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STIFFNESS OF CONNECTIONS OF FAST GROWING EUCALYPTUS GRANDIS WITH NAILS OF SMALL DIAMETER

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ABSTRACT: The stiffness of joints of fast-growing *E. grandis* with 2.5mm-diameter nails was investigated through an empirical research project carried out according to European standards. The results confirmed the effectiveness of the criterion adopted by the European design rules for calculating the instantaneous slip modulus in joints loaded parallel to the grain and exhibiting the recommended spacing and end distances. The empirical results also revealed that the stiffness of the connections was related to the angle of load to grain, which is not taken into account by the European criterion. An important decrease of the slip modulus was found in joints loaded perpendicular to the grain.

KEYWORDS: stiffness, connections, slip modulus, nails, *grandis*

1 INTRODUCTION

The connections with nails of small diameter at nodes of plane trusses built-up with boards of fast-growing Eucalyptus grandis have acquired importance in Argentina. This type of timber structures is mainly destined to industrial buildings exhibiting span dimensions normally ranging between 12m and 16m [1]. The utilization of power-driving equipment using compressed air allows fast installation of nails reducing the cost of execution.

The load-carrying capacity of joints with nails of small diameter was investigated by Sosa Zitto *et al*. [2] for both, joints where the spacing requirements adopted by the Eurocode 5 [3] are satisfied and joints where the spacing and end distance in grain direction are reduced. The results reported by this paper showed a particularly high load-bearing capacity of these connections, which also exhibited a ductile behaviour. The published results showed that the joint area may be decreased up to 31 % - in relation to the area corresponding to the recommended geometrical parameters- without reducing the load-carrying capacity below the characteristic value determined according to the European design rule. The results reported by Sosa Zitto *et al.* [2], which were obtained from tests carried out according to EN 1380 [4], were then confirmed for connections with 2.5mm-diameter nails at nodes of trusses with structural sizes [1]. These outcomes allow designers and builders to solve the problem connected with the relatively small dimensions normally available for spacing at nodes of trusses [5,6] without affecting the safety requirements.

The deflection of trusses due to slip in the connections can frequently exceed that due to the elastic deformations of the members [7] and the use of fastenings with stiff slip characteristics is often recommended in order to minimize deflections [6]. Since significant deformations can be expected for connections with slender nails [8,9] and the joints of Argentinean Eucalyptus grandis with nails of small diameter exhibit a failure mode with characteristics common to both j and k modes of the European design rule [2], the study of the stiffness of this type of connections is very important for the verification of serviceability requirements. Measurements carried out on structural-sized trusses of Argentinean Eucalyptus grandis with this type of connections at nodes demonstrated that the deformation requirements under service load were fulfilled. However, no information connected with the influence of the joint slip on the structure deflection was provided [1].

The Eurocode 5 [3] provides an expression to calculate the instantaneous slip modulus (Kser) of nailed connections without predrilled holes. According to this criterion, the value of Kser under service load may be calculated as a function of the mean density and the nail diameter. However, the convenience of carrying out an empirical project aimed at thoroughly studying the stiffness of this type of connections is supported by the following reasons: i) these joints are frequently used with reduced spacing and end distances taking advantage of their particularly high load-carrying capacity and ductility, ii) loading at angle to the grain is normally transferred from a web member through a nailed connection to an external member (chord) in a trussed structure and the influence of the angle of load to the grain on the joint stiffness is not explicitly considered by the European design rule.

The aim of this paper is to present and discuss the results of an empirical project regarding the stiffness of connections with 2.5mm-diameter nails pneumatically driven in timber-to-timber joints of fast-growing Argentinean *Eucalyptus grandis*. The instantaneous slip modulus is analysed for joints loaded parallel to the grain exhibiting both the recommended and reduced

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geometrical parameters. A comparison between the stiffness results corresponding to connections loaded parallel and perpendicular to the grain is presented. The effectiveness of the equation adopted by the Eurocode 5 [3] for calculating the slip modulus is discussed.

