A straightforward method to obtain the cohesive laws of bonded joints under mode I loading

M.F.S.F. de Moura, J.P.M. Gonçalves, A.G. Magalhães

A B S T R A C T

A simple procedure to measure the cohesive laws of bonded joints under mode I loading using the double cantilever beam test is proposed. The method only requires recording the applied load–displacement data and measuring the crack opening displacement at its tip in the course of the experimental test. The strain energy release rate is obtained by a procedure involving the Timoshenko beam theory, the specimen's compliance and the crack equivalent concept. Following the proposed approach the influence of the fracture process zone is taken into account which is fundamental for an accurate estimation of the failure process details. The cohesive law is obtained by differentiation of the strain energy release rate as a function of the crack opening displacement. The model was validated numerically considering three representative cohesive laws. Numerical simulations using finite element analysis including cohesive zone modeling were performed. The good agreement between the inputted and resulting laws for all the cases considered validates the model. An experimental confirmation was also performed by comparing the numerical and experimental load–displacement curves. The numerical load–displacement curves were obtained by adjusting typical cohesive laws to the ones measured experimentally following the proposed approach and using finite element analysis including cohesive zone modeling. Once again, good agreement was obtained in the comparisons thus demonstrating the good performance of the proposed methodology.

Keywords:
Bonded joints
Cohesive laws
Mode I
Double cantilever beam test

1. Introduction

The use of bonded joints in structural applications has been increasing in the most recent years as a consequence of the advantages of this joining method relative to classical alternatives, as is the case of fastening. The main advantages are lower weight, less sources of stress concentration and better fatigue properties. The application of this joining method in transportation industries, like automobile and aeronautical, requires more demanding design methods in order to better describe the mechanical behavior of the bonded joints. In fact, classical approaches based on stress or strain analysis are not able to deal with several details influencing the mechanical behavior of the bonded joints. For example, when these methods are applied through finite element analysis it is verified that mesh dependency problems arise, due to the presence of singularities. In this context, cohesive zone models (CZM) emerge as an appealing alternative solution. These methods are based on a constitutive relationship between stresses (σ) and relative displacements (w) and allow simulation of damage initiation and propagation. They use the strength of materials approach to identify damage onset and fracture mechanics concepts to deal with its growth. The CZM are usually implemented in a finite element analysis by means of interface finite elements connecting solid elements [1]. Some issues, like non-self-similar crack growth and the presence of a non-negligible fracture process zone (FPZ), are well managed by CZM. The FPZ is the region in the vicinity of the crack tip where plasticity, micro-cracking and several other inelastic processes take place. When ductile adhesives are used, the size of the FPZ is non-negligible and its incorporation in the predictive method is fundamental to provide reliable design [2,3].

One of the crucial aspects of CZM is the definition of the cohesive law that characterizes the bonded joint. There are two main methods to get these laws: inverse method and direct measurement during a fracture characterization test. The inverse method assumes a pre-defined cohesive law and the respective parameters are determined by fitting the numerical and experimental load–displacement curves using a manual iterative procedure [4] or an automatic optimization strategy [5]. The drawback intrinsic to this procedure is the need to impose a pre-defined law. In fact, this task requires some previous knowledge of the joint's behavior which is not available in many cases.

Alternatively, the cohesive law can be measured directly during a fracture characterization test. Sørensen [6] determined experimentally the cohesive law by means of a J-integral based approach. The author performed double cantilever beam (DCB) tests where the specimens were loaded with pure bending moments which required the development of a special experimental setup. Using this procedure, the J-integral can be calculated continuously during the test as a function of the applied moment using a simple closed-form solution. The end–opening displacement (w) at the crack tip was monitored by extensometers mounted at pins located at the neutral axis of the specimen arms. The cohesive law ($\sigma = \mathrm{f}(w)$) is obtained from differentiation of J with respect to w. Andersson and Stigh [7] obtained the stress–elongation relation for an adhesive layer loaded in peel using the DCB test. These authors used a common test configuration to perform the DCB tests, i.e., the specimens were loaded with a wedge force. However, in this case the J-integral estimation required the measurement of the beam rotation at the loading point by means of a specific shaft encoder thus allowing the determination of J-integral by using a closed-form solution.

