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**Load-carrying capacity of timber-to-timber joints of fast-growing Argentinean *Eucalyptus grandis* with nails of small diameter laterally loaded in double shear.
Analysis according to the criterion adopted by European standards**

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Abstract

The present paper reports the results of an investigation regarding the study of the load-carrying capacity of connections with nails of small diameter pneumatically driven in timber-to-timber joints of fast-growing Argentinean *Eucalyptus grandis*. The effectiveness of the equations provided by the Eurocode 5 (EN 1995-1-1 2005) for calculating the lateral load-carrying capacity of these joints was checked for the specimens exhibiting the geometrical parameters adopted by the European design rule and also for those with reduced spacing and end distances. A failure mode presenting features common to both j and k types of failure according to the criterion of the European design rule confirmed that the plastic hinges could be developed before brittle failure due to splitting or block shear occurred, even if the specimens present reduced spacing and end distances. The load-slip curves confirmed ductile behaviour for all cases. The empirical results showed that the structural design is situated on the conservative side if the equations adopted by the Eurocode 5 (EN 1995-1-1 2005) are applied to the analysed connections when the spacing and end distances recommended by this design rule are used. The results also showed that the joint area may be decreased up to 31% in relation to that corresponding to the recommended spacing and end distances without reducing the load-bearing capacity below the characteristic value determined according to the European design rule.

Tragfähigkeit von zweischnittigen Holz-Holz-Verbindungen aus *Eucalyptus grandis* aus Argentinien mit auf Abscheren beanspruchten Nägeln mit kleinem Durchmesser.



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Analyse nach europäischen Normen.

Zusammenfassung Dieser Beitrag fasst die Ergebnisse einer Studie zusammen, in der die Tragfähigkeit von Verbindungen aus *Eucalyptus grandis* aus Argentinien mit auf Abscheren beanspruchten Nägeln mit kleinem Durchmesser untersucht wurde. Die Gültigkeit der Gleichungen des Eurocodes 5 (EN 1995-1-1 2005) zur Bestimmung der Tragfähigkeit dieser Verbindungen wurde überprüft für Proben mit den erforderlichen Mindestnagelabständen und für Proben mit verkleinerten Nagelabständen. Der Versagensmechanismus und die Last-Verschiebungs-Beziehung zeigten ein plastisches Verhalten für alle Proben. Die empirischen Ergebnisse zeigten, dass die Anschlussfläche dieser Verbindungen stark vermindert werden kann, wenn die charakteristische Tragfähigkeit nach dem Kriterium des Eurocodes 5 berechnet wird.

1 Introduction

Eucalyptus grandis is one of the most important renewable species cultivated in Argentina (INTA 1995) and the construction of trusses with boards of this fast-growing species has acquired great importance. Dowel-type fasteners are commonly used for mechanical connections at nodes. Since plantations of this timber species are harvested at an early age, no large dimensions are expected for the cross section of the pieces obtained by sawing the trees. Consequently, the problem related to the relatively small dimensions normally available for spacing as well as edge and end distances at nodes of trusses (Hartl 1995; Kessel 1995) increases when structural members of this species are concerned. This problem increases when connections at nodes are designed for transmitting the full axial capacity of the jointed members.

Nails are the most commonly used dowel-type fasteners at nodes of trusses in Argentina. Nevertheless, in many cases it is not possible to fulfil the spacing requirements due to the problem mentioned above. The Johansen model has been adopted by many design rules for predicting the strength of connections with this type of fasteners and it is based, in addition to geometrical parameters, on two material properties: the embedding strength of the timber and the yield moment of the dowel (EN 1995-1-1 2005; NDS 2005; NCh 1198 2007). This model assumes rigid-plastic behaviour for the fasteners as well as for the wood. The load-slip characteristic of this type of connections is assumed to be plastic at ultimate load level and, consequently, a plastic deformation capacity of the dowel is essential to provide bending capacity also after considerable deformation of the joint.



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Ductile behaviour is preferred over brittle behaviour because the former allows the development of plastic hinges which evens the load distribution within the joint, increasing the load-carrying capacity and improving the ability to dissipate energy. However, it is important to point out that splitting and block shear reduce the load-bearing capacity and the ability to dissipate energy of a multiple-fastener joint if they occur at load levels below the capacity predicted by the Johansen model. This reduction occurs because splitting and block shear prevent a full redistribution of the load within the connection (Blaß 1991, 1995; Johnsson and Stehn 2004; Stehn and Börjes 2004).

Results of a project aimed at studying the embedding strength of this timber species in joints with dowel-type fasteners, carried out according to the European standards, were published by Sosa Zitto et al. (2012). However, up to the present neither test results related to the load-carrying capacity of multiple-fastener connections nor data documenting the splitting tendency of this timber species have been published.

A possible way of reducing the size of multiple connections is the use of power-driven nails of small diameter. Since significant plastic deformations can be expected for connections with slender nails (Blaß 1995; Johnsson and Stehn 2004), an empirical project aimed at investigating the mechanical behaviour of joints with nails of small diameter - driven by a pneumatically operated machine- was carried out. In order to avoid undue splitting, the Eurocode 5 (1995) provides spacing and distance requirements for nailed joints which are based upon an extensive experience. However, the most suitable values for spacing and distances vary from species to species and are related to the timber properties as well as the type and dimensions of the nail, among others. Consequently, and taking into account that no information related to the splitting tendency of the investigated species is available, the empirical project enclosed both, connections satisfying the distance requirements adopted by the European design rule, and connections presenting four different arrangements with reduced spacing and end distances in grain direction. Since the difficulties related to the fulfilment of the spacing and end distance requirements increase with an increasing number of nails, this project was focused on the behaviour of connections presenting a load-bearing capacity similar to the design value of the maximum axial loading transmittable by the boards normally used as members of the trusses mentioned before.

The aim of this paper is to present and discuss the results of an investigation regarding the mechanical behaviour of connections with nails of small diameter



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pneumatically driven in timber-to-timber joints of fast-growing Argentinean *Eucalyptus grandis*. The validity of the equations provided by the Eurocode 5 (EN 1995-1-1 2005) for calculating the lateral load-carrying capacity of these joints was checked for both, joints where the distance requirements adopted by the European design rule are satisfied and joints where the spacing and end distance in grain direction are reduced. Test results corresponding to specimens laterally loaded in grain direction and in double shear according to EN 1380 (2009) are discussed and compared with the load-bearing capacity calculated by following the procedures of the European design rule.

