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LOAD-BEARING CAPACITY OF METAL CONNECTOR PLATES DEPENDING ON LOCATION AND GEOMETRY OF THE NAIL

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ABSTRACT

This paper presents results of the experimental determination of the load-bearing capacity of structural timber connections realized by nail metal connector plates as a function of nail location, length and diameter. Three different diameters of the nails have been used, specifically 2.0, 2.5, and 3.1 mm. The length of the metal nails in connectors has been determined after the detailed analysis, and kept at 20 mm during the experimental research. Nails distribution over the connector plate is such that it forms the series of equilateral triangles, so that a side of the triangle equals five times the diameter of the nails used. Preceding the testing, and while using the above listed parameters certain analysis has been done. In order to experimentally determine the load-bearing capacity of the nail metal connectors, the penetration depth, i.e. the length of the nails has been kept constant, while using three different nail diameters. The testing has been done on multiple samples in the accordance with Eurocode 5.

KEYWORDS: Failure mode, load-bearing capacity, metal connector plate, nails, nail length, nail diameter.

INTRODUCTION

Connectors are modern mechanical connection used for timber constructions, developed as a result of an extensive research with intention to improve load bearing connections and create joint connections in timber trusses (Tekić 2007). Nail metal connectors differ from the standard metal connectors made by the various manufactures worldwide. While these connectors use metal nails perpendicular to the connecting plate, standard metal connectors use prongs created by punching holes in the metal plate.

The distribution of the nails on a plate could vary and it is dictated by the minimum allowed spacing of the nails used in the connection of the timber elements in combination with thin or thick steel plates. The geometrical distribution of the nails in a connection is dictated by the set or rules. These rules are derived from a basis principles stating that integrity of the connection must be preserved not allowing any cracks while creating the connections and during the explorations. The lines and the rows have been used to create a nail connection. Nails driven along the wood grain create lines, and nails driven perpendicular to the wood grain crate rows (Kujundžić et al. 2004). Keeping this in mind, a nail connection can be formed by distributing nails in full and alternating rows (Fig. 1).

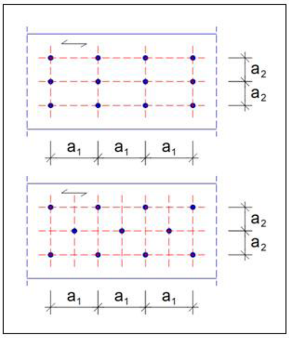

Fig. 1: Mutual positions of the nails in connection.

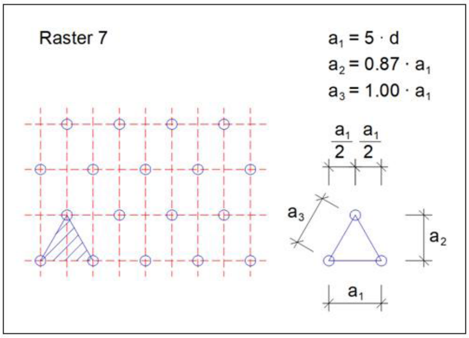

Fig. 2: Mutual positions of the nails in nail metal connector plate.

A load-bearing capacity of the nail connection has been based on the load-bearing capacity of the single nail, and it represents the sum of all the individual values of all nails used to form that connection. For this reason, in order to achieve higher load-bearing capacity of a connection, larger number of nails must be used. The concept of nail metal connectors considers the minimum spacing of nails in a connection according to the permissible stress design and the limit state design. One such analysis showed that the largest number of nails is achieved if the connection is formed by using the alternate rows. This resulted in a concept in which nail metal connectors form an equilateral triangle, in which the nails form the vertices of the triangle and a length of a side of a triangle is equal to the value of several diameters of the nail, but not less that the value of the five times the diameter of a nail (Tekić et al. 2017) (Fig. 2). The largest number of nails per unit of connector obtained this way will result in the greater load-bearing capacity of the connection.

The concept of nail metal connector plate includes the use of a nail that has circular cross-section, which eliminates the angle α (angle between direction of force and direction of longitudinal axis of connector) which is defined in the case of standard types of metal connectors.

This simplifies the procedure of dimensioning of connections realized by nail metal connector plates, since the verification of the anchorage capacity has been done only in function of angle β (angle between direction of force and direction of the longitudinal axis of timber member).

In addition to the placement of the nails in a connection, the diameter of a nail and its penetration depth into the wood are additional variables that can significantly influence the load bearing capacity of a nail metal connector plate which can also have an economic impact in use and mass production of it. It is also important to notice that the connectors have been used on the both sides of a member and that penetration depth must not be greater than the half of the member's cross section. A classic nail connection allows overlapping of the opposite pairs of the nails, while standard types of metal connectors using prongs do not permit such connections. Depending on the manufacturer, the length of the prongs in standard types of metal connectors is between 8 mm and 20 mm. For this reason, the maximum reach of the tip of the nail in nail metal connector is allowed to reach the middle of the cross section of the timber element. Since the cross section of the most commonly used timber members is from 40 to 60 mm, the recommendation is that the penetration depth of the nail into the timber be no more than 20 mm. Due to local cracking of the wood during impression of the connector into the timber element, the diameter of the nail should be limited to $d<4.2$ mm.

Further down in this paper, load-bearing capacity of a different diameter metal nails will be determined analytically in accordance with Eurocode 5 (EC5). The values obtained this way will allow comparing how the different diameters of the nails are influencing the load-bearing capacity of the nails in the connection, and the conclusions will be drawn on how to determine the length of the nail and its penetration depth into the wood as a function of its radius. Also, this analytical analysis of the load-bearing capacity of the nails is significant because its results will be used to compare and understand the differences with the ones obtained experimentally.

Side by side analysis of analytical and experimental results should determine if there is a correlation between these values of the load-bearing capacities of the nails, and if this approach can be used to conceptualize nail metal connectors. The nails that will be the subject of further analysis and later used to design the nail metal connector are of circular cross section with three different diameters 2.0 mm, 2.5 mm and 3.1 mm. Their length will be determined in the detailed analysis that follows.

Load-bearing capacity for nails in single shear steel-to-timber connections

Dimensioning of connections in timber structures, realized by metal dowel-type fasteners is conducted according to Johansen's theory (Johansen 1949). This theory is the basis for determining the load-bearing capacity of the fasteners defined in Eurocode 5 (EN 1995, 2004). Fig. 3 shows possible failure modes for steel-to-timber connections (for thin and thick steel plates in single shear connections) in function of the thickness of the connected timber member, diameter of the fastener and thickness of the steel sheet (EN 1995, 2004). Thin steel plates are classified as plates of thickness $t \leq 0.5.d$, while thick steel plates are classified as plates of thickness $t \geq d$, with the tolerance on holes diameters being less than $0.1.d$, where t is the steel plate thickness, and d is the fastener diameter (EN 1995, 2004). Depending on the geometry of the connection and mechanical properties of the timber and steel, the load being distributed through the connection can cause two types of deformations (Blass 2003):

- in thin plates, the connecting fastener is rotated with the respect to its starting, non-deformed line of symmetry (pinned connection - failure A and B),
- in thick plates, the connecting fastener and the steel plate are fixed to a certain degree (fixed connection - failure C, D and E).

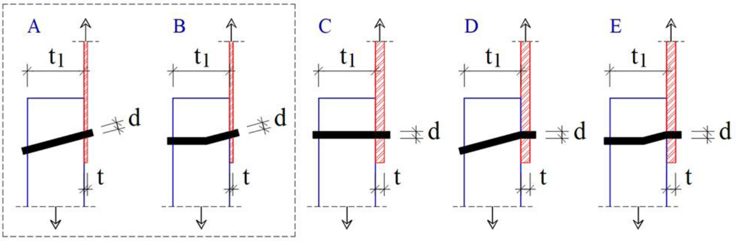

Fig. 3: Possible failure modes for steel-to-timber connections.

Since the thickness of the plate used in the connection is d=1.0 mm, failure modes A and B are relevant for analytical calculation of the load-bearing capacity of the fastener in the connection. The characteristic load-bearing capacity of the fasteners in single shear steel-to-timber connections, for thin steel plates, i.e. for t≤0.5.d, should be adopted as the lowest value obtained from the following terms:

$$F_{v,Rk} = \min \begin{Bmatrix} 0.4 \cdot f_{h,k} \cdot t_1 \cdot d \\ 1.15 \cdot \sqrt{2 \cdot M_{y,Rk} \cdot f_{h,k} \cdot d} + \dfrac{F_{ax,Rk}}{4} \end{Bmatrix}, \quad \text{(N)} \qquad (1)$$

For nails with diameters up to 8 mm, without predrilled holes, the following characteristic embedment strengths in timber apply:

$$f_{h,k} = 0.082 \cdot \rho_k \cdot d^{-0.3}, \qquad (\mathrm{N{\cdot}mm^{-2}}) \qquad (2)$$

For smooth round nails produced from wire with a minimum tensile strength of f_u=600 N·mm^{-2} the following characteristic values for yield moment should be used:

$$M_{y,Rk} = 0.3 \cdot f_u \cdot d^{2.6}, \qquad (\mathrm{N{\cdot}mm^{-2}}) \qquad (3)$$

Tab. 1 and Fig. 4 show the results for the load-bearing capacity of the nails according to the predefined conditions, and for the length of the nails of L=20 mm, and their penetration depth of s=19 mm.

Tab. 1: Load-bearing capacity of the nails in single shear connections according to EC5.

Symbol	Unit	Nail		
		E 20/20	**E 25/20**	**E 31/20**
d	mm	2.0	2.5	3.1
L	mm	20	20	20
s	mm	19	19	19
ρ_k	kg·m^{-3}	400	400	400
$f_{h,k}$	N·mm^{-2}	23.31	21.80	20.44
$M_{y,Rk}$	Nmm	1091.30	1949.47	3410.46
$F_{v,Rk,1}$	N	354	414	482
$F_{v,Rk,2}$	N	367	530	756

The presented symbols are defined as:
t - steel plate thickness, (mm)
t_1 - timber thickness or penetration depth, (mm)
d - nail diameter, (mm)
L - nail length, (mm)
s - penetration depth of the nail, (mm)
ρ_k - characteristic density of wood, ($kg \cdot m^{-3}$)
$f_{h,k}$ - characteristic embedment strength in the timber member, ($N \cdot mm^{-2}$)
$M_{y,Rk}$ - characteristic yield moment of the nail, (Nmm)
$F_{v,Rk,1}$ - characteristic load-bearing capacity per shear plane per nail (failure A), (N)
$F_{v,Rk,2}$ - characteristic load-bearing capacity per shear plane per nail (failure B), (N)
f_u - tensile strength of the wire, ($N \cdot mm^{-2}$)
$F_{ax,Rk}$ - characteristic axial withdrawal capacity of the nail, (N).

