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Integrative experimental characterization and engineering modeling of single-dowel connections in LVL

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HIGHLIGHTS

- Tests of single-dowel connections as well as of steel dowels and LVL.
- Tests under different load-to-grain angles up to large dowel displacements.
- Quantification of the effects of anisotropy of wood on connection properties.
- Validation of engineering model for the design of single-dowel connections.
- Comparison of test data with Eurocode 5 design equations.

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ABSTRACT

In order to be able to realistically and consistently elucidate and subsequently simulate the load–displacement behavior of single-dowel connections, the material behavior of the individual components, namely steel dowels and wood, needs to be investigated. The behavior of slotted-in, single-dowel steel-to-laminated veneer lumber (LVL) connections with dowel diameters of 12 and 20 mm is thoroughly discussed here in relation to steel dowel and LVL properties. In addition to connection tests at different load-to-grain directions of 0°, 45° and 90°, the corresponding embedment behavior of LVL was tested up to dowel displacements of three times the dowel diameter. The material behavior of steel dowels was studied by means of tensile and 3-point bending tests and accompanying finite element simulations. A pronounced nonlinear behavior of the single-dowel connections was observed for all load-to-grain directions. In case of loading perpendicular to the grain, a significant hardening behavior was obvious. Due to the anisotropic material properties of wood, enforcing a loading direction of 45° to the grain resulted in an additional force perpendicular to the load direction which was quantified in a novel biaxial test setup. Thus, a comprehensive and consistent database over different scales of observations of dowel connections could be established, which subsequently was exploited by means of engineering modeling. The comparison of experimental and numerical data illustrates the potential of the engineering modeling approach to overcome drawbacks of current design regulations, which are unable to appropriately predict stiffness properties of dowel connections. Moreover, the quasi-elastic limit of dowel connections was calculated and discussed by means of the model.

1. Introduction

Dowel connections in timber structures are composed of steel dowels that are embedded into timber elements, mostly in combination with steel plates. Their mechanical behavior consequently depends on properties of the two components. The objective of this study is the consistent experimental assessment and quantification of single-dowel connections from the local material behavior of laminated veneer lumber (LVL) manufactured of spruce wood with parallel oriented veneers and steel dowels up to the global behavior of single-dowel connections. Moreover, this data will subsequently be exploited by an engineering model for

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single-dowel connections in order to validate and to illustrate the perspectives of this design approach.

Herein, a double-shear steel-to-LVL connection was investigated. Since the inherent mechanical behavior of wood is anisotropic with respect to the grain orientation, the behavior of this connection was studied under different load-to-grain orientations, namely parallel (0°), inclined (45°) and perpendicular (90°) to the grain. Such loading conditions for single dowels are typically observed in dowel groups loaded by bending moments [2,3]. However, single-dowel connection tests, as well as embedment tests of wood and wood products were so far mainly limited to loading parallel and perpendicular to the grain (see, e.g., [9] and references therein). Only limited data is available for other load-to-grain orientations (see, e.g., [25]).

Also, tests were usually limited to small displacements due to brittle failure of connections. However, recent developments in timber engineering allow for the design of highly ductile connections [4,5,7]. Different reinforcement techniques are available [30], whereby self-tapping screws are very efficient and economical, and consequently often used in practical applications [20]. In ductile dowel connections, large dowel deformations are encountered. Hence, the embedment behavior of LVL as well as the behavior of single-dowel connections should be investigated for such large deformations, these being beyond test limits typically in use today.

In this study, the behavior of connections with dowel displacements of up to twice the dowel diameter was studied. Extensive splitting of the timber was avoided by using self-tapping screws as reinforcement. The embedment behavior of steel dowels in LVL was tested by means of embedment tests on full-hole specimens. The material behavior of steel dowels was studied by means of tensile tests as well as by means of 3-point bending tests. In order to get insight into the uniformity of material properties over the cross section of dowels and the development of plastic deformations, three-dimensional finite element simulations of the bending tests were performed. The influence of the dowel diameter was assessed by using dowels with a diameter of 12 and 20 mm.

A deviation between the load and the deformation directions of the steel dowel will be observed in case of a deviation of the load direction from the principal material directions of wood (parallel and perpendicular to the grain). This effect is a consequence of the anisotropic mechanical behavior of wood. On the contrary, considering a restrained loading direction of the dowel connection, as tested herein, a lateral reaction force and consequently a lateral dowel force will be encountered. As a novel issue, the corresponding forces were quantified in biaxial tests on single-dowel connections, which allowed quantifying the deviation between load and deformation directions.

