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Global sensitivity analysis in the identification of cohesive models using full-field kinematic data

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ABSTRACT

Failure of adhesive bonded structures often occurs concurrent with the formation of a non-negligible fracture process zone in front of a macroscopic crack. For this reason, the analysis of damage and fracture is effectively carried out using the cohesive zone model (CZM). The crucial aspect of the CZM approach is the precise determination of the traction-separation relation. Yet it is usually determined empirically, by using calibration procedures combining experimental data, such as load–displacement or crack length data, with finite element simulation of fracture. Thanks to the recent progress in image processing, and the availability of low-cost CCD cameras, it is nowadays relatively easy to access surface displacements across the fracture process zone using for instance Digital Image Correlation (DIC). The rich information provided by correlation techniques prompted the development of versatile inverse parameter identification procedures combining finite element (FE) simulations and full field kinematic data. The focus of the present paper is to assess the effectiveness of these methods in the identification of cohesive zone models. In particular, the analysis is developed in the framework of the variance based global sensitivity analysis. The sensitivity of kinematic data to the sought cohesive properties is explored through the computation of the so-called Sobol sensitivity indexes. The results show that the global sensitivity analysis can help to ascertain the most influential cohesive parameters which need to be incorporated in the identification process. In addition, it is shown that suitable displacement sampling in time and space can lead to optimized measurements for identification purposes.

1. Introduction and motivation

Interfaces play a significant role on the overall mechanical performance of adhesive bonded joints in a variety of applications, including aerospace, electronics, construction and solar energy (Adams et al., 1997; Kinloch, 1987; Sridharan, 2008). These structures show a rich array of potential fracture mechanisms, but interfacial debonding of the adjacent layers is the most widely encountered in actual applications (Sridharan, 2008). Interfacial adhesion, and in turn susceptibility to debonding, is intimately connected to sources of energy dissipation occurring at different length-scales, such as the breakage of intrinsic adhesion forces at the nano-scale (e.g., primary bonds and physical interactions), micro-scale fibrillation in the vicinity of the crack tip (van den Bosch et al., 2008), and macro scale bulk plasticity in the bonded substrates (Alfano et al., 2011). As a result joint failure often occurs concurrent with the development of large scale bridging (or cohesive) zone. In these circumstances, the magnitude of cohesive tractions across the adhesive layer plays a significant role on the overall deformation of the system and the small scale yielding conditions breaks down. Since linear elastic fracture mechanics is no longer fully adequate (Cavalli and Thouless, 2001), the analysis of damage and fracture in adhesive bonded structures is effectively carried out using the cohesive zone model (CZM) (Dugdale, 1960; Barenblatt, 1962).

Several recent contributions, which reviewed advantages and limitations of the CZM approach, have highlighted that the crucial aspect of the methodology is the determination of the traction-separation relation[1] Park and Paulino, 2013. This theme has been vigorously pursued in recent times. Earlier works focused on semi-empirical calibration procedures combining experimental testing

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[1] The link between cohesive interaction and opening displacements.

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performed on beam-like adhesive bonded samples (e.g. Double Cantilever Beam Alfano et al., 2011, End Notch Flexure Lee et al., 2010) and finite element (FE) simulations of fracture. Typical experimental data employed in the calibration include point data, such as the load–displacement curve, sample deflection and crack opening profile (Alfano et al., 2011; Yang et al., 1999; Yang et al., 2001; Yang and Thouless, 2001; Sun et al., 2008; Alfano et al., 2011; Gowrishankar et al., 2012). On the other hand, recent progress in image correlation enabled relatively accurate and low cost measurements of full field kinematic data by using Digital Image Correlation (DIC) (Sutton et al., 2009). A correlation algorithm compares the local features of a pair of digital images searching for the displacement field which provides the best match between pixel intensities. Compared to classical measurement devices (e.g. extensometers), DIC can resolve a very large number of kinematic unknowns. Abanto-Bueno and Lambros (2005) and Tan et al. (2006) employed DIC to measure the displacement field across the fracture process zone in photodegradable copolymers and bulk explosives (PBX 9501), respectively. Model traction separation relations were determined by correlating the calculated opening stress with the measured opening displacements across the fracture plane. Specifically, the crack opening profile was extracted from the measured displacement field, while cohesive tractions were estimated through the derived strain field and bulk constitutive material properties. The usefulness of this method is essentially limited to materials displaying linear elastic bulk behavior; moreover, it is not readily adaptable to bonded samples. Alternative full field techniques could be also employed, however, recent works mostly focused on DIC because it does not require costly hardware or complicated procedures and provides accurate results. Specifically, it is often assumed that when the displacement field is measured by DIC the primary sources of errors are from digital image resolution and the DIC algorithm itself. Image resolution depends on the acquisition device. Usually the quality that can be guaranteed with modern CCD or CMOS sensors, in conjunction with high magnification lens, is in the scale of 10^0–10^2 microns per pixel (Shen et al., 2010). Resolution of the DIC software is measured as a fraction of pixel, and sub-pixel precision can be also achieved. The combined effect can lead to maximum errors in order of tens of microns for accurate measurements, that is quite satisfactory for a reliable determination of cohesive fracture properties (Shen et al., 2010).

