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Calculation model to assess the structural behavior of LVL-concrete composite members with ductile notched connection

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ABSTRACT

This paper presents an analytical model of timber-concrete composite slabs made of laminated veneer lumber (LVL) with notched connection. Timber-concrete composite slabs could be used as alternative to timber slabs or conventional reinforced concrete slabs and represent an interesting solution due to ecologic, economic and structural advantages. The use of LVL products guarantees for controllable and homogeneous properties of the timber part of the composite member and allows taking advantage of the high mechanical properties of hardwood (e.g. beech). The advantages of the notch as timber-concrete connection system are its high stiffness and the possibility to achieve a ductile compressive failure of timber. The presented analytical model is based on simple equilibrium formulations and allows the development of a ductile and reliable design procedure based on notch yielding. Because of the difference between the material properties of LVL and concrete, local LVL deformations within the notches may compromise the shear-carrying mechanism in concrete, leading to premature failure of the composite member. This problem can be solved by installing vertical reinforcement. The model has been validated by means of full scale bending tests on timber-concrete composite members made of beech LVL plates.

1. Introduction

Timber-concrete composite structures usually consist of a timber part in the tensile zone, a concrete layer in the compressive zone, and a connection between timber and concrete [1]. In general, timber-concrete composite slabs show several advantages over traditional timber floors, e.g. increased strength and stiffness under gravity load, better seismic resistance, improved sound insulation and fire resistance. The development of timber-concrete composite structures already started in Europe after World Wars I and II as a consequence of shortage of steel for reinforced concrete and 1939 a patent for a timber-concrete composite slab with connection made of steel Z-profiles and I-profiles was filed in Switzerland [2]. In the US, Richart and Williams [3] reports tests on timber-concrete composite beams with different shear connections including triangular plates, spikes and notch details. In the last 50 years, interest in timber-concrete composite systems has increased, resulting in the construction of bridges, upgrading of existing timber floors and the construction of new buildings [4].

As shear connections markedly affect the efficiency of timber-concrete composite structures, several research projects have focused on the development and testing of connection systems for timber and concrete composite action. As a result many different connection systems with steel fasteners (screws, dowels, nailplates, etc.) and notched details cut from the timber members have been proposed thus far [5–8]. Further, several short-term experimental analyses and numerical simulations looked at the global structural behavior of timber-concrete composite structures at normal temperature [9–11] and in fire [12]. The long-term behavior of timber-concrete composite structures was extensively studied as well and different approaches were proposed to account for the time-dependent phenomena of timber, concrete and connection [13–16].

Almost all connection systems are flexible, i.e., they cannot prevent a relative slip between concrete and timber. Thus, flexible connections develop only partial composite action and therefore the structural analysis requires the consideration of interlayer slip between the subcomponents. Common calculation models are based on the differential equation for the partial composite action [17,18] and assume a linear elastic behavior of the subcomponents (timber, concrete and connection) until failure. Analytical solutions of the differential equation for simply supported beams with constant slip stiffness subjected to

