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Modeling the fiber bridging effect in cracked wood and paperboard using a cohesive zone model

Yujun Li*, Stefanie Reese, Jaan-Willem Simon

Institute of Applied Mechanics, RWTH Aachen University, Mies-van-der-Rohe Str. 1, D-52074 Aachen, Germany

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ABSTRACT

Wood and paperboard are two of the most widely used structural and packaging materials. Their fracture mechanical properties play a critical role in their performance for the practical applications. Cracks may lead to the creation of bridging fibers across the crack surfaces in both materials, which complicates fracture measurements and modeling. The aim of this study is to predict the fracture behavior including the fiber bridging contribution by using a potential based cohesive law in a phenomenological way. The cohesive energy potential was constructed using an exponential function, and the cohesive traction-separation relationships were obtained from the gradient of the potential. The model was applicable to various traction increasing responses, i.e. convex and concave. The proposed model was evaluated by simulating the double cantilever beam (DCB), end-notched flexure (ENF), and mixed mode tests. The results agree well with experimental data.

1. Introduction

Wood and paperboard are two of the most widely used materials in the world. Wood is a hierarchical, anisotropic and heterogeneous composite material, while paperboard, a wood fiber composite, is in general composed of fiber network bonded together by starch or adhesive material. Their relatively low price, sustainability and energy efficient production process make them increasingly attractive nowadays in both structural and packaging applications.

The fiber misalignment phenomenon is very obvious in wood and paperboard. The misaligned fibers do not only determine bulk properties of the materials [1], but also affect the crack initiation and propagation [2,3]. The natural fiber composites usually develop a relatively extensive fracture process zone due to pronounced fiber bridging in the wake of the crack tip. Such zones can significantly increase the energy release rate because the bridging length is comparable to or exceeds one of the dimensions of the specimen. Therefore, the fracture performance strongly depends on the specimen configuration. Its characterization plays an important role in damage tolerance design of structural components and delamination prediction of packaging processes. One conventional way to model this behavior is given by the use of the cohesive zone element technique. The process zone is then described by the cohesive law that defines the crack surface tractions as a function of the crack opening displacement. This method can serve to predict the crack growth and global structural response. However, the practical use of such laws requires determining the traction-separation relations from experiments in advance.

A number of studies focus on the mechanical properties of wood and paperboard, such as stiffness and strength [4–8], but only few of them specially address their fracture performance. The fracture properties of wood and paperboard can be obtained from the widely used double cantilever beam (DCB), end-notched flexure (ENF) and mixed-mode bending (MMB) tests [14,9–13,15,16].

* Corresponding author.
E-mail address: yujun.li@rwth-aachen.de (Y. Li).

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Nomenclature

T_n	normal traction, MPa
T_t	tangential traction, MPa
δ_n	normal separation, mm
δ_t	tangential separation, mm
$\sigma_{\max}$	maximum traction for mode I, MPa
$\tau_{\max}$	maximum traction for mode II, MPa
δ_{nc}	critical separation for mode I, mm
δ_{tc}	critical separation for mode II, mm
δ_{nf}	final separation for mode I, mm
δ_{tf}	final separation for mode II, mm
$\bar{\delta}_{nf}$	conjugate final separation for mode I, mm
$\bar{\delta}_{tf}$	conjugate final separation for mode II, mm
G_{IC}	mode I energy release rate, J/mm^2
G_{IIC}	mode II energy release rate, J/mm^2
Φ	potential for mixed mode I/II, J/mm^2
K	stiffness in contact, MPa/mm
$\delta_{n,\max}$	largest value reached by δ_n, mm
$\delta_{t,\max}$	largest value reached by δ_t, mm
α	exponent
β	exponent
a	intermediate parameter
b	intermediate parameter

Additionally, several special test methods have been developed to determine the fracture toughness in the paper community, such as Z-test [17], Scott Bond test [18,19], and SCAN-test [20]. However, the presence of fiber bridging complicates the fracture measurements for several reasons. The main reason is that the fiber bridging makes it difficult to visually identify the crack tip and measure crack lengths; these lengths are needed for data reduction. This issue is overcome by measuring the strain field ahead of the crack tip using digital image correlation (DIC) methods. For example, Matsumoto and Nairn [21] and Mohammadi and Nairn [22] have used this method to study the crack behavior of medium density fiberboard (MDF) and wood under mode I loading. Xavier et al. [11,12] have coupled DCB and ENF tests with DIC method to directly identify the mode I and mode II cohesive laws of *Pinus pinaster*, respectively. Other related studies on wood fracture are referred to [23,24].