The objective of this work is to present a simpler methodology to determine the cohesive laws of bonded joints under mode I loading using the DCB test. The method only involves the data given by the load–displacement curve and monitoring of the crack opening displacement (COD) at the crack tip. Evolution of the specimen's compliance during the experimental test is used in combination with the Timoshenko beam theory and the equivalent crack concept to determine the strain energy release rate. The cohesive law is obtained by the derivative of the strain energy release rate as a function of the COD. Following this procedure it is not necessary to employ neither a specific experimental setup nor the measurement of the specimen's arms rotation during the course of the test. The proposed method is validated numerically by means of a finite element analysis including cohesive zone modeling and also experimentally, performing DCB tests on steel-epoxy bonded joints.

2. Model description

The proposed model is applied to evaluate the cohesive law of a bonded joint under mode I loading using the DCB test. The method is based on direct measurement of the COD (represented in equations by w) at the crack tip and on the evaluation of the J-integral or energy release rate by a procedure which is different from the approaches presented in the literature. The cohesive law ($\sigma = \mathrm{f}(w)$) can be obtained from differentiation of the following Eq. [8]:

$$J_{\mathrm{I}} = \int_0^w \sigma(w)\, dw \tag{1}$$

leading to

$$\sigma(w) = \frac{dJ_{\mathrm{I}}}{dw} \tag{2}$$

This means that obtaining the J_{I}–w relation is a crucial issue of the procedure. In this context, a method based on the specimen's compliance, the Timoshenko beam theory and the crack equivalent concept is presented to estimate the evolution of strain energy release rate as a function of w.

According to the Timoshenko beam theory, the compliance versus crack length relationship ($C = \mathrm{f}(a)$) considering isotropic adherends is [5]

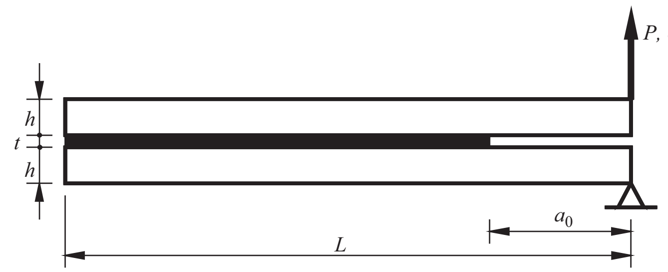

Fig. 1. Schematic representation of the DCB test ($L = 120$, $a_0 = 40$, $h = 3$, and $t = 0.2$; specimen width $B = 25$; all dimensions in mm).

$$C = \frac{8a}{EBh}\left(\frac{a^2}{h^2} + \frac{3(1+\nu)}{5}\right) \tag{3}$$

where a is the crack length, B and h are the specimen's width and the adherend's height, respectively (Fig. 1), and ν is Poisson's ratio. An equivalent elastic modulus (E_{e}), accounting for the combined effects of adherends and adhesive, specimen variability and stress concentrations at the crack tip, can be obtained from the previous equation taking into account the initial conditions. Considering the initial compliance C_0 obtained from the early linear part of the load-displacement curve and initial crack length a_0 corrected to account for root rotation effects, the E_{e} becomes

$$E_{\mathrm{e}} = \frac{8(a_0 + \Delta)}{C_0 Bh}\left(\frac{(a_0+\Delta)^2}{h^2} + \frac{3(1+\nu)}{5}\right) \tag{4}$$

The crack length correction Δ can be obtained numerically for each specimen fitting the initial compliance C_0 with the experiments for the real a_0. Afterwards, two additional numerical analyses considering different initial crack lengths should be performed, thus defining three points in the graphic representation of the $C^{1/3} = \mathrm{f}(a)$ relation. The interception of this line with the abscissa axis allows the definition of the crack length correction [4]. This modus operandi can also be executed experimentally considering three different initial crack lengths and performing the fracture characterization test from the smaller initial crack length. See details in Ref. [9].

During propagation, Eq. (3) can be used to estimate the equivalent crack length a_{e} as a function of the current compliance C. The resulting equation is

$$\frac{8a_{\mathrm{e}}^3}{E_{\mathrm{e}}Bh^3} + \frac{24(1+\nu)a_{\mathrm{e}}}{5E_{\mathrm{e}}Bh} - C = 0 \tag{5}$$

whose analytical solution [5] can be obtained from the Matlab® software. Using this procedure the FPZ effect is accounted for, since its presence influences the load–displacement curve, i.e., the compliance C, which is used to estimate the a_{e}. The strain energy release rate is obtained combining the Irwin-Kies equation

$$J_{\mathrm{I}} = \frac{P^2}{2B}\frac{dC}{da} \tag{6}$$

with Eq. (3) and considering the equivalent quantities a_{e} and E_{e} instead of a and E, respectively,

$$J_{\mathrm{I}} = \frac{12P^2}{E_{\mathrm{e}}B^2h}\left(\frac{a_{\mathrm{e}}^2}{h^2} + \frac{1+\nu}{5}\right) \tag{7}$$