2 MATERIAL AND METHODS

The whole empirical work was performed according to the criterion adopted by [4]. Boards of the considered timber species are commonly produced with a thickness of 25.4 mm and a width ranging between 76.2 mm and 152.4 mm. For this reason, boards with nominal sizes of 25.4 mm in thickness and 102 mm in width were randomly selected from the material produced by sawing trees harvested in a plantation of *Eucalyptus grandis* grown in Concordia, Entre Ríos, which is one of the main provenances for this species in Argentina [10]. Once kiln-dried, the material was transported to the laboratory and conditioned in the climate required by the test standard mentioned before for preparing the test specimens. The nominal thickness and width of all boards after surfacing were 22 mm and 100 mm respectively.

No values of the slip modulus were reported for laterally loaded joints with nails of small diameter (hereafter d) of this timber species cultivated in Argentina. Consequently, and with the purpose of exhaustively studying the stiffness for different joint configurations normally used at nodes of trusses built-up with boards of this species, 5 sub-samples enclosing a total of 53 specimens were prepared. Taking into account that previous investigations with this timber species reported characteristic values for density (ρ_k) lower than 420 kg/m^3 [2,11] the spacing and end/edge distances recommended by Eurocode 5 [3] for timber with $\rho_k \leq$ 420 kg/m^3 was considered as reference values.

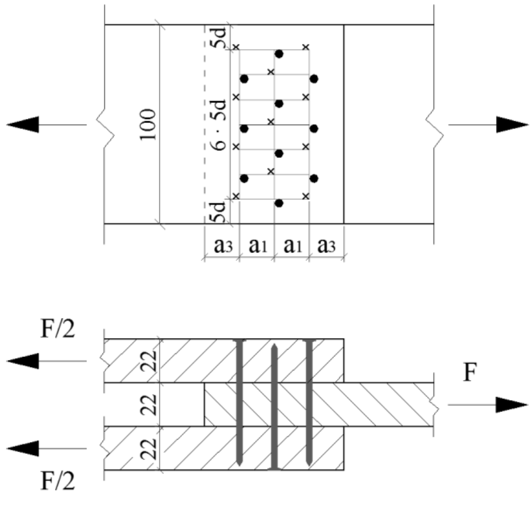

Figura 1: *Test arrangement corresponding to the 3 sub-samples prepared for testing parallel to the grain. Number of nails (2.5 mm-diameter and 65 mm long) in each connection: 21 nails (7 rows of 3 nails each).Spacing in grain direction (a_1) and between nail and loaded end (a_3):*
a_1 =10d, a_3 = 15d for Sub-sample $Pa_{10/15-ref}$ with 12 specimens;
a_1 = 7d, a_3 = 12d for Sub-sample $Pa_{7/12}$ with 12 specimens;
a_1 = 7d, a_3 = 10d for Sub-sample $Pa_{7/10}$ with 13 specimens

Three sub-samples with the same spacing perpendicular to the grain and edge distance (5 d) but different spacing parallel to the grain (a_1) and end distance (a_3) were arranged for testing in tension parallel to the grain (Figure 1). Sub-sample $Pa_{10/15-ref}$ -enclosing 12 specimens- was prepared with the spacing parallel to the grain and the end distance recommended by Eurocode 5 [3] for nailed connections with d < 5 mm and timber with $\rho_k \leq$ 420kg/m^3: a_1 = 10 d, a_3 = 15 d. Hereafter this sub-sample will be considered as reference sub-sample for the discussion. Two sub-samples were prepared with the reduced geometrical parameters in grain direction usually adopted for decreasing the joint area [2]: i) Sub-sample $Pa_{7/12}$ -enclosing 12 specimens- with a_1 = 7 d, a_3 = 12 d and, ii) Sub-sample $Pa_{7/10}$ -enclosing 13 specimens- with a_1 = 7 d, a_3 = 10 d.

