



Characterization of a cohesive-zone model describing damage and de-cohesion at bonded interfaces. Sensitivity analysis and mode-I parameter identification

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ABSTRACT

The identification of mode-I parameters of a cohesive-zone model for the analysis of adhesive joints is presented. It is based on an experimental–numerical methodology whereby the optimal parameters are obtained as the solution of a nonlinear programming problem. The data set for inverse analysis is provided either by local kinematic data, by global static data, or a combination of the two. Parameter sensitivities are computed via direct differentiation and identification exercises are discussed that show the effectiveness of the procedure and its stability with respect to noise and time–space sampling.

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1. Introduction

The development of new and advanced materials puts new challenges on processing technology. This is particularly true when different materials have to be joined together in a way to retain the individual beneficial properties of the component products. In this perspective, the choice of the joining technique is often as important as that of materials themselves. Traditional joining techniques possess a number of disadvantages. For instance, welding may alter the specific properties of the material within the heat-affected zone, riveting provides stress transfer in a non-uniform way and, in general, both may weaken and/or damage the material. On the contrary, adhesive bonding allows stress transfer in a more uniform way, prevents shape distortion since it requires little or no heat input, and does not damage the components being joined unlike when rivets or screws are used (Brockmann et al., 2008).

In last years adhesive bonding technologies have become widespread in industry and at present they are being employed on a daily basis. Actually, in modern world adhesives are almost ubiquitous and applications include everyday products as food packaging materials (Choi et al., 2006), electronics, where soldering tech-

niques are being replaced by bonding in order to connect integrated components in a stress-free way (Li and Wong, 2006), and high-tech solutions such as in the body of Formula 1 racing cars, where innovative joints and extreme combinations of materials are realized by bonding parts together (Savage, 2006). This virtually unlimited range of applications calls for an intensive research and development work in order to fully exploit the potential of adhesive joints.

As for most structural components consisting of the assembly of individual elements, failure of adhesive joints due to damage growth at bonded interfaces, leading to fracture development by sliding and separation, is one of the most important failure modes. For its simulation the cohesive-zone concept, initially proposed by Barenblatt (1962) and Dugdale (1960) and first used by Hillerborg et al. (1976) in a Finite Element (FE) context, has become increasingly popular in recent years. One of the reasons of its success is probably the flexibility of the cohesive approach to fracture, which provides a phenomenological description of the complex microscopic processes leading to the progressive decay of cohesive forces and the formation of traction-free surfaces, see (Gustafson and Waas, 2009) for a recent literature review.

A basic requirement of any cohesive model is the availability of material parameters governing the traction-relative displacement law. However, the general coherence between the data reduction schemes and the FE model in which the cohesive law is used is not a secondary aspect since the assumptions made for computing the material parameters from experiments have a direct impact on the results of computations.

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In this study an inverse methodology is presented, suitable to determine the mode-I parameters governing the damage mechanics-based formulation developed by Valoroso and Champany (2006). The basic data set for the identification process is provided by full-field kinematic measurements; these can be obtained by a Digital Image Correlation (DIC) procedure, and concern the deformation process of the tested specimens or of a suitable Region of Interest (ROI) extracted from them (Fedele et al., 2009). The material parameters are estimated as the solution of a nonlinear programming problem in which a least-squares norm is used as objective function, that quantifies the discrepancy between experimental data and the analogous quantities computed via finite elements as a function of the unknown parameters. In this work the data set is only pseudo-experimental, i.e., it has been generated via the numerical model with a priori known material parameters, and then corrupting the response by artificial noise.

The computation of the displacement gradients with respect to the parameters to identify, referred to in the literature as sensitivity analysis, is another key ingredient for identification purposes since, apart from providing the search direction in a gradient-based minimization algorithm, it may also allow to determine the location of optimal measurements during experiments. In this study the sensitivities are computed using the Direct Differentiation Method (DDM). This requires, at each step of the forward FE analysis, the solution of an auxiliary linear problem whose right-hand side is a pseudo-load vector and the coefficient matrix is the mechanical tangent. The sensitivity analysis has been implemented in a customized version of the FE code FEAP (Taylor, 2002) that has been interfaced with Matlab (The MathWorks Inc, 2009), where the identification procedure is carried out. Results of the identification exercises are then presented for the Double Cantilever Beam (DCB) specimen subject to pure mode-I bending under displacement control.

