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Simplified nonlinear model for timber-concrete composite beams

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ABSTRACT

Timber-concrete composite (TCC) structures have been emerging in several industrial applications due to potential to simultaneously optimize their structural stiffness, dynamic vibration and ecological imprint. However, when one considers nonlinear behaviour of timber-to-concrete connections and the cracking of the concrete slab, the structural analysis of the composite system becomes quite complex. The scope of this article is to provide a powerful one-dimensional model accounting for the nonlinear behaviour of steel dowel connections and cracking of the concrete slab for better understanding the structural behaviour of TCC structures. First, we extended the existing Winkler model of a beam on an elastic foundation for calculating the load-slip deformation of a steel dowel connecting concrete to timber. Then, we extended the composite beam theory with the secant stiffness approach to account for the nonlinear behaviour of the connection and the cracking of concrete in a TCC beam. An original 4-level model for predicting the structural behaviour of a TCC beam starting from the behaviour of the steel dowel connection is developed by combining three upscaling models. The model has been implemented in a Finite Element Method and has been validated with experimental tests available in literature. An in-depth discussion of the results shows the usefulness of such simplified engineering model to better understand the structural behaviour of TCC beams in terms of the composite action, cracking distribution and structural ductility.

1. Introduction

In the last decades timber-concrete composite (TCC) structures have been emerging for retrofit and strengthening of existing timber floors as well as for new residential and public building floors, bridges and prefabricated floors and walls [1–5]. For instance, in TCC floors, the composite action of the concrete slab on timber beams allows significantly increasing the stiffness and reducing the natural frequency while keeping the lightness and the ecological imprint of the construction. Furthermore, composite systems have been recently applied in tall timber buildings as an economically efficient solution for optimizing the floor performance, horizontal diaphragms and the vertical bracing system [6].

The behaviour of TCC structures under bending is fairly complex as it depends on the composite action (i.e., the self-equilibrated normal action in each connected member), which, in turn, depends on connection behaviour and the slip distribution along the timber-concrete interface. Indeed, the shear force transferred by the connection develops axial forces in the connected members, which contribute to their resistant moments. The analysis of TCC structures is complicated by phenomena such as nonlinear behaviour of the materials and connections under short- and long-term loads. Most of the models developed for composite structures with partial composite action are applicable to TCC systems [7–10]. In general, the composite beam theory describes the behaviour of a composite beam made of two Euler-Bernoulli beams connected by means of a linearly behaving connection. For instance, Annex B of Eurocode 5 [11] proposes a linear version of the composite beam theory in the γ-method for analysing the initial linear behaviour of a composite beam. However, this approach is limited by the following assumptions: the members have constant sections, the applied load has a sinusoidal distribution in order to have exact solutions, and the materials and joints are linear elastic. Other models have been developed to overcome these limitations. For instance, Natterer and Hoeft [12] presented a model derived from the general differential equation to consider different loading conditions.

The behaviour of the timber-concrete connection is often assumed to be nonlinear, especially in the case of steel dowels [13].

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Furthermore, in order to reduce the overall cost in residential applications, it is sometimes convenient to reduce the number of connections, which may result in greater slip and decrease of composite action. The nonlinear behaviour of the connection can be accounted for by an analytical method based on compliance matrix in the case of linear-perfectly plastic connectors [14]. However, without considering the concrete cracking the result can be non-conservative, as it will be demonstrated in detail below. Salari et al. [15] included a comprehensive formulation of the nonlinear slip behaviour of deformable shear connectors using the Finite Element Method (FEM). However, regular concrete has a very low tensile strength and it is likely to be damaged with several cracks under flexural loading [16]. One solution to account for the concrete cracking is the use of three-dimensional FEM, as tried by different authors [17–19]. The results of three-dimensional FEM analyses capture the local behaviour of the connections in terms of the stress and strain quite accurately; however, interpretation of the results in terms of internal forces and moments in the concrete and timber members is not straightforward.

Simplified linear-elastic models for TCC structures, such as the γ-method [20], do not provide good predictions of the failure loads in the case of plasticity of the connections or significant cracking of the concrete slab [21,22,14]. Furthermore, there may be special cases for which the knowledge of the full non-linear response and ductility may be relevant; e.g., the use of small screws or nails, the use of special classes of concrete with high tensile post-cracking resistance, such as ultra-high performance reinforced concrete [23]), the use of statically determined structures, or the use of TCC in high-rise building for better dissipating seismic energy [24,25].