Two sub-samples exhibiting typical joint configurations of a web member (vertical) to an external member (chord) were arranged for testing perpendicular to the grain (Figure 2). Both sub-samples were prepared with the geometrical parameters recommended by the European design rule excepting the spacing along the rows of the vertical boards loaded parallel to the grain (7 d instead of 10 d, see Figure 2).

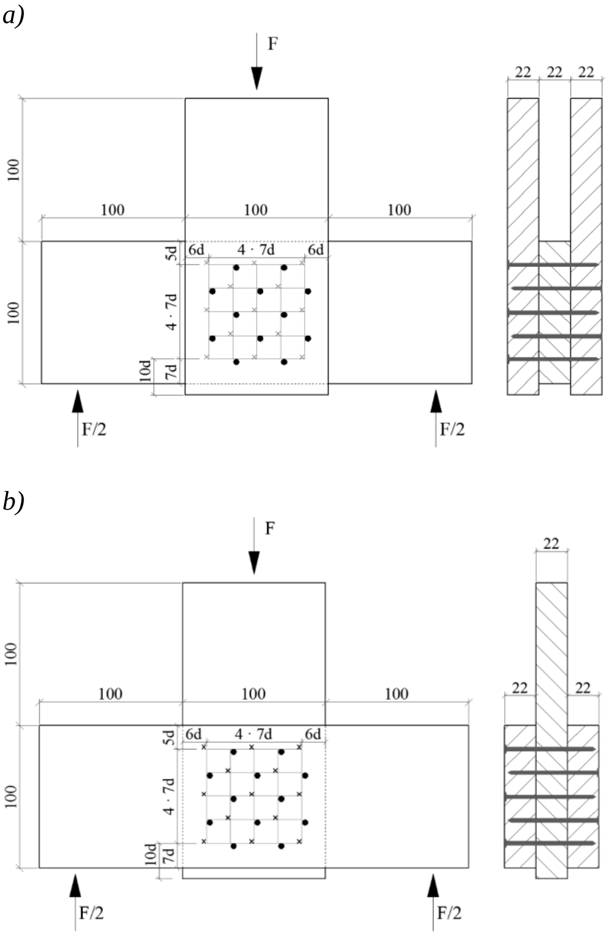

Figure 2: *Test arrangement corresponding to the 2 sub-samples prepared for testing perpendicular to the grain*
a) Sub-sample Pe_{1b} with 7 specimens. b) Sub-sample Pe_{2b} with 9 specimens. Number of nails 2.5 mm-diameter and 65 mm long in each connection: 25 nails (5 rows of 5 nails each)

Sub-sample Pe_{1b} -enclosing 7 specimens- was prepared with one centre (horizontal) board destined to be loaded perpendicular to the grain and two side (vertical) boards. Sub-sample Pe_{2b} -enclosing 9 specimens- was arranged with two side boards destined to be loaded perpendicular to the grain and one centre (vertical) board.

Helical machine nails (2.5 mm-diameter) driven by a pneumatically operated machine were used. For each specimen, half of the nails were driven into one side member and the other half into the other. The nails were displaced one diameter from each other along each row. Considering that the board thickness was 22mm after surfacing, one length was selected for all nails i.e. 65mm which fulfil the requirements of Eurocode 5 [3] related to the point side penetration length. The number of nails in each connection was calculated to obtain connections with a load-carrying capacity similar to the axial resistance of the boards normally used as members of trusses built with this timber species [2] and is in line with the usual practice adopted by designers and builders.

