Construction and Building Materials 173 (2018) 238–250

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

New criteria for the determination of the parallel-to-grain embedment strength of wood

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HIGHLIGHTS

- Embedment strength is a main parameter in the dowel-type timber connections analysis.
- The work proposes to consider it as a system instead of a material property.
- A new formula is presented, with a non-linear relation with timber density.
- Dowel diameter is discarded as a primary factor.
- The influence of steel properties on the embedment strength should be considered.

ARTICLE INFO

Article history:
Received 11 August 2017
Received in revised form 12 March 2018
Accepted 17 March 2018

Keywords:
Timber
Dowel type fasteners
Embedment
Parallel-to-grain
Eurocode 5
Hardness
Wood density
Non-linear relationship

ABSTRACT

The calculation of the capacity of structural timber connections with dowel-type-fasteners requires the embedment strength of timber, which relies on expressions based on experimental tests. Most of the existing formulae were fitted for softwoods. However, in the case of hardwoods, which are being increasingly used in construction, their embedment strength is considerably underestimated. Herein, a different approach for the determination of the embedment strength is presented, compared against existing models, calibrated and validated with an extensive experimental data set of embedment tests. The study concludes that the consideration of the dowel diameter as a main factor in the parallel-to-grain direction case should be rejected. Instead, dowel material properties (here the hardness is proposed) have to be introduced as a main factor.

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1. Introduction

Recent concerns on sustainable building materials, and the late improvements and developments in wood construction have led to an increasing interest on building with timber. And this interest is not only restricted to softwood, since also hardwood products are increasingly being used and developed (see e.g. the special session “Hardwood in structural engineering” [1] in the 2016 World Conference on Timber Engineering). This increasing interest requires the development of appropriate formulae for the analysis which take hardwoods into account. For that reason, an analytic procedure valid for a wide range of wood species, which provides a predictable behaviour of joints with mechanical fasteners, is of utmost importance.

Dowel-type connections are the most common types of joints used nowadays in construction. Their calculation is usually based upon the methods described in the European timber engineering design standard EN 1995-1-1 (Eurocode 5, EC5) [2].

These calculation methods are mainly based on the so-called European Yield Model (EYM), originally proposed by Johansen [3]. By determining the corresponding load leading to different possible plastic mechanisms, the designer is able to obtain the strength of a connection with one dowel type fastener (which will allow to develop the capacity of a multiple fastener connection), depending on the number of shear planes (one or two), the material of the members (timber or steel) and the dowel slenderness.

In any case, the embedment strength is a main factor, required for every calculation. Till now it has usually been considered a property of the timber members in contact with a dowel. It is

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https://doi.org/10.1016/j.conbuildmat.2018.03.127
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obtained from experimental tests, as described in EN383 [4], from which it is derived as the maximum load divided by the area of contact between the dowel and the timber element.

For practical reasons the experimentally obtained values are divided by a simplified rectangular area (the dowel is thus assumed to behave rigid, which is assured in the standard by means of geometrical parameters), given by the dowel diameter and the member thickness. And, therefore, the embedment strength is given by:

$$f_{h,0} = \frac{F_v}{td} \quad (1)$$

where $f_{h,0}$ is the embedment strength parallel to the grain, F_v is the experimental capacity, t is the thickness of the timber member, and d is the dowel diameter.

This work deals with the development of a practical formula for the determination of the embedment strength, which may later be used in practice. It provides a different perspective. It considers the embedment strength being a system property instead of a material property, as explained by Ehlbeck and Werner [5]: “the embedding strength depends on the type of fastener, the joint configuration (such as member thickness, end and edge distances as well as spacing of the fasteners), the manufacturing of the joint (e.g. predrilled holes), and the wood species or the quality of the wood-based materials. Thus, the embedding strength is not a special material property, but a system property”. It is a complex problem, which may be simplified for practical purposes to formulae similar to those already existing, but which should be studied in detail for the development of future approaches which employ physically based parameters which are meaningful to the designer.

