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# Mode I fracture characterization of wood using the TDCB test

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ABSTRACT

The Tapered Double Cantilever Beam test (TDCB) was analysed in the context of wood fracture characterization under mode I loading. A simpler linear slender increase of the cross-section is proposed to replace with accuracy the contoured nonlinear specimen profile, dictated by the presence of non-negligible shear effects. A finite element analysis including cohesive zone modelling was performed considering three different data reduction schemes: compliance calibration, Mostovoy and compliance based beam method (CBBM). All the methods provided good agreement in the plateau region of the *Resistance*-curves with the value of fracture energy used as input in the numerical simulation, especially the Mostovoy and CBBM ones, which have the remarkable advantage of being independent of crack length monitoring during the test. Additional experimental and numerical analyses were performed to settle the validity of the proposed approaches. All the results confirm the appropriateness of the TDCB test with linear tapering and proposed data reduction schemes as valuable tools for suitable wood fracture characterization under mode I loading.

## 1. Introduction

The employment of wood for structural applications has been increasing due to economic and ecological reasons. Consequently, the development of better design strategies is becoming a relevant aspect. This is the case of wood fracture characterization accounting for material specificities, as is the case of complex microstructural fracture mechanisms, characterized by micro-cracking and fibre bridging ahead of crack tip [12]. These fracture mechanisms are responsible for the development of a non-negligible fracture process zone ahead of the crack tip that should be accounted for in design analysis.

Considering the orthotropic morphology of wood, three distinct directions of symmetry are identified (Fig. 1): the longitudinal (L) direction following the fibres arrangement; the radial (R) direction regards the concentric growth rings; and the tangential (T) direction. Hence, the RL and TL fracture systems (with the first letter indicating the normal direction of the crack plane and the second specifying the direction of crack propagation (Fig. 2)), are the most important ones owing to an higher propensity of crack to propagate along the grain (fibre direction) under mode I loading [13]. Several experimental tests have been proposed to estimate the critical energy release rate in mode I for the referred fracture systems, *i.e.*, $G_{\mathrm{Ic}}^{\mathrm{RL}}$ and $G_{\mathrm{Ic}}^{\mathrm{TL}}$. The most common fracture tests are the Compact Tension test (CT), the Double Cantilever Beam (DCB) and the Single-Edge-Notched beam loaded in Three-Point-Bending (SEN-TPB) (Figs. 3 and 4). The CT test [1] is similar to the DCB one, differing on the specimen length perpendicular to loading, which makes it shorter in length and higher in height comparatively to the DCB (Fig. 3). The application of the CT test in the context of wood fracture characterization reveals some difficulties. One of them is the impracticality of applying beam theory based methods for data reduction purposes. The viable alternative is using the compliance calibration method to establish the $C = \mathrm{f}(a)$ relation. Experimentally, this can be done by two different ways. One of them consists in considering several specimens with different pre-crack lengths and determine the respective initial compliance. The inherent material variability among different specimens, characteristic of natural materials as is the case of wood can be considered an important drawback of this method, since erroneous estimations of toughness will certainly occur. In alternative, the crack length can be monitored in the course of the CT fracture test, which is very difficult to perform with the required accuracy in wood. Another drawback of the CT test in the context of wood fracture characterization is related with the typical material softening behaviour due to several toughening mechanisms acting during the fracture process. In fact, the quasi-brittle behaviour of wood leads to the development of a non-negligible fracture process zone (FPZ), which is incompatible with the short ligament length characteristic of the CT specimen. Similar to the CT test is the Wedge Splitting Test (WST) proposed by Tschegg et al. [12] which has been used by other authors [7]. The test consists in splitting a notched specimen into two parts by means of a stiff wedge acting in the specimen extremities through roller bearings. The

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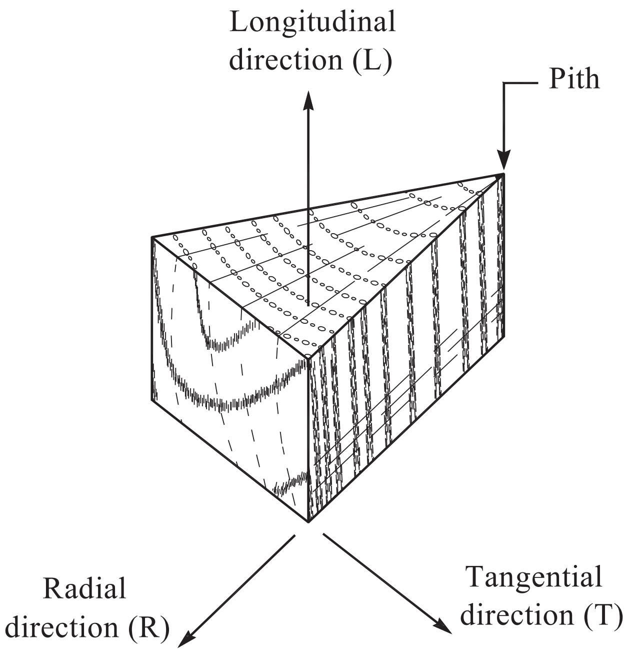