After assembly, the specimens were conditioned in a controlled climate at 20+/- 2 ºC and 65+/- 5 % relative humidity for one week. A loading machine Shimadzu UH 1000kN, capable for applying loads with adequate rate of movement of the loading-head and accuracy of 1% of the load applied was used. Slip was measured by means of two extensometers capable of registering 0.001mm and attached at opposite points to minimise the effects of distortion. The instantaneous slip modulus (K_s) was calculated according to Equation (1) adopted by EN 26891 [12] as follows:

$$K_s = 0.4\ F_{max,est} / \nu_{i,mod} \qquad (1)$$

where:

$F_{max,est}$: maximum estimated load

$\nu_{i,mod} = 4\ (\nu_{04} - \nu_{01}) / 3$

ν_{04} and ν_{01}: slip at 40 % and 10 % of $F_{max,est}$, respectively

Moisture content and density (ρ) were calculated according to the procedures of ISO 3130 [13] and ISO 3131 [14] respectively, after all static tests. Density values were adjusted to a reference moisture content of 12 % according to EN 384 [15] and the characteristic value of this property (ρ_k) was calculated by following the procedures of this European standard.

3 RESULTS

The characteristic density (ρ_k), obtained according to EN 384 [15] for the whole samples (see Table 1), reached 408 kg/m^3. This result confirms the geometrical parameters adopted for the Sub-sample $Pa_{10/15\text{-}ref}$ –considered as reference Sub-sample- according to the criterion adopted by the Eurocode 5 [3] for timber with $\rho_k \leq 420$kg/m^3. The whole samples exhibited a mean moisture content of 11.1 % with a coefficient of variation (COV) of 5 % and, consequently, an unequal influence of moisture content on the test results may be disregarded for this project.

The main results corresponding to the specimens laterally loaded according to EN 1380 [4] are presented in Table 1. Since the stiffness of dowel-type joints is considered as a property highly correlated with density by the European design rule, a summary of the results for both the instantaneous slip modulus per nail (K_s) and density (ρ) is presented separately for each sub-sample in this table. The results of an analysis of variance proved that the hypothesis that the sub-samples presented in Table 1 have the same density mean value may not be rejected at a significance level of 0.05 and, consequently, an equal influence of this property on the Ks results obtained for the different sub-samples was assumed.

Table 1. *Summary of the experimental results for slip modulus per nail (K_s) and density (ρ)*

Sub samples	n	K_s (N/mm)		$\rho^{(1)}$ (kg/m^3)	
		Mean	COV	Mean	COV
$Pa_{10/15\text{-}ref}$	12	1652	45%	495	13%
$Pa_{7/12}$	12	1074	28%	512	14%
$Pa_{7/10}$	13	1082	25%	510	13%
Pe_{1b}	7	636	32%	485	12%
Pe_{2b}	9	422	31%	486	15%

n: number of specimens

(1): corrected to a reference moisture content of 12%

3.1 STIFFNESS OF THE CONNECTIONS TESTED PARALLEL TO THE GRAIN

The maximum K_s mean value of those found for the sub-samples tested parallel to the grain (1652 N/mm) was exhibited by the reference Sub-sample ($Pa_{10/15\text{-}ref}$). Curiously, this sub-sample showed the maximum spread of K_s results (COV = 45 %) whereas the sub-samples with reduced geometrical parameters showed much lower dispersion with COV values of 28 % for $Pa_{7/12}$ and 25 % for $Pa_{7/10}$. However, the relatively high spread of K_s results found for the reference Sub-sample could not be explained by means of a detailed analysis.

The K_s mean values obtained for the sub-samples with reduced geometrical parameters ($Pa_{7/12}$ and $Pa_{7/10}$) were 35 % lower than that found for $Pa_{10/15\text{-}ref}$. The development of a small number of light cracks during the driving-in of the nails -due to the reduced spacing and end distance- may explain the diminution of the stiffness in the sub-samples $Pa_{7/12}$ and $Pa_{7/10}$. The presence of these small cracks observed and registered during the preparation and testing of the specimens, is congruent with the results obtained by Sosa Zitto et al. [2] through an exhaustive analysis of the development of fissures in this type of connections.