The outline of the paper is as follows. In Section 2 the one-dimensional (mode-I) interface relationship object of the present study is synthetically described. In Section 3 the virtual test considered for the identification exercises is then presented. The classical data reduction schemes and the proposed one based on the FE model are briefly discussed and the implementation of sensitivity analysis is shown. The description of the inverse methodology is given in Section 4 and a discussion on the results of identification is finally provided in Section 5.

2. Mechanical model

The geometry of the joint considered in this study, schematically represented in Fig. 1, consists of two adherends connected

by a planar thin adhesive layer. It is assumed that: (i) the joined bodies remain elastic throughout the loading process; (ii) an initial flaw of length a is present; (iii) fracture can occur only along the pre-determined trajectory defined by the bond line.

Basically, the analysis of the problem at hand can be carried out either via the Linear Elastic Fracture Mechanics (LEFM) approach, that in these conditions leads to singular crack tip fields, or using the cohesive-zone concept introduced by Barenblatt (1962), that in the last decade has evolved as a very popular method to deal with fracture problems.

In the general case the formulation of a cohesive-zone-like model relies upon two main ingredients: the definition of a traction–separation law describing the relationship between the interface tractions \mathbf{t} and displacement jumps $\llbracket \mathbf{u} \rrbracket = \mathbf{u}^+ - \mathbf{u}^-$, and the introduction of a damage criterion to be met for the cohesive process zone to grow and the crack to advance. In particular, in this paper we shall make reference to the interface model proposed by Valoroso and Champany (2006) and consider only the one-dimensional (mode-I) case, whose equations are summarized in the following.

2.1. One-dimensional interface model

The constitutive equations for the interface traction and the damage-driving force respectively read

$$\begin{aligned} t &= (1 - D)k\langle\llbracket u \rrbracket\rangle_+ + k^-\langle\llbracket u \rrbracket\rangle_- \\ Y &= \frac{1}{2}k\langle\llbracket u \rrbracket\rangle_+^2 \end{aligned} \quad (1)$$

where $\llbracket u \rrbracket$ denotes the displacement discontinuity in the direction normal to the interface, $D \in [0, 1]$ is the scalar damage variable and k and k^- are the undamaged interface stiffnesses in tension and compression. In the above expression the impenetrability constraint is introduced in penalty form via the stiffness coefficient k^- , and by explicitly distinguishing between the positive $\langle\cdot\rangle_+$ and negative part $\langle\cdot\rangle_-$ of the displacement jump.

As in classical internal variable theories, the damage-driving force Y has to be bounded by a threshold value that, owing to non-reversibility of damage, is only allowed to increase. This can be obtained via a monotonically increasing positive function F of the argument D and using the appropriate Karush–Kuhn–Tucker conditions. Typical forms of F are that of power laws or exponential functions, and their explicit expressions are constructed in a way to ensure that the energy dissipated in the formation of a new unit traction-free surface equals the critical strain energy release rate G_c , see also (Valoroso and Champany, 2006) for a detailed

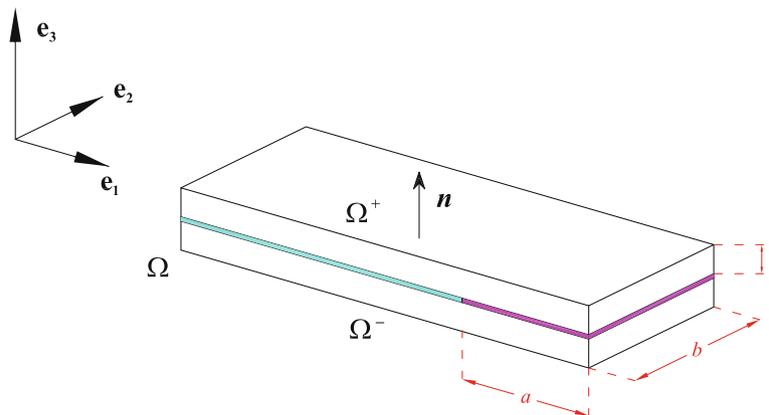


Fig. 1. Adhesive joint schematization.

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