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Cyclic and monotonic responses of double shear single dowelled timber connections made of hardwood species: Experimental investigations

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HIGHLIGHTS

- Monotonic and cyclic characterization of the structural responses of joints made of hardwood species.
- Comparison between joints made of hardwood and softwood species.
- The amount of energy dissipated and the viscous damping ratio were assessed for all wood species.
- The accuracy of the European Yield Model predictions have been evaluated for hardwood species.

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ABSTRACT

This paper presents experimental investigations on monotonic and cyclic behaviours of hardwood timber joints. Two sets of connections have been tested: double shear single dowelled timber-to-timber and slotted-in steel plate-to-timber joints. Three wood species have been considered: two hardwood species, namely beech and oak, and spruce for comparison purpose. Both monotonic and cyclic performances of joints have been evaluated and compared to the corresponding values calculated based on the Eurocode 5. The obtained results show clearly the potential interest and performances of hardwood structural joints for high load bearing capacity, as compared to their equivalent softwood joints. The obtained results showed also that the predictions of the European Yield Model regarding the load-carrying capacity penalize the joints made of hardwood species.

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1. Introduction

In the design of timber structures, the deformation properties of connections have a crucial role on the overall stability of the structure and on the distribution of internal forces [1]. The connections are generally recognized, on one hand, as dissipative zones and, on another hand, the weakest points of timber structures and the large majority of collapses originate at connections [2]. Extensive and comprehensive experimental and numerical research studies on timber joints are available in the literature. These studies include monotonic quasi-static [1–8] and cyclic loadings [9–12], among others. In most of these studies, the relationship between the applied load and displacement of connections was measured. In general, measurements include: slip modulus, load-carrying capacity and dissipated energy of joints. All of these works, however, are mostly dealing with joints made of softwood species, since a greater proportion of structural elements and components in timber construction are currently obtained from those species. In fact, very much less attention was paid to the hardwood species despite their availability and their high mechanical performances, as compared to the most softwood species.

Nowadays, the use of hardwood species in timber construction is increasingly popular and, therefore, the need arises to evaluate the mechanical performances of joints made of hardwood species for a safe design and reliable full-scale practical timber structures.

The effect of density on the resistance of steel dowelled connections has been extensively studied in the literature through the evaluation of the embedding strength of different timber species, see for example [13–18] among others. On the other hand, the so-called European Yield Model (EYM), which is proposed in the Eurocode 5 [19], uses different equations to predict the lateral load-bearing capacity of steel dowelled connections which are depending on the embedment strength of timber, the yield

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moment of the steel dowel and the geometry of the connection as well. To assess the embedding strength of timber, the Eurocode 5 suggests an empirical equation depending on the density of timber and the fastener diameter. However, several authors [20–23] reported that predictions of the embedding strength of the Eurocode 5 equation are penalising wood species with high density, like hardwood species. Thus, several empirical equations are proposed, as an alternative to the Eurocode 5 equation, to more closely predict the embedding strength of some wood species, especially wood with high density. One common point of all these studies is that the Eurocode 5 equation is not a general predictive way to describe more closely the embedding strength of all wood species. Up to now, the knowledge on the impact of the Eurocode 5 prediction of the embedding strength on the load-bearing capacity of joints made of hardwood species is very limited, which makes the present study worthy of investigation.

The present paper deals with an experimental program including monotonic quasi-static and cyclic loadings. Three wood species have been considered: beech, oak and spruce (for comparison purpose). Two sets of connections have been considered: double shear single dowelled timber-to-timber connection, double shear single dowelled slotted-in steel plate-to-timber connections. The experimental characteristic values of connections have been assessed experimentally and compared to the corresponding values computed according to the Eurocode 5.

2. Materials and methods

2.1. Materials

The materials used in this study were beech, oak and spruce. All the assembled timber members were conditioned at ambient temperature of 20 °C and kiln-dried to an equilibrium moisture content which fluctuated from 9% to 12% for all species. The densities of all wood species have been determined from free defects samples, prior to testing: The average density values are as follows: 665 kg/m^3, 620 kg/m^3 and 420 kg/m^3 for beech, oak and spruce respectively.