Since the knowledge of K_s allows structural designers to estimate the slip that will occur when the service load is applied to a connection [7], the equations provided by the European standards [4,12] to calculate K_s are based on the load-slip information collected between the beginning of the test and 40 % of the maximum estimated load ($F_{max,est}$). Consequently, and with the purpose of better understanding the differences found between the K_s values presented in Table 1, the initial stretch (up to 0.4 $F_{max,est}$) of the load-slip curves corresponding to the 5 sub-samples were displayed in Figure 3. In order to clarify the typical behaviour of every joint configuration, each curve depicts the relationship between the applied load (per nail) and the average slip of the connections enclosed in the corresponding sub-sample. In relation to the sub-samples tested parallel to the grain, it is interesting to observe that: i) the three curves show a similar shape but the slip of $Pa_{7/12}$ and $Pa_{7/10}$ are greater than that of $Pa_{10/15\text{-}ref}$ for a given load value and, ii) the curves corresponding to $Pa_{7/12}$ and $Pa_{7/10}$ are almost coincident. The load-slip relationships displayed in this figure are congruent with the K_s results presented in Table 1 for the three sub-samples tested parallel to the grain. It also confirms a non-linear behaviour in this stretch of the curves even though a relatively rapid increase of the load may be appreciated -mainly for the reference sub-sample- at the beginning of the test.

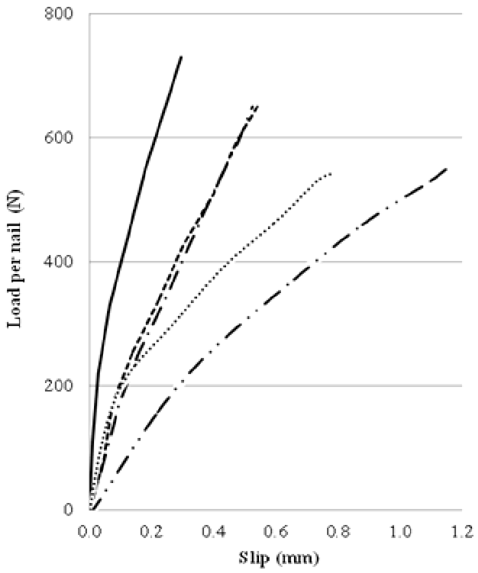

Figure 3: *Load-slip curves*
——: $Pa_{10/15\text{-}ref}$; —·—: $Pa_{7/12}$; ----: $Pa_{7/10}$; ····: Pe_{1b}; —··—: Pe_{2b}

3.2 STIFFNESS OF THE CONNECTIONS TESTED PERPENDICULAR TO THE GRAIN

When comparing the stiffness results obtained for the two sub-samples tested perpendicular to the grain with those found for the three sub-samples tested parallel to the grain (Table 1) it is possible to appreciate that the former are significantly lower than the latter. Although the five sub-samples enclosed three-member connections laterally loaded in double shear and built-up with boards presenting the same cross-sectional dimensions, an accurate comparison requires the consideration of the geometrical parameters adopted for each sub-sample. Since the specimens enclosed in Pe_{1b} and Pe_{2b} were prepared with the geometrical parameters recommended by the European design rule excepting the spacing along the rows of the vertical boards loaded parallel to the grain (7 d instead of 10 d, see Figure 2), it may be concluded that the K_s results obtained for Pe_{1b} and Pe_{2b} may be properly compared to those determined for $Pa_{7/10}$ (see also Figure 1). According to the data provided in Table 1, the K_s mean values determined for Pe_{1b} (636 N/mm) and Pe_{2b} (422 N/mm) exhibit a decrease of 41 % and 61%, respectively, in relation to the corresponding result found for $Pa_{7/10}$ (1082 N/mm).

Taking into account that two boards were loaded perpendicular to the grain in the specimens enclosed in Pe_{2b} (Figure 2, b), only one board was loaded perpendicular to the grain in those enclosed in Pe1b (Figure 2, a) and no board was loaded perpendicular to the grain in those of $Pa_{7/10}$ (Figure 1), these results suggest that the stiffness of the tested connections is strongly related to the angle of the applied load to the grain direction of the jointed members. These outcomes may be clearly appreciated in Figure 3 by comparing the load-slip behaviour of the sub-samples $Pa_{7/10}$, Pe_{1b} and Pe_{2b}.

