : \Delta \geqslant \Delta^{(c)} \end{cases} \tag{3}$$

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being $\Delta^{(c)}$ is the normal cohesive displacement jump at failure. The equivalent cohesive displacement jump corresponding to the maximum normal traction, considering the elasticity of the adhesive results,

$$\Delta^{(o)}_{eq} = \frac{T^{max}}{E'_a} t_a \tag{4}$$

where t_a is the adhesive thickness and the apparent Young modulus E'_a is commonly assumed as,

$$E'_a = E_a \tag{5}$$

The apparent Young modulus is also used for transversal plane strain condition as,

$$E'_a = \frac{(1-\nu_a)\ E_a}{(1+\nu_a)\,(1-2\nu_a)} \tag{6}$$

where ν_a is the Poisson ratio of the adhesive. In both approaches, the stiffness behaviour on the adhesive layer is assumed as a constant value.

In a recent work [10], the authors presented a general model that takes into account the transition of stress states within the adhesive layer. Using empirical corrections of the stress distribution in adhesive layer as a function of the transversal position in the adhesive midplane. directions. Using this approach the apparent Young's modulus of the adhesive reads,

$$E'_a(x,z) = \frac{(1-\nu_a)E_a}{(1+\nu_a)(1-2\nu_a) + \nu^2\left[\mathrm{e}^{-x/(3\nu_a t_a)} + \mathrm{e}^{-z/(3\nu_a t_a)}\right]} \tag{7}$$

In proposed model by [10], the apparent Young modulus is a function of the x and z position of the adhesive layer $E'_a = f(x,z)$, allowing to consider the variable stiffness in the width of the adhesive. Following this approach, this works suggest to obtain the ratio between the cohesive law properties obtained at the outer visible face of DCB specimens, and the inner center plane, view Figure 2.

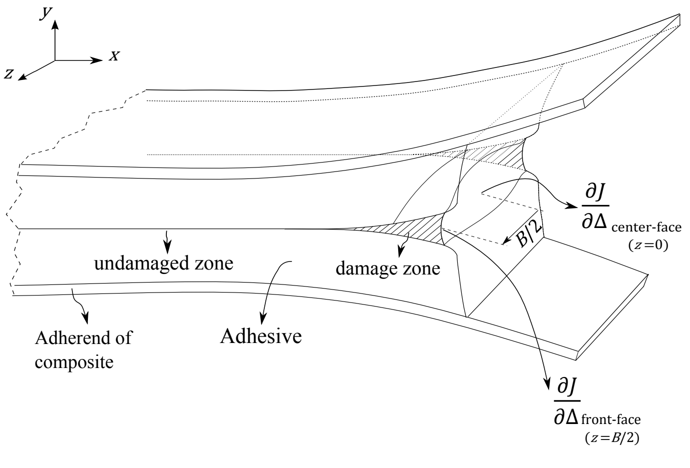

Figure 2. Scheme used to study the influence of the specimen width in the procedures to obtain cohesive laws by J-integral method.

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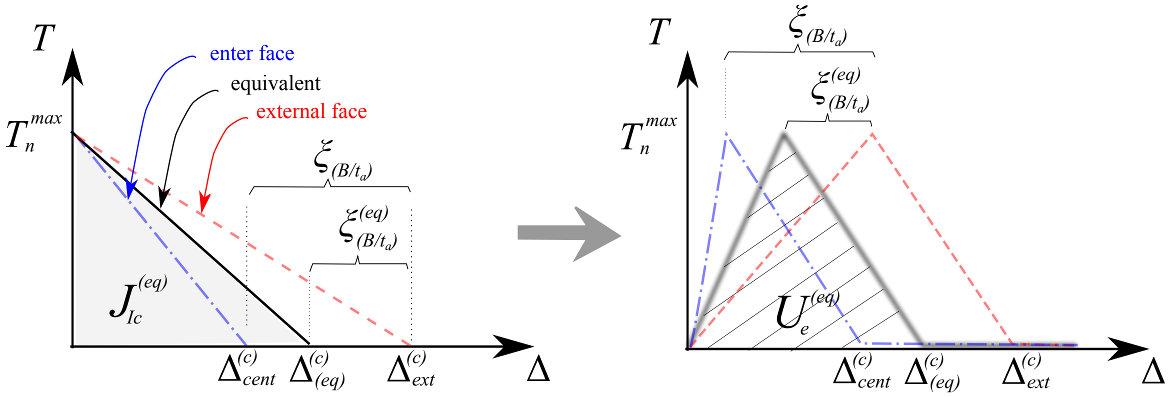
Taking into account that in the crack front $z = 0$ and the interface cohesive stress is equal to the bulk stress, the equivalent cohesive law for both faces in the elastic range are,

$$\frac{\partial J}{\partial \Delta_{ext}} = T^{e}_{ext} = E_a \frac{\Delta^{e}_{ext}}{t_a} \tag{8}$$

$$\frac{\partial J}{\partial \Delta_{cent}} = T^{e}_{cent} = \frac{(1-\nu_a)E_a}{(1+\nu_a)(1-2\nu_a) + \nu^2\left[1 + \mathrm{e}^{-(1/6\nu_a)(B/t_a)}\right]} \frac{\Delta^{e}_{cent}}{t_a} \tag{9}$$

