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Procedia Structural Integrity 66 (2024) 344–349

Structural Integrity Procedia

www.elsevier.com/locate/procedia

8th International Conference on Crack Paths

Comparison among methods for identification of CZM parameters from ENF test

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Abstract

The knowledge of fracture behavior of adhesive joints is crucial in the design of new structural elements or in retrofitting existing ones. Cohesive zone model (CZM) is a robust approach to describing the interface behavior of bonded joints. This paper deals with a comparison of direct and inverse methods for identification of CZM law parameters under mode II of fracture, considering the same formulation for the evaluation of the strain energy release rate (ERR) based on the J-integral approach. The obtained traction-separation laws were used for predicting the decohesion process by finite element analyses of an end notched flexure (ENF) test. Numerical responses of virtual test, in terms of load-displacement curve and adhesive tangential displacement trend, were compared with experimental data. Differences between direct and indirect methods were addressed to point out adequateness of such methodologies in the assessment of bonded joint decohesion process in mode II.

Keywords: Cohesive Zone Model (CZM); Digital Image Correlation (DIC); Finite Element Method (FEM); Bonded joint; End Notched Flexure (ENF) test

1. Introduction

Fracture mechanics approaches the study of cracks formation and their propagation in materials, providing critical insights for the development of safer and more efficient structural components.

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2452-3216
10.1016/j.prostr.2024.11.085

The Cohesive Zone Model (CZM) stands out as an advanced tool in this field, enabling the detailed analysis of fracture processes by defining a cohesive law at the crack tip. With this aim, many CZM laws have been presented in literature (Park, 2011), such as the triangular and the trapezoidal traction-separation (TS) law, the exponential, the polynomial and the interpolation-based TS equations. Though advantageous for computational purposes in numerical analysis, predefining a traction-separation law shape can impact the accuracy of predicting the decohesion response of bonded joints.

Several significant studies have contributed to the advancement of CZM. For instance, recently, Cricrì (2019) presented an exact inverse solution for identifying cohesive laws in adhesive layers subjected to shear loads, enhancing the precision in predicting fracture behavior. Additionally, research by Perrella et al. (2018), Berardi et al. (2019), and Cricrì et al. (2022) focused on determining CZM parameters through interface layer displacement fields in bonded joints, providing a deeper understanding of cohesive parameters.

In this paper, a comparison between direct and inverse, or also called indirect, methodologies, based on the same modelling of ERR, for the identification of CZM law of ENF test are presented. Numerical simulations were performed by using CZM parameters identified with direct and indirect methods. The comparison of numerical outcomes with experimental response pointed out the differences of such approaches in the assessment of decohesion of bonded joints under mode II loading condition.

Nomenclature

E	Young's modulus
ν	Poisson's ratio
h	adherend thickness
a_0	initial crack length
L	span length
L_t	specimen length
B	specimen width
δ_s	tangential slip displacement
G_{II}	mode II energy release rate
G_{IIc}	critical mode II energy release rate
P	load
τ	cohesive shear stress
J_c	fracture toughness
J	J-integral
K_0	initial stiffness
P_{max}	maximum load
τ_{max}	maximum cohesive shear stress

2. Material and methods

The CZM identification analyses were conducted on experimental data from end notched flexure (ENF) tests, presented in a previous work (Cricrì et al., 2022). Adhesive interface layer tangential slip displacements were obtained by digital image correlation (DIC) analysis, whilst the applied load and displacement of loading pin were acquired from load cell and linear variable displacement transducer (LVDT) of testing machine. The main geometrical dimensions of ENF specimen and the mechanical properties of the adherends and adhesive materials are reported in Figure 1. The width, B, of the specimen is equal to 24 mm.

Simulations of decohesion process under mode II loading conditions were performed using the commercial FEM code ABAQUS. About 6000 2D cohesive elements CPS4 were employed to model the adhesive interface layer.

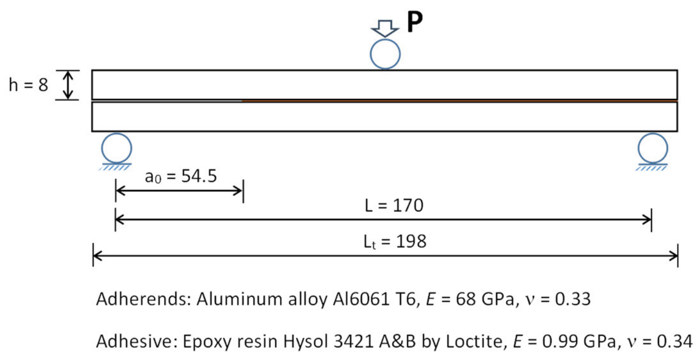

Fig. 1. Geometrical dimensions of ENF specimen and mechanical properties of materials.