Since the influence of the angle of load to grain on the joint stiffness -which may be explained by the wood anisotropy- is disregarded by the European experience [3] and also by both the North American [16] and South American [17,18,19] experiences, and in order to scrutinize if the difference between the K_s values obtained by testing parallel and perpendicular to the grain (Table 1) was related to the particularly small diameter of the nails used in these connections, a study of the stiffness in joints of the same timber species built-up with a rigid nail was carried out. For this purpose, information available at the database of the Argentinean Universidad Tecnológica Nacional and obtained from tests carried out by following the procedures of EN 383 [20] was used. According to the information available at the database, the specimens of Argentinean *Eucalyptus grandis* were prepared with a 5.5 mm-diameter nail and the limits established in EN 383 [20] for the ratio of the specimen thickness to the fastener diameter were fulfilled. Since the information available at the database was organised independently for specimens prepared with and without predrilled holes, the stiffness and density values were also calculated separately considering the two types of joints.

Table 2: *Summary of the results for slip modulus (K_s) and density (ρ) obtained from tests carried out on single connections with a rigid nail*

Sub samples		n	K_s (N/mm)		$\rho^{(1)}$ (kg/m^3)	
			Mean	COV	Mean	COV
Parallel to the grain	PD	25	3472	44%	474	11%
	No PD	24	3453	57%	478	10%
	Whole parallel	49	3463	50%	476	11%
Perpendicular to the grain	PD	25	2038	63%	458	12%
	No PD	23	1975	76%	480	13%
	Whole perpendicular	48	2008	68%	468	13%

n: number of specimens. PD: specimens with predrilled holes. No PD: specimens without predrilled
(1): corrected to a reference moisture content of 12% according to EN 384 (2010).

The main results are presented in Table 2 and, in contradiction with the criterion adopted by the European design rule [3], the calculated values show no influence of the pre-drilling on the stiffness. Consequently, it is possible to compare the K_s results calculated for the whole sub-sample tested parallel to the grain to those calculated for the whole sub-sample tested perpendicular to the grain. The K_s mean value corresponding to the latter (2008 N/mm) is 42 % lower than that corresponding to the former (3463 N/mm) and the similarity found between the density values allows us to disregard an unequal influence of this property on these results. The COV values of Ks are much higher than those presented in Table 1 for the sub-samples with nails of small diameter. Although Ks usually shows an important spread of results even for connections with

rigid fasteners [21], an exhaustive study of the information available at the database was carried out in order to clarify the particularly high COV values obtained in this case. Nevertheless, it was not possible to explain this behaviour by means of the detailed analysis.
The relationship between the applied load (up to 0.4 $F_{max,est}$) and the average slip of the connections with a rigid nail is depicted separately for the two sub-samples in Figure 4 where it is remarkable that: i) the almost linear behaviour shown by the 49 specimens loaded parallel to the grain visibly differs from the clear non-linear performance exhibited by the 48 specimens loaded perpendicular to the grain and, ii) the slope of the curve corresponding to the latter strongly decreases from a load level of approximately 0.2 $F_{max,est}$ (around 800 N) up to 0.4 $F_{max,est}$ which is congruent with the lower slip modulus found for these specimens (Table 2). These results confirm that the important difference in stiffness found by testing parallel and perpendicular to the grain multiple connections of fast-growing Argentinean Eucalyptus grandis with nails of small diameter is also exhibited by single joints of this timber species with a rigid nail.

