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Engineering modeling of semi-rigid joints with dowel-type fasteners for nonlinear analysis of timber structures

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ABSTRACT

Plastic analysis in engineered structures requires ductility of structural components, which in timber structures is primarily provided by joints made of dowel-type fasteners. A prerequisite for nonlinear analysis is realistic modeling of joint stiffness and load distribution in dowel-type joints. A joint model suitable for structural analysis is presented and validated in this contribution. The semi-analytical joint model is based on kinematic compatibility and equilibrium considerations. It accounts for local fastener slip by means of nonlinear elastic springs. Influences of nonlinearity and orientation dependence of fastener slip are assessed. Elastic deformations of the timber in between dowels are however neglected. The model allows for predicting global joint stiffness, as well as load distribution within the joint, taking explicitly the effect of simultaneously acting internal forces into account. Model validation builds upon an experimental database that spans from embedment testing on the material scale up to joint testing on the structural scale. Application examples demonstrate the broad applicability of the model for structural analysis. Moreover, they illustrate effects of assumptions of fastener slip on the joint and structural behavior. Limitations, as well as pros and cons of these assumptions are discussed. Special attention is drawn to load distribution within the joint, since it is important for fastener-based design, currently prescribed by the European design standard. Load distribution in joints is also important for verification against brittle failure modes. As an alternative to fastener-based design, joint-based design, by means of a framework for applying the presented model to plastic design of timber structures with ductile joints, is proposed.

1. Introduction

Plastic analysis is a well established method for the engineering design of a large number of construction materials and connections, that allow for a ductile behavior of structures. Especially for steel and also for reinforced concrete, plastic design can be applied, e.g., based on the European design standards EN 1993-1-1 [1] and EN 1992-1-1 [2], respectively.

General notes on ductility in timber structures, and benefits of a plastic design were given by Jorissen and Fragiacomo [3]. They emphasized that ductility in timber structures is preferably found in joints and formulated four benefits of ductile structures: (i) structural failure is announced by large deformations; (ii) stresses and forces can be redistributed within a cross-section and structure; (iii) ductile joints allow for energy dissipation under seismic loading; and (iv) that structural robustness is increased. Brühl et al. [4] gave general requirements for ductile connections and a plastic design of joints. A capacity design method was presented, following the idea of determining an overstrength factor to avoid brittle failure of elements before plasticity is achieved. Since timber members usually fail in a brittle manner when loaded in bending or tension, ductility in timber structures is almost exclusively related to ductility in timber joints. Brittle failure in joints can be avoided by an appropriate design including reinforcement techniques [5]. Design rules and design methods for a kinematically compatible nonlinear plastic design of joints in timber structures are however missing in design standards. Models for the design of dowel joints will be discussed in this contribution, nevertheless the framework of the study and proposed design rules will also be valid for other types of dowel-type joints.

Plasticity is partly implicitly taken into account in the European design standard for timber structures EN 1995-1-1 [6] (EC5). Design equations for single-fastener connections are based on a limit state approach [7], making use of a plastic embedment strength and a plastic yield moment of steel fasteners. However, only elastic stiffness of single-fastener connections is provided by means of an empirical equation, which in addition is independent of the load orientation even for large diameter dowels. Design equations for multiple-fastener joints are missing and only general design rules are given. Thus, EC5 is

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primarily directed towards the behavior of single-dowels, or more generally, single-fasteners. Previous studies showed that using EC5 equations, might lead to a strongly simplified linear elastic–ideal plastic slip curve of joints and to an underestimation of displacements at the ultimate limit state [8,9].

Not only the global joint slip, but also load distribution among dowels in joints is essential for verification against brittle failure modes and design of reinforcement measurements, respectively. Previous studies highlighted loading direction dependence in dowel connections and elastic deformations of the timber matrix in dowel groups as main effects on load distribution, and thus, also on global joint slip [10,11]. Moreover, deviation between displacement and force orientation, as a peculiarity of anisotropic materials such as timber [8,12], might effect load distribution.

In order to be able to incorporate ductile joint behavior in structural analysis and engineering design, a trade-off between accuracy and calculation effort of a joint model has to be found. Previously proposed calculation models for joints have been reviewed and compared in Bader et al. [10]. The interaction of internal forces, namely axial force, transverse force and bending moment, under two-dimensional loading situations, has been emphasized. The terms *axial force* and *transverse force*, are equal to the commonly used expressions *normal force* and *shear force* in beam theory, respectively. As regards practical design, two-dimensional FEM models [10] of joints, or even a combination of beam-on-foundation model for single-dowel connections [8,13,14] and a three-dimensional discretization of the timber, might be desired since these models allow to consider effects of the deformable timber between fasteners and non-uniform stresses over the timber thickness [11,15]. However, computational efforts are too high for integration in structural analysis for engineering design. Strongly simplified linear and analytical models [16] on the contrary, fail in a realistic description of load distribution, especially when considering interaction of internal forces. This might lead to underestimation of dowel loads.

