MODE I FRACTURE CHARACTERIZATION: WOOD SEN-TPB

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ABSTRACT

The single edge notched beam loaded in three-point-bending (SEN-TPB) was used in this study to induce mode I fracture in wood (*Picea abeas* L.). Numerical analyses of stress profiles along the specimen length revealed a stress relief region as crack grows in size. Based on this data, beam theory and crack equivalent concepts were employed to develop an expedite data reduction scheme to estimate the *Resistance*-curve, taking advantage of a simplification performed on the revealed stress relief region. Besides allowing the evaluation of wood fracture toughness without crack length monitoring during loading, the developed procedure provides a user-friendly method when compared to other sophisticated procedures. Experiments involving the SEN-TPB were performed to evaluate fracture toughness in wood.

INTRODUCTION

A significant interest for wood as a structural material is increasing in the developed countries, motivated by environmental concerns and energy needs. Hence, the improvement of adequate failure criteria to be used in timbre construction deserves a particular attention. Therefore, Fracture Mechanics (FM) criteria arise as particularly adequate due to its capacity to treat stress singularities fairly present in most timber elements. Also, FM criteria stem on energetic analysis is exceptionally adequate (Morel, 2005; de Moura, 2008; Dourado, 2008) in particular when high heterogeneity is observed in the material. In this work a meticulous analysis of stress profiles both at the crack ligament and along the specimen length x (Fig. 1) has been performed to evaluate the stress relief region (SRR) in the SEN-TPB. A new data reduction scheme based on beam theory and crack equivalent concept was developed to determine the *Resistance*-curve (R-curve) in wood, considering a rectangular shape of the SRR, for simplicity.

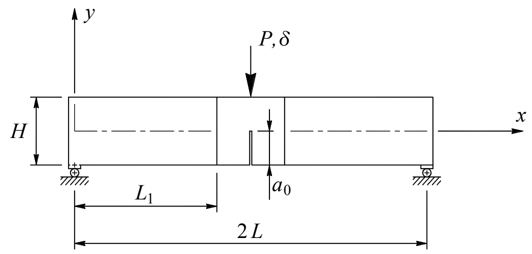

Fig.1. Schematic representation of the SEN-TPB test

Stress analyses

Stress analyses along the specimen length and ligament length were performed considering cohesive zone modeling with a bilinear softening law (Fig. 2). Stress profiles along the ligament length were obtained by means of cohesive elements located at the crack section for the specimen size H = 280 mm.

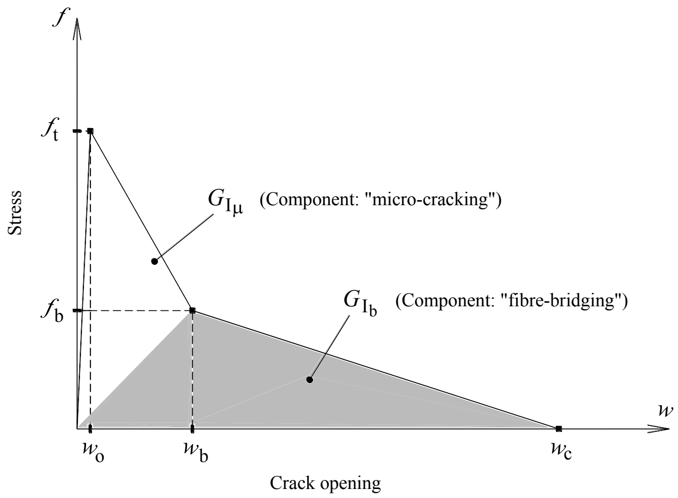

Fig. 2. Bilinear softening law used in the numerical computations.

According to these analyses detailed in Dourado, 2011 the stress relief region presents the shape shown in Fig. 3. Clearly, a triangular approximation simulates better the obtained profile. However, as thoroughly discussed in de Moura, 2008 the consideration of a triangular approximation originates a cumbersome analysis requiring the numerical solution of the compliance equation. In order to overcome these difficulties a rectangular approach to the stress relied region is assumed. In this particular case, the equation establishing the relationship between the equivalent crack and compliance has an analytical solution, which is much more straightforward to apply.

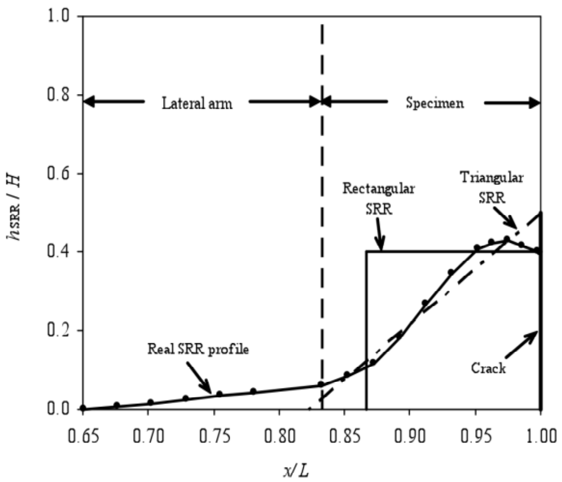

Fig. 3. Plotting of real and simplified approaches of the SRR in the normalized SRR height (h_{SRR}/H) versus normalized specimen length (x/L) space.

