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Mixed mode fracture properties characterization for wood by Digital Images Correlation and Finite Element Method coupling

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ABSTRACT

This paper seeks to characterize the mixed-mode energy release rate for orthotropic media subjected to a mixed-mode complex loading under service conditions. Experimental full-field information on Digital Image Correlation along with numerical modeling by the Finite Element Method have been considered as complementary approaches to determining fracture behavior in wood. An optimization technique allows calculating the kinematic state from Crack Relative Displacement Factor. A finite element analysis is performed in the local stress field characterization based on Stress Intensity Factor. This hybrid method has proven that the mixed-mode energy release rate uncoupling for fracture mode separation is achieved without taking into account local elastic mechanical properties; these properties can then be deduced by computing reduced elastic compliances from the additional information provided by Digital Image Correlation and Finite Element Method coupling. Such a hybrid method has been employed for cracked Douglas fir specimens undergoing complex loading in tension for various mixed-mode ratio values.

1. Introduction

Wood used as a lightweight building material has many advantages over other materials also possessing good environmental and thermal properties. Progress in the field of timber structures is currently being impeded by durability issues. More precisely, natural or accidental cracks induce, during a timber structure's life cycle, a decrease in lumber strength by means of concentrating mechanical stresses in the crack tip vicinity. An understanding of the crack growth process under mixed-mode conditions is therefore an important aspect when analyzing timber structural integrity. In accordance with orthotropic specifications, the energy balance for crack growth initiation refers to a fracture multi-criterion that seeks the separation of each fracture mode part [1,2]. Within this field of study, several numerical investigations have been carried out in the literature for the purpose of characterizing crack tip parameters through use of the energy method for mixed-mode configurations [3–9], for isotropic and orthotropic media. At present, these efficient techniques require an explicit knowledge of material properties; for orthotropic cases in particular, the complete compliance tensor is needed. In recognition of the fact that wood is a rather heterogeneous material, these methods are not yet applicable.

To circumvent these difficulties, the promising set of tools developed are proposed herein in order to predict crack tip parameters for a fracture mode separation analysis conducted on a wood specimen without any *a priori* knowledge of its orthotropic mechanical properties. This novel method utilizes the combined Digital Image Correlation (DIC) plus Finite Element Method (FEM) and moreover integrates DIC and FEM as complements rather than alternatives, as is the case with most characterization studies. DIC and FEM have already been considered as complementary tools for predicting fracture

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Nomenclature

Latin symbols

a	crack length
$[a]$	matrix of polar functions integrating the rigid body motion
$[a]^T$	transpose of a matrix
$A_I^i, A_{II}^i, A_\alpha^i$	weighting coefficients of the power series for opening and shear modes
C_α	reduced elastic compliance ($\alpha = 1;2$)
C_1	reduced elastic compliance in x_1 – direction (or Longitudinal direction of wood material)
C_2	reduced elastic compliance in x_2 – direction (or Radial direction of wood material)
$\widetilde{C}_1$	arbitrary reduced elastic compliance, corresponding to open mode
$\widetilde{C}_2$	arbitrary reduced elastic compliance, corresponding to shear mode
dV	elementary volume
$\widetilde{E}_L$	arbitrary longitudinal modulus
$\widetilde{E}_R$	arbitrary radial modulus
F	external force
G	energy release rate
G_1	part of energy release rate for open mode
G_2	part of energy release rate for shear mode
$\widetilde{G}_{LR}$	arbitrary shear modulus in wood Longitudinal-Radial system
i	integer representing the singularity level
f_i, g_i, l_i, z_i	polar functions
K_α^σ	Stress Intensity Factor ($\alpha = 1;2$)
K_1^σ	Stress Intensity Factor corresponding to opening mode
K_2^σ	Stress Intensity Factor corresponding to shear mode
${}^uK_\alpha^\sigma$	real stress intensity factors
${}^vK_\alpha^\sigma$	virtual stress intensity factors
K_α^ε	Crack Relative Displacement Factor ($\alpha = 1;2$)
K_1^ε	Crack Relative Displacement Factor corresponding to opening mode
K_2^ε	Crack Relative Displacement Factor corresponding to shear mode
N	power series number
M	subsets number
$M\theta$	integral $M\theta$
r	radial distance in polar coordinate system
r_k	distance of r^{th} point in polar coordinate system
$\tilde{p}_\alpha, \tilde{q}_\alpha$	arbitrary elastic properties
R	rigid body rotation
$\vec{T}$	rigid body translation vector
T_1	rigid body translation in x_1 – direction
T_2	rigid body translation in x_2 – direction
$\tilde{s}_\alpha$	characteristic equation roots
$\widetilde{S}_{ij}$	arbitrary compliance tensor components
$[u]_1$	relative displacement vector of the crack lips in x_1 - direction
$[u]_2$	relative displacement vector of the crack lips in x_2 - direction
$\vec{u}$	displacement vector
$u1$	displacement in x_1 – direction of a point located on the crack lips
$u2$	displacement in x_2 – direction of a point located on the crack lips
$\{u\}$	vector of displacement fields
$\{u\}^T$	transpose of u vector
u_1^k	displacement of kth point in x_1 – direction
u_2^k	displacement of kth point in x_2 – direction
$\vec{v}$	virtual displacement vector
$v_{i,k}$	gradient of virtual displacement vector
V	integration domain
x_1, x_2	cartesian coordinate
x_1^k, x_2^k	cartesian coordinate of kth point
x_1^0	correction of the crack tip position in x_1 – direction
x_2^0	correction of the crack tip position in x_2 – direction
$\{X\}$	matrix of unknowns parameters
$\{X\}^T$	transpose of X matrix