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Measuring mode I cohesive law of wood bonded joints based on digital image correlation and fibre Bragg grating sensors

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ABSTRACT

This work addresses the experimental identification of mode I cohesive law of wood bonded joints. The approach combines the double cantilever beam (DCB) test with both digital image correlation (DIC) and embedded fibre Bragg grating (FBG) sensors. The spectrum geometric mean of the FBG reflected spectral response was determined, and the wavelength evolution was used to define the fracture process zone (FPZ) development phase. This evaluation allowed a consistent selection of experimental range of over which the identification procedure of mode I cohesive law is build up. Mode I crack length, Resistance-curve and cohesive law parameters are characterised and discussed. The strain energy release rate (G_I) is determined from the P–δ curve by the compliance-based beam method (CBBM). The crack tip opening displacement (w_I) is determined by post-processing displacements measured by DIC. The cohesive law in mode I (σ_I–w_I) is then obtained by numerical differentiation of the G_I–w_I relationship.

1. Introduction

Adhesive technologies have been playing an important role in new applications and innovation of modern wooden constructions. Although there have been great advances in the science and engineering of wood adhesion, the characterisation and modelling of the adhesive bond strength at the adherent wood interface remains an open problem. Moreover, the crack initiation and propagation in adhesives evolve into a fracture process zone (FPZ) ahead of the crack tip. An effective way to deal with such complex fracture phenomena and mechanisms is through cohesive zone models (CZM), conjointly with interface finite elements [1–4]. Accordingly, the entire FPZ is collapsed into the cohesive crack surfaces, being the material behaviour described by a cohesive law that relates the cohesive stresses to the relative displacements of the adjacent cohesive surfaces [3]. This approach has some advantages with regard to the classical fracture mechanics approach. A relevant one is the possibility to completely describe the fracture event, starting from the undamaged material, without the presence of an initial crack and it is not almost mesh independent.

Although the widespread use of CZM, the experimental identification of the cohesive laws poses several difficulties. One way of tackling this problem is by an inverse method, in which a particular shape for the cohesive law is assumed and its constitutive parameters determined from global experimental tests using optimisation procedures [5–7]. However, this type of indirect identification method is impaired with an important limitation. Indeed, the *a priori* choice of a shape for the cohesive law does not guarantee its transferability from the laboratory tests to an arbitrary geometry. Moreover, this approach can be computationally time consuming and the uniqueness of the minimisation problem is not guaranteed. In order to overcome these drawbacks, several authors [8–11] have developed direct methods to identify the cohesive law without any prerequisite assumption about its shape. They are based on the simultaneous measurement of the crack opening displacement (COD) and the related strain energy release rate (G) during the fracture test. The cohesive law comes up through the differentiation of G versus COD relationship. This approach was recently applied to wood and composites bonded joints under both mode I [6,12,13] and mode II [14,15] loading. The opening displacement at the initial crack tip (CTOD) was

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evaluated by post-processing the crack tip displacements measured by means of digital image correlation (DIC) [16,17], whereas Resistance-curves (*R*-curves) were determined using the compliance-based beam method (CBBM) [5]. However, the identification of the cohesive law must be obtained from the experimental response of the specimen during the development of the FPZ, i.e., after the initial elastic response of the specimen up to the self-similar crack propagation. Hence, a central issue in determining the cohesive law directly from load (P), load-point displacement (δ) and CTOD is the clear identification of the FPZ development phase. In the case of bonded joints, embedded fibre Bragg grating (FBG) sensors can be a feasible way to accomplish this goal [18].

A direct method for evaluating the cohesive laws of *Pinus pinaster* Ait. wood bonded joints under mode I is examined in the present work. The double cantilever beam (DCB) test was selected. The identification method requires the continuous monitoring of CTOD and the evaluation of the strain energy release rate in mode I ($G_{\rm I}$). A simple data reduction scheme (CBBM) based on the elastic crack equivalent concept ($a_{\rm e}$) is used to determine the evolution of $G_{\rm I}$ during the test. DIC was employed for determine CTOD in mode I ($w_{\rm I}$). An FBG sensor embedded in the glue line, at the initial crack tip, was employed in order to assist in the identification of FPZ development phase. These measurements were analysed in view of the direct identification of mode I cohesive law of wood bonded joints.

