Composites Science and Technology 128 (2016) 65–74

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Measuring and modeling fiber bridging: Application to wood and wood composites exposed to moisture cycling

B. Mirzaei, A. Sinha, J.A. Nairn*

Wood Science and Engineering, Oregon State University, Corvallis, OR 97330, USA

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form
15 March 2016
Accepted 17 March 2016
Available online 21 March 2016

Keywords:
Wood
Durability
Fracture toughness
Computational mechanics
Fibre bridging

ABSTRACT

We propose a new method for determining fiber-bridging, cohesive laws in fiber-reinforced composites and in natural fibrous materials. In brief, the method requires direct measurement of energy released during crack growth, known as the *R* curve, followed by a new approach to extracting a cohesive law. We claim that some previous attempts at determining cohesive laws have used inappropriate, and potentially inaccurate, methods. This new approach was applied to finding fiber bridging tractions in laminated veneer lumber (LVL) made from Douglas-fir veneer and four different adhesives. In addition, the LVL specimens were subjected to moisture exposure cycles and observations of changes in the bridging cohesive laws were used to rank the adhesives for their durability. Finally, we developed both analytical and numerical models for fiber bridging materials. The numerical modeling was a material point method (MPM) simulation of crack propagation that includes crack tip propagation, fiber bridging zone development, and steady state crack growth. The simulated *R* curves agreed with experimental results.

1. Introduction

Many materials develop process zones in the wake of crack tip propagation including both synthetic composites [1,2] and natural materials such as bone [3], wood [4–6], or wood composites [7–9]. For both fiber-reinforced composites and fiber-based natural materials, a common type of process zone is a fiber bridging zone. Such zones can be a significant component of a material's toughness because the zone size can be comparable to, or larger than, the specimen size [8]. One way to guide interpretation of experiments or to design structures that use fiber bridging materials is to model the process zone with a cohesive law that gives crack surface tractions as a function of crack opening displacement. The practical use of such laws, however, requires methods to measure them. This paper describes a new approach to measuring cohesive laws with application to wood and wood composites. The measured laws were used to characterize materials and were implemented in a numerical model to validate their role in modeling crack propagation.

A key concept for understanding crack propagation in the presence of a process zone is that there are two crack tips — the actual “crack tip” at the leading edge of the process zone and the “notch root” at its trailing edge (see Fig. 1A). When a crack propagation experiment begins, the crack tip and notch root coincide at the “initial” crack tip. When loading causes energy release rate for crack tip growth to exceed the initiation toughness, the crack tip propagates, but the notch root does not. Instead, a “developing” process zone is left in the wake of the crack tip that grows as the crack tip propagates. During this phase, the crack resistance, *R*, increases, which is known as the material's *R* curve. Eventually the crack opening displacement (COD) at the notch root, δ_{root}, exceeds the critical COD for the process zone, δ_c. After δ_c is reached, the crack tip and the notch root propagate together in a regime termed “steady state” crack growth. In steady state crack growth, *R* is constant at a plateau called the steady state toughness, G_{ss}. In brief, the material's *R* curve increases until the notch root starts to propagate and thereafter remains constant at G_{ss}.

Fig. 1A shows a contour Γ from the bottom crack surface to the top surface that completely encloses the process zone. When part of the crack within the contour is connected by a bridging law, Bao and Suo [10] derived the *J* integral along the enclosing contour, called here the far-field *J* integral or $J_{ff}(\delta_{root})$, as:

* Corresponding author.
E-mail address: john.nairn@oregonstate.edu (J.A. Nairn).

http://dx.doi.org/10.1016/j.compscitech.2016.03.017
0266-3538/

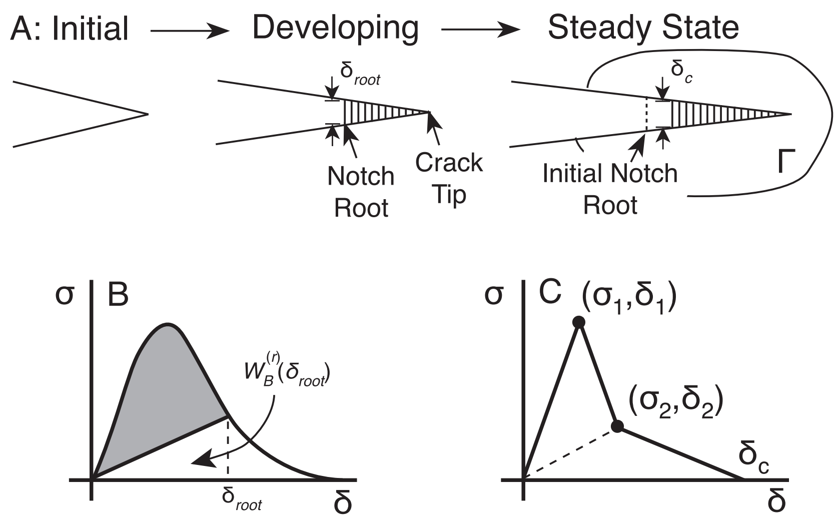

Fig. 1. A. Stages of crack propagation in the presences of a process zone, which is defined by two crack tips — the actual crack tip and the notch root. B. Schematic drawing for a cohesive law. The shaded region is the energy dissipated in the zone and $W_B^{(r)}(\delta_{root})$ is the recoverable energy in the zone (shown here as elastic recovery, but other types of recovery could be modeled). C. A representation of fiber bridging tractions as a trilinear traction law derived for modeling purposes.