Another valid approach is to measure the strains developed in the specimen during delamination by incorporating fiber Bragg grating sensors and then calculating the bridging tractions through an inverse-numerical approach. Sorensen et al. [25] have adopted this method to extract the mode I cohesive law of fiber reinforced polymers (FRP). This approach can not be used to study the fiber bridging phenomenon in the natural composites as the sensors need to be embedded during fabrication. Furthermore, for identifying a given softening law, it is possible to avoid the crack growth measurement by fitting the numerical and experimental load-displacement curves. This process does not always give a unique solution, although it has provided a good agreement between numerical simulation and experiments in [26,27]. Furthermore, instead of practical experiments, Canal et al. [28] have recently developed a micromechanical model to simulate the fiber bridging effect in the DCB test in order to extract the cohesive law.

In the literature, most of measurements indicate that the trilinear cohesive law can describe the fiber bridging effect under pure mode loading [29–35]. The behavior of this model is characterized by a linear initial part in which the traction rapidly increases with the applied separation and by a second region, representing the damage, in which the traction decreases following two lines with different slopes down to zero. The amount of dissipated energy is made up of two contributions – one associated with matrix cracking and the other with fiber bridging. This model has provided a reasonable interpretation and prediction of fracture behavior of wood products and FRP [11,27]. However, the direct extension of such cohesive law to mixed mode shows several limitations. First of all, since the kink point in the damage softening region highly depends on the crack mode mixity, it is difficult to identify these parameters under mixed mode loading. Additionally, it might not properly predict the delamination behavior in a mixed mode bending (MMB) test when obvious fiber bridging occurs [36]. To reasonably simulate the mixed mode crack, Borotto [36] has modified the cohesive law by introducing a mode mixity indicator, but this treatment at the same time complicated the parameter identification process.

Alternatively, the exponential type cohesive models [37–41] and polynomial cohesive models [42–44] can be used to represent the nonlinear cohesive properties. The advantage of the exponential type cohesive models is that the exponential function is continuous for both of the traction and its derivative, which is attractive from computational point of view. Recently, Park and Paulino [45–47] have assessed a few such models and addressed their advantages and disadvantages. However, most of these models don't account for the initial interfacial cracking mechanism explicitly. Recently, Höwer et al. [43] proposed a traction-separation law to include this effect when studying mode I facesheet to core delamination of sandwich panels. In general, these models can be classified into potential-based models and non-potential-based models. The non-potential-based models may not provide a monotonic decrease of cohesive traction with the increase of damage across fracture surfaces and they cannot account for all possible separation paths within the softening region as discussed in [46]. Instead, the presence of a potential makes it convenient to evaluate whether the traction evolution is physically reasonable for an arbitrary separation path [37]. As a consequence, a potential based cohesive model is proposed to describe the fiber bridging phenomenon in the fracture of wood and paperboard in the current work. The cohesive energy potential is constructed using an exponential function, and the gradient of the potential leads to the cohesive traction versus separation relationships.

The remainder of this study is organized as follows. In Section 2 a brief description of the investigated wood and paperboard specimens is provided, followed by the experimentally observed cohesive behavior. Section 3 illustrates the cohesive law for the pure mode as well as the mixed mode I/II. Section 4 is concerned with numerical applications in the DCB, ENF, and mixed mode tests of wood and paperboard, the results of which are compared with the experimental data. Finally, conclusions are drawn in Section 5.