The dataset established in this experimental campaign was utilized by means of numerical simulations. Several researchers studied dowel connections by using three-dimensional finite element method (FEM) simulations of connections with elasto-plastic and brittle material models for wood [8,14,26,28]. Also, embedment characteristics (e.g., [29]) and the influence of reinforcements on dowel connections [6] have been studied with FEM simulations. These simulations allow gaining insight into the development of plastic deformations in steel dowels and the distribution of stresses in the timber members [15]. However, in most cases, they were based on small strain theory, which limits the maximum strains in the timber and, consequently, maximum dowel deformations in case of plastic hinges in steel dowels. Furthermore, 3D FEM simulations are uneconomic for the daily use by engineers. Alternatively, for a long time, beam-on-foundation models have been developed for the prediction of load–slip curves of dowel connections (see, e.g., [16]). Corresponding modeling approaches are reviewed, e.g., in [24]. This approach also served as a basis for the development of analytical solutions for load–displacement properties of dowel connections [17]. However, their potential for engineering application is not fully exploited yet. Thus, in this study, we applied an engineering design model for dowel connections, based on beam on nonlinear elastic foundation principles as described in Hochreiner et al. [18]. The suitability of this modeling approach was assessed.

Finally, test results and model predictions were compared to calculations based on the current European design standard for timber structures (Eurocode 5, EC5, [13]). The current design approach goes back to the work of Johansen [19], Möller [22], and Meyer [21] and is based on a limit state approach, assuming ideal plastic material properties of steel dowels in bending and of wood under embedment stresses (European yield model, EYM). Consequently, only limit loads but no deformations are obtained. Nevertheless, consistent slip curves for semi rigid connectors are needed as input in structural engineering software for the consistent assessment of building structures at serviceability and ultimate load states. Thus, an engineering model to overcome this drawback of the EYM is expected to have high relevance for the design of engineered timber structures.

2. Materials and methods

2.1. Mechanical characterization of steel dowels

Tension tests were performed with dowels cut from circular steel rods of 12 and 20 mm diameter made from a candidate material, SIS-2142 according to the Swedish standard. This grade fulfills requirements for grade S355J2 according to EN 10025-2 [10]. Initially, it was planned to characterize the material used for the steel dowels by simple uniaxial tensile tests and 3-point bending tests to measure the yield strength and the material's deformation capacity at large strains in bending. However, it turned out that there was a considerable difference in the behavior of the rods of different diameters. Details about the tests and results are given in Appendix A. The conclusions drawn from these pre-tests were:

- There seemed to be an influence of the diameter of the base material from which the dowels were manufactured.
- Differences between the test specimens indicated the presence of a thin zone, with higher strength, close to the rod's surface.
- The material did not have a pronounced yield limit as would have been preferred and was not as ductile as expected (considerable necking at <10% nominal strain).

Finding an explanation for the dependence on the diameter is beyond the scope of this paper, but probable reasons are related to the manufacturing process (e.g., the smaller diameter bar could possibly have been cold drawn). As a consequence of the above conclusions it was decided to select a milder steel grade and also to have the material undergo a heat treatment before testing, so as to counteract any effects of possible cold drawing and to relax any possible eigenstresses.

Rods with circular cross section and diameters of 12 and 20 mm made from steel quality S235 [10] were used. This material is normally not delivered as polished rods, but the rods are "compressed", meaning that during manufacturing axial compression is applied. This resulted in a rod with improved properties in terms of strength and, more important, the thin and rough surface layer that results after cooling is peeled off during the compressing process. Not only a smooth surface without the need for polishing, but also a rather well-defined diameter is obtained. The heat treatment included heating to 750 °C in a low oxygen environment in order to avoid oxides on the surface. This temperature was kept for two hours before the oven was switched off. The oven was opened when the temperature had decreased to 700 °C and the material was left in the open oven until the temperature had decreased to 500 °C, which took approximately two hours.

Dog-bone shaped, circular tensile test specimens with a diameter of 10 mm were manufactured from the 12 mm rods, while tensile specimens manufactured from the 20 mm rods had 14 and 16 mm diameters for the untreated and the heat treated steel, respectively. Additionally, three-point bending tests were performed according to the setup shown in Fig. 1. Tests were performed both for material with and without heat treatment on two specimens each. Since no bending test setup according to EN 409 [12] was available, a 3-point bending test was chosen. The load was applied by a stiff steel loading device. The support plates were separated by rollers in order to allow them to slide in relation to each other during the test. The lower support plate was in turn supported by a pinned support, allowing both horizontal and vertical reactions to be transferred to ground, and ensuring a constant span for later evaluation of the bending moment. The tests were performed in a uniaxial servo-hydraulic test frame (MTS 810, MTS Systems Corporation, Eden