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3D finite element analysis and experimental investigations of a new type of timber beam-to-beam connection

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ABSTRACT

A new type of semi-rigid timber beam-to-beam connection and its behavior under bending is presented. This connection consists of four identical steel parts, which are inserted into the timber beams in the tension and compression zone of the connection. These steel parts are easily connected by mounting bolts on the construction site. In order to avoid initial slip, gaps between the timber and the steel parts are filled using two different types of filler materials, namely cement based (CEM) or polyurethane based (PUR) filler. In this study, the connection is modeled by means of the Finite Element (FE) Method and the modeling results are compared to the results of an experimental assessment of the proposed connection under bending. The material model for timber encompasses a Hill criterion in combination with cohesive surface contact in order to depict both, yielding in compression and brittle failure in shear and tension perpendicular to the grain. The experimentally observed decisive failure mode, i.e. shear block failure, could be reproduced by the model. Subsequently, the FE model was used to investigate the effect of using different filler materials, or not considering the filler in the analysis at all. In addition, a particular influence of clamping bolts in the timber on the strength of the connection was revealed. The FE analysis excluding these bolts showed good agreement with the experiments in terms of the strength of the connection, while considering these bolts led to an overestimation of the strength. This is a consequence of the considerable influence of the clamping bolts on stresses perpendicular to the grain in the timber in the block-shear area, and therefore, on shear failure initiation. Using the CEM filler hardly changed the overall behavior of the connection as compared to the analyses without filler material, while the PUR filler leads to a less ductile overall behavior. This is well in line with experimental observations. The application of modeling approaches for timber has proven suitable for the analysis of such a type of timber beam-to-beam connection and, consequently, might be used for further optimization of this connection.

1. Introduction

The most complex and challenging process during the design and analysis of timber structures is the proper design and analysis of timber connections. Particular attention is generally paid to the design of mounting connections for timber elements that exceed the maximum transport or production length. In this case, the connection is often designed to bear bending moments, but should also be easy to mount on site. As regards the mechanical behavior of timber connections, they can be idealized as moment rigid or pinned connections in engineering models. Furthermore, several types of fasteners cause relative deformations of adjacent structural elements during load transfer. Consequently, moment-resisting connections of such type of fasteners have to be treated to act semi-rigid. Their mechanical behavior, e.g. bending stiffness or tensile stiffness, is characterized by moment–rotation angle or force–deflection curves, respectively [1–4]. According to the current European design standard [5], the stiffness of connections must be considered in the structural analysis, since it influences the distribution of internal forces within and the corresponding deformation of a timber structure. The corresponding moment–relative rotation behavior of a new type of timber beam-to-beam connection is investigated in this study.

Herein, numerical investigations of this new type of mounting connection are presented. During the design of the connection, special emphasis was given to an easy production and simple assembly at the construction site, in addition to the aim of designing a moment-stiff connection. For this purpose, a steel-to-timber connection with steel parts embedded into the timber beam was designed, which will be connected by means of mounting bolts on site. The initial contact between the timber beams and the steel

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parts is ensured by filling the gaps between these parts with filler. This avoids initial free movement between steel and timber, and thus, increases the initial stiffness of the connection. In order to obtain the required stiffness and strength of the connection, the dimensions of the steel parts relative to the dimensions of the timber beam can be adjusted. The behavior of the connection will be studied by means of a Finite Element (FE) analysis in addition to experimental investigations.

Several different types of timber connections using different fasteners are available to design mounting connections. A review of previously investigated semi-rigid mounting timber connections was performed by the authors, by consulting the world's patent database espa@cent [6]. There, 81 connections were found, which can be treated as semi-rigid mounting connections and are able to transmit bending moments, axial and shear forces. In total, five different types of load transmitting systems from timber to steel may be distinguished: (1) steel plates and dowels, (2) steel rods glued into the timber, (3) steel gusset plates or wedges, (4) steel plates and large diameter bolts, and (5) full threaded screws under an angle to the grain. Glued-in steel rods are widely used in timber structures, joining timber elements in length [7] or for knee joints [8,9]. Dowel type timber connections have become very common as well, mostly due to their easy production and assembling at the construction site [10]. They are also used both for beam-to-beam connections [11] as well as for knee joints [3]. Timber connections usually show some free initial movement because its separate components (i.e. timber beams, steel parts, bolts, dowels, etc.) are initially not in tight contact. To overcome this initial slip, steel gussets or wedges may be used to enforce initial contact [12] or the free gaps may be closed by applying a cementitious or polymeric filler to the connection after its assembly [13]. Very stiff connections can also be achieved using screws under an angle to the grain [14].

