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Progressive failure analysis of DCB bonded joints using a new elastic foundation coupled with a cohesive damage model

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ABSTRACT

A new analytical model to predict progressive failure in a double cantilever beam (DCB) bonded joint is proposed. The model is based on the Winkler elastic foundation theory and coupled with a damage model based on the cohesive zone approach. The elastic behaviour of the adhesive layer is accounted for defining a new general stiffness foundation function. The model is compared and validated against experimental and finite element simulations using cohesive elements. Bonded DCB specimens with flexible and stiff adhesives and different width to thickness ratios have been tested and simulated. The new coupled model accurately predicts the load-displacement curve, damage process zone, crack propagation and stress-strain distribution response of the DCB test, whatever the thickness or stiffness of the adhesive layer. Moreover, a very low computational cost/time is required in comparison with finite element simulations.

1. Introduction

The increase of new materials in modern industry is a challenge for joint processes on assembled parts. Different techniques are used with this purpose but in recent years adhesively bonded joints have been of special interest due to the advantages when different materials are bonded together (Pasternak and Ciupack, 2014). In the last decades, numerous analysis methods have been specially developed for the design of adhesive bonded joints, nevertheless there is not still a general model valid for any kind of adhesive. Advanced computational techniques, such as the finite element method (FEM), are becoming the principal tools used for designing adhesive joints, however analytical models remain of interest to designers due to their ability to provide fast calculations.

There are different analytical models to predict the elastic behaviour and failure of adhesive joints (da Silva et al., 2009; Quispe Rodríguez et al., 2012; Heβ, 2016). These models generally make assumptions and are limited to certain loading conditions and failure modes. Under mode I loading, the double cantilever beam (DCB) test is a common setup to study the failure process on adhesive bonded joints. The simplest DCB analytical model is based on simple beam theory, assuming a clamped condition at the crack front of the specimen and crack growth is predicted based on linear elastic fracture mechanics (LEFM) approaches, i.e., when the energy release rate available at the crack tip reaches the fracture toughness of the adhesive. However, this approach is limited to very stiff adhesives and thin adhesive layers, and does not describe the true deflection of the specimen arms near the crack front. In order to improve the estimation of the stiffness, correction factors have been incorporated to the formulation (Mao et al., 2013) (Corrected Beam Theory data reduction method). But these approaches are limited to very thin adhesive layers, whose elastic contribution is dismissed in the formulation.

Additionally, enhanced DCB models have been proposed in the literature incorporating interface elasticity into the model using Winkler elastic foundation beam theory (Wang and Zhang, 2009; Jumel et al., 2011; Budzik et al., 2012; Morais, 2013). With these models the energy release rate is obtained as a function of an equivalent crack and the apparent Young's modulus of the adhesive. To obtain the apparent Young's modulus different approaches are considered. One that has enjoyed great success is the work of Jumel et al. (2011) for thin adhesive layers, which assumes a transversal plane strain condition for the adhesive. However, the model has some limitations such as it is only applicable in cases when the thickness of the adhesive is small to the other dimensions

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of the specimen and that it only applies for compressible materials, i.e., the adhesive Poisson's ratio ν_a is not too close to 0.5. For incompressible materials, the apparent Young's modulus E'_a using Jumel's model tends to infinite and therefore, the model based on the elastic foundation turns into a Single Beam Theory based model. Nowadays this may be a limitation, since there has been an increase in the use of polymeric flexible adhesives in modern industry, and many of these adhesives are incompressible materials where $\nu_a = 0.5$. For each adhesive type and width/thickness relationship the stress-strain state is different, therefore, Jumel's approach is only valid in limit case of the stress-strain state. To solve these limitations, a general model was recently proposed by the authors (Cabello et al., 2016a). Cabello's model uses an empirical correction of the stress distribution on the adhesive layer. The apparent Young's modulus of the adhesive is a function of the transverse position in the adhesive midplane. Using this correction, the stress distribution assumed within the adhesive layer is more accurate. The model predicts the elastic behaviour of the adhesive layer but it does not include any mechanism to simulate the crack propagation.

It is not straightforward to obtain the energy release rate using Griffith's approach and predict failure in bonded joints, (i.e. to apply a linear elastic fracture mechanics criterion to predict adhesive failure). It assumes a well-defined crack tip, while in practice it is difficult to be detected (or even it does not exist) due to the damage process zone that is developed. An alternative can be the use of the J-integral method (Sarrado et al., 2015; Goutianos and Sørensen, 2016), which is a more robust procedure. The J-integral does not depend on the crack growth process which is commonly obtained by visual procedures providing significant errors.