**Fig. 1.** Wood anatomical directions: Longitudinal, Radial and Tangential.

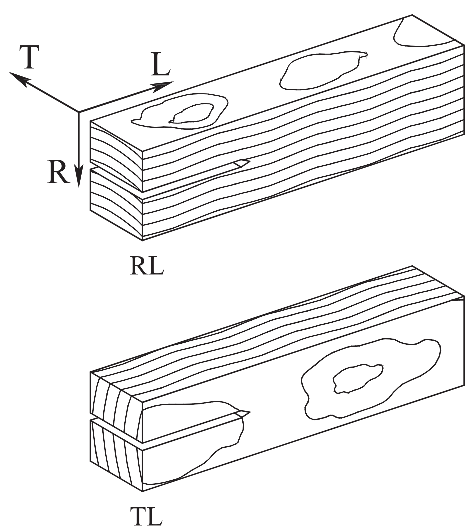


**Fig. 2.** Fracture systems in wood.

limitations ascribed to the CT test can also be pointed to the WST owing to similarities between both tests. The DCB test [4] is preferable in view of its quite longer ligament length in the specimens. Anyway, the problem of crack length monitoring with the necessary accuracy persists in this fracture test. To overcome this difficulty, a data reduction scheme based on crack equivalent concept and beam theory can be used to evaluate fracture toughness in wood [4]. This procedure uses the specimen compliance and beam theory to estimate an equivalent crack length, which makes it susceptible to spurious phenomena influencing the specimen compliance. The SEN-TPB test (Fig. 4) is also used in the context of wood fracture characterization under mode I loading [5]. The test is easy to execute and allows fracture characterization in different wood fracture systems. However, two drawbacks can be pointed to the SEN-TPB test. In fact, previous works [6] have shown that in small specimens the ligament length is insufficient to provide self-similar crack growth due to development of normal compressive stresses induced by bending above the specimen neutral axis. These compressive stresses interact with the developed fracture process zone (FPZ) which is a key damage mechanism [8], leading to a spurious increase of the measured fracture energy. In addition, crack length monitoring is also difficult to perform with accuracy. Therefore, an equivalent crack length defined as a function of the current compliance was developed for this fracture test [3] to overcome this difficulty.

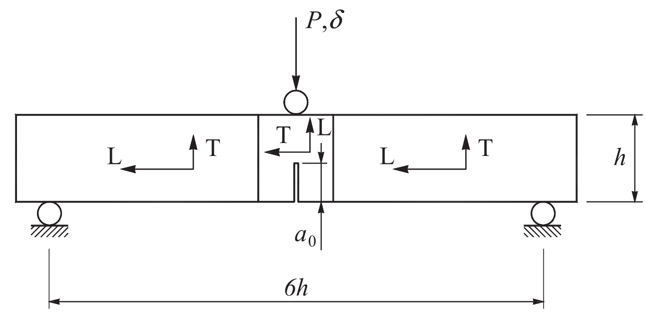


**Fig. 4.** The SEN-TPB test.

The analysis of these tests reveals that the most common tests used for mode I fracture characterization of wood present some disadvantages related to confinement of the process zone (CT and SEN-TPB) and difficulties inherent to crack length monitoring, which are common to all tests. An appealing alternative to solve the referred shortcomings is the employment of the Tapered Double Cantilever Beam test (TDCB), which provides stable crack growth through a constant crack speed propagation [9]. The specimen geometry (Fig. 5) is based on a slender increase on the cross-section along the crack extent, *i.e.*, $h = \mathrm{f}(x)$. The goal is to design the specimen so that the compliance changes linearly with crack length, leading to a constant $dC/da$ relation [2,11] for a given crack extension. The consequence is that strain energy release rate $G_{\mathrm{I}}$ becomes independent of crack length $a$, *i.e.*, it varies only as a function of the applied load during crack growth, which simplifies markedly the evaluation of fracture toughness [10]. However, shear effects should be accounted for in wood, which leads to a

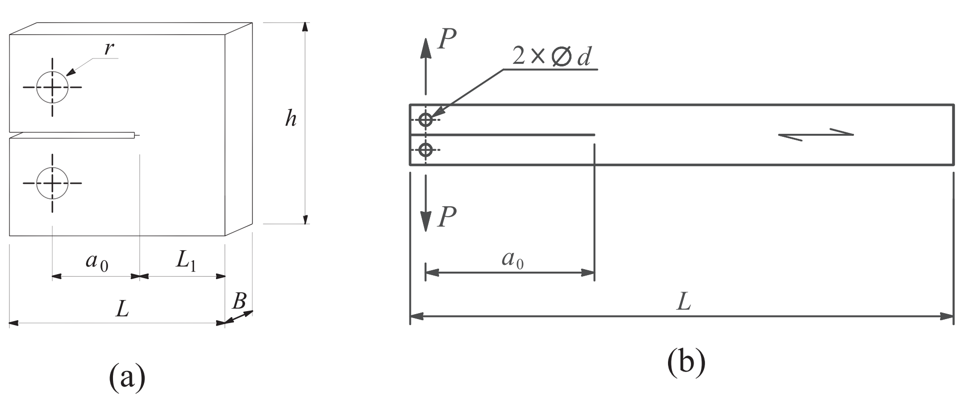


**Fig. 3.** (a) CT test; (b) DCB test.