Following this methodology the evolution of the strain energy release rate during the test is obtained exclusively by means of the data provided by the load–displacement curve, and in a straightforward manner combined with the measured COD. It is not necessary to monitor the crack length, since in this case the equivalent crack length is a calculated parameter as a function of the current compliance. It should be noted that a_{e} accounts indirectly for the presence of the FPZ since it is obtained from the current compliance that is influenced by the FPZ effects. Moreover, the DCB tests can be performed using the simple classical setup. Additionally, it is not necessary to measure the rotation of the arms at the loading point.

3. Numerical validation

In order to validate the method, numerical analyses considering three different cohesive laws representative of the mechanical behavior of bonded joints were performed. The mesh used (Fig. 2) is more refined in the region where crack propagation occurs having 2624 eight-node plane-stress solid elements and 320 six-node cohesive elements with null thickness located at the specimen's mid-height. The cohesive elements are used to simulate crack growth in the adhesive. The joint is assumed to have steel adherends ($E=210$ GPa and $\nu=0.3$) bonded by an epoxy adhesive whose cohesive parameters for each law are shown in Figs. 3, 6 and 7. The adhesive thickness was not considered in the simulations but its presence is indirectly taken into account by the interface stiffness $k=E/t$. In the present case the adhesive Young modulus was assumed to be 2 GPa, thus leading to $k=1E4$ N/mm^3 which defines the slope of the first branch of the cohesive laws considered.

During simulations the values of load, applied displacement and COD were recorded. The COD corresponds to the relative displacement between the pair of homologous points positioned at the crack tip and belonging to each specimen's arm. This relative displacement must be recorded from the beginning of the test till complete failure at this pair of points occurs and crack propagates. The bilinear cohesive law (Fig. 3) was the first analyzed since it is the simplest one and also widely utilized. The data provided by the load–displacement curve (Fig. 4) was used to get the evolution of strain energy release rate (Fig. 5), applying the methodology proposed in the previous section. A polynomial of sixth degree was adjusted to the $J_I=f(w)$ curve (Fig. 5) and subsequently differentiated in order to get the cohesive law (Eq. (2)). Good agreement between the resulting law and the inputted one was found (Fig. 3). Clearly, the inputted law is well reproduced thus demonstrating the good performance of the method.

A similar procedure for two more sophisticated laws was followed. The tri-linear law (Fig. 6) considers a bilinear softening

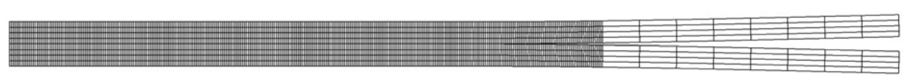

Fig. 2. Mesh used in the numerical analysis.

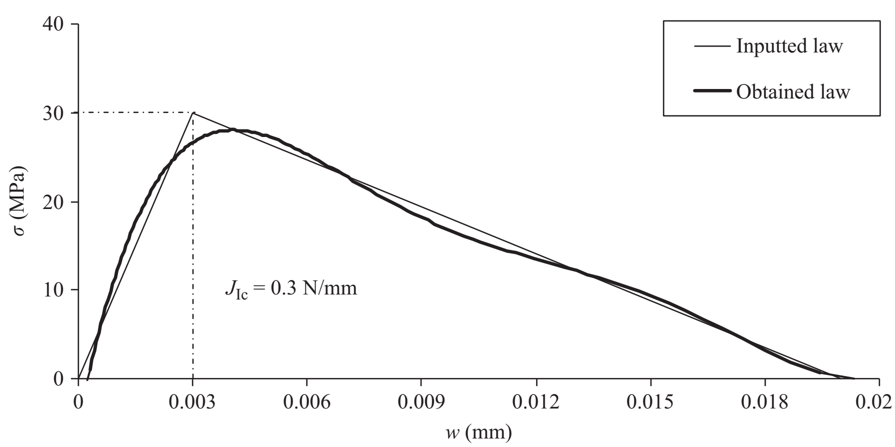

Fig. 3. Bilinear cohesive law.