The steel dowels have been also characterized under monotonic tensile tests until failure, using an Instron machine with 100 kN load cell capacity: the yield stress (f_y) and the ultimate stress (f_u) were 527 MPa and 770 MPa, respectively.

2.2. Methods

The main mechanical characteristics of the different studied connections made of three wood species were assessed experimentally and the obtained results were compared against their corresponding values from the Eurocode 5 [19]. For comparison purpose, all specimens in each set of connection have the same dimensions. All tests were conducted until complete failure by displacement control with a crosshead speed set to 2 mm/min. The slip of all connections was recorded with linear variable displacement transducers (LVDTs).

2.2.1. Monotonic push-out shear tests

The geometry of the studied timber-to-timber connections under monotonic tests is shown in Fig. 1a. Monotonic push-out shear tests were conducted using standardised experimental procedure (Fig. 1b) according to the EN 26891 standard [24]. The required maximum load F_{max} was gathered from two preliminary experimental tests conducted until final failure. A total of five monotonic push-out shear tests were performed for each timber species.

According to the Eurocode 5 [19], the load carrying capacity of double shear single dowel timber-to-timber connection may be taken as the minimum value computed from the equations Eq. (1) below, corresponding to the failure modes shown in Fig. 2:

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k}t_1 d & (g) \\ 0.5 f_{h,2,k}t_2 d & (h) \\ 1.05\frac{f_{h,1,k}t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}t_1^2 d}}-\beta\right]+\frac{F_{ax,Rk}}{4} & (j) \\ 1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk}f_{h,1,k}d}+\frac{F_{ax,Rk}}{4} & (k) \end{cases} \quad (1)$$

where

$$f_{h,k} = 0.082(1-0.01d)\rho_k \quad (2)$$

$$M_{y,k} = 0.3 f_u d^{2.6} \quad (3)$$

The slip modulus, K_{ser}, for the service limit state, can be evaluated either using the empirical equation Eq. (4) suggested by the Eurocode 5, per shear plane, depending on the timber density and the dowel diameter or using the experimental load-slip curves by means the Eq. (5).

$$K_{ser} = \rho_w^{1.5}\frac{d}{23} \quad (4)$$

$$K_{ser} = \frac{0.4F_{est}}{\frac{4}{3}(v_{04}-v_{01})} \quad (5)$$

The ductility has been calculated using the Eq. (6), as the ratio between the yield and the ultimate displacements [25]. The ultimate displacement in the case of spruce specimens has been taken at a load level of 0.8 $F_{\max}$.

$$D_u = \frac{V_u}{V_y} \quad (6)$$

2.2.2. Cyclic tensile tests

The schematic illustration of the studied slotted-in steel plate-to-timber connections under cyclic tests is shown in Fig. 3a. Cyclic tensile tests were conducted using standardised experimental procedure according to the EN 12512 standard [25] (Fig. 3b). It is worth noting that all specimens were subjected to non-reversed loading due to the restrained movement of the joints in compression. The elastic displacement, V_y, required for the cyclic loading procedure was gathered from two preliminary experimental monotonic tests. A total of five cyclic tensile tests were performed for each timber species. The loading amplitudes were: $0.25V_y, 0.5V_y, 0.75V_y, 1V_y, 2V_y, 4V_y, 6V_y$. For each amplitude level three loading cycles were repeated, expect for the amplitudes $0.25V_y$ and $0.5V_y$ which were performed by considering one loading cycle.

According to the Eurocode 5 [19], the load carrying capacity of double shear single dowel slotted-in steel plate-to-timber connection may be taken as the minimum value of the system of equations Eq. (7), corresponding to the mode of failures shown in Fig. 4.

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k}t_1 d & (f) \\ f_{h,1,k}t_1 d\left[\sqrt{2+\frac{4M_{y,Rk}}{f_{h,1,k}t_1^2 d}}-1\right]+\frac{F_{ax,Rk}}{4} & (g) \\ 2.3\sqrt{M_{y,Rk}f_{h,1,k}d}+\frac{F_{ax,Rk}}{4} & (h) \end{cases} \quad (7)$$

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