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Strength and stiffness of timber joints with very high strength steel dowels

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ABSTRACT

Tests on double-shear timber-to-timber joints and double-shear timber joints with slotted-in steel plates loaded parallel-to-grain were undertaken. The used species were spruce, beech, cumaru and azobé (ekki) with one, three and five dowels in a row. Two different steel qualities were used, high strength steel (hss) and very high strength steel (vhss) dowels. The experimental results have shown that the load carrying capacity of joints with vhss dowels is higher than for joints using hss dowels whilst still providing enough plastic deformation capacity to allow for ductile failure modes. No correlation between load carrying capacity and density within one wood species could be observed. The observed effective number of fasteners is lower for the joints with vhss dowels and depends also on the used wood species and the slenderness of dowels. Also for the stiffness K_{ser}, an effective number of fasteners for the joints with more than one dowel in a row could be observed. The well-established Johansen model can be used to design these types of joints.

1. Introduction

Timber joints are generally created using slender metal dowel-type fasteners. These may be nails, screws, bolts or dowels. The main aim of using slender dowels is to guarantee yielding of the fastener in the ultimate limit state, thus creating yielding of the joints and consequently large deformations and load redistribution before eventual structural failure. In many design codes, e.g. DIN 1052 [1], the steel grade of the dowels was regulated and steel grades S235, S275 and S355 were allowed with characteristic strengths of 360, 430 and 510 MPa respectively. For bolts, a maximum grade of 8.8 was allowed with a characteristic strength of 800 MPa.

High-performance timber joints are favoured for large engineered timber structures such as large span trusses, moment-resisting corner joints or any other heavy structure requiring joints. The joints must be able to transfer high loads whilst remaining ductile. With large timber members, dowel lengths and diameters increase, increasing the costs considerably. The European standard for timber design, Eurocode 5 [2], does not specify a minimum or maximum steel grade, allowing also very high strength steels to be used. In design practice however, this option is not used frequently, mainly because possible brittle failures are feared. Generally, steel dowels in large timber structures have diameters between 8 and 24 mm when glued laminated timber is used and even up to 30 mm in bridges made with heavy tropical hardwoods such as azobé (*Lophira alata*) [3]. With the introduction on the market of steels having yield strengths of more than 1200 MPa, new possibilities for optimisation of timber joints with dowels have arrived. Exchanging the currently used steels by very high strength steels, a number of potential advantages can be identified:

- High yield strengths leading to high yield moments of the fasteners may result in increased load carrying capacity per fastener in a timber joint.
- Fewer fasteners may lead to the same load carrying capacity as with ordinary steel fasteners.
- Costs are reduced as less fasteners are needed, holes can have smaller diameters and drilling is faster.
- Smaller diameter fasteners can be applied, with relative increase in embedment strength and relative decrease of timber section sizes.
- As fastener spacings and diameters determine the effective number of fasteners, the load carrying capacity of joints with multiple fasteners is improved.

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An important requirement is that these very high strength steels not only have a high yield strength, but also a sufficient plastic deformation capacity. Only then, the requested ductile behaviour of the joints remains intact when designed properly.

The already available database of test results on timber joints with dowels and bolts as fasteners is huge (e.g. [4–7]). However, most of the research was focussed on softwood and only some research was done with hardwood (e.g. [4,5]). In Schmid [8], very high strength steel (vhss) dowels were used primarily to ensure brittle failure modes. The vhss dowels were combined with small member thicknesses avoiding yielding of the dowels and leading to brittle failure. Gehri and Fontana [5] investigated the influence of dowels of higher steel grades on the load carrying capacity of joints. Van de Kuilen and de Vries [9] reported on positive results of vhss dowels in spruce and azobé. Gehri and Fontana stated that an increase of the load carrying capacity between 25% and 30% could be reached by replacing lower grade dowels with dowels with higher steel grades, provided the dowel slenderness was bigger than 4.5.

In order to quantify the possible gain when using vhss fasteners instead of ordinary steel fasteners, an extensive experimental programme has been carried out using vhss dowels with a yield strength between 800 and 1300 MPa. A number of wood species with densities varying between 350 and 1100 kg/m^3, different joint configurations with both timber-to-timber joints as well as timber joints with slotted-in steel plates loaded parallel-to-grain have been studied. Comparative tests with ordinary steel dowels have been carried out to assess the expected gain in load carrying capacity.

For fasteners in timber joints, vhss grades are already used for self-tapping screws. Self-tapping screws however are used mostly in softwood and not in tropical hardwoods, have small inner diameters and are usually more slender than dowels. Furthermore, the working principle differs between the two fastener types. Whereas dowels only work in bending, in joints with self-tapping screws advantage is taken of their high withdrawal strength. In addition, for very heavy timber structures with slotted-in steel plates, dowels remain the preferred option, as diameters can be bigger und consequently higher load carrying capacities per fastener are possible.