Data reduction scheme

The first step consists on the establishment of the relation between specimen compliance and crack length considering the presence of the square SRR in half specimen (Fig. 4). This procedure uses the Euler-Bernouly beam theory which leads to

$$C = 2\left[\frac{L_1^3}{E_L bH^3} + \frac{L_2^3 - L_1^3}{E_T bH^3} + \frac{L^3 - L_2^3}{E_T b(H - ka)^3}\right] \tag{1}$$

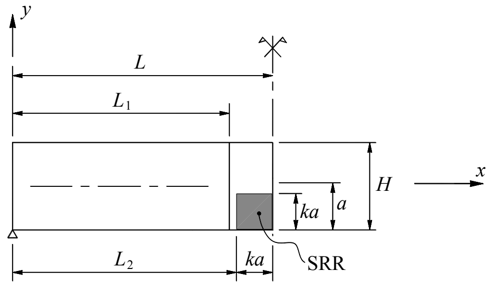

Fig. 4. Schematic representation of the SEN-TPB half specimen and profile of SRR.

In order to account for material variability and all the aspect not included in beam theory, an equivalent elastic modulus can be determined from the initial conditions (C_0, a_0)

$$E_{Tf} = \left(\frac{L_2^3 - L_1^3}{bH^3} + \frac{L^3 - L_2^3}{b(H - ka_0)^3}\right)\left(\frac{C_0}{2} - \frac{L_1^3}{E_L bH^3}\right)^{-1} \tag{2}$$

to overcome this difficulty. An estimate of the equivalent crack length a_e can be obtained, isolating a_e from Equation (1) and using E_{Tf} instead of E_T, as follows,

$$a_e = \frac{1}{k}\left\{H - \left[\left(\frac{C}{2} - \frac{L_1^3}{E_L bH^3} - \frac{L_2^3 - L_1^3}{E_{Tf} bH^3}\right)^{-1} \frac{L^3 - L_2^3}{E_{Tf} b}\right]^{1/3}\right\} \tag{3}$$

Consequently, fracture energy can now be obtained by means of the Irwin-Kies equation

$$G_I = \frac{P^2}{2b}\frac{dC}{da} \tag{4}$$

applied to Equation (1), which leads to

$$G_I = \frac{3P^2}{b^2}\frac{\left(L^3 - L_2^3\right)k}{E_{Tf}\left(H - ka_e\right)^4} \tag{5}$$

Using this methodology, the *Resistance*-curve (*R*-curve) as a function of the equivalent crack (i.e., $G_I = f(a_e)$) is easily obtained by means of Equations (1), (2) and (5). The *R*-curve propitiates a concrete estimation of the fracture energy, providing that a plateau value is attained.

RESULTS AND CONCLUSIONS

Specimens with H = 280 mm were experimentally tested in three-point-bending. *Picea abeas L.* wood was used in the tests and fracture occurred in the TL plane. Six tests were performed considering a mechanical spindle-driven tension-compression machine (20 kN total capacity) to induce fracture in mode I. A load cell with the capacity of 1 kN has been installed and crosshead displacement rate of 3 mm/min were considered during fracture tests. The load-displacement curves were registered, since the specimen compliance is the key factor of the method. Previous analyses (Dourado, 2011) have shown that the "SRR size parameter" k tends to 0.8. This value was used in the analysis of the experimental tests. Figure 5 presents all the R-curves obtained for this wood species. The fracture values vary roughly between 0.15 and 0.20 N/mm which is acceptable for a natural material as wood. In addition, the obtained values are in agreement with values previously determined following other non self-similar data reduction schemes (Dourado, 2008).

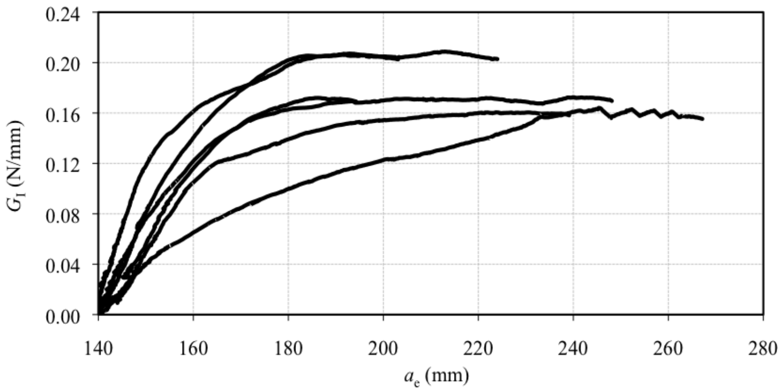

Fig. 5. R-curves obtained for H = 280 mm in *Picea abeas L.*

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