$$J_{ff}(\delta_{root}) = J_{tip,c} + \int_0^{\delta_{root}} \sigma(\delta)d\delta \quad (1)$$

where $\sigma(\delta)$ is a traction law associated with the process zone. But, as is known in *J*-integral analysis, this *J* is only equal to the energy release rate when the crack growth is "self similar" [11]. When a process zone is involved, self similarity implies that the process zone length is constant during crack growth and this condition only occurs in the steady state regime with constant *R*. Prior to steady state, the energy required to propagate the crack needs to account for energy required both to propagate the crack tip and to enlarge the process zone. Nairn [12] has shown that in the region prior to steady state where the crack tip is propagating but the notch root is not, the increasing *R* curve should be found not from $J_{ff}(\delta_{root})$, but rather from:

$$R(\delta_{root}) = J_{ff}(\delta_{root}) - W_B^{(r)}(\delta_{root}) = J_{tip,c} + \int_0^{\delta_{root}} \sigma(\delta)d\delta - W_B^{(r)}(\delta_{root}) \quad (2)$$

where $W_B^{(r)}(\delta_{root})$ is recoverable energy in the process zone, which is non-zero when $\delta_{root}<\delta_c$. The amount of recoverable energy will depend on the mechanics of the process zone. A reasonable approximation for fiber bridging is that the process zone is an elastic zone undergoing damage such that recoverable energy is found by unloading back to the origin or $W_B^{(r)}(\delta_{root}) = \delta_{root}\sigma(\delta_{root})/2$ (see Fig. 1B) [12]. Stated differently, $J_{ff}(\delta_{root})$ is always the correct *J* integral, but that single quantity cannot simultaneously give energy release rate both for process zone development (where crack tip propagates but notch root does not) and for steady-state crack growth (where crack tip and notch root propagate together as self-similar propagation). The solution is to use Eq. (2) to find the *R* curve. This calculation of *R* will differ from $J_{ff}(\delta_{root})$ during process zone development, but will equal it during steady-state crack growth.

Accepting the model that fracture with a fiber-bridging process zone can be modeled using fracture mechanics and a cohesive law, Eqs. (1) and (2) suggest three valid methods for determining $\sigma(\delta)$. The first is to measure $J_{ff}(\delta_{root})$ during process zone development and then differentiate to get:

$$\sigma(\delta) = \frac{dJ_{ff}(\delta_{root})}{d\delta_{root}} \quad (3)$$

Unfortunately, in general it is not possible to measure $J_{ff}(\delta_{root})$ from typical fracture specimens because the calculated result depends on the cohesive law. One exception, as pointed out by Rice [11], is a pure moment-loaded, double cantilever beam specimen. Lindhagen and Berglund [2] used such a specimen to measure cohesive laws in several glass mat composites with random in plane fiber orientation and observed monotonic softening behavior. Two drawbakcs of this approach are that it requires special fixturing to apply a pure moment and it only works for one specimen geometry. This approach could never, for example, be used to probe important questions about potential changes in cohesive laws depending on specimen loading method. We also note that although $J_{ff}(\delta_{root})$, when it can be measured, can be used to find $\sigma(\delta)$, it cannot be used to measure the material's *R* curve (if that is of interest). As seen in Eq. (2), the material's *R* curve (*i.e.*,$R(\delta_{root})$) is not equal to $J_{ff}(\delta_{root})$ prior to steady state (because $W_B^{(r)}(\delta_{root}) > 0$ in that phase).

A second, valid approach is to avoid measurement of $J_{ff}(\delta_{root})$ or $R(\delta_{root})$ by directly measuring displacements in the arms of a double cantilever beam specimen and then numerically solving the inverse problem to find the traction law required such that the calculated and measured displacements agree. This approach was used by Botsis and coworkers [13–16]; they measured arm displacements using an embedded Fiber Bragg Grating (FBG) sensor and used finite element analysis to extract a cohesive law. The drawbacks of this approach are that specimens with FBGs are expensive and the technique is limited to synthetic composites where FBGs can be embedded during fabrication. The approach could not be used for studying fiber bridging in natural materials, such as solid wood. Vasic and Smith [17,18] developed a similar method where cohesive law was found by numerically matching finite element predictions to crack opening displacements in wood measured in a scanning electron microscope.

A third option is to directly measure $R(\delta_{root})$ using energy tracking methods [4–9]. Differentiating this result using Eq. (2) and