The rich information provided by DIC prompted the development of additional inverse techniques. These have been recently reviewed in Avril et al. (2008), and include the finite element model updating method (FEMU), the constitutive equation gap method (CEGM), the virtual fields method (VFM), the equilibrium gap method (EGM) and the reciprocity gap method (RGM). The FEMU approach combines finite element (FE) simulations and full field kinematic data. In this method, a least squares norm, which quantifies the discrepancy between experimental data and the corresponding finite element counterpart, is minimized so as to get the unknown material parameters. This technique was initially deployed in order to identify elastic, elasto- plastic and viscoelastic bulk constitutive material properties (Avril et al., 2008; Pottier et al., 2011; Lubineau, 2009; Florentin and Lubineau, 2010; Blaysat et al., 2012; Moussawi et al., 2013). Subsequently, it was also used to supplement the existing methods for the determination of cohesive fracture properties, see Shen et al. (2010), Shen and Paulino (2011), Gain et al. (2011), Fedele et al. (2009), Valoroso and Fedele (2010) and Fedele and Santoro (2012) to list a few. In these simulation-based identification frameworks, cohesive properties were iteratively adjusted in order to minimize the difference between computed and measured surface displacements across sample surface (Shen and Paulino, 2011; Gain et al., 2011) or a suitable sub-region (Fedele et al., 2009; Valoroso and Fedele, 2010). These works have shown that the determination of cohesive models poses challenges both in terms of measurement and identification. Primarily, the quantity (and quality) of experimental data obtained using DIC have to be carefully taken into account. A large set of data with low sensitivity not only adversely affects the identification process, but also increases the problem size and computational cost owing to the accumulation of unresolved residuals (Valoroso and Fedele, 2010). Therefore, the actual sensitivity of the measured displacement fields to variation of cohesive zone parameters has a key role on the outcome of the identification process.

From this standpoint, the information provided by a sensitivity analysis (SA) may allow one to recognize the most informative measurable quantities (over space and time) for identification purposes. In other words, the results of a SA can be employed to perform an effective time–space displacement sampling which can ultimately improve the whole identification process. Sensitivity analyses can be roughly divided in *local* and *global* analyses (Saltelli et al., 2008). Local sensitivity analyses allow one to study the fluctuations of the output variables as a consequence of small variations of the input data near a given observation point. Local sensitivity analyses have been carried out in previous related works concerning the identification of cohesive zone models in adhesive joints (Fedele et al., 2009; Valoroso and Fedele, 2010; Fedele and Santoro, 2012). However, local SA is not able to explore the whole space of the input factors, but only selected base points. On the other hand, global sensitivity analysis deals with the variability of the output due to the fluctuations of the input data throughout the potential domain of variation – which is often idealized as a hypercube. It is worth noting that in the case of linear problems, local and global approaches provide essentially similar results. However, for highly non linear models the sensitivity can largely vary from point to point and, as a result, a local approach may not be appropriate. In these cases, a global sensitivity analysis prevails over other methods (e.g. sigma-normalized derivatives, standardized regression coefficients, as it is more effective in handling complex non-linear models. The Sobol variance-based global analysis is a very popular global sensitivity analysis method which allows one to quantify the amount of variance that each input parameter (e.g. cohesive strength) contributes to the unconditional variance of the model output (e.g. surface displacements or a suitable *cost function* thereof). The Sobol method makes use of the Monte-Carlo simulation framework to compute sensitivity indexes. The values of the input variables are sampled using a quasi random sequence. If compared to other distributions (e.g. gaussian, uniform), it allows one to explore, in a more uniform fashion, the whole range of variability of the input parameters. With such sampling, a reduced number of model evaluations are needed and a reasonable convergence speed is therefore ensured. In this work, the Sobol method has been employed to perform a sensitivity analysis in the identification of selected cohesive zone models using full field kinematic data. As the focus herein is on mode I fracture, the analysis is carried out considering a model Double Cantilever Beam (DCB). A cost function is defined in terms of the residual between computed and experimental surface displacement data. Displacement data concern a suitable region of interest (ROI) across the fracture process zone which includes portions of the joined substrates close to the adhesive layer. The global sensitivity analysis is carried out to assess the sensitivity of the objective function to displacement sampling in *time* (i.e. selected loading step) and *space* (i.e. size of the ROI). The first order sensitivity indexes (Saltelli et al., 2008) are calculated for the cohesive fracture properties pertaining to various cohesive models, including bilinear, trapezoidal and potential based models (Alfano et al., 2009; Park et al., 2009). The influence of cohesive strength, cohesive energy and other parameters are considered simultaneously. As it will be shown in this paper, selecting the most informative

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