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Parameterization equations for the nonlinear connection slip applied to the anisotropic embedment behavior of wood

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ABSTRACT

Nonlinear numerical models for the engineering design of mechanical connections in anisotropic materials require nonlinear material behavior of their components, which are essentially determined by material or structural testing. Herein, a multi-step approach for the parameterization of the nonlinear and anisotropic connection slip behavior is presented and applied to the ductile embedment behavior of steel dowels in wood. For this purpose, previously proposed regression functions for the slip behavior are reviewed, and further possible equations are discussed. Their suitability in the description of typical shapes of slip curves observed in connection testing is assessed before certain combinations are applied to an experimental dataset of embedment tests of steel dowels embedded in Laminated Veneer Lumber. The dependence of the regression parameters on the displacement range in the experimental dataset and the benefit of using parameters with a physical interpretation, for being able to exploit connection test data reported in literature, is highlighted.

1. Introduction

Increased awareness for sustainable building materials in combination with improvements and new developments in wood products and connection techniques led to a renaissance of building with timber in recent years. Breaking new ground by building complex, statically indetermined, wide-spanning and high-rising timber structures, the deformation behavior of joints with mechanical fasteners, linking single timber elements, gets more and more important. This is particularly the case for joints made of dowel-type connections, due to their pronounced nonlinear load-deformation behavior [1,2], which is a consequence of the anisotropic, nonlinear single fastener slip behavior [3,4]. The latter is currently strongly simplified by means of an elastic slip modulus for dowel-type connections in the European timber engineering design standard EN 1995-1-1 (Eurocode 5) [5].

Engineering modeling of dowel-type connections (see e.g. Hochreiner et al. [6], Bader et al. [3]) has been shown to efficiently and realistically depict the nonlinear connection slip based on a kinematically compatible description of the embedment behavior of wood or wood-based products and steel dowel properties. In other words, numerical modeling can effectively predict causal relationships between the deformation behavior of connections and the deformation behavior of their components, avoiding the need for an experimental database on the connection level for the assignment of connection stiffness.

However, what hampers a broad application of this numerical method in engineering design is an appropriate database for material properties, reflecting not only strength but also deformation characteristics of wood and wood-based products. The complex stress state in anisotropic materials, like orthotropic composites such as wood, under embedment loading [7] makes experimental investigations of dowel-type fasteners embedded in timber indispensable. Testing standards for the embedment behavior of wood (e.g. EN 383 [8], ASTM D5764 [9] or ISO/DIS 10984-2 [10]) encompass rules for deformation measurements. However, these deformation data are rarely thoroughly reported and thus, cannot be exploited in engineering design equations. Current deformation properties according to testing standards assume linear quasi-elastic loading, unloading and reloading paths, which do not allow for a realistic nonlinear slip definition. Moreover, the embedment strength is currently defined as an ideally plastic material property, neglecting pronounced displacement hardening for loading close to perpendicular to the grain in the case of reinforced ductile connections [11,12]. Orientation dependence of connection properties is typical for composite materials in general. Anisotropic slip behavior has been reported in experiments on bolted connections in 3D woven composites in Mounien et al. [13], as well as in glass fiber reinforced polymers in Ascione et al. [14] and corresponding nonlinear finite-

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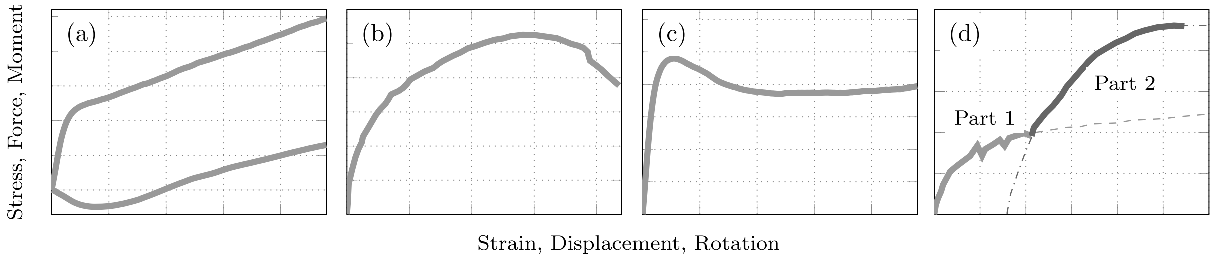

Fig. 1. Typical slip curves from connection tests in timber structures.

element simulation in Nerilli and Vairo [15].

For the design of joints in timber structures, the same simplifications as for embedment testing are assumed on the connection level, where a rigid-ideally plastic limit design approach is used for the calculation of connection strength together with loading orientation independent linear elastic connection stiffness [5]. This calls for a new paradigm for definition of material characteristics from testing, which allow for a nonlinear slip definition by means of parametric equations, suitable for numerical modeling of connections and structures.