As suggest the Figure 3, it is possible to find a relation between the equations (8) and (9), which define the relation between a cohesive law obtained in external face with a cohesive law associate to any B/t_a relationship.



a) b)

Figure 3. Correction of the linear cohesive law with coupled elastic behaviour form external face to any center face and equivalent integrated value.

Assuming a adherend rigid enough in comparison with adhesive properties and avoiding the effects of anticlastic curvature, the bulk displacement before the damage begins is the same on external and center face $\Delta^{e}_{ext} = \Delta^{e}_{cent} = \Delta$. Taking into account this condition before the damage begins and dividing equations (8) and (9) is obtained the new relation $\xi_{(B/t_a)} = T^{e}_{ext}/T^{e}_{cent}$ as,

$$\xi_{(B/t_a)} = 1 - \frac{\nu^2}{(1-\nu_a)}\left[1 - \mathrm{e}^{-(1/6\nu_a)(B/t_a)}\right] \tag{10}$$

Integrating the equation (10) along B/t_a, $\int_0^{B/t_a} \xi_{(B/t_a)}\, d(B/t_a)$, and dividing between them, an equivalent function of the an equivalent correction depending on the width/thickness ratio present in the adhesive layer is obtained.

$$\xi^{(eq)}_{(B/t_a)} = 1 - \frac{\nu^2}{(1-\nu_a)} + \frac{6\nu^3}{(1-\nu_a)} \frac{\left[1 - \mathrm{e}^{-(1/6\nu_a)(B/t_a)}\right]}{B/t_a} \tag{11}$$

The behaviour of the equivalent correction function for three different values of Poisson's ratios are represented in Figure 4.

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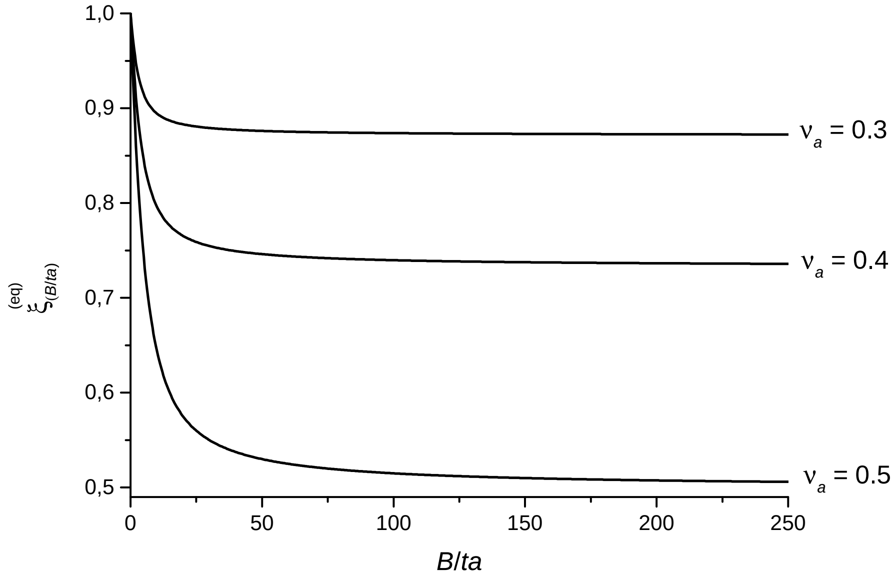

Figure 4. Curves of the equivalent correction function against B/t_a relation and the influence of the Poisson's ratio.

As shown, for high values of Poisson's ratio, the requered correction is greater. Moreover, for large B/t_a relations the correction tends to a constant value associate to a perfect plan strain sate. However, if small B/t_a ratios are present, corrections are required for the J-integral values obtained from common DCB test since the plane strain model do not provide accurate results.

Equation (11) define a new correction function of the cohesive laws and in terms of an equivalent fracture energy (J-integral) results,

$$J^{(eq)} = J^{ext}\, \xi^{(eq)}_{(B/t_a)} \tag{12}$$

To obtain an appropriate cohesive law to model a DCB test, is required to correct the cohesive displacement jump at failure $\Delta^{(c)}$ and equivalent cohesive displacement jump corresponding to the maximum normal traction $\Delta^{(o)}_{eq}$ given in equations (2) and (3) multiplying by equation (11).