The paper is organised as follows: in Section 2, previously proposed expressions for the embedment strength will be presented and described; Section 3 describes and analyses a consistent data set from Sandhaas [6], which is used as reference and calibration data set in Section 4 for the development of the proposed formula; furthermore, in Section 5 the proposed formula is validated and compared to previous proposals by means of the comprehensive database of embedment tests compiled by Leijten et al. [7].

2. Review of previous proposals

2.1. Proposals in the literature

There are several proposed formulae to estimate the embedment strength of wood. Most of them, including those in the design standards, are experimentally based. There is a physically based proposal, but it was developed for particle boards, not for solid wood [8].

All the following proposals come from fitting techniques to experimental tests. As a result, when applying a mean density ρ_m it is assumed that the mean embedment strength $f_{h,0,m}$ is obtained. However, it cannot be assured that when applying a characteristic density ρ_k the result will be at the characteristic level as well. This issue should be further studied in detail in the future.

All the embedment formulae are unit sensitive. The three main parameters are: the embedment strength $f_{h,0}$ in MPa, the wood density ρ in kg/m^3, and the dowel diameter d in mm.

2.1.1. Fahlbusch [9], Norén [10]

Early works by [9] derived the embedment strength from the experimental embedment strength of a dowel of 10 mm diameter $f_{h,0,d10}$ [MPa]:

$$f_{h,0} = f_{h,0,d10}\left(0.9 + \frac{1}{d}\right), \quad (2)$$

The same approach was later adopted by Norén [10]:

$$f_{h,0} = f_{h,0,d10}\left(\frac{66-d}{56}\right). \quad (3)$$

In both expressions, (2) and (3), the embedment strength increases for dowel diameters lower than the reference 10 mm diameter, and decreases for higher diameters. The parameter in the proposal by Fahlbusch [9] provides a lower reduction in comparison to Norén [10].

Apparently, there is no parameter in the formulae related to timber. Those timber related properties are in fact included in the reference embedment strength, $f_{h,0,d10}$.

2.1.2. Ehlbeck and Werner [5]

Ehlbeck and Werner [5] proposed a formula based on both softwood and hardwood embedment tests in which the obtained strength is proportional to the timber density ρ and has a slight correction depending on the dowel diameter d:

$$f_{h,0} = 0.102(1 - 0.01d)\rho. \quad (4)$$

The structure of this proposal is quite similar to that later included in the Eurocode 5 [2]. The reason to include the diameter as a parameter is related to the assumption that not only the wood beneath the connector is compressed, although this additional area does not increase much with the increase of the diameter, as explained by Jorissen [11].

2.1.3. Jumaat et al. [12]

Jumaat et al. [12] proposed an expression similar to Ehlbeck and Werner [5], in which the coefficients were slightly different. Their proposal is based on tests carried out with Malaysian hardwood, all of them of higher density than the common European species. The influence of the dowel diameter is also increased.

$$f_h = 0.103(1 - 0.014d)\,\rho \quad (5)$$

2.1.4. Leijten et al. [7]

The work by Leijten et al. [7] differs in its aim from the previously presented proposals. They carried out a reliability analysis. To that mean they compiled an extensive database of previously reported embedment tests of both softwood and hardwood (which will be described and used for validation in Section 5) and obtained a fitted expression to the mean value.

Their resulting fitted expressions are non-linear. This proposal results in a smooth non-linear relation with timber density. Moreover, they are the only authors to propose the use of different expressions based on the used wood species, coniferous (softwood) or deciduous (hardwood) species:

$$f_{h,0} = 0.097\rho^{1.07}d^{-0.25} \quad \text{for coniferous species}, \quad (6)$$

$$f_{h,0} = 0.087\rho^{1.09}d^{-0.25} \quad \text{for deciduous species}. \quad (7)$$

2.1.5. Sawata and Yasumura [13]

Based on the results of tests with Japanese softwood, Sawata and Yasumura [13] proposed a formula apparently based only on the compressive strength of the wood, $f_{c,0}$

$$f_{h,0} = 0.9f_{c,0}. \quad (8)$$

However, the compression strength [MPa] is given in relation to the timber density ρ, as

$$f_{c,0} = 0.0973\rho \quad (9)$$

and therefore, (8) becomes

$$f_{h,0} = 0.08757\rho, \quad (8')$$

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