2. Mode I cohesive law

The DCB test, coupled with DIC and FGB measurements, is schematically shown in Fig. 1. The specimen consists of two $L \times h \times B$ rectangular beams, glued by an adhesive with thickness t. Moreover, an initial crack length a_0 is assumed in the reference configuration. The basic equation to evaluate $G_{\rm I}$ is the Irwin–Kies equation,

$$G_{\rm I} = \frac{P^2}{2B}\frac{{\rm d}C}{{\rm d}a} \tag{1}$$

where C and a are the specimen compliance and crack length in the current configuration, respectively. The CBBM is a straightforward data reduction scheme to determine dC/da, circumventing the previous calibration of specimen compliance or the monitoring of crack length during the fracture test [5,19]. Furthermore, the CBBM is suitable to deal with the variability of elastic properties, which is particularly important for biological materials. Considering the Timoshenko beam theory and the Castigliano theorem, it can be shown that C is given explicitly as a function of a by the following relationship [5]

$$C = \frac{8a^3}{Bh^3E_{\rm L}} + \frac{12a}{5BhG_{\rm LR}} \tag{2}$$

where $E_{\rm L}$ and $G_{\rm LR}$ represent the elastic longitudinal and shear moduli, respectively. By replacing the initial crack length and specimen compliance (i.e., a_0 and C_0) in Eq. (2), an equivalent elastic modulus ($E_{\rm f}$) can be obtained that accounts for the presence of adhesive, material variability between specimens and stress concentration in the vicinity of the crack tip

$$E_{\rm f} = \frac{8(a_0 + h\Delta)^3}{Bh^3}\left(C_0 - \frac{12(a_0 + h\Delta)}{5BhG_{\rm LR}}\right)^{-1} \tag{3}$$

where Δ is a crack length correction that accounts for root rotation elastic effects. This parameter can be obtained numerically in two steps [20]. Firstly, the initial compliance is adjusted for the considered a_0. Secondly, two numerical simulations considering two different initial crack lengths must be performed in order to establish the $C^{1/3} = {\rm f}(a)$ relation. The interception of this line with the abscissa axis allows the evaluation of Δ. During the crack propagation, Eq. (2) can be used to determine the equivalent elastic crack length ($a_{\rm e}$) from the current specimen compliance (C), taking into account E_f (Eq. (3)) instead of E_L. The R-curve in mode I can therefore be obtained combining the Irwin–Kies equation (1) with Eq. (2) yielding

$$G_{\rm I} = \frac{6P^2}{B^2h}\left(\frac{2a_{\rm e}^2}{E_{\rm f}h^2} + \frac{1}{5G_{\rm LR}}\right). \tag{4}$$

It should be referred that $G_{\rm LR}$ has a minor influence on the results [5] which means that a typical value can be used. Experimentally, the elastic properties of wood can be determined from both quasi-pure mechanical tests such as off-axis, Iosipescu and Arcan [21,22] or heterogeneous tests such as the unnotched Iosipescu test [23,24] or annual ring-pattern tests [25].

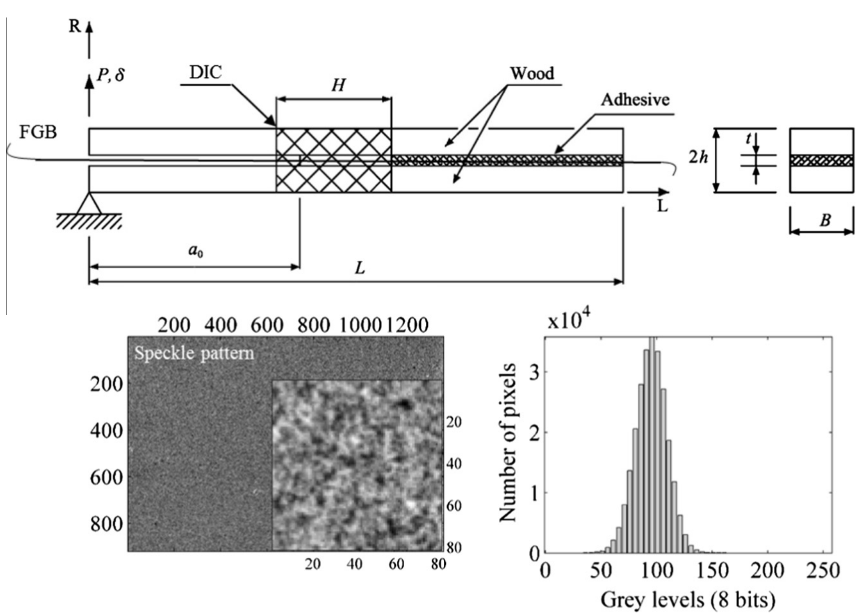

Fig. 1. Schema of the DCB test ($2h$ = 20 mm, B = 20 mm, t = 0.1 mm, L = 500 mm, H = 40 mm, and a_0 = 100 mm) coupled with DIC (speckle pattern and its histogram over a region of interest of 24.5 × 16.6 mm^2) and FBG.