3. Validation of the proposed correction

3.1. Experimental DCB test

In order to validate the new correction proposed in previous section, an experimental campaign of 7 DCB test was carried out in order to compare the results of a finite element model with cohesive law using the new correction proposed. For DCB tests an universal testing machine using the setup recommended in standard ISO-25217 [11] was used. The specimens consist on two composite laminates $[0, 45, 90, -45]_s$ with carbon fibber (T700s) and epoxy matrix bonded by an adhesive layer. The adherends were of 1.5 mm of thickness with 200x20 mm dimensions. The Young's modulus of the adherends was obtained in [12] as E_s = 68884 MPa. A flexible Silkron-H100 adhesive, cured during 7 days at 50^0C, was used with thickness t_a = 1 mm. The adhesive Young's modulus, Poisson's ratio and ultimate strength were given in [13] by means of and appropriate procedure as E_a = 4 Mpa, ν_a = 0.4996 and 2.2 MPa respectively. The adhesive thickness was of t_a = 1 mm so that a ration B/t_a = 20 was obtained.

Two inclinometers, located at the load application points, were used to determine the J-integral as was propose by [14]. In addition it was used a calibrate video camera to obtain the crack opening displacement on external face by a visual method. The J-integral in terms of middle value for all DCB test performed, result J_{Ic}^{ext} = 5.48 N/mm. For a linear cohesive law, the normal displacement jump at failure was $\Delta_{cent}^{(c)}$ = 4.98.

Applying the proposed correction obtained by equation (11), for this case results $\xi_{(B/t_a)}^{(eq)}$ = 0.58, the equivalent J-integral result $J_{Ic}^{(eq)}$ = 3.18 N/mm.

3.2. Load-displacement curve predictions by different corrections at numerical simulation

An representative load-displacement curve obtained by experimental DCB test is compared with the predictions of three models based on finite element method, view Figure 5.

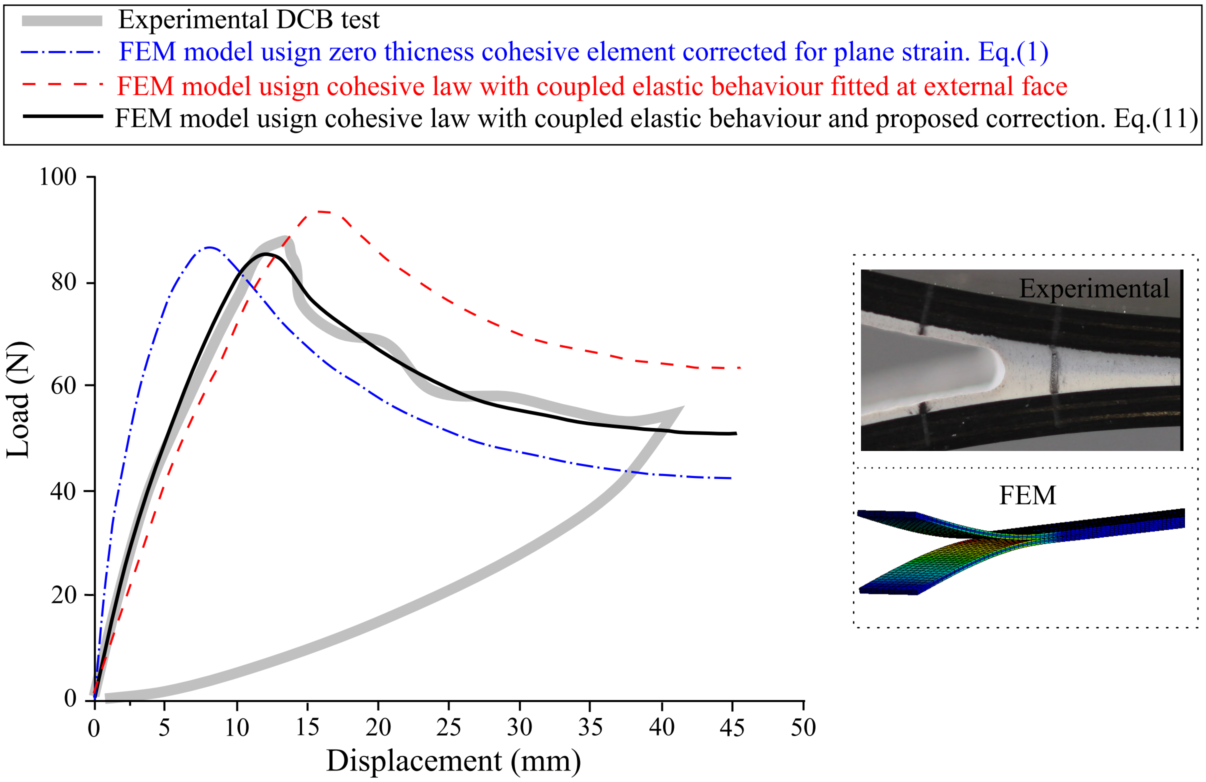

Figure 5. Load-displacement curve obtained by difference corrections on the cohesive law in comparison with experimental DCB test.