The direct application of fracture mechanics models it is not always suitable for failure prediction of bonded joints, where the size of the damage zone is not negligible. Therefore, unlike analysis methods based on linear elastic fracture mechanics, Cohesive Zone Models (CZM) are able to accurately reproduce the fracture process zone (FPZ) that develops ahead of a crack tip and, therefore, accurately simulate the load redistribution due to damage and the progressive failure of adhesive joints. Moreover, other damage models (e.g. (Marotti de Sciarra, 2009)) can be used, however cohesive zone models are usually developed in a finite element framework (Legarth and Niordson, 2010; Gurvich, 2011; Lee et al., 2015; Turon et al., 2015; He, 2011; Diehl, 2008; Zhu et al., 2015). They are actually the most common numerical method to predict the adhesively interface separation, however fine meshes and higher computational cost are required to obtain accurate results. Different cohesive laws have been proposed in the literature, but normally assumptions of zero adhesive thickness are made. Recently, Sarrado et al., 2016 presented a finite cohesive element with thickness to capture the influence of the adhesive elasticity on the damage development. At the same line, to capture the influence of the adhesive elasticity, Hesebeck, proposed a finite element model (FEM) considering the lateral contraction of the adhesive layer in a bonded joint. The constitutive relations were obtained from analytical expressions proposed for rectangular adhesive layers in (Tsai, 2005).

Apart from implementations in a finite element framework, there also exist analytical models that combine an elastic foundation approach with a cohesive zone model. For example, de Morais et al. (Morais, 2013) presented an analytical model where a stiffness foundation model was proposed associating the stiffness of the foundation to a cohesive behaviour. The model was aimed at delamination analysis in composite materials and the thickness of the foundation was assumed zero. Therefore, Morais model can only be used to really thin adhesive layers, since the model does not take into account the influence of the adhesive elasticity.

The aim of the present paper is to propose a new analytical model with coupled progressive cohesive damage to predict failure process of an adhesive joint loaded under mode I. The model is based on Euler beam on Winkler elastic foundation theories. The foundation stiffness accounts for the elasticity of the adhesive layer and is coupled with a cohesive zone model (Fig. 1).

The model is used for the analysis of bonded joints with two different adhesives (flexible and stiff). The progressive failure of the DCB specimen predicted by the proposed model has been compared to different experimental results and finite element simulations.

2. Analytical model based on beam on elastic foundation coupled with cohesive damage

2.1. General analytical DCB model based on beam on elastic foundation

The general model presented by the authors (Cabello et al., 2016a) in a recent publication is used as the basis of the formulation of the coupled model. The general DCB model is based on beam on elastic foundation and it is defined using beam theory assumptions and modelling the behaviour of the adhesive layer using an infinite set of springs with stiffness k (Fig. 2). The initial length of the springs is equal to the thickness of the adhesive layer and their deformation defines the magnitude of an equivalent distributed load q; view more details in (Cabello et al., 2016b; Bennati et al., 2009).

Using an Euler beam theory with Winkler elastic foundation, the differential equation and the boundary conditions, independent of the stiffness foundation approach used, results in

$$\frac{d^4u_y}{dx^4}+\frac{1}{E_sI_s}q=0; \quad \Rightarrow BC=\left\{\begin{matrix} \frac{d^2u_y}{dx^2}(L-a_0)=0; & \frac{d^3u_y}{dx^3}(L-a_0)=0 \\ \frac{d^2u_y}{dx^2}(-a_0)=0; & \frac{d^3u_y}{dx^3}(-a_0)=\frac{P}{E_sI_s} \end{matrix}\right\} \quad (1)$$

where E_s and I_s are respectively the Young's modulus and the moment of inertia of the adherend, L is the length of the DCB specimen, a_0 is the initial crack length and u_y is the deflection of the adherend. The distributed load q given by the imaginary springs located at the adhesive midplane is

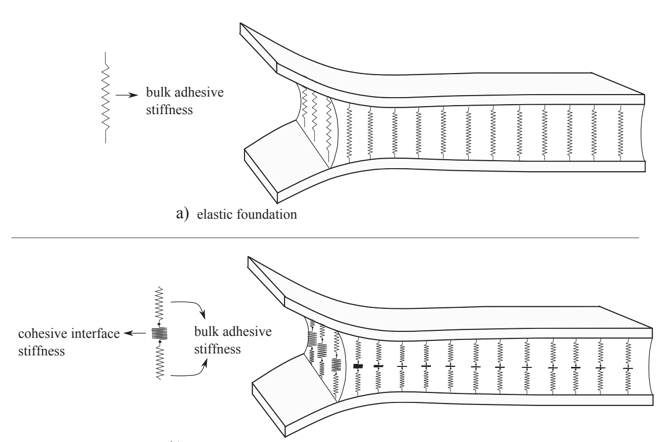

Fig. 1. Comparison between a DCB model based on elastic foundation beam theory a) without a progressive damage b) coupled with a cohesive zone model.