2.1. Direct method for identification of CZM parameters

The identification of CZM parameters via direct method is achieved avoiding the imposition of an a priori traction-separation law. Moreover, only the experimental data provided by testing machine and DIC analysis are necessary. The direct methodology is based on the evaluation of an experimental fracture energy, *J*, based on *J*-integral formulation. The value of strain energy release rate, *G,* considering materials as linear elastic, can be obtained from the simplified equation by Leffler et al. (2007):

$$G = J(\delta_s) \cong \frac{9}{16} \cdot \frac{(P \cdot a_0)^2}{EB^2h^3} + \frac{3}{8} \cdot \frac{P \cdot \delta_s}{Bh} \tag{1}$$

where a_0 is the distance of pre-crack tip from the support, *P* is the load, δ_s is the tangential displacement of adhesive layer, *E* is the adherend Young's modulus, *B* and *h* are respectively the adherends width and thickness.
From the resulting data set of experimental $J_k(\delta_s)$ is calculated the numerical derivative of $J(\delta_s)$ to obtain the cohesive shear stress, as expressed by the analytical equation:

$$\tau(\delta_s) = \frac{\partial J(\delta_s)}{\partial \delta_s} \tag{2}$$

Sequentially, a traction-separation law can be obtained by means of a single function or a system of equations, which best interpolate the data set obtained by equation (2).

2.2. Inverse method for identification of CZM parameters

The integral form of equation (2) can be used to analytically found the fracture energy as function of tangential slip displacement of adhesive layer and of CZM parameters. The indirect method requires first choosing a TS law.
By considering an exponential traction-separation law, i.e. the equation by Xu and Needleman (1993), specified for mode II loading conditions, it follows

$$\tau(\delta_s) = \frac{2J_c}{\delta_{sc}} \cdot \left(\frac{\delta_s}{\delta_{sc}}\right) \cdot e^{-\left(\frac{\delta_s}{\delta_{sc}}\right)^2} \tag{3}$$

where δ_s is the displacement jump in the shear direction, δ_{sc} is the scale factor of the tangential slip, *e* is the Neper number, and J_c is the fracture toughness.

The integral form of equation (2), replacing the general traction separation law with equation (3), results:

$$J(\delta_s) = \int_0^{\delta_s} \tau(x)dx = J_c\left(1 - e^{-\left(\frac{\delta_s}{\delta_{sc}}\right)^2}\right) = f(\delta_s; J_c, \delta_{sc}) \quad (4)$$

A best fitting procedure between the analytical and the experimental fracture energy, obtained from equations (4) and (1), respectively, allowed parameters identification (Cricrì et al., 2022). The calculation of the latter energy is attained, in form of an array of points J_k, by means of applied load P_k, resulting from the acquired samples from load cell, and corresponding tangential split displacements δ_s, carried out from DIC analysis. By solving the following minimization problem:

$$\min_{J_c, \delta_{sc}} \sum_k \left(f(\delta_s; J_c, \delta_{sc}) - J_k(P_k \cdot \delta_{sk})\right)^2 \quad (5)$$

it is possible to obtain the unknown parameters J_c and δ_{sc}.

3. Results and discussion

The data fitting procedure of direct method highlighted that the adhesive layer behaviour was well described by means of three analytical equations. These formulas can be easily implemented in a FEM code for predictive purposes. More specifically, the mode II cohesive traction-separation obtained via direct method was expressed by the equation system:

$$\tau(\delta_s) = \begin{cases} K_0 \cdot \delta_s\ , & \delta_s \leq \delta_{s\_max} \\ A \cdot e^{-\frac{\delta_s}{d}}\ , & \delta_{s\_max} < \delta_s < \delta_{s\_tr} \\ \tau_{tr} - K_{\mathrm{f}} \cdot \left(\delta_s - \delta_{s\_tr}\right)\ , & \delta_{s\_tr} < \delta_s < \delta_{s\_f} \end{cases} \quad (6)$$

where the term $K_0 = \tau_{max}/\delta_{s\_max}$ is the cohesive elastic stiffness, δ_{s_max} is the displacement at the maximum shear stress τ_{max}, whilst the slip displacement δ_{s_f} corresponds to the full damage condition when cohesive stress have null value. The softening behaviour was expressed by coupling an exponential stage, described by the parameters *A* and *d*, and a linear branch that better represented the brittle failure of bonded joint. The transition between the two branches of the softening stage occured at the displacement δ_{s_tr} corresponding to the stress τ_{tr}. The coefficient K_{f} is the final softening rate:

$$K_{\mathrm{f}} = \frac{\tau_{tr}}{(\delta_{s\_f} - \delta_{s\_tr})} \quad (7)$$

The values of identified CZM law parameters from direct and inverse methods are listed into Table 1. In addition, the critical energy release rate J_c, represented by the area under the curve $\tau(\delta_s)$, and the maximum cohesive stress are listed into the same table. The resulting traction-separation laws are plotted in Figure 2.

