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Review

Grain angle and temperature effect on embedding strength

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HIGHLIGHTS

- A continuous function of the reduction factor of the embedding strength is proposed.
- The influence of the temperature on the embedding strength for different grain angles.
- The relation between the glass transition temperature and the decrease of the embedding strength.

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ABSTRACT

The objective of this research is to evaluate the effect of temperature and grain angles on the wood embedding strength in the range from 20 to 140 °C. To this end, a reduction factor of the wood embedding strength is proposed as a continuous function of the grain angle and the temperature, for use in modeling of timber bolted connections. Embedding tests were carried out with 252 specimens of *Eucalyptus grandis*, according to ASTM D 5764-97a [35] standard. The embedding strength, reduction factor, glass transition temperature and moisture content were determined. The minimum values of the characteristic embedding strengths, parallel ($f_{h,0,k}$) and perpendicular ($f_{h,90,k}$) to the grain, were observed at 60 and 80 °C, respectively. For all grain angles, except 15°, the embedding strength presented the first relative minimum at 60 °C. Based on the experimental results, a continuous function of the reduction factor of the embedding strength was then determined. To predict the load-bearing capacity of bolted joints through numerical models, the reduction factor of the embedding strength from the present paper can be used in future research.

Contents

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1. Introduction

The wood embedding strength is the main parameter in order to assess the load-bearing capacity for the design of bolted connections. In normal reference conditions, the wood embedding strength, parallel and perpendicular to the grain, is determined at 20 °C and 12% moisture content. However, the physical, chemical and mechanical wood properties are modified under thermal action [1–7]. Some studies have shown that the embedding strength, parallel and perpendicular to the grain, and the load-bearing capacity of timber connections decrease when subjected to high temperatures [8–14].

Manriquez [7] evaluated embedding strengths parallel and perpendicular to the grain of the *Eucalyptus saligna* in the range from 20 to 230 °C. The author observed decreases of embedding strength by 33% at 70 °C in the parallel direction and by 43% at 100 °C in the perpendicular direction. As a similar study, Moraes et al. [8] noticed that the embedding strength parallel to the grain of the *Pinus sylvestris* drops by 30% at 80 °C.

The reduction of the mechanical properties as function of the temperature is not taken into consideration in the EN 1995-1-1: 2004 standard [15]. However, it is contemplated for structural fire design in the EN 1995-1-2 standard [16], in which the reduction factor for strength and modulus of elasticity parallel to the grain of softwood are presented as function of the temperature.

The reduction of the mechanical properties with increase of the temperature may be related to the glass transition temperature of wood. Conform with the literature [17–19], the lignin glass transition temperature is between 60 and 90 °C. Within this temperature range, the lignin softening may arise, causing then the reduction of the wood strength.

Standards only describe experimental procedures to determine the wood embedding strengths parallel (0°) and perpendicular (90°) to the grain of the wood. For other grain angles, the Hankinson equation is used, requiring the wood strengths perpendicular and parallel to the grain [15,20–26]. As this equation was initially developed for room temperature (25 °C), embedding strength behavior in other temperatures and grain angle conditions are unknown.

Usually, the load-bearing capacity of the wood bolted connection is estimated by the mathematical model of a beam under a deformable foundation, formulated by Johansen [27] or by the finite elements method [28–31]. In the Johansen model [27], the limit analysis theory defines the load-bearing capacity of a single connector, in which the ideal plasticity of both steel and timber is assumed and, besides that, the dowel is assumed rigid-plastic. In this theory, the stress level of the wood plastic failure is represented by the embedding strength, while, in the many models based on finite elements, the wood compressive strength is used as failure parameter. From Hong and Barret [32], the finite element models are based on compressive strength. However, the wood behavior in compression differs from the one in embedding situation, due to the stresses at the contact zone between the wood and the bolt.

In bolted joints under bending moment, the direction of the efforts on the bolts varies in relation to the grain. In order to estimate the joint load-bearing capacity, the embedding strength should be considered as a function of the loading direction according to the grain [33].

Therefore, the objective of this research is to evaluate the effect of the temperature and the grain angles on the wood embedding strength in the range from 20 to 140 °C. To that end, a reduction factor of the wood embedding strength is proposed as a continuous function of the grain angle and the temperature, which can be used in modeling of timber bolted connections.

2. Material and methods

2.1. Sample and specimens

In this research, 252 clear specimens of *Eucalyptus grandis*, with density of 718 kg/m^3 and mean moisture content of 15%, were used. The specimens were assembled in order to present sets with statistically homogeneous densities (Table 1). The homogeneity was verified by variance analysis (ANOVA) with 95.0% confidence level [34]. The experimental program considers 6 temperature levels and 7 grain angles. For each combination of one temperature level and one grain angle, 6 specimens were used.

The specimens are featured by rectangular parallelepiped elements with half a dowel hole across one face, by modifying the grain angles α with respect to the vertical loading applied on the fastener as shown in Fig. 1. Conform with ASTM D 5764-

Table 1
Mean densities of the samples.

Grain angle (°)	Density (kg/m^3)					
	Temperature (°C)					
	20	60	80	100	120	140
0	740 (78)	719 (75)	739 (75)	706 (120)	706 (90)	713 (85)
15	730 (85)	699 (84)	714 (71)	709 (96)	697 (79)	702 (69)
30	720 (80)	735 (93)	749 (84)	719 (114)	712 (101)	712 (77)
45	716 (84)	726 (92)	735 (90)	721 (112)	703 (100)	714 (84)
60	724 (75)	734 (92)	745 (91)	736 (119)	705 (100)	724 (96)
75	731 (84)	715 (92)	723 (87)	710 (120)	693 (106)	705 (85)
90	733 (72)	713 (88)	726 (86)	706 (119)	713 (92)	712 (87)

Values between parentheses are the standard deviations.