Diversified shapes of slip curves from experimental investigations on connections in timber structures are illustrated in Fig. 1. A typical example of a continuously increasing embedment stress-displacement curve measured in embedment test of steel dowels embedded in reinforced wood specimens [12] is shown in Fig. 1a. The second type, illustrated in Fig. 1b, is more common for connection tests in ductile single dowel joints [16] or nailed joints [17] and additionally encompassess softening behavior. Slip curves with a local maximum followed by a quasi yield plateau, as shown in Fig. 1c, can for example be found for traditional carpentry joints [18], or for modern approaches of glued-in dowels with a soft interlayer [19], but might also be observed in single fastener connection tests parallel to the grain. A similar slip behavior was found for 3D woven composites as well [13]. Slip curves with two or more distinct parts, as illustrated in Fig. 1d, have been measured in connection tests with a change in the load-bearing mechanism during testing [20–22]. As prime example, a multi-dowel connection loaded by a pure bending moment, which gets in contact with a stiff element after a certain rotation, could be mentioned [1]. Another example might be slip-critical connections in steel structures, or structures made of pultruded fiber reinforced polymers (PFRP). In the latter case, the first part of the joint slip is driven by friction between PFRP and steel plates, before in the second part additional bolt-bearing resistance is activated [23]. For the first slip curve type (Fig. 1a) parametric equations able to describe curves with a linear part at the beginning and end of the curve, connected by a curved transition zone, are required. The same equations might be used for the second type (Fig. 1b) with the additional requirements of being able to handle a large transition zone and a negative inclination at the end of the slip curve. The third type (Fig. 1c) might call for different parametric equations compared to the first two types, in order to sufficiently describe the local maximum. For the last type in Fig. 1d, it might be suitable to analyze distinct parts of different load-bearing mechanisms separately, and subsequently combine these parts. This would allow to use the same basic parametric equations as applied for the first slip curve types in Fig. 1a and b.

Parametric equations for the slip behavior of connections, in order to tackle the aforementioned requirements from experimental studies, have been proposed previously. For timber joints, this goes back to the work on nailed connections of Jansson [24] and Norén [25]. Similar definitions for connections in general, not limited to timber, have been used by Foschi [26], Yee and Melchers [27], as well as by Richard and Abbott [28]. These methods are based on exponential or power functions, while Biscaia et al. [29,30] used a combination of a power and exponential function to describe the bond-slip of fiber reinforced polymer (FRP) laminates with concrete [29] and with old timber [30], respectively. Others like Jensen [31] or Glos [32] used polynomial definitions for applications in timber engineering. In addition Jensen [31] presented an approach, which used both, exponential and polynomial functions. Sauvat [33] presented a function to describe the foundation modulus of dowel joints in timber structures subjected to complex cyclic loadings, and Mohamadi-Shoore [34] proposed and reviewed parametric equations for the moment-rotation behavior of bolted steel endplate connections. Another type of equations used in timber engineering are trigonometric functions or combinations of trigonometric functions, such as the well-known interaction criterion for compression strength at an angle to the grain proposed by Hankinson [35], which is currently used to calculate embedment strength of wood at an angle to the grain. A similar approach, called root-mean-square (RMS), was used by Gupta and Sinha [36] for the shear strength of Douglas-fir at an angle to the grain.

From a holistic point of view, the analytical description of the empirically determined slip behavior is a multi-dimensional problem since embedment stress or connection load depend not only on the dowel displacement but also on parameters such as load-to-grain angle, dowel diameter, wood species, density and moisture content of the wood. In this contribution, the authors aim on the description of the nonlinear slip behavior as function of the anisotropy. As a novel contribution, parametric equations for nonlinear connection slip are extended to the anisotropic behavior of wood, or anisotropic composites in general, yielding a closed mathematical expression. Parameterization of anisotropic slip substantially facilitates simplified FEM-models that use spring elements for modeling embedment behavior or connection slip. The aim of this contribution is to close the gap between experimentally determined material or connection properties, and phenomenological but nonlinear and anisotropic connection and joint models.

For describing the nonlinear slip as function of the anisotropy, the multi-dimensional problem decreases to a three-dimensional problem, which is tackled by a three-step approach. Firstly, regression analysis of the slip behavior in various directions to the grain is performed, before, in a second step, a parametric equation for the regression parameters over the load-to-grain angle is derived. These two regression steps are combined in a third step. As a future effort, further steps could be added to include additional influence parameters in the slip equations.

The analysis work is based on a comprehensive experimental database established for reinforced, and thus ductile Laminated Veneer Lumber dowel connections, which includes embedment tests at constrained dowel displacement boundary conditions [12]. Since testing was performed at various angles to the grain, the anisotropic connection behavior has been captured. Moreover, biaxial testing gave even access to lateral reaction forces, which are evoked for loading at an angle between the principal material orientations. Thus, the dataset includes typical slip curves for ductile dowel-type connections and their dependence on the anisotropy, which will form the starting point for the analysis.

The paper is organized as follows: The general parameterization strategy is outlined in Section 2, before previously suggested or possible regression equations are reviewed in Section 3. The suitability of these