FRACTURE ZONE CHARACTERIZATION—MICRO-MECHANICAL STUDY

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(Received November 2000)

ABSTRACT

The experimental and numerical characterization of the fracture process zone in softwoods is presented. In-situ real-time Scanning Electron Microscopy (SEM) was used as a tool to examine the physical mechanism of fracture in softwoods (spruce) using end-tapered Double Cantilever Beam specimens. Fracture process zone has been characterized in terms of failure mechanisms. It was found that bridging behind the crack tip is the main toughening mechanism, which contributes to nonlinear wood behavior in the presence of stress concentrations.

Keywords: Fracture mechanics, fracture zone, *in-situ* real-time SEM observations, crack profiles, fiber bridging, toughening.

INTRODUCTION

Since the first successful attempts to apply the theory of fracture mechanics to wood (Attack et al. 1961), various research studies have focused on fracture characterization, test methods, and interpretation of fracture parameters applicable to engineering problems. Fracture mechanics has also provided valuable concepts for evaluation of the influence of crack-like defects, notches, and other stress raisers in structural members and wood-adhesive joints.

The crucial level of characterization of wood fracture behavior is related to the definition of the damage zone ahead of a crack tip. Compared to the body of knowledge about modes of wood failure at the macroscopic level, our perception and understanding of the character and size of the process zone ahead of a major crack tip are rather poor. No research studies (prior to Vasic 2000) have been found in the literature that focused on the delicate task of qualitative and/or quantitative characterization of the fracture zone. Because

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Wood and Fiber Science, 34(1), 2002, pp. 42–56

of the apparent brittleness of wood, the Linear Elastic Fracture Mechanics (LEFM) approach has commonly been considered as an attractive and promising tool for wood strength predictions and engineering applications. Yet, the LEFM approach holds to a good approximation only when the process zone is small in respect to the crack length or the dimensions of the cracked body. The basic assumptions of the LEFM are, however, often violated. The relatively large volume of literature on the subject of LEFM applications to wood is flooded with rather conflicting and confusing experimental data (Valentin et al. 1991). There seems to be a lack of objectivity and relevance outside the original specific testing configurations. There is a growing body of opinion that wide discrepancies in results are associated with failure mechanisms in the process zone ahead of the crack tip. A process zone is not elastic and not accounted for in the single parameter **K** characterization of the crack-tip stress field (e.g., Bostrom 1992; Yeh and Schniewind 1992; Smith and Chui 1994; Smith and Hu 1994; Vasic and Smith 1996a, b, 1998, 1999; Vasic 2000).

The experience gained through the applications of fracture mechanics to other quasi-brittle materials, e.g., concrete, ceramics, and rocks, has provided the definition of the process zone size as a ". . . measure of the deviation from linear elastic behavior shown by the material" (Atkinson 1987). The macroscopic inelastic behavior is completely controlled by heterogeneities on the 'grain scale' and their interaction under triaxial stress (or strain) induced at the major crack tip. It is therefore, rational to presume that the damage process zone characterization is fundamental to understanding the mechanism of crack growth.

Experimental evidence for the existence of an inelastic process zone ahead of a wood crack can be found throughout the results from different laboratories. Such evidence is most often obscured because parameters varied between investigations. While seeking originality, various investigators have used quite different experimental techniques and testing conditions. Due caution must be exercised in distinguishing the effects of an intrinsic damage zone development from other potential influences.

THE LIMITATIONS OF LEFM APPLIED TO WOOD

The evaluation of the basic parameters of Linear Elastic Fracture Mechanics (LEFM) presumes that the following principles hold:

1. The material is a homogeneous, isotropic (or orthotropic, Sih et al. 1965) linear elastic medium.
2. The preexisting crack always propagates along the original crack direction, i.e., in a self-similar manner.
3. Crack-tip displacements can be separated into three different modes, namely in plane tension, in-plane shear, and out-of-plane shear.
4. The intensity of the corresponding stress distributions in the vicinity of the single crack tip is fully characterized by the stress intensity factors K_I, K_{II}, and K_{III}.
5. The inelastic process zone is confined to a small volume at a crack tip. It has a radius (r) small enough to satisfy the condition $r/a < 0.02$ (**a** is the crack length, or any dimension of the cracked body).
6. Crack surfaces are traction-free at all stages of loading, and the crack tip is anatomically sharp.
7. Once the critical fracture condition (fracture toughness K_c or critical strain energy release rate G_c) has been reached or exceeded, the crack propagates dynamically at some terminal velocity.