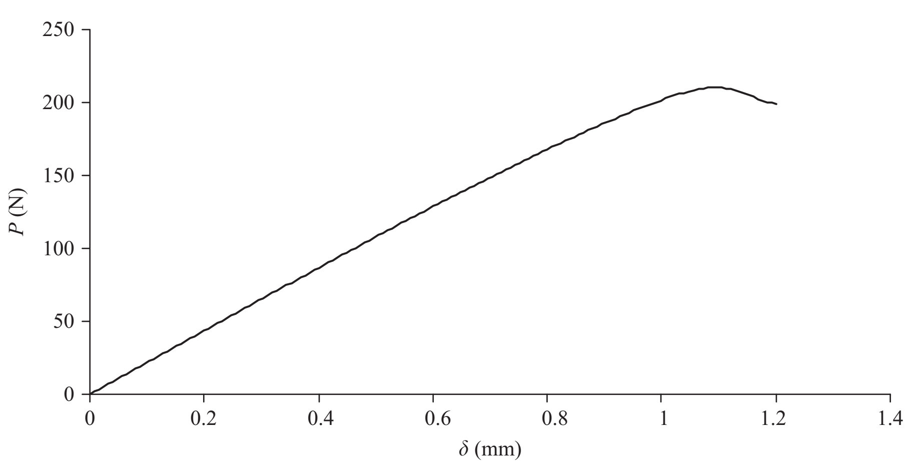

Fig. 4. Load–displacement curve of the DCB test considering the bilinear cohesive law.

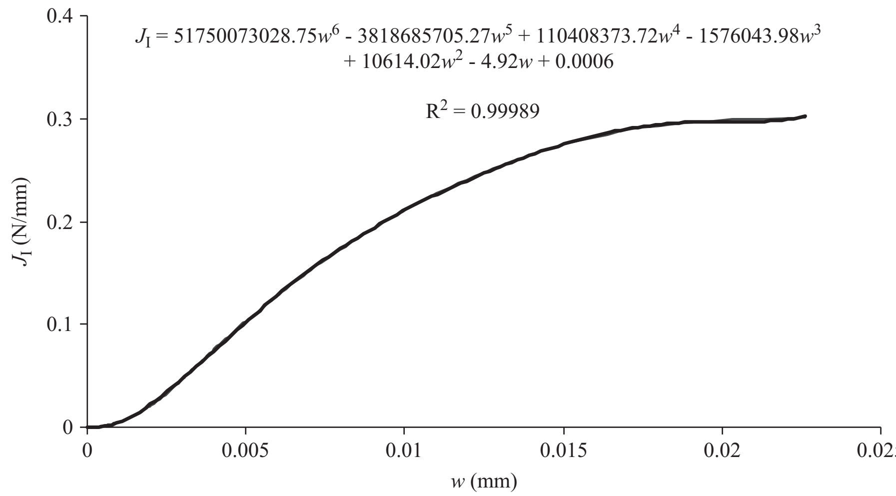

Fig. 5. The $J_I = f(w)$ curve fitted by a sixth degree polynomial considering the bilinear cohesive law.

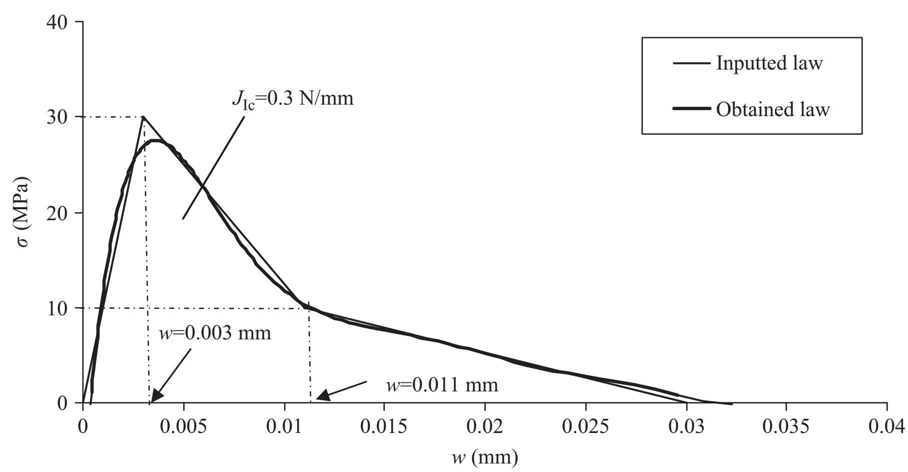

Fig. 6. Tri-linear cohesive law.