2. Materials and methods

2.1. Johansen model and current design rules

The design equations in Eurocode 5 [2] for both timber-to-timber and steel-to-timber joints with dowel-type fasteners are based on the theory of Johansen [10]. In the Johansen equations (basis of the so-called European yield model, EYM), apart from the joint geometry data, two further parameters are necessary, embedment strength f_h and the fastener's yield moment M_y. For steel-to-timber joints with slotted-in steel plates and fasteners in double shear, the following Johansen equations are valid where the corresponding failure modes f, g and h are given in Fig. 1 (f, g, h correspond to the nomination as in Eurocode 5):

$$F_{v,R} = \min \begin{cases} f_{h,1} \cdot t_1 \cdot d & \text{f} \\ f_{h,1} \cdot t_1 \cdot d \cdot \left[\sqrt{2 + \frac{4 \cdot M_y}{f_{h,1} \cdot t_1^2 \cdot d}} - 1 \right] & \text{g} \\ \sqrt{4 \cdot M_y \cdot f_{h,1} \cdot d} & \text{h} \end{cases} \qquad (1)$$

with $F_{v,R}$ the load carrying capacity per shear plane, $f_{h,1}$ the embedment strength of the (outer) timber member, t_1 the thickness of the (outer) timber member, d the fastener diameter and M_y the yield moment of the fastener.

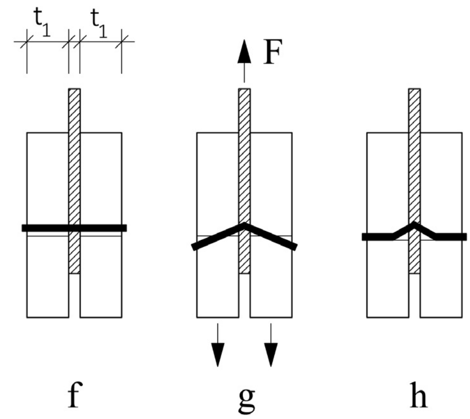

Fig. 1. Failure modes for timber joints with slotted-in steel plates [2].

In Eurocode 5, the characteristic values for M_y and $f_{h,1}$ are used. Furthermore, Eq. (1) has been extended with (i) pre-factors considering different partial safety coefficients of steel ($M_{y,k}$) and timber ($f_{h,1,k}$) and (ii) the rope effect.

2.1.1. Yield moment

In Eurocode 5, the characteristic yield moment of the fastener is given as:

$$M_{y,k} = 0.3 \cdot f_{u,k} \cdot d^{2.6} \qquad (2)$$

where $f_{u,k}$ is the characteristic tensile strength of the steel in MPa and d is the fastener diameter in mm.

Eq. (3) instead gives the yield moment according to mechanics theory:

$$M_y = 1/6 \cdot f_y \cdot d^3 \qquad (3)$$

where f_y is the yield strength of the steel.

Eq. (2) is based on work carried out by Blaß et al. [11] who investigated the influence of the steel grade and the dowel bending angle on the yield moment. EN 26891 [12] states that joints should be tested up to ultimate load or up to a deformation of 15 mm. A slip of 15 mm however means that thin dowels approach a full plastic hinge whereas thick dowels may not. The latter need much less deformation to reach a global joint deformation of 15 mm, thus not necessarily reaching a fully yielded cross section. Eq. (2) was derived based on the above considerations as it was argued that the theoretical Eq. (3) is not safe enough because the calculated theoretical bending capacity (Eq. (3)) of the dowels is too high. Experimental results confirmed that bending angles of dowels in joints were much less than 45° [6]. Blaß et al. [11] concluded that the full plastic capacity of the dowels is not used at failure. They assumed that the activated yield moment of the dowels will lie between the elastic and the full plastic capacity (Eq. (3)). Concerning used steel grades, Blaß et al. [11] considered steel grades with a ratio between yield and ultimate strength of about 0.65 which is not the case for hss and vhss dowels (see Table 4). Based on both assumptions and on a large experimental database, Eq. (2) was derived.

As can be seen in Fig. 2, Eq. (2) is particularly punishing for large diameter fasteners and high steel grades which was already observed by Blaß et al. [11]. The difference between Eqs. (2) and (3) depends thus on the ratio of the yield and ultimate strength of the used steel and on the different exponent of the diameter. The influence of the fastener diameter on the yield moment is especially important for diameters larger than about 20 mm, see Fig. 2. If the *yield* moment for a 24 mm vhss dowel with the properties given in Table 4 is calculated according to Eq. (2) a value of