To evaluate the behavior of timber structures until failure, special emphasis must be given to the analysis of timber connections. Due to the often complex geometry of such connections, FE methods are commonly applied. While the material behavior of the steel parts within the connection is isotropic and, thus, straightforward to describe, the physical and mechanical properties of timber are anisotropic. Timber shows different mechanical properties in different material directions. Using a rectangular coordinate system aligned with the grain direction and the orientation of the annual ring structure, it can be described as orthotropic, with the main material directions in longitudinal, radial and tangential (*L*, *R*, and *T*) direction. Various material models for the elastic and plastic behavior have been applied in previous FE analysis of timber structures. The Hill yield criterion, as a classical yield criterion, [15] has been applied to study yielding upon compression along and perpendicular to the grain [16–18]. Failure in dowel type timber connections with embedded steel plates often occurs due to a combination of shear stresses and tensile stresses perpendicular to the grain [19]. Normally, tension perpendicular to the grain is the decisive factor because timber tension strength perpendicular to the grain is 5 times less than shear strength [20–22]. Brittle failure in tension perpendicular to the grain and in shear has also been modeled by the additional use of cohesive elements or surface based cohesive contact next to a C_1-continuous multi-surface plasticity model for the compression regime [23]. In addition to the material behavior, the interaction of the individual components of the timber connection plays a major role during its FE analysis. The normal and tangential behavior within the contact surface has to be defined. This may include the definition of a contact stiffness in normal direction or the definition of friction properties in tangential direction, e.g. using Coloumb methods [16,18] or Augmented Lagrangian methods [24].

In this study, numerical investigations on the bending behavior of a new type of timber mounting connection, i.e. a timber beam-to-beam connection, is presented. After a thorough description of the connection and its envisaged mechanical behavior in Section 2, in Section 3, experimental investigations of the connection using a four-point bending test are described. This is followed by the description of the FE model of the connection and the corresponding material models in Section 4. In Section 5, results of the numerical model and the comparison with experimental results are discussed, before the paper is concluded.

2. Description of the beam-to-beam connection

Fig. 1 shows the structure and the individual elements of the beam-to-beam connection, designed at Vilnius Gediminas Technical University. The aim of this connection is to link two glued laminated timber (GLT) beams rigidly, with respect to bending moments with special emphasis given to an easy production and simple assembly at the construction site. For this purpose, two welded steel parts (see Fig. 1) are embedded and consequently anchored into the GLT elements and fixed by means of four steel clamping bolts (holding together the timber side members with the steel plate but not transferring any lateral force) on each side of the connection. Four steel mounting bolts on the top and on the bottom at the front of the connection, put into place during assembly, establish the connection between the two GLT beams. The steel elements in the timber beam are designed to be able to transmit both tensile and compressive forces as well as shear forces from the steel element to the GLT beam. Thus, they can be applied in both the tension and compression zone of the connection upon global bending. In order to avoid considerable initial slip due to unavoidable manufacturing tolerances, the gaps between the GLT and the steel elements are closed with filler. This is only the case at the T-shaped end of the steel plate, while the gaps along the steel plate are empty. During hardening of the filler materials, casting barriers were inserted to ensure that the gaps along the steel plate remained open. Two different types of fillers are used in this investigation: a two-component polyurethane based filler (Purbond CR 421 *Purbond AG*, Sempach, CH) and a cement based filler with polymer micro-fibers (Emaco Nanocrete R4, *BASF Construction Chemicals Ltd*, Manchester, UK). According to the manufacturers' declared technical data, these fillers do not show shrinkage during solidification if applied in thicknesses below 8 mm, which is well above the gaps within the analyzed connection of 3–6 mm.

A typical dimension of a GLT beam was used in this study, with a height of 400 mm and a width of 200 mm. The GLT beam was made of strength class GL24 h. The length of the 12 mm thick steel part embedded in grain direction (anchoring length) is 315 mm and its height is 120 mm. The steel plate inserted in the timber beam perpendicular to the grain has dimensions of 90 mm in width, 120 mm in height and 20 mm thickness. All steel parts had a strength class S 275. Clamping steel-to-timber bolts with a diameter of 12 mm are inserted in pre-drilled holes of 15 mm in diameter (see Fig. 1). They are designed to clamp the timber but to not transfer loads from the steel part to the timber. For this purpose, also the corresponding holes in the steel parts are larger and oval shaped (see Fig. 1). For mounting of the connection, i.e. for joining adjacent steel parts, mounting bolts with a diameter of 16 mm are used (see Fig. 1).

If such a type of timber connection is subjected to global bending, failure may occur in both the timber elements or in the steel parts. In the timber element (position 1 according to Fig. 1), there are three different failure modes: (1) tensile failure of the remaining cross-section in the lower tension part of the connection, (2) compressive failure of the timber in the contact area of timber and the anchored steel part in the connection's lower and upper zones, and (3) shear failure of the timber, which anchors the steel part into the timber element in case of tension forces. The steel part (position 2 according to Fig. 1) may fail in several ways,