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Novel internally LVL-reinforced glued laminated timber beams with large holes

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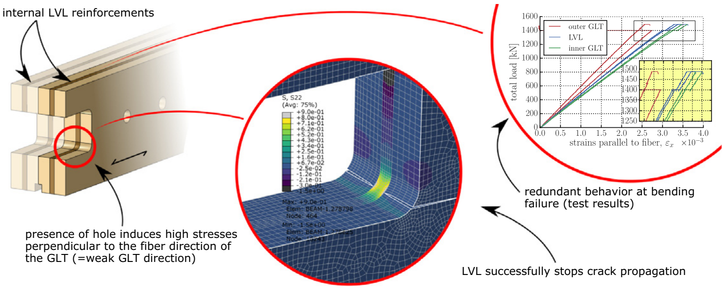
HIGHLIGHTS

- Study of a novel composite of softwood glulam with internal beech LVL layers.
- The composite is damage-tolerant and excelled by non-brittle fracture.
- The LVL layers enhance the strength perpendicular to the beam axis.
- The composite enables a safe arrangement of multiple large holes.
- The load-sharing between layers near the holes needs further consideration.

GRAPHICAL ABSTRACT



internal LVL reinforcements

presence of hole induces high stresses perpendicular to the fiber direction of the GLT (=weak GLT direction)

redundant behavior at bending failure (test results)

LVL successfully stops crack propagation

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ABSTRACT

A novel timber composite is presented, consisting of glued laminated timber (GLT) from softwoods and intercalated cross-layered plates of laminated veneer lumber (LVL) made of hardwood species, specifically beech. The structure is especially suited for beams with multiple, large rectangular holes, where the LVL acts as a highly efficient internal reinforcement and contributes to a damage-tolerant ultimate load behavior. The load capacity of the composite beam is not induced by the stress concentrations at the corners of the hole, which, in contrast to generic GLT, lead to a sudden propagation of cracks and brittle failure. It is shown that the structure, including the holes, can be designed analytically in a transparent manner by using beam theory, a parallel system approach, and modifications from FEM analysis for the verification of tensile forces at the hole periphery. The composite, firstly used in a recent multi-story building in Australia, significantly improves the competitiveness of timber in building works, which have been limited to steel and reinforced concrete structures.

1. Introduction

Glued laminated timber, known as glulam (GLT), and laminated veneer lumber (LVL) are wood composite materials; they are the most important and frequently used monolithic engineered timber products in the world, considering only beam type applications. To date, GLT has been almost exclusively used as a stand-alone building component, whereas LVL has frequently been used for flanges for I-beams, with webs made of oriented strand board (OSB) or high-density fiberboard. Occasionally, LVL is used as local reinforcement for glulam, as well. In the case of both materials with rectangular cross-sections reaching depths up to 2.5m, boring round and/or rectangular holes, such as passages of ventilation and sewage pipes, is often an architectural and technical requirement. Nevertheless, despite the widespread use of openings in solid walled beam structures, the European timber design code EN 1995-1-1 [32], (EC 5-1-1), does not contain any provisions on holes in either GLT or LVL beams. In contrast to EC 5-1-1, the German National Annex [24] incorporates design and construction rules for unreinforced and reinforced holes as well in GLT and LVL