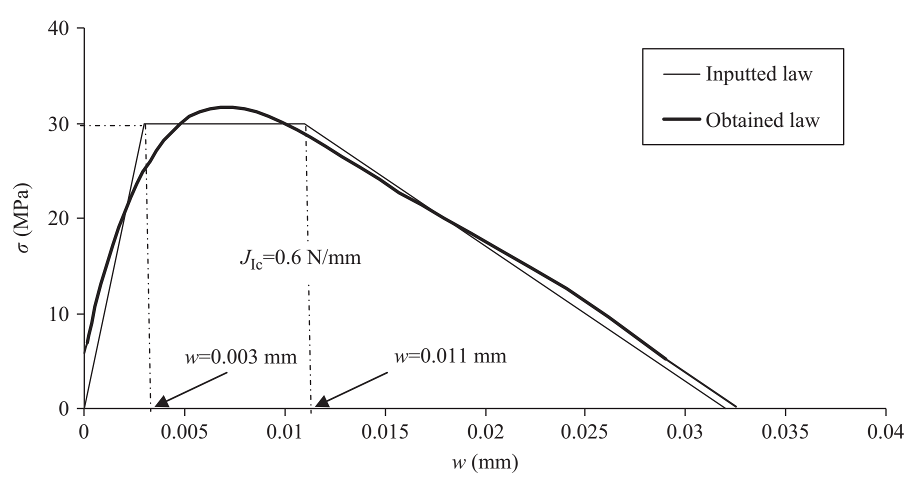

Fig. 7. Trapezoidal cohesive law.

relationship which is more appropriate when different failure mechanisms take place ahead of the crack tip [3]. The trapezoidal law (Fig. 7) should be utilized when adhesives exhibit a ductile behavior [2]. Consequently, in this case the fracture energy was considered to be twice relative to that of the other laws (J_{Ic}=0.6 N/mm). Figs. 6 and 7 put into evidence the good agreement obtained in both cases, thus numerically validating the proposed procedure.

4. Experimental validation

With the objective of verifying the performance of the method when applied to experiments, some DCB tests on bonded joints were performed. The tests were conducted with the exclusive purpose of validating the method. Hence, for each specimen, a typical cohesive law is adjusted to the one measured experimentally by the proposed methodology. This fitted law is used in a finite element analysis including cohesive zone modeling. The objective is to verify whether the numerical load–displacement curve agrees with the experimental one, which was used to get the experimental cohesive law. The joints consist of DIN Ck45 steel adherends (E=210 GPa and ν=0.3) bonded by the adhesive Araldite® 2015 (E=1.85 GPa and ν=0.33). The joints preparation included roughening the surfaces to be bonded with sandpaper and cleaning them with acetone to increase the adhesion and avoid adhesive failures. Subsequently, the adherends were bonded and curing process took place at room temperature. A constant adhesive thickness (0.2 mm) was guaranteed by placing, during the curing process of the adhesive, calibrated steel bars (0.20 ± 0.01 mm) between the adherends. The final adhesive thickness was measured in order to verify its accuracy. Piano hinges were welded to the adherends allowing the application of the load. The initial crack was introduced with a razor blade, using calibrated bars on both sides to guide it through the specimen, thus assuring its position in the adhesive mid-thickness. In order to avoid a blunt crack, the initial crack was propagated 1–2 mm by a slight stroke with the razor blade after

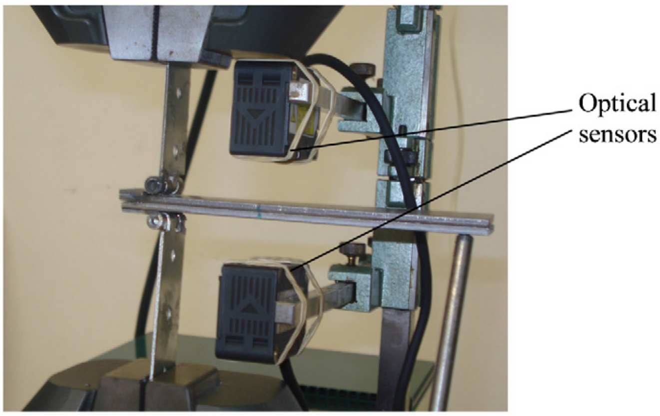

Fig. 8. Experimental setup.