A 3D numerical DCB model was implemented using finite element method (FEM) by ANSYS software. The mesh was constructed taking advantage of the automatic meshing algorithms of ANSYS and a manual resizing procedure obtaining an element size of 0.25 mm. The adherend parts was modelled with SOLID185 8-node quadrilateral elements with equivalent linear elastic properties and a cohesive interface has been used to model the adhesive using a zero thickness INTER205 8-node linear interface

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element. The cohesive law was assumed bilinear and the properties were parametrically introduces according to three approaches. The model using cohesive law with coupled elastic behaviour and the new correction parameter proposed provide more accurate predictions than other two which were compared.

4. Conclusion

An new correction function of the cohesive law obtained by J-integral procedure in external face has been proposed. The correction depends on the width/thickness and Poisson ratio, and it is a generalization of the literature approach based on plane strain assumption. The correction is specially required when large thickness of flexible adhesives are used.

A numerical model has been implemented by means of the interface cohesive elements in combination with the new propose correction in a coupled elastic behaviour and compared with experimental DCB tests. The purpose correction on cohesive law provide more accurate results than a simple zero thickness cohesive law with plane strain approach.

Acknowledgments

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References

[1] Hartmut Pasternak and Yvonne Ciupack. Development of Eurocode-based design rules for adhesive bonded joints. *International Journal of Adhesion and Adhesives*, 53:97–106, sep 2014.

[2] Bent F Sørensen. Cohesive law and notch sensitivity of adhesive joints. *Acta Materialia*, 50:1053–1061, 2002.

[3] Bent F. Sørensen and Torben K. Jacobsen. Determination of cohesive laws by the J integral approach. *Engineering Fracture Mechanics*, 70(14):1841–1858, 2003.

[4] A. Turon, P. P. Camanho, J. Costa, and C. G. Dávila. A damage model for the simulation of delamination in advanced composites under variable-mode loading. *Mechanics of Materials*, 38(11):1072–1089, 2006.

[5] A B De Morais. Mode I cohesive zone model for delamination in composite beams. *Engineering Fracture Mechanics*, 109:236–245, 2013.

[6] Julien Jumel, Naoufel Ben Salem, Michal K. Budzik, and Martin E.R. Shanahan. Measurement of Interface Cohesive Stresses and Strains Evolutions with combined Mixed Mode Crack Propagation Test and Backface Strain Monitoring Measurements. *International Journal of Solids and Structures*, 52:33–44, October 2015.

[7] Olaf Hesebeck. Consideration of the restriction of lateral contraction in the elastic behaviour of cohesive zone models. *International Journal of Adhesion and Adhesives*, 2015.

[8] Carlos Sarrado, Frank A. Leone, and Albert Turon. Finite-thickness cohesive elements for modeling thick adhesives. *Engineering Fracture Mechanics*, mar 2016.

[9] M. Cabello, A. Turon, J. Zurbitu, J. Renart, and F. Martínez. Progressive failure analysis of DCB bonded joints by means of an improved analytical elastic foundation formulation coupled with a cohesive damage model. *Submitted to: International Journal of Platicity*, pages –, 2016.

Excerpt from ISBN 978-3-00-053387-7

[10] M. Cabello, J. Zurbitu, J. Renart, A. Turon, and F. Martínez. A general analytical model based on elastic foundation beam theory for adhesively bonded DCB joints either with flexible or rigid adhesives. *Submitted to: International Journal of Solids and Structures*, pages –, 2016.

[11] ISO. ISO-25217 Determination of the mode 1 adhesive fracture energy of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens. Technical report, International Organization for Standardization, 2009.

[12] M. Cabello, M. Asensio, F. Martínez, and M .J. Lamela. Accelerated Flexural Fatigue Test Rig To Characterize High Strength Composite Materials. In *16th EUROPEAN CONFERENCE ON COMPOSITE MATERIALS (ECCM16)*, number June, pages 22–26, Seville, 2014.

[13] M. Cabello, J. Zurbitu, J. Renart, A. Turon, and F. Martínez. A non-linear hyperelastic foundation beam theory model for double cantilever beam tests with thick flexible adhesive. *International Journal of Solids and Structures*, 80:19–27, 2016.

[14] Filipe J. P. Chaves, L. F. M. da Silva, M. F. S. F. de Moura, D. a. Dillard, and V. H. C. Esteves. Fracture Mechanics Tests in Adhesively Bonded Joints: A Literature Review. *The Journal of Adhesion*, 90(12):955–992, jun 2014.

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