2 Material and Methods

Since the boards of this timber species are produced with a nominal thickness of 25.4mm and a width normally ranging between 76.2mm and 152.4mm, pieces exhibiting nominal sizes of 25.4 mm in thickness, 102 mm in width and a length ranging from 1.5 m to 1.8 m were selected for this project. The boards were taken from the material produced by sawing a total of 550 trees harvested in a plantation of *Eucalyptus grandis* grown in Concordia, Entre Ríos. This is one of the main provenances for this species in Argentina (INTA 1995). The boards were randomly selected from those assigned to the best strength class (strength class 1) according to the criterion of the Argentinean standard IRAM 9662-2 (2006). The use of boards assigned to the best grade was decided taking into account that they present higher strength than -but similar density to- those assigned to the inferior grades of this deciduous species (IRAM 9662-2 2006). These characteristics allow the study of joints exhibiting: i) a load-carrying capacity similar to the design value of the maximum axial loading transmittable by the boards normally used as members of the trusses, ii) a wood density similar to that expected for the other grades and, consequently, an embedding strength and a mechanical behaviour also similar to those expected for connections built-up with boards of this species assigned to the other grades. After kiln drying the boards were surfaced and transported to the laboratory.

No values were reported for laterally loaded multiple nailed joints of this timber species. As a consequence and with the aim of thoroughly studying the load-carrying capacity for different spacing and end distances, a total of 10 sub-samples enclosing 118 specimens were prepared by following the procedures prescribed in EN 1380 (2009) for testing in tension parallel to the grain (see Table 1 and Figure 1). Considering that a



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previous research with this timber species (Sosa Zitto et al. 2012) reported characteristic values for density (ρ_k) ranging from 375kg/m^3 to 388kg/m^3 , the sub-samples $1_{2.5-E5,ref}$ and $1_{2.2-E5,ref}$ were prepared with the spacing and end/edge distances recommended by Eurocode 5 (EN 1995-1-1 2005) for timber with $\rho_k \leq 420\text{kg/m}^3$. Hereafter these sub-samples will be considered as reference sub-samples for the discussion of results. The spacing and end distances corresponding to the other sub-samples were adopted after analysing the results of preliminary tests carried out with the purpose of thoroughly studying the splitting tendency of this timber species when nails of small diameter are driven pneumatically. In order to avoid undue splitting, the geometrical parameters adopted for sub-samples $5_{2.5}$ and $5_{2.2}$ were empirically confirmed as an inferior limit.

Helical machine nails 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 perpendicularly to the grain along each row. With the aim of studying the influence of the diameter (d) on the mechanical behaviour of the joints, the two smallest sizes normally available were selected: $d = 2.5\text{mm}$ and $d = 2.2\text{mm}$. Taken into account 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 (EN 1995-1-1 2005) related to the point side penetration length (Figure 1). The number of nails was calculated to obtain connections with a load-carrying capacity similar to the design value of the maximum axial resistance of the boards normally used as members of trusses built with this timber species. Since the compression capacity is related to the member slenderness and compression members present unloaded ends which require lower end distance compared to loaded ends, the tension capacity was considered to be the axial capacity of these boards. This capacity was calculated by considering the characteristic strength in tension parallel to the grain adopted by IRAM 9662-2 (2006) for the best strength class of this timber species ($f_{t,0,k} = 18\text{N/mm}^2$) and the cross section of the boards used in this project (see Figure 1). After carrying out some preliminary tests with the nailed connections, it was decided to adopt 24 nails for the joints with 2.2mm -diameter nails and 21 nails for the joints with 2.5mm -diameter nails (Figure 1 and Table 1).

After assembly, the specimens were conditioned in a controlled climate at 20 ± 2 °C and 65 ± 5 % relative humidity. All tests were carried out in tension parallel to the grain according to the procedures of EN 1380 (2009) and EN 26891 (1991). The maximum



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load per nail within 15 mm slip of the joint, hereafter F_{max} , was registered in each test, and the characteristic value of F_{max} was calculated according to EN 14358 (2007). Slip was measured by means of two extensometers capable of registering 0,001mm. They were attached at opposite points to minimise the effects of distortion according to the procedures of EN 1380 (2009). Some details of the arrangement adopted for measuring slip may be appreciated in Figure 2.

In order to accurately determine the withdrawal capacity of the nails, 40 specimens (21 with 2.5mm-diameter nails and 19 with 2.2mm-diameter nails) were prepared and tested according to the procedures adopted by EN 1382 (2000). After determining the withdrawal parameter (f_{ax}) for each test, the corresponding characteristic value ($f_{ax,k}$) was calculated according to the criterion of EN 14358 (2007). The results of these tests were destined to accurately consider the additional resistance due to the rope effect which is taken into account by the Eurocode 5 (EN 1995-1-1 2005) in the equations corresponding to the failure modes (double shear) j and k.

Since the characteristic value of the fastener yield moment ($M_{y,RK}$) plays an important role in the equations adopted by the Eurocode 5 (EN 1995-1-1 2005) for calculating the capacity corresponding to the failure modes j and k, and with the aim of accurately determining the yield moment of the nails, 49 2.5mm-diameter nails and 48 2.2mm-diameter nails were tested by following the procedures adopted by EN 409 (2009). After determining the yield moment (M_y) for each nail at a bending angle of 45°, the characteristic value ($M_{y,RK}$) was calculated according to the criterion of EN 14358 (2007).

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 for all static tests. Moisture content and density (ρ) were calculated according to the procedures of ISO 3130 (1975) and ISO 3131 (1975) respectively, after all static tests. The characteristic value of density (ρ_k) was calculated according to EN 384 (2010).

3 Results and discussion

The characteristic density (ρ_k), obtained according to EN 384 (2010) for the whole samples (see Table 1), reached 411kg/m³. This result confirms the spacing and end distances adopted for the sub-samples 1_{2.5-E5,ref} and 1_{2.2-E5,ref} -considered as reference sub-samples- according to the criterion of Eurocode 5 (EN 1995-1-1 2005) for timber with $\rho_k \leq$



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420kg/m³. The whole samples exhibited a mean moisture content of 11.3% with a Coefficient of Variation (COV) of 0.05 and, consequently, an unequal influence of moisture content on the test results may be disregarded for this project.

3.1 Load-carrying capacity of the connections tested according to EN 1380 (2009)

The main results corresponding to the specimens laterally loaded according to EN 1380 (2009) are presented separately for each sub-sample in Table 2. No failure outside the connection area was registered. Since the load-carrying capacity of nailed joints was reported as a property highly correlated with density (Hilson 1995a, 1995b), a summary of the results for both properties 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 2 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 F_{\max} results obtained for the different sub-samples is assumed.

Table 2 shows that the maximum load-carrying capacity was found for the reference sub-samples ($1_{2.5.E5.ref}$ and $1_{2.2.E5.ref}$) and, as a general trend, both the mean and the characteristic value of F_{\max} decrease with decreasing spacing and end distances which is in line with the European experience (Blaß 1995; Hilson 1995a, 1995b). Sub-samples $2_{2.5}$ and $3_{2.5}$ exhibit a relatively low variability of F_{\max} results (COV = 9%) in comparison with that obtained for sub-samples $1_{2.5.E5.ref}$, $4_{2.5}$ and $5_{2.5}$ (COV ranging between 13% and 15%). COV values ranging from 5% to 27% show a high variability of the load-carrying capacity for the sub-samples enclosing specimens with 2.2mm-diameter nails. It is also possible to observe that, as a general trend, the COV values obtained for these sub-samples increase with decreasing spacing and end distances.

Sub-sample $4_{2.2}$ exhibits a particularly high F_{\max} mean value (1602N) in relation to its geometrical parameters and it presents the highest F_{\max} maximum value (2391N) of those obtained for the specimens with 2.2mm-diameter nails. Since it also shows the greatest variability of results (COV = 27%), its characteristic value (884N) is in line with the general trend observed for the characteristic values. A detailed analysis showed that the maximum value corresponding to Sub-sample $4_{2.2}$ (2391N) was obtained from a specimen presenting a particularly high density: 692kg/m³ for a middle member and 731kg/m³ / 607kg/m³ for the side members. However, the particular behaviour of the other specimens



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enclosed in this sub-sample could not be explained by means of the detailed analysis. It is also interesting to observe that the characteristic value of F_{\max} found for Sub-sample 1_{2.2-E5,ref} (1738N) is higher than that found for Sub-sample 1_{2.5-E5,ref} (1592N) which may be explained by the particularly low variability of F_{\max} results presented by the former (COV = 5%). Nevertheless, the unusually low variability of these F_{\max} results could not be explained by means of a detailed analysis carried out with the purpose of studying the particular behaviour of this sub-sample.

The F_{\max} results presented in Table 2, applied to the number of nails driven in each joint, confirm that the load-carrying capacity of the tested connections is similar to the axial capacity of the jointed boards, which may be calculated by means of the strength value (in tension parallel to the grain) and the cross section dimensions provided in Material and Methods. Since $a_2 = 5d$ in all cases (Table 1) and the boards of this timber species are produced with a constant thickness, the arrangement adopted for the connections in this project may be adapted for achieving the axial capacity of boards presenting different widths simply by adding (or reducing) the number of rows.

3.2 Failure mode of the connections

Mean values for the measured slip at maximum load range from 8.2mm to 10.9mm in the sub samples enclosing specimens with 2.5mm-diameter nails and from 7.6mm to 10.5mm in those containing specimens with 2.2mm-diameter nails (see Table 2). These values are in line with results previously reported for nail connections exhibiting a ductile failure (Johnsson and Stehn 2004). For the specimens with 2.5mm-diameter nails, the maximum slip mean value (10.9mm) was found for Sub-sample 1_{2.5-E5,ref} and the minimum mean value (8.2mm) was registered for Sub-sample 5_{2.5}. These results are in line with a higher utilization of the potential plastic capacity (Blaß 1995) by the specimens enclosed in the reference sub-sample. However, no clear relation between the geometrical parameters and slip at maximum load is observed for the sub-samples 2_{2.5}, 3_{2.5} and 4_{2.5}. For the specimens with 2.2mm-diameter nails, the sub-samples 5_{2.2} and 4_{2.2} exhibit the lowest slip mean values (7.6mm and 8.3mm respectively) which is congruent with their relatively small spacing and end distance. Nevertheless, no general relation between the geometrical parameters and slip at maximum load may be appreciated for the sub-samples 1_{2.2-E5,ref}, 2_{2.2} and 3_{2.2}.



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The load-slip curves displayed in Figure 3 illustrate the typical behaviour of the connections enclosed in sub-samples $1_{2.5-E5.ref}$, $3_{2.5}$ and $5_{2.5}$ which exhibit the highest, the intermediate and the lowest value of spacing and end distance of the connections with 2.5mm-diameter nails, respectively (see Table 1 and Figure 1). Even though the three curves show similar load-slip behaviour and no important differences may be appreciated for slip at maximum load (see also Table 2), it is interesting to observe that the load increases with increasing spacing and end distance for a given slip value, which indicates that the additional load-carrying capacity that could be activated after beginning the formation of plastic hinges also increased with increasing spacing and end distance. A relatively rapid increase of the load may be appreciated in the three curves up to approximately 40% of the maximum load. After that begins a range showing a continuous decrease of the slopes up to approximately 70% of the maximum load. Afterwards the slopes increase when the additional resistance due to the rope effect (Bejtka and Blaß 2002) is engaged and, finally, the slopes decrease gradually till the end of the test. Similar load-slip behaviour was also found for the connections with 2.2mm-diameter nails. The clear non-linear behaviour exhibited in Figure 3 shows that the formation of plastic hinges in the fasteners started at relatively low load levels in all sub-samples which may be explained by the relatively high slenderness (length to diameter ratio) of the nails. Johnsson and Stehn (2004) reported a linear behaviour up to a slip of 2.4mm for steel-to-timber (single shear) connections exhibiting a ductile failure and built-up with nails presenting a lower slenderness than that adopted in this research.

The development of fissures was analysed in detail for all sub-samples. It is important to point out that, before testing, practically no fissures were observed in the specimens enclosed in the sub-samples $1_{2.5-E5.ref}$ ($1_{2.2-E5.ref}$) and $2_{2.5}$ ($2_{2.2}$), a reduced number of light cracks developed during the driving-in of the nails were detected in those comprised in the Sub-sample $3_{2.5}$ ($3_{2.2}$) whereas the number and sizes of cracks increased in the sub-samples exhibiting the lowest spacing and end distances: $4_{2.5}$ ($4_{2.2}$) and $5_{2.5}$ ($5_{2.2}$). The development of new small cracks and the propagation of the pre-existent ones were visible and audible at approximately 40% / 50% of the maximum load. Even though at this load level the crack dimensions were not important in regard to the strength criterion, in all cases their number and sizes increased with decreasing spacing and end distance. The propagation of fissures strongly increased at approximately 85% / 90% of the maximum load and continued up to the end of the test. The presence of fissures at failure may be



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appreciated in Figure 4 for specimens belonging to three different sub-samples. The specimen of the Sub-sample $1_{2.5-E5,ref}$ shows only few light cracks whereas the number and sizes of fissures is much higher in the specimen belonging to Sub-sample $5_{2.5}$ which exhibits through-the-thickness fissures in some rows. An intermediate condition may be appreciated in the specimen belonging to Sub-sample $3_{2.5}$.

Two test specimens opened after reaching the maximum load are exhibited in Figure 5. The specimen belonging to Sub-sample $1_{2.5-E5,ref}$ was opened along a row without fissures whereas that corresponding to Sub-sample $5_{2.5}$ was opened along a row presenting an important through-the-thickness fissure in the side member (see also Figure 4). It may be clearly appreciated in Figure 5 the presence of plastic hinges in both cases but they exhibit a different level of development. On the one hand, the specimen of the reference sub-sample presents nail yield in bending at two plastic hinge points, which are situated in the middle member and the side member containing the head of the nail. This failure mode, which exhibits characteristics common to both j and k modes of Eurocode 5 (EN 1995-1-1 2005), also presents crushing of wood fibres near the shear planes. On the other hand, the specimen of Sub-sample $5_{2.5}$ exhibits only one plastic hinge developed in the middle member which is in line with the j mode of the European design rule. The important fissure developed in the row along which the specimen was opened may explain the absence of the plastic hinge in the side member containing the head of the nail. A detailed analysis showed that, even though with differences caused by the presence of fissures in some rows, the plastic hinges could be developed in all sub-samples.

No shear block was found in the Sub-sample $1_{2.5-E5,ref}$, whereas 25%, 15%, 36% and 94% of the specimens enclosed in sub-samples $2_{2.5}$, $3_{2.5}$, $4_{2.5}$ and $5_{2.5}$, respectively, exhibited shear block at failure as that illustrated in Figure 6. No shear block was found in the Sub-sample $1_{2.2-E5,ref}$ either whereas 9%, 10%, 36% and 40% of the specimens comprised in the sub-samples $2_{2.2}$, $3_{2.2}$, $4_{2.2}$ and $5_{2.2}$, respectively, exhibited this type of failure. The absence of shear blocks in both reference sub-samples confirms that the criterion adopted by Eurocode 5 (EN 1995-1-1 2005) is also suitable for the small-diameter nails used in this research. It is important to underline the important presence of shear-blocks in sub-samples $4_{2.2}$, $4_{2.5}$, $5_{2.2}$ and $5_{2.5}$ and, in particular, in the latter. However, the information collected during the testing process confirmed that shear block failures occurred after a significant deformation of the connections which is in line with the relatively high values found for slip at maximum load (Table 2) and also with the



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development of plastic hinges in the nails of all sub-samples (Figure 5).

According to the failure mode described in this subchapter, the differences in load-carrying capacity found between the different sub-samples (Table 2) may be explained as follows: i) the geometrical parameters adopted for the reference sub-samples ($1_{2.5-E5,ref}$ and $1_{2.2-E5,ref}$) minimized the development of fissures and avoided the presence of shear blocks at failure. Consequently, F_{max} was reached in these cases at load levels near the full potential plastic capacity of the connections, ii) the reduced spacing and end distances adopted for the other sub-samples provoked the development of fissures in some rows. Due to the relatively small diameter of the nails, the fissures normally exhibited small sizes up to approximately 85% / 90% of the maximum load. Consequently, the slender nails driven in these rows also developed plastic hinges, but they did not reach their full plastic capacity. This behaviour enhanced the non-uniform load distribution between the nails in the connection (Blaß 1991, 1994) and the failure occurred at a load level below the potential capacity of the joint, iii) shear block failures in the sub-samples with reduced geometrical parameters occurred after a significant deformation of the connections and also after the development of the fissures mentioned before. Therefore, they showed a global ductile behaviour -i.e. revealed capacity to deform and redistribute forces before brittle failure due to splitting or block shear occurred (Blaß 1995; Johnsson and Stehn 2004; Stehn and Börjes 2004)- even though they reached failure at load levels below their potential plastic capacity.

3.3 Load carrying capacity obtained according to the Eurocode 5

With the purpose of comparing the F_{max} characteristic values obtained empirically (Table 2) with those calculated according to the criterion of Eurocode 5 (EN 1995-1-1 2005), the equations provided by this European design rule for yield modes g, h, j and k of timber-to-timber joints (double shear) were applied to the investigated connections.

The European design rule considers the additional resistance caused by the rope effect (Bejtka and Blaß 2002) by adding $F_{ax,Rk}/4$ in the equations corresponding to the failure modes j and k, where $F_{ax,Rk}$ is the characteristic withdrawal load of the fastener. The European design rule also provides guidance for obtaining $F_{ax,Rk}$ as a function of the characteristic value of density, the nail diameter, and the point side penetration, but it is valid only for common smooth steel wire nails. Since this is not the type of nails used for



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this research and for accurately considering this additional resistance, 40 specimens were tested in withdrawal according to EN 1382 (2000) and the results are presented in Table 3. The f_{ax} values found for the specimens with 2.5mm-diameter nails are slightly higher than those obtained for the specimens with 2.2mm-diameter but the latter exhibit lower variability (COV = 23%) than the former (COV = 29%). Consequently, the characteristic value found for the withdrawal parameter ($f_{ax,k}$) was higher for the specimens with 2.2mm-diameter nails in spite of having a lower f_{ax} mean value. Since $l_p = t_1 = 21\text{mm}$ and taking into account the $f_{ax,k}$ values presented in Table 5, the additional resistance per nail according to the criterion of Eurocode 5 (EN 1995-1-1 2005) is: $F_{ax,Rk}/4 = f_{ax,k} l_p d/4 = 59\text{N}$ for the connections with 2.5mm-diameter nails and 60N for the joints with 2.2mm diameter nails.

The characteristic value of the fastener yield moment ($M_{y,Rk}$) plays an important role in the equations adopted by the Eurocode 5 (EN 1995-1-1 2005) for calculating the capacity corresponding to the failure modes j and k. The European design rule also gives guidance for obtaining $M_{y,Rk}$ as a function of the minimum tensile strength and the diameter of the nail, but it is valid only for common smooth steel wire nails. Since this is not the type of nails used for this research and, in addition, considering that results previously reported (NDS 2005) indicate that the bending yield strength increases with decreasing nail diameter, 97 specimens were tested and the results are presented in Table 4. The relatively high COV results presented in Table 4 indicate a variability of M_y results that may be considered excessive for steel fasteners. However, they are similar to those reported by Chui et al. (2000) for power-driven nails manufactured in Canada which reached values up to 13%. Anyway, the results were obtained in this research by following the procedures prescribed in EN 409 (2009) and show the real behaviour of the nails used in the analysed connections.

Since a thickness of 22mm was common to all members and a nail length of 65mm was used for all connections, the point side penetration into the side members (t_1) and the penetration into the main members (t_2) reached 21mm and 22mm respectively. Sosa Zitto et al. (2012) reported a characteristic embedding strength of 23.0 N/mm^2 for specimens of this timber species (without predrilling) with 5.5mm-diameter nails and exhibiting a characteristic density of 388kg/m^3 . The characteristic embedding strength of the specimens tested in this research was derived from the value reported in the paper mentioned before considering the influence of both the nail diameter and the wood density on this property.



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For this purpose, the criterion adopted by the Eurocode 5 (EN 1995-1-1 2005) was adopted. Consequently, and taking into account that the characteristic density found in this study reached 411kg/m^3 , the characteristic values of the embedding strength equal to 30.9N/mm^2 and 32.1N/mm^2 for the specimens with 2.5mm-diameter nails and 2.2mm-diameter nails respectively.

The load-carrying capacity per nail, calculated for the specimens with 2.5mm-diameter nails by means of the equations provided by the European design rule, reached 3245N, 1700N, 1356N and 1042N = $F_{v,Rk}$ for the failure modes g, h, j and k, respectively. The corresponding values for the specimens with 2.2mm-diameter nails were 2966N, 1554N, 1245N and 935N = $F_{v,Rk}$. These results, which show that the calculated load-carrying capacity is reached with the development of plastic hinges, are congruent with the failure modes found empirically; even though the full development of the plastic hinges was hampered in some rows due to the presence of fissures (see Sub-chapter 3.2 and Figure 5).

3.4 Comparison of experimental results and values obtained according to the Eurocode 5 (2005)

A comparison between the F_{max} characteristic value obtained empirically for the Sub-sample $1_{2.5-E5,ref}$ (1592N) and that calculated according to the criterion of the European design rule for the specimens with 2.5mm-diameter nails ($F_{v,Rk} = 1042\text{N}$) shows that the former is 53% higher than the latter. When comparing the corresponding values for the joints with 2.2mm-diameter nails the difference reaches 86%. However, in the latter case it is necessary to take into account that the F_{max} characteristic value obtained for the Sub-sample $1_{2.2-E5,ref}$ (1738N) is particularly high due to its exceptionally low COV (5%) as it was mentioned before. The empirical results proved that the structural design is situated on the conservative side if the equations adopted by the Eurocode 5 (EN 1995-1-1 2005) are applied to the analysed connections. Since the sub-samples $1_{2.5-E5,ref}$ and $1_{2.2-E5,ref}$ were prepared with the spacing and end/edge distances recommended by the European design rule and the properties of both the timber and fastener were determined according to the European standards, the important difference found between the empirical and the calculated load-carrying capacity may not be explained in this case. Nevertheless, it is important to take into account that the additional resistance caused by the rope effect is



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substantially greater for short-term loading -as that applied in this research- than for long-term loading. The Eurocode 5 (2005) considers the long-term effect by applying the modification factor (k_{mod}) to the characteristic value of the load-carrying capacity ($F_{v,Rk}$). However, the influence of the long-term behaviour on the load-carrying capacity of connections may be more unfavourable than that measured by means of the k_{mod} value.

According to the results of this study, the geometrical parameters adopted for sub-samples 5_{2.5} and 5_{2.2} should be disregarded for practical purposes connected with the structural design because they allow the development of excessive fissures and shear blocks at failure. Consequently, the analysis of the load-carrying capacity obtained for sub-samples 3_{2.5}, 4_{2.5}, 3_{2.2}, and 4_{2.2} becomes important. The F_{max} characteristic value exhibited in Table 2 for Sub-sample 4_{2.5} (1090N) is 5% higher than that of $F_{v,Rk} = 1042N$ calculated according to the Eurocode 5 (2005) for the joints with 2.5mm-diameter nails. Contrarily, the F_{max} characteristic value found for Sub-sample 4_{2.2} (884N) is 5% lower than that of $F_{v,Rk} = 935N$ calculated for the joints with 2.2mm-diameter nails. These results show that the geometrical parameters adopted for sub-samples 4_{2.5} and 4_{2.2} should be disregarded for these connections when the load-carrying capacity is calculated according to the European design rule. On the other hand, the F_{max} characteristic values obtained empirically for Sub-sample 3_{2.5} (1409N) and 3_{2.2} (1139N) are 35% and 22% higher than those of $F_{v,Rk} = 1042N$ and $F_{v,Rk} = 935N$, respectively. Consequently, and taking into account that the row lengths of these sub-samples reach 69% of the row lengths corresponding to the reference sub-samples, an important reduction (31%) of the connection length (and area) may be achieved without reducing the load-bearing capacity below the characteristic value determined according to the European design rule. In addition, the empirical results show that these joints developed ductile failures, i.e. exhibited ability to deform and redistribute forces (Stehn and Börjes 2004), in spite of their relatively low spacing and end distances.

4 Conclusions

The criterion adopted by the Eurocode 5 (EN 1995-1-1 2005) for calculating the lateral load-carrying capacity of nailed joints was checked for sawn timber of fast-growing Argentinean *Eucalyptus grandis* through the results of an empirical study aimed at analysing the mechanical behaviour of connections with power-driven nails of small diameter. 5 sub-samples enclosing a total of 64 specimens with 2.5mm-diameter nails and



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5 sub-samples enclosing a total of 54 specimens with 2.2mm-diameter nails were tested according to European standards. The load-slip behaviour of the analysed connections showed ductile failures even if they present a relatively low spacing and end distances and, consequently, they may advantageously perform in structures with relatively small dimensions at nodes. The empirical results showed that: i) the connections with reduced spacing and end distances exhibited a ductile behaviour but they did not reach their full plastic capacity. The additional resistance that could be activated after beginning the formation of plastic hinges decreased with decreasing spacing and end distances which is in line with the European experience, ii) the structural design is situated on the conservative side if the equations adopted by the Eurocode 5 (EN 1995-1-1 2005) are applied to the analysed connections when the spacing and end distances recommended by this design rule are used, iii) the joint area may be decreased up to 31% in relation to the area corresponding to the recommended spacing and end distances without reducing the load-bearing capacity below the characteristic value determined according to the European design rule. The results of this research encourage further studies aimed at thoroughly explaining the particular mechanical behaviour of these connections.

References

- Bejtka I, Blaß HJ (2002) Joints with inclined screws. Paper 35-7-5, Proceedings, CIB-W18 Meeting, Kyoto, Japan.
- Blaß HJ (1991) Untersuchungen zur Lastverteilung in Nagelverbindungen. Holz als Roh- und Werkstoff 49: 21-26
- Blaß HJ (1995) Multiple fastener joints. In: Timber Engineering STEP 1, pp. C15/1-C15/8. Centrum Hout, The Netherlands
- Blaß HJ (1994) Variation of load-slip behaviour in nailed joints: variation parallel to the grain. Forest Products Journal 44(1): 15-20
- Chui, Ying H, N Chun (2000) Performance of wood joints fastened with power-driven nails. Proceedings of the 6th World Conference on Timber Engineering (WCTE2000), British Columbia, Canada.
- EN 384 (2010) Structural timber–Determination of characteristic values of mechanical properties and density. European Committee for Standardization, Brussels
- EN 409 (2009) Timber structures–Test methods–Determination of the yield moment of



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- dowel type fasteners. European Committee for Standardization, Brussels
- EN 1380 (2009) Timber structures–Test methods–Load bearing nails, screws, dowels and bolts. European Committee for Standardization, Brussels
- EN 1382 (2000) Timber structures–Test methods–Withdrawal capacity of timber fasteners. European Committee for Standardization, Brussels
- EN 1995-1-1 (2005) Eurocode 5: Design of timber structures–Part 1-1: General–Common rules and rules for buildings. European Committee for Standardisation, Brussels
- EN 14358 (2007) Timber structures–Calculation of characteristic 5-percentile values and acceptance criteria for a sample. European Committee for Standardization, Brussels
- EN 26891 (1991) Timber structures–Joints made with mechanical fasteners. General principles for the determination of strength and deformation characteristics. European Committee for Standardization, Brussels
- Hartl H (1995) Truss connections with dowel-type fasteners. In: Timber Engineering STEP 2, pp. D1/1-1/13. Centrum Hout, The Netherlands
- Hilson BO (1995a) Nailed joints. In: Informationsdienst Holz, Holzbauwerke, STEP 3. Arbeitsgemeinschaft Holz e. V., Düsseldorf, pp 7/1-7/22
- Hilson BO (1995b) Nailed joints I. In: Timber Engineering STEP 1, pp. C4/1-C4/8. Centrum Hout, The Netherlands
- INTA (1995) Manual for producers of eucalyptus of the Argentinean Mesopotamia. Forestry Group, National Institute of Technology for Farming, EEA Concordia, Argentina (In Spanish)
- IRAM 9662-2 (2006) Glued laminated timber. Visual strength grading of boards, part 2: boards of *Eucalyptus grandis*. Argentinean Institute for Standardization and Certification, Buenos Aires (In Spanish)
- ISO 3130 (1975) Wood–Determination of moisture content for physical and mechanical tests. International Organization for Standardization
- ISO 3131 (1975) Wood–Determination of density for physical and mechanical tests. International Organization for Standardization
- Johnsson H, Stehn L (2004) Plug shear failure in nailed timber connections. Holz als Roh- und Werkstoff 62: 455-464
- Kessel MH (1995) Trusses. In: Timber Engineering STEP 1, pp. B12/1-B12/8. Centrum Hout, The Netherlands
- NCh 1198 (2007) Wood-wood constructions-calculation. National Institute for Standardization



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Facultad Regional Concepción del Uruguay

INN-Chile, Santiago (In Spanish)

NDS (2005) National Design Specification for Wood Construction. American Forest & Paper Association, Washington

Sosa Zitto, M.A., Köhler J., Piter J.C. (2012) Embedding strength in joints of fast-growing Argentinean *Eucalyptus grandis* with dowel-type fasteners. Analysis according to the criterion adopted by European standards. *European Journal of Wood and Wood Products* 70(4): 433-440

Stehn L, Börjes K (2004) The influence of nail ductility on the load capacity of a glulam truss structure. *Engineering Structures* 26: 809-816



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Table 1. Samples prepared for testing according to EN 1380 (2009)

a_1 : spacing parallel to the grain; a_2 : spacing perpendicular to the grain; a_3 : loaded end distance; a_4 : edge distance; d : nail diameter; n : number of specimens

Tabelle 1. Teilstichproben

a_1 : Abstand zwischen den Nägeln innerhalb einer Reihe in Faserrichtung; a_2 : Abstand zwischen den Nägeln rechtwinklig zur Faserrichtung; a_3 : Abstand zum beanspruchten Hirnholzende; a_4 : Abstand zum unbeanspruchten Rand; d : Nageldurchmesser; n : Anzahl der Prüfkörper

Nail diameter (mm)	Description of the connection	Whole Samples	Spacing and end distances adopted for the sub-samples				
			$a_1=10d$; $a_3=15d$	$a_1=7d$; $a_3=12d$	$a_1=7d$; $a_3=10d$	$a_1=7d$; $a_3=7d$	$a_1=5d$; $a_3=7d$
			Sub-samples				
2.5	21-nail specimens (7 rows of 3 nails each) $a_2= a_4=5d$ for all sub-samples	(n=64)	$1_{2.5-E5.ref}$	$2_{2.5}$	$3_{2.5}$	$4_{2.5}$	$5_{2.5}$
			(n=12)	(n=12)	(n=13)	(n=11)	(n=16)
2.2	24-nail specimens (8 rows of 3 nails each) $a_2= 5d$; $a_4=5.2d$ for all sub-samples	(n=54)	$1_{2.2-E5.ref}$	$2_{2.2}$	$3_{2.2}$	$4_{2.2}$	$5_{2.2}$
			(n=12)	(n=11)	(n=10)	(n=11)	(n=10)



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Table 2. Summary of results corresponding to the connections tested according to EN 1380 (2009)

a_1 : spacing parallel to the grain; a_3 : loaded end distance; (1): maximum load per nail within 15mm slip according to the criterion of EN 1380 (2009) and EN 26891 (1991). (2): characteristic value obtained according to EN 14358 (2007); (3): corrected to a reference moisture content of 12% according to EN 384 (2010); n: number of specimens

Tabelle 2. Ergebnisse für die Verbindungen geprüft nach EN 1380 (2009)

a_1 : Abstand zwischen den Nägeln innerhalb einer Reihe in Faserrichtung; a_3 : Abstand zum beanspruchten Hirnholzende; (1): maximale Last pro Nagel nach EN 1380 (2009) und EN 26891 (1991); (2) charakteristischer Wert berechnet nach EN 14358 (2007); (3) umgerechnet auf eine Bezugsfeuchte von 12% nach EN 384 (2010); n: Anzahl der Prüfkörper

Nail diameter		Sub samples					
		1 _{2.5-E5,ref} (n=12)	2 _{2.5} (n=12)	3 _{2.5} (n=13)	4 _{2.5} (n=11)	5 _{2.5} (n=16)	
2.5mm	$F_{max}^{(1)}$ per nail (N)	Min	1714	1476	1434	1121	920
		Mean	2213	1624	1708	1462	1220
		Max	2560	1855	2041	1728	1626
		COV (%)	15	9	9	13	15
		Charact. ⁽²⁾	1592	1354	1409	1090	900
	Slip at maximum load (mm)	Min	6.1	5.0	5.7	3.5	3.0
		Mean	10.9	9.0	10.0	9.1	8.2
		Max	16.8	12.6	12.4	12.9	11.3
		COV (%)	27	29	22	28	30
	Density ⁽³⁾ (kg/m ³)	Mean	495	512	511	510	522
		COV (%)	13	14	13	13	12
	2.2mm	$F_{max}^{(1)}$ per nail (N)	Min	1762	1181	1185	1001
Mean			1940	1403	1359	1602	1099
Max			2113	1717	1561	2391	1406
COV (%)			5	11	8	27	15
Charact. ⁽²⁾			1738	1116	1139	884	800
Slip at maximum load (mm)		Min	4.4	4.7	6.3	3.6	4.7
		Mean	8.9	10.0	10.5	8.3	7.6
		Max	12.0	14.5	13.1	12.6	10.9
		COV (%)	25	31	18	34	31
Density ⁽³⁾ (kg/m ³)		Mean	502	541	506	553	514
		COV (%)	13	15	13	15	14



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Table 3. Summary of results corresponding to the specimens tested in withdrawal according to EN 1382 (2000)

(1): withdrawal parameter; $F_{ax,max}$: maximum withdrawal load per nail (N); d: nail diameter (mm); l_p : length of penetration (mm); (2): characteristic value obtained according to EN 14358 (2007); (3): corrected to a reference moisture content of 12% according to EN 384 (2010); n: number of specimens

Tabelle 3. Ergebnisse der Ausziehtragfähigkeit

(1): Ausziehparameter; $F_{ax,max}$: maximale Ausziehlast pro Nagel (N); d: Durchmesser eines Nagels (mm); l_p : Eindringtiefe des Nagels (mm); (2): charakteristischer Wert berechnet nach EN 14358 (2007); (3) umgerechnet auf eine Bezugsfeuchte von 12% nach EN 384 (2010); n: Anzahl der Prüfkörper

2.5mm-diameter	$f_{ax}^{(1)} = F_{ax,max} / (d \cdot l_p)$ (N / mm ²)	Min	4.2
		Mean	8.9
		Max	13.8
	(n=21)	COV (%)	29
		$f_{ax,k}^{(2)}$	4.5
		Density ⁽³⁾ (kg/m ³)	Mean
(n=21)	COV (%)	12	
2.2mm-diameter	$f_{ax}^{(1)} = F_{ax,max} / (d \cdot l_p)$ (N / mm ²)	Min	4.5
		Mean	8.4
		Max	12.7
	(n=19)	COV (%)	23
		$f_{ax,k}^{(2)}$	5.2
		Density ⁽³⁾ (kg/m ³)	Mean
(n=19)	COV (%)	9	



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Table 4. Summary of results corresponding to the yield moment of the nails tested according to EN 409 (2009)

(1): characteristic value obtained according to EN 14358 (2007)

Tabelle 4. Ergebnisse des Fließmoments von den Nägeln

(1): charakteristischer Wert berechnet nach EN 14358 (2007)

2.5mm-diameter	M_y (Nmm) (n=49)	Min	922
		Mean	1356
		Max	1684
		COV (%)	13
		$M_{y,Rk}^{(1)}$	1044
2.2mm-diameter	M_y (Nmm) (n=48)	Min	731
		Mean	1123
		Max	1309
		COV (%)	11
		$M_{y,Rk}^{(1)}$	890



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Figure 1. Test arrangement.

Board sizes after surfacing: $b = 100\text{mm}$, $t_2 = 22\text{mm}$; point side penetration into the side member: $t_1 = 21\text{mm}$; number of nails 2.5mm-diameter and 65mm long in each connection: 21 nails (7 rows of 3 nails each); number of nails 2.2mm-diameter and 65mm long in each connection: 24 nails (8 rows of 3 nails each)

Abbildung 1. Prüfanordnung

Brettabmessungen nach dem Hobeln: $b = 100\text{mm}$, $t_2 = 22\text{mm}$; Einbindetiefe auf der Seite der Nagelspitze: $t_1 = 21\text{mm}$; Anzahl von Nägeln für jede Verbindung mit Nägeln mit 2.5mm-Durchmesser und 65mm Länge: 21 Nägel (7 Reihe mit 3 Nägel pro Reihe); Anzahl von Nägeln für jede Verbindung mit Nägeln mit 2.2mm-Durchmesser und 65mm Länge: 24 Nägel (8 Reihe mit 3 Nägel pro Reihe)

Figure 2. Arrangement adopted for measuring slip

Abbildung 2. Anordnung der Messpunkte zur Ermittlung der Verschiebung

Figure 3. Load-slip curves from tests

(—): sub-sample $1_{2.5-E5,ref}$, (-----): sub-sample $3_{2.5}$, (.....): sub-sample $5_{2.5}$

Abbildung 3. Lastverschiebungskurven von Versuchen

(—): Probe $1_{2.5-E5,ref}$, (-----): Probe $3_{2.5}$, (.....): Probe $5_{2.5}$

Figure 4. Development of fissures at maximum load

Abbildung 4. Ausbildung von Rissen unter der Bruchlast

Figure 5. Test specimens opened after testing

Abbildung 5. Aufgetrennter Prüfkörper nach dem Versuch

Figure 6. Shear block in the middle member of one specimen



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Abbildung 6. Blockscherversagen im Mittelholz

Figure 1

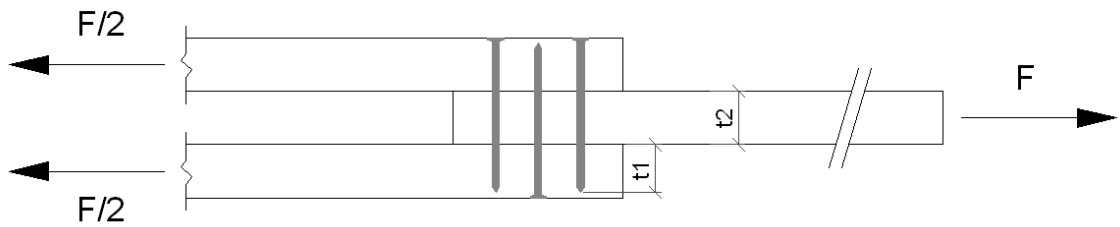
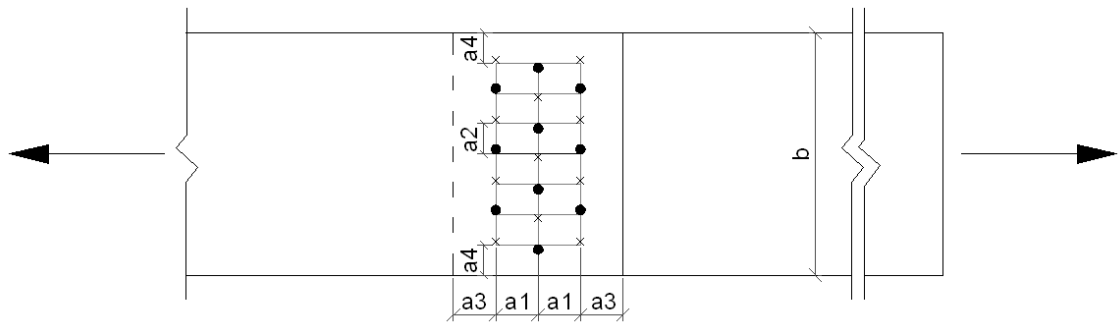


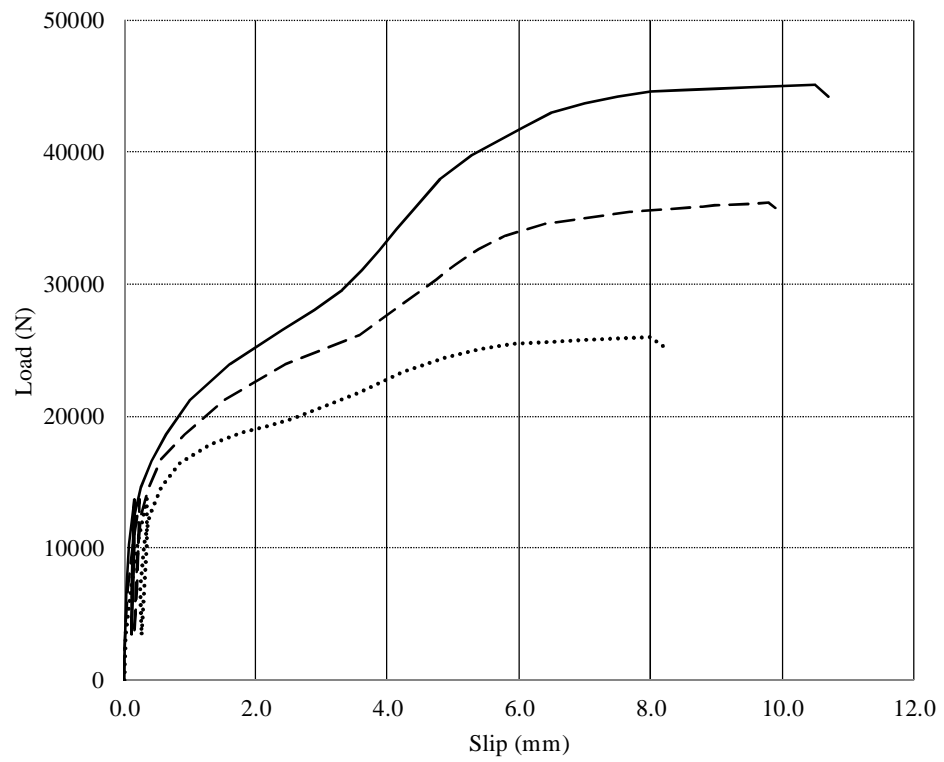
Figure 2



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Figure 3





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Figure 4

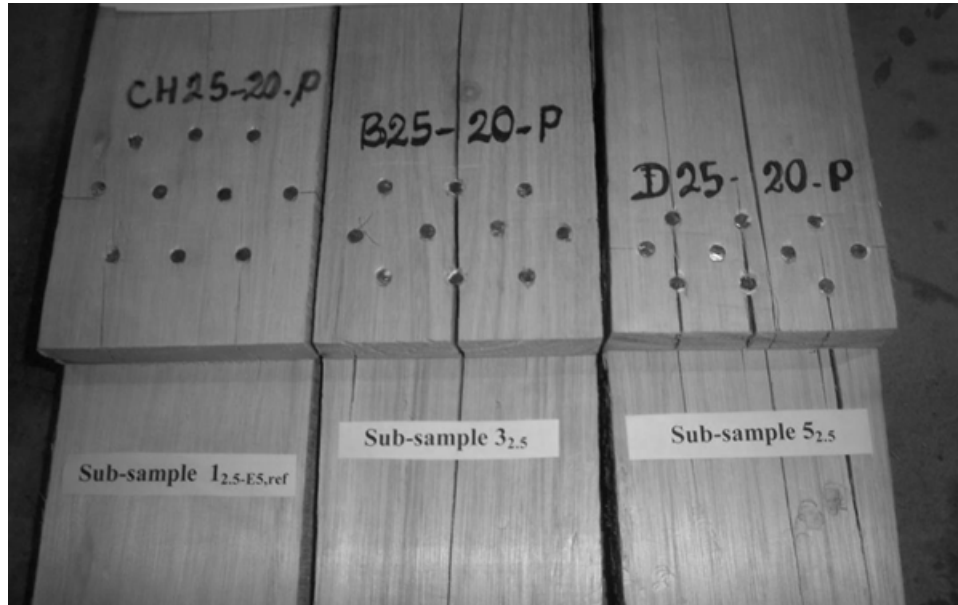
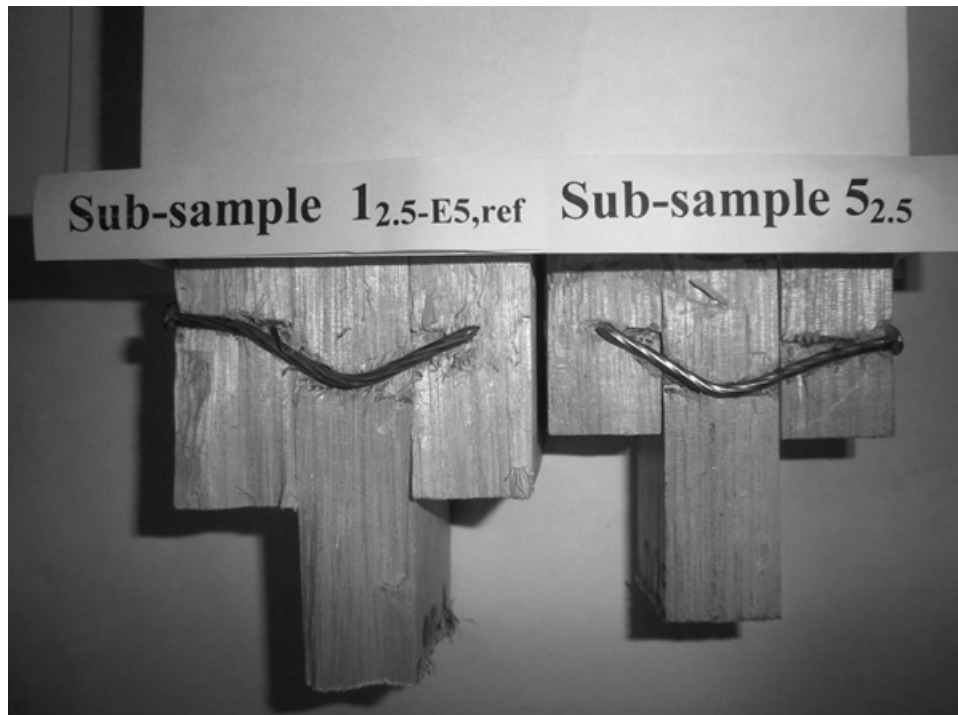


Figure 5





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Figure 6