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Notation

A_i	cross section area of the member i
A_{Ni}	contact area of the notch i
b	width
C_i	compression force in concrete
cr	cracking; crack; crack depth
d	diameter
E_i	modulus of elasticity of the member i
EI_I	bending stiffness of the composite cross section during state I
EI_{II}	bending stiffness of the composite cross section during state II
$f_{c,i}$	compressive strength of the member i
f_s	tensile strength of a steel reinforcement
$f_{t,i}$	tensile strength of the member i
$f_{t,0,2}$	tensile strength of timber parallel to the grain
h	height
h_{cr}	crack depth
K	shear stiffness of a timber-concrete connection
I_I	moment of inertia of the composite cross section during state I
I_{II}	moment of inertia of the composite cross section during state II
I_i	moment of inertia of the member i
l	length; span
l_{pl}	length of a plastic zone
M	bending moment
N	axial force
Ni	notch i
n_i	ratio between the modulus of elasticity of the member i and the reference modulus of elasticity of the composite member
q	uniformly distributed vertical load
s	distance between two timber-concrete connections in longitudinal direction
T	horizontal shear force introduced in a timber-concrete connection
T_{Ni}	horizontal shear force introduced in connection i
$T_{y,Ni}$	yielding shear force of connection i
t_{Ni}	depth of notch i
u	ultimate limit state
u	horizontal relative displacement at the interface between the components of a composite member
u_i	horizontal relative displacement between timber and concrete close to notch i
$W_{1,b,I}$	section modulus corresponding to the bottom edge of the concrete layer during state I
$W_{2,II}$	section modulus corresponding to centroid of the LVL cross section during state II
w	deflection
x	neutral axis depth
x	coordinate of the cross section (in longitudinal direction)
y	yielding
y	coordinate of the cross section (in direction of the cross section width)
z	coordinate of the cross section (in direction of the cross section height)
γ_i	γ-factor of member i
ε	axial strain
ε_{cu}	maximum compressive strain of concrete
θ	rotation angle of a hinge
σ	axial stress
$\sigma_{2,y}$	axial stress which occurs in the centroid of the LVL member starting from notch yielding
$\sum T_{y,Ni}$	sum of the forces which cause compressive failure of LVL within the notches between the support and the position of the maximal bending moment
τ	shear stress
χ	cross section curvature.

different load cases are described by many writers [19]. For more general boundary conditions or different slip stiffness along the beam numerical solutions need to be obtained because the differential equation has no general analytical solution for such cases [20,21]. For design purposes, EN 1995-1-1 [22] provides a simplified calculation method for mechanically jointed beams with a flexible elastic connection based on the differential equation for partial composite action [23]. This approach, known as the γ-method, introduces an effective bending stiffness in order to account for the flexibility of the timber-concrete shear connection and it is widely used for the design of timber-concrete composite structures.

This paper focus on the structural behaviour of timber-concrete composite slabs made of LVL beach plates and a notch connection. Beech LVL is an efficient structural material because it is able to combine the high strength and stiffness of beech wood with the consistency of mechanical properties of LVL [24]. Moreover, in Europe, beech wood is available in large quantities, but typically used for non-structural applications (e.g. furniture) [25,26]. Different details for timber-concrete composite slabs with a notch connection have been developed and studied in Europe (e.g. [5,27–29]), in the US (e.g. [7]) and New Zealand [30,31]. The results of the research projects show that the notch length and depth affects the strength and stiffness of the connection and a vertical reinforcement in the notch (e.g. lag screws) improves ductility. Generally, it was found that a notch connection exhibits high stiffness and high load carrying capacity and can fail in a ductile way if a compressive failure of timber is the governing failure mode. Frangi and Fontana [32] developed an elasto-plastic model for timber-concrete composite members with ductile connection, based on equilibrium of the timber part and on the assumption of a rigid perfectly plastic connection behavior. The results of a series of bending tests on timber-concrete composite members made of glued laminated timber beams with notches and glued steel dowels showed that, after plasticity has occurred, this model gives a better prediction of the failure loads than the γ-method [32]. However, the model is not able to predict the ultimate deformation capacity of the composite system. Ceccotti [33] put emphasis to the fact that a ductile connection should not be over-designed. Otherwise, linear elastic behavior of the composite member with brittle failure may occur.

This paper presents an analytical model for the calculation and design of timber-concrete composite slabs made of LVL beach plates and a notch connection. The focus is on the description of the structural behavior of the composite system with different stages from linear-elastic to plastic behavior at ultimate limit state. One main objective of the development of the analytical model aims at ensuring that yielding of the notches governs the global structural behavior of the composite system leading to a non-linear ductile behavior with large deformations before failure occurs. Furthermore, the model allows a better understanding of several structural aspects of notched connections, such as shear behavior in concrete and the benefit of notch yielding on global slab ductility. Finally, this paper presents a comparison between the test results and the model calculation and discusses strategies for a ductile design of timber-concrete composite slabs made of LVL beach plates and a notch connection.

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