The scope of this article is to develop a simplified one-dimensional model, which accounts for the nonlinearity of the connections and the concrete cracking of TCC beams. The article is structured as follows: Section 2 presents details of the proposed model; Sections 2.1 and 2.2 extend the existing Winkler model of a beam on an elastic foundation [26,21] to calculate the entire shear force vs. slip curve, which describes the behaviour of a steel dowel connection; Section 2.3 develops and implements the composite beam theory in the FEM; Section 3 validates the model with experimental results available in literature; Section 4 presents an in-depth analysis of the structural behaviour of a TCC beam with the emphasis on the composite action, cracking distribution and structural ductility; Section 5 presents an application of the model to predict the effect of the dowel diameter and spacing on the structural response. Annexes A and B present details of the FEM formulation for a TCC beam.

The original contribution of this work is threefold: (i) extend the Winkler model of a beam on elastic foundation to describe nonlinear behaviour of a discrete connector working essentially in bending, such as dowel-type connection; (ii) extend the composite beam theory with a secant stiffness approach to account for the nonlinearity of the concrete cracking and of any connection (discrete or continuous) with known behaviour; and (iii) combine the developed models in a FEM to provide a powerful tool for practicing engineers to predict the nonlinear behaviour of TCC structures.

2. A new 4-level model for TCC structures

The 4-level model scales the behaviour of a dowel-type connection up to the flexural behaviour of the TCC structure through the shear behaviour of the connection as illustrated in Fig. 1. The upscaling models and the numerical algorithms are explained in detail in the following sections.

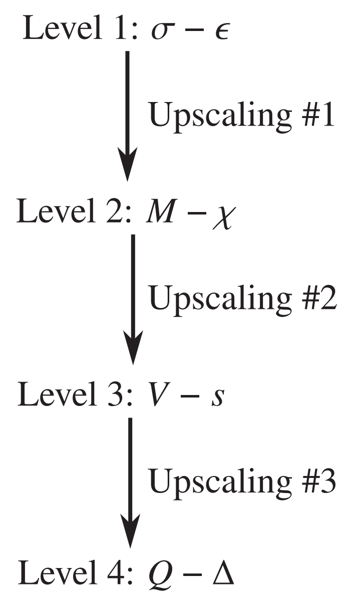

Fig. 1. General algorithm of the proposed 4-level model.

2.1. Upscaling model #1: from the steel material law (level 1) to the moment-curvature relationship of a steel dowel (level 2)

This step aims at calculating the moment-curvature relationship ($M-\chi$) (Fig. 2(b)) of a steel dowel directly from the uniaxial stress-strain relationship ($\sigma-\epsilon$) law of steel by means of a classical sectional analysis within the framework of Euler-Bernoulli beam theory as schematically shown in Fig. 2(a). It is assumed that the strain distribution is linear and the sections remain plain. First, the section of the dowel is subdivided in several layers as shown in Fig. 2(d). The sectional analysis algorithm is the same as presented in the works of Paultre [27] and Kwak and Kim [28] and consists of the following steps:

1. Assume the initial curvature $\chi^{(1)} = 0$ and the position of the neutral axis $c^{(1)} = d_F/2$;
2. Increase the curvature by an increment ($\chi^{(n)} = \chi^{(n-1)} + \Delta\chi$);
3. Calculate the linear strain distribution over the section layers (Fig. 2(e));
4. From the stress-strain law ($\sigma - \epsilon$), calculate the stress in each section layer (Fig. 2(f));
5. Calculate the resultant moment (M) and force (N) (Fig. 2(g));
6. Iterate on the value of $c^{(n,j)}$ to satisfy the equilibrium of force ($N=0$) within an acceptable tolerance $\left(\left| \frac{c^{(n,j)} - c^{(n,j-1)}}{c^{(n,j)}} \right| < \epsilon \right)$ by repeating the steps 3 and 4;
7. Save the moment-curvature ($M-\chi$) point at the n^{th} step;
8. Repeat steps from 2 to 7 until the maximum value χ_{max} of the curvature is reached.

2.2. Upscaling model #2: from the moment-curvature relationship of the dowel (level 2) to the shear force-slip law of the connection (level 3)

This step aims at calculating the connection law in terms of shear force vs. slip ($V - s$) from the moment-curvature relationship ($M - \chi$) of the dowel and the properties of concrete and timber. For this purpose, the dowel is modelled as a beam on an elastic foundation as schematically presented in Fig. 3. Kuenzi [26] were the first to apply this method to timber connections with dowel-type fasteners assuming a linear elastic bearing behaviour of the timber, i.e., an elastic foundation. Gelfi et al. [21] derived an extension of the model for a beam on elastic foundation to