Table 1. CZM law parameters from identification methods and fracture parameters.

Method	A	d	K_0	δ_{s_max}	K_f	τ_{max}	J_c	δ_{sc}
Direct	45.51	0.0492	1165.20	0.024	2441.77	27.96	1.39	
Indirect						23.40	1.42	0.0607

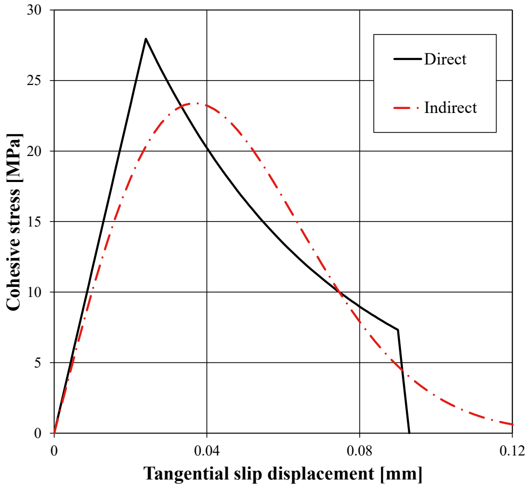

Fig. 2. CZM laws from direct and indirect identification methods.

It is worth noting that the direct method identifies a fracture toughness value lower than the one by inverse method, while the maximum stress value is higher. This can be ascribable to the fact that the direct method can take account of quasi brittle behavior of the considered bonded joint by means of the second branch of softening stage in the traction-separation law.

The outcomes of virtual tests using the CZM laws expressed by equation (3) and (6) are reported in Figure 3. The predicted maximum load with direct and inverse methods is respectively 7% and 1% greater than experimental value. A percentage difference of about 15% and 11% is instead found for the values of the slope of numerical load-displacement curves with respect to the experimental one. The trends of tangential slip displacements of the adhesive interface, measured at location corresponding to the initial crack tip, globally show a satisfactory agreement of predictions from a practical standpoint.

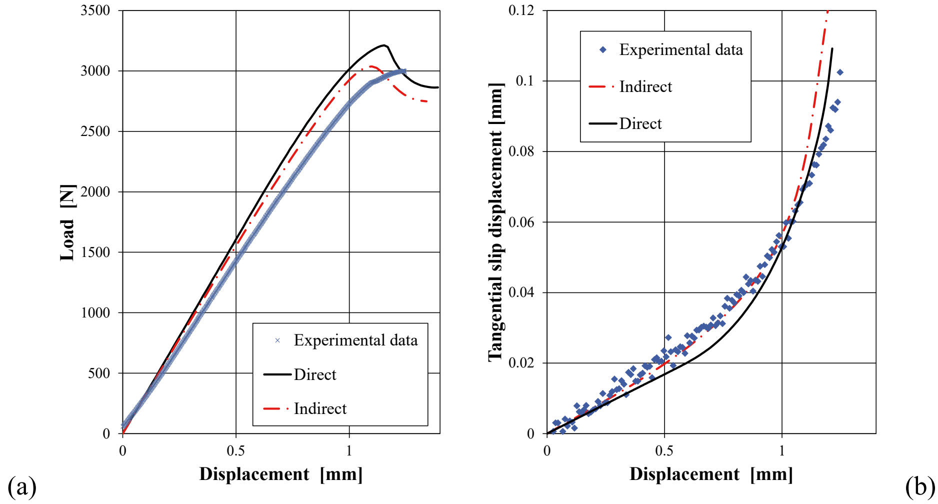

Fig. 3. (a) Load-displacement curves; (b) Trend of tangential slip displacements of the adhesive interface at the initial crack tip.

5. Conclusions

The behavior of adhesive interface layer of bonded joint under pure mode II loading condition was investigated. A comparison of direct and inverse methodology for identification of CZM law was also presented. The same formulation for energy release rate evaluation was adopted in the identification methods and the resulting traction separation relationships were implemented in a FEM code for predictive purposes. The response of bonded joint, in terms of load-displacement curve and tangential slip displacements over time, were reported and compared with experimental outcomes highlighting a good agreement from a practical standpoint. Direct methods have the advantage of not imposing a cohesive law a priori, but of adapting shapes that are more representative of experimental behaviour. Indeed, non-consistent CZM law shape can affect the predicted behaviour of adhesively bonded joints.

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