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List of Symbols

Abbreviations

GLT	glued laminated timber
LVL	laminated veneer lumber

Mechanical and geometric parameters

δ	Deflection at mid-span
ℓ_A	distance from the vertical end of the beam to the closest edge of a hole
ℓ_Z	minimum spacing along the beam axis between vertical edges of adjacent holes
ℓ_{cr}	crack length
$\ell_{t,90}$	length of the decaying tensile stress field perpendicular to the beam axis at hole corners
η	stiffness ratio
v	Poison's ratio
ψ_2	factor for the quasi-permanent value of the design-relevant action
σ_m	bending stress
τ	shear stress
φ	angle between the horizontal axis and the crack initiation position
$\xi_{\tau,\text{corn}}$	shear stress concentration factor at the corner of the hole
a	width of hole parallel with the beam axis
b	total width of beam
d	distance from the mid-depth of the beam to the mid-depth of the hole
E	modulus of elasticity
e	normalized modulus of elasticity
F	total load applied
f_c	compressive strength
f_m	bending strength
f_t	tensile strength
f_v	shear strength
$F_{t,90}$	vertical tensile force perpendicular to beam axis at hole's corner
G	shear modulus
h	depth of beam
h_d	depth of hole
h_n	depth of notch
I	moment of inertia
I_{full}	moment of inertia of full cross-section
I_{hole}	moment of inertia of the (virtual) hole cross-section
k_{def}	creep factor dependent on service class
k_{mod}	modification factor for strength depending on accumulated time of loading and service class
$k_{t,90}$	size effect factor for the strength
M	bending moment
r	radius of curvature of hole corners
$R_{t,90}$	resistance force at the corner of the hole
t	thickness of glulam laminations
t_{veneer}	thickness of LVL plate
V	shear force
w_n	width of notch
y_{na}	position of cross-sectional neutral axis
$y_{C,\text{hole}}$	position of the mid-depth of the hole

Subindices

i	denotes the material: $1 = GLT, 2 = LVL$
k, 05	characteristic value, 5%-quantile
u	ultimate state of beam
0	parallel with the grain
90	perpendicular to the grain
A	test configuration A
B	test configuration B
lo	reduced cross-sectional depth beneath the hole
max	maximum value of a property
mean	mean value of property
up	reduced cross-sectional depth above the hole

beams. In the United States, the design of unreinforced GLT holes is based on a Weibull stress approach [7], detailed in Ref. [4] and not discussed here, whereas no design rule exists for reinforced holes in GLT.

According to DIN EN 1995-1-1/NA [24], a distinction can be made between external reinforcements by laterally glued-on LVL or plywood panels and internal GLT hole reinforcements by glued-in rods or self-tapping screws.

First tests in 1971 with laterally plywood-reinforced GLT beams are reported in Ref. [9]. A series of three experimental campaigns (see Ref. [42]) with full-scale GLT-beams with large rectangular openings, reinforced laterally either by beech plywood or a specific plate made of angle-layered spruce boards [48], is summarized in Ref. [44]. The results proving the high efficiency of both reinforcements, lead to the first internationally published recommendations [43] for reinforcement of apertures in GLT beams. These comprise i.a. the required plywood-GLT thickness ratio dependent on the shear stress at the center of the hole, derived by elementary beam theory. Details on plate sizes and bonding requirements are specified as well. The bespoken specifications were then adopted with minor modifications in DIN 1052-1[23]. FEM and analytical analysis [42] of (un) reinforced holes revealed that the disturbed shear stress flow around holes leads to tensile stresses perpendicular to the GLT beam and fiber axis at diagonally opposite hole corners. A comprehensive reevaluation of the research [42] published in Refs. [12,13] led to the former and today's German hole reinforcement design rules, based on the resultant tensile forces at the hole corners [22,24]. Recent results on lateral plywood reinforcement of apertures in GLT [6] revealed that some of the code provisions [24] are insufficient. This refers, e.g. to the minimum plate reinforcement width adjacent to the vertical hole edges, which is too small. Further, the normal stress spread over the reinforcement thickness, assumed to be constant, is inappropriate.

Lateral GLT fiber reinforcements, either locally for apertures or globally, although promising, are not covered by any standards today. First investigations on glass-fiber reinforcement of curved GLT beams perpendicular to the fiber direction were reported in [45]. A series of reports dealing with multiple aspects of local and global glass and carbon fiber strengthening of GLT is presented in Ref. [15]. Reinforcement of very large rectangular holes in GLT by means of glass-fiber composite are reported in Refs. [36,37]. The failure mechanics are analyzed theoretically in Ref. [38].

First profound theoretical and experimental investigations on internal reinforcement of GLT with round holes, by screw- or bar-type steel elements, were presented in 1983 in Ref. [41]. A significant load capacity increase compared to the case with unreinforced holes has been encountered. Further, partially threaded screws arranged perpendicular to beam axis, in pre-drilled bore-holes, performed better than inclined rods. Pioneering investigations with fully threaded self-tapping screws for internal reinforcement of round and rectangular holes in GLT are reported in Ref. [10]. Contrary to [41] now inclined screws, as opposed to