An attractive alternative related to the accuracy-calculation time trade-off, are semi-analytical joint models based on kinematic and equilibrium considerations with the assumption of rigid members and nonlinear springs for dowel slip. The only drawback of these assumptions is that non-uniform stresses over the timber thickness and elastic deformations of the timber matrix are neglected. The latter is most pronounced in the quasi-elastic loading path and for loading perpendicular to the grain [10]. Corresponding models with rigid members and springs have been presented by Descamps et al. [17] and by Jensen [18]. Jensen focused on nailed-connections and provided models for both, uncoupled and coupled description of the joint behavior, i.e., taking into account interaction of internal forces. Coupling in connection models was investigated by Vessby et al. [19] as well. Model derivation in Jensen [18] was either based on the joint or fastener slip, and even included elements for end-grain contact situations. In addition, concepts for implementation in structural analysis using the finite element method (FEM) were proposed and applied to calculation examples. This modeling strategy will be taken up herein, with the aim of validation and application to engineering design situations. It is expected to highlight possibilities for enhanced insight into load distribution and joint slip, including coupling of internal forces and inhomogeneous joints. Emphasis will be placed on the study of linear and nonlinear single-dowel slip models and their effect on the global joint and structural behavior. This will form the basis for joint-based nonlinear analysis of timber structures with ductile joints. To demonstrate model capabilities when integrated in structural analysis and to propose a framework for design rules are further objectives of this contribution. Herein, modeling is limited to monotonic behavior of joints subjected to in-plane loading, namely axial force, transverse force and in-plane bending moment.

The paper is organized as follows: Calculation steps of the joint model and its specialization for different dowel slip models are described in Section 2. In Section 3, the model is validated by means of comparing simulated an experimentally determined joint slip curves. Application of the model to joint design examples is investigated in Section 4, before strategies for model implementation in the structural analysis and example calculations are reported in Section 5. Finally, in Section 6, proposals for a joint-based design with nonlinear analysis of timber structures are presented and the paper is concluded in Section 7.

2. Joint modeling approach

2.1. Modeling strategy and assumptions

Starting with joint modeling from a structural engineering point of view, the relationship between relative deformations, $\mathbf{\Delta u}$, and internal forces, $\mathbf{R}$, can be expressed as

$$\mathbf{R} = \mathbf{K}\cdot\mathbf{\Delta u}, \tag{1}$$

by defining the stiffness matrix $\mathbf{K}$. In general, relative deformations encompass six degrees of freedom, with three relative translations and three relative rotations. The following derivation is limited to in-plane loading situations. Thus, the constitutive equation includes three relative deformations (relative axial displacement, Δu_x, relative transverse displacement, Δw_z, and relative rotation around y-axis, $\Delta\varphi_y$) and three associated internal forces (axial force, N_x, transverse force, V_z, and in-plane bending moment, M_y), and reads (see Fig. 1)

$$\begin{bmatrix} N_x \\ V_z \\ M_y \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xz} & K_{xy} \\ K_{zx} & K_{zz} & K_{zy} \\ K_{yx} & K_{yz} & K_{yy} \end{bmatrix} \cdot \begin{bmatrix} \Delta u_x \\ \Delta w_z \\ \Delta\varphi_y \end{bmatrix}, \tag{2}$$

with coefficients K_{ij} ($i,j = x,z,y$) of the stiffness matrix. In the following, components of the joint stiffness matrix will be determined based on number of dowels in a joint and their spatial distribution, taking into account their load–slip behavior.

Diagonal coefficients of the stiffness matrix $\mathbf{K}$, namely K_{ii} ($i = x,z,y$), describe the relationship between a relative deformation and the associated internal force component at the joint level. Loading at the *center of joint stiffness* is a necessary but not sufficient prerequisite for an uncoupled joint behavior, which is characterized by diagonal elements of $\mathbf{K}$ being the only non-zero elements. Non-diagonal components of the stiffness matrix in Eq. (2), describe coupled behavior of the joint, i.e., coupling of relative displacements with the bending moment or relative rotation with axial or transverse force.

In the general case of an arbitrary joint layout with orientation dependent and nonlinear dowel slip, it is difficult to choose the reference point for loading being equal to the *center of joint stiffness*, since the center of joint stiffness is a function of the single-dowel connection stiffness, and might change during loading. Thus, internal forces become a function of all relative deformations at the joint, i.e., Δu_x,Δw_z and $\Delta\varphi_y$. Coupling of internal forces and relative deformations is also a consequence of interaction of internal forces and their effect on load distribution within the joint. Thus, coupling of internal forces affects diagonal and non-diagonal components of the stiffness matrix, $\mathbf{K}$. In addition, non-diagonal components might be *unsymmetric* with respect to the diagonal of $\mathbf{K}$, as a reason of (i) interaction between internal forces; (ii) anisotropic nonlinear dowel slip; as well as of (iii) loading at a reference point different from the *center of joint stiffness*.

The joint model, presented herein, rests on kinematic compatibility and equilibrium of forces, and is based on the following *assumptions*:

- Timber is assumed to be rigid, which means that elastic deformations of wood between single dowels are neglected.
- Steel plates are assumed to be rigid, which implies that the position of the single dowels does not change during loading. Thus, dowel displacements can be directly related to relative joint deformations. The same can be assumed for timber-to-timber joints, which is a stronger simplification, since timber exhibits a comparable soft and