In respect to these features of LEFM, fracture behavior of wood may be characterized and compared as follows:

1. Wood is a heterogeneous, approximately cylindrically orthotropic material with discontinuities on both micro- and macro-structural levels. Brittle wood fracture usually occurs while in an elastic range.
2. For all strongly anisotropic materials, the

crack does not necessarily grow along the original crack orientation, e.g., in unidirectional composites the crack always grows along the fibers. In wood the initial crack extension is always parallel to the grain, even when the starter crack lies across the grain (Ashby et al. 1984). Only for the special case of an original crack along the fiber direction, does this deviation from the principles of LEFM vanish. It is likely that the crack in wood never propagates in a strictly self-similar manner, due to heterogeneous and discrete natured micro- and macrostructure. Microscopically, probably with no exception, fractured surfaces are irregular and tortuous.

3. In the terms of the above discussion, it can be concluded that it is only when a crack propagates in a self-similar manner that the displacements determined with the aid of Westergaard's equations are not of mixed mode. Hence, only then can displacements be separated into three independent modes (Knott 1973; Broek 1982).
4. Popularity of fracture mechanics has been associated with the attractiveness of a simple one-parameter K_n (n = I, II, III) description for all complex fracture phenomena that different materials may exhibit. Yet, whenever all the principles of LEFM do not strictly hold for the specific material behavior, the simplicity of K characterization must be sacrificed.
5. The principle of 'smallness' of the inelastic process zone appears to be the most important issue for satisfactory applications of LEFM (Fig. 1). As emphasized previously, this zone in wood (or wood-composite products) has not yet been characterized appropriately, either by experimental observations, or by understanding the failure mechanisms involved.
6. It seems reasonable to speculate that crack surfaces are not traction-free during episodic slow crack growth in wood, and that the crack is not anatomically sharp. It could be further speculated that while the crack is seeking the planes of least resistance, on the microscale it leaves some 'islands' of intact-material behind the advancing fracture front. This mechanism is known as 'ligamentary bridging.' No matter the type of micro-failure, the ligamentary bridging mechanism is likely to occur, because longitudinal cells (tracheids/fibers) overlap rather than being arranged in linear longitudinal rows. The above implies that forms of energy dissipation other than surface energy are involved in wood crack propagation. These other forms are not accounted for in the LEFM.
7. The phenomenon called 'subcritical crack growth' is associated with crack propagation in a stable, quasi-static manner at values of K and G that are substantially below the critical values K_c and G_c (Atkinson and Meredith 1987). It is commonly related to systems subjected to long-term loading that causes delayed, static-fatigue failure. It is well known that the stability and rate of crack velocity can be controlled through appropriate choice of the rate of loading and experimental arrangement. Experimental evidence indicates that subcritical crack growth is characteristic of wood fracture behavior (Mai 1975; Yeh and Schniewind 1992).

Some recent research studies explicitly address the existence of an inelastic process zone ahead of the crack tip in wood. The application of J integral method (Yeh and Schniewind 1992) to single-edge notched Douglas-fir and Pacific madrone specimens revealed considerable differences between critical values of J_{Ic} and G_{Ic}, which are defined as equivalent in LEFM when material exhibits linear elastic behavior. The overall 'degree of plasticity' values (defined as relative differences between J_{Ic} and G_{Ic}) varied between 34 and 60% for Pacific madrone and 17 and 40% for Douglas-fir. The degree of plasticity increased for higher moisture contents (12, 18%, and green wood), higher temperature (70 to 140°F), and lower displacement loading rates (0.02 and 0.002 in./min). The general trends of the data