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Fracture analysis of glued laminated timber beams with a hole using a 3D cohesive zone model

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ABSTRACT

Introducing a hole in a glued laminated timber (glulam) beam generally results in a significant decrease in load bearing capacity. Global strength is most often limited by perpendicular to grain fracture with crack initiation at hole periphery and crack propagation in the grain direction. Strength analysis and design is far from trivial, which is reflected by the lack of design criteria in contemporary engineering design codes. This paper presents nonlinear 3D FE-analyses of beams with a hole, carried out using a cohesive zone model based on plasticity theory. Results of numerical analyses are compared to experimental tests showing good agreement. Results of a numerical parameter study relating to beam width and growth ring pattern are presented, showing decreasing nominal beam strength with increasing beam width and that the beam strength is affected by the growth ring pattern. Furthermore, some analyses of the influence of different types of initial cracks are presented.

1. Introduction

Wood is in many aspects a very appealing structural material. It does however possess some unique and complex properties, demanding careful considerations in design in order to utilize the material in a proper way and to its full potential. Among these properties are the strongly orthotropic strength and stiffness properties of great importance. Wood is comparatively weak when loaded in tension perpendicular to grain and in shear and the associated failure type, with cracking along grain, commonly has a brittle course. This type of loading is for timber structures a common cause of damage [1]. A beam with a hole is a typical example of a structural element for which the global strength commonly is limited by perpendicular to grain fracture, with crack initiation at hole periphery and crack propagation along the grain. In spite of the research effort within the area, a lack of knowledge is reflected by the absence of design criteria for beams with a hole in the current European timber engineering design code EN-1995-1-1:2004 [2].

Glued laminated timber (glulam) beams with a hole are in practical design often reinforced, using either internal or external reinforcement. The use of reinforcement appears to be due to the significant strength reduction related to the introduction of a hole in combination with a lack of knowledge and the lack of code design criteria regarding the strength of unreinforced beams. Studies of unreinforced beams with a hole are hence motivated.

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Nomenclature

a_{cr}	length of initial crack
A_{net}	beam net cross section area at hole center
A_{yy}	scaling parameter in opening mode
A_{xy}	scaling parameter in shear mode
A_{yz}	scaling parameter in shear mode
b_{cr}	width of initial crack
B	beam width
c	model parameter used in softening law
E_i	modulus of elasticity where $i = L, R, T$
f	updated/current yield function
f_{it}	uniaxial tensile strength where $i = L, R, T$
f_{ic}	uniaxial compressive strength where $i = L, R, T$
f_{ij}	shear strength where $i, j = L, R, T$ and $i \neq j$
F	initial yield function
F_{yyyy}	fictitious strength parameter
F_{xyxy}	fictitious strength parameter
F_{yzyz}	fictitious strength parameter
G_{ij}	modulus of shear where $i, j = L, R, T$ and $i \neq j$
$G_{f,yy}$	fracture energy in opening mode
$G_{f,xy}$	fracture energy in shear mode
$G_{f,yz}$	fracture energy in shear mode
h	out-of-plane height of predefined potential crack plane
H	beam height
K	softening parameter
L, R, T	local material longitudinal-, radial and tangential directions
m	model parameter used in softening law
$\mathbf{P}$	matrix related to Tsai–Wu criterion
$\mathbf{q}$	column matrix related to Tsai–Wu criterion
r	local crack plane coordinate
s	distance between lower edge of lamella and crack plane
V	shear force
V_c	shear force strength with respect to perpendicular to grain fracture
V_{cB}	value of V_c with respect to cracking at bottom hole corner
V_{cT}	value of V_c with respect to cracking at top hole corner
x, y, z	global coordinate system
y', z'	local coordinate system for a lamella
y'_p, z'_p	location of pith in local coordinate system
δ_{eff}	effective dimensionless deformation, internal variable
δ_{yy}	plastic deformation in y-direction, cohesive crack opening
δ_{xy}	plastic deformation in xy-direction, cohesive crack slip
δ_{yz}	plastic deformation in yz-direction, cohesive crack slip
$\boldsymbol{\varepsilon}^p$	plastic strain vector
$\dot{\lambda}$	plastic multiplier
ν_{ij}	Poisson's ratio where $i, j = L, R, T$ and $i \neq j$
$\boldsymbol{\sigma}$	stress vector

Abbreviations

CZM	cohesive zone model
CB	crack plane at bottom hole corner
CT	crack plane at top hole corner
LEFM	linear elastic fracture mechanics

The strength of beams with a hole has in several studies been analyzed using 2D linear elastic fracture mechanics (LEFM) approaches by assuming a predefined crack of a certain length at a critical location, see e.g. [3–8]. Drawbacks of such approaches include the inherent dependence between crack propagation load and length of the assumed crack. LEFM can furthermore be expected to give accurate results only for large enough structural elements, where the fracture process zone is small compared to the length of the crack and other relevant dimensions.