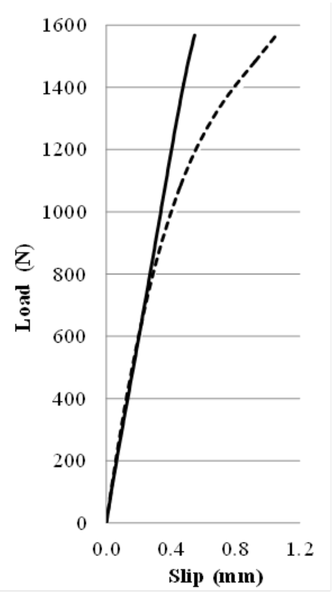

Figure 4: *Load-slip curves from the beginning of the test up to 0.4 $F_{max,est}$ obtained from tests carried out on single connections with a rigid nail.*
——: parallel to the grain; — —: perpendicular to the grain

3.3 STIFFNESS OF THE CONNECTIONS CALCULATED ACCORDING TO THE CRITERION OF THE EUROCODE 5 (EN 1995-1-1 2005)

With the purpose of comparing the empirical results presented in Table 1 with that calculated according to the criterion of Eurocode 5 [3], the expression provided by this design rule to calculate the instantaneous slip modulus (K_{ser}) in nailed joints without pre-drilling was applied to the investigated connections. According to the criterion of the European design rule the value of K_{ser} per shear plane per nail under service load may be obtained as a function of the mean density (ρ_m in kg/m^3) and the nail diameter (d in mm) as follows: $K_{ser} = \rho_m^{1.5}\ d^{0.8}/30$. Taking into account that this design rule recommends minimum spacing and end and edge distances for nails, in the present case the given expression is only applicable to the reference Sub-sample ($Pa_{10/15\text{-}ref}$) which was prepared according to the recommended geometrical parameters. Since the tested specimens presented two shear planes and substituting ρ_m = 495 kg/m^3 (Table 1) and d = 2.5 mm, the value of the slip modulus per nail reaches: $K_{ser} = 2\ 495^{1.5}\ 2.5^{0.8}/30 = 1528$ N/mm.
It is possible to appreciate in this table that the slip modulus per nail calculated according to the European criterion compares well with that obtained experimentally for the reference Sub-sample loaded parallel to the grain (K_s = 1652 N/mm) and the difference between the empirical and the calculated results (8 %) may be disregarded for practical purposes connected with the structural design. Nevertheless, the behaviour of both the connections with reduced geometrical parameters ($Pa_{7/12}$ and $Pa_{7/10}$) and the joints loaded perpendicular to the grain (Pe_{1b} and Pe_{2b}) was not accurately expressed in this case by the European criterion and the stiffness of these connections is overestimated by using the equation provided by the European design rule.

4 CONCLUSIONS

The results obtained by testing multiple connections with 2.5mm-diameter nails loaded parallel to the grain showed an important decrease in stiffness for joints with reduced geometrical parameters. The mean value of the instantaneous slip modulus obtained for joints presenting reduced end distance (10 d instead of 15 d) and spacing along a row in grain direction (7 d instead of 10 d) was 35 % lower than that found for joints with the geometrical parameters recommended by the European design rule.
The research also revealed that the slip modulus per nail of the tested connections was related to the angle of the applied load to the grain direction of the jointed members. A reduction of 41 % and 61% in stiffness was found for three-member joints with one and two members laterally loaded perpendicular to the grain, respectively, in relation to that obtained for joints loaded parallel to the grain. The important diminution of the stiffness in the multiple connections with nails of small diameter loaded perpendicular to the grain was also confirmed for single connections of the same timber species with a rigid nail.
The criterion adopted by the Eurocode 5 [3] for calculating the slip modulus in nailed connections without pre-drilling was applied to the studied joints. The value calculated by means of the equation provided by this design rule compares well with the empirical result obtained for multiple connections loaded parallel to the grain and exhibiting the recommended spacing and end distance. However, serviceability requirements may be affected if the slip of joints exhibiting reduced geometrical parameters or loaded perpendicular to the grain is estimated by applying the procedures adopted by the Eurocode 5 [3].
The results of this research encourage further studies aimed at designing a simple method that allows structural designers to estimate the instantaneous slip of the analysed connections when the load is applied at an angle to grain and when the geometrical parameters are

reduced in relation to those recommended by the European design rule.

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