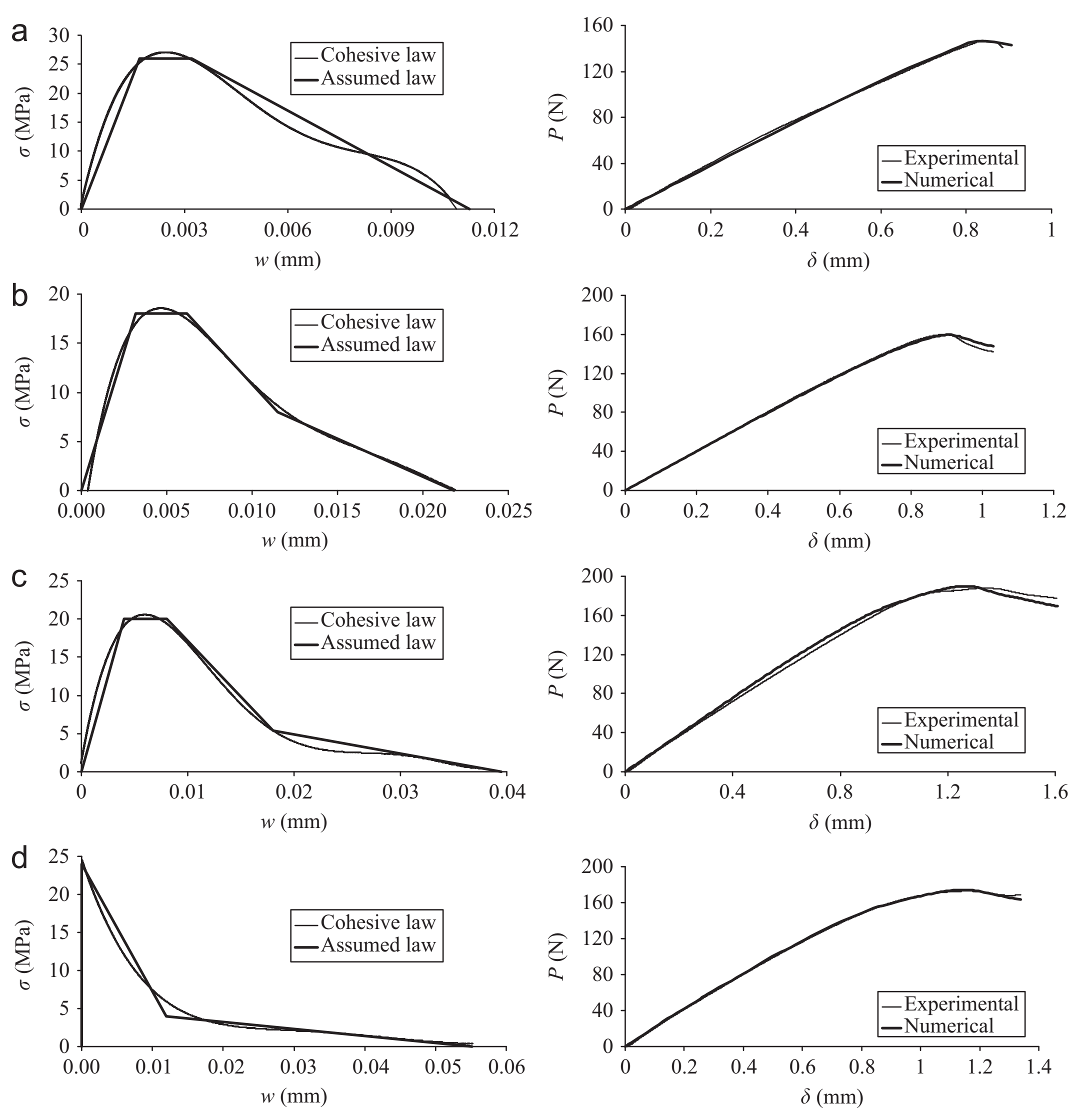

Fig. 9. Cohesive laws and the respective load–displacement curves: (a) specimen 1, (b) specimen 2, (c) specimen 3, and (d) specimen 4.

which a_0 was measured in an optical microscope at both specimen sides to guarantee crack alignment. During the DCB tests, the joints were subjected to a tensile loading under displacement control (1 mm/min). The load–displacement curves were recorded during the tests. In the numerical simulations it was verified that the maximum von Mises equivalent stress in the adherends along the fracture test is about 208 MPa which is far below the elastic limit of the used steel (350 MPa). This is a crucial aspect, since it must be guaranteed that the fracture process in the adhesive is the unique source of energy dissipation. The COD was monitored by means of two optical sensors placed at both sides of the specimen (Fig. 8) and attached to an external bar. The distance between each sensor and the specimen was carefully chosen in order to allow the convergence of the beam light in a point. Hence, each sensor was pointed to the spots of the upper and lower specimen surfaces aligned with the pre-crack tip. The signals of the control devices were combined to allow a differential reading corresponding to the COD. This differential signal, in volts, is an external signal inputted in the testing machine providing a synchronized recording of all parameters to be monitored, i.e., applied load and displacement, and the COD. Four specimens were tested on a testing machine (Shimadzu Autograph) at room temperature.

Fig. 9 presents the cohesive laws and load–displacement curves for the specimens tested. Typical cohesive laws were adjusted to the ones measured experimentally following the above proposed methodology. The fitted laws were used in the simulations of the DCB tests and the resulting numerical load–displacement curves were compared to the respective experimental ones. Globally, it can be concluded that excellent agreement was obtained for all specimens. It should be emphasized that the agreement was not influenced by the fact that different typical cohesive laws (trapezoidal in specimen 1, trapezoidal with bilinear softening in specimens 2 and 3 and tri-linear in specimen 4) have been used to adjust the ones obtained experimentally, which reinforces the soundness of the model.

5. Conclusions

A simpler procedure to evaluate cohesive laws in bonded joints under mode I loading using the double cantilever beam test is proposed. The method is based on the load–displacement curve and on the crack opening displacement which are both measured during the fracture characterization test. The simplification was achieved by an analytical approach involving the specimen's compliance, the Timoshenko beam theory and the crack equivalent concept. Following the proposed methodology, the cohesive law can be obtained by performing a typical double cantilever beam test. This avoids the utilization of a special setup or the measurement of beam rotation during the experimental test. Additionally, the method accounts indirectly for the presence of the fracture process zone via the equivalent crack, which is a fundamental issue especially when ductile adhesive are being characterized.

The method was validated numerically by means of a finite element analysis including cohesive zone modeling and considering three different representative cohesive laws. It was verified that the resulting cohesive laws exhibit good agreement with the inputted ones, which confirms the accuracy of the procedure. Additionally, experimental tests were also performed with the exclusive purpose of validating the model experimentally. Typical cohesive laws were adjusted to the ones obtained experimentally and subsequently used in the simulations to get numerical load–displacement curves that were compared with the experimental ones. Excellent agreement was obtained thus demonstrating the model soundness.

References

[1] Gonçalves JPM, de Moura MFSF, Magalhães AG, de Castro PMST. Application of interface finite elements to three-dimensional progressive failure analysis of adhesive joints. Fatigue Fract Eng Mater Struct 2003;26:479–86.

[2] Yang QD, Thouless MD, Ward SM. Numerical simulations of adhesively-bonded beams failing with extensive plastic deformation. J Mech Phys Solids 1999;47:1337–53.

[3] Andersson T, Biel A. On the effective constitutive properties of a thin adhesive layer loaded in peel. Int J Fract 2006;141:227–46.

[4] de Moura MFSF, Campilho RDSG, Gonçalves JPM. Crack equivalent concept applied to the fracture characterization of bonded joints under pure mode I loading. Compos Sci Technol 2008;68:2224–30.

[5] de Moura MFSF, Morais JJL, Dourado N. A new data reduction scheme for mode I wood fracture characterization using the double cantilever beam test. Eng Fract Mech 2008;75:3852–65.

[6] Sørensen BF. Cohesive law and notch sensitivity of adhesive joints. Acta Mater 2002;50:1053–61.

[7] Andersson T, Stigh U. The stress–elongation relation for an adhesive layer loaded in peel using equilibrium of energetic forces. Int J Solids Struct 2004;41:413–34.

[8] Suo Z, Bao G, Fan B. Delamination *R*-curve phenomena due to damage. J Mech Phys Solids 1992;40:1–16.

[9] Dourado N, de Moura MFSF, Morais JJL, Silva MAL. Estimate of resistance-curve in wood through the double cantilever beam test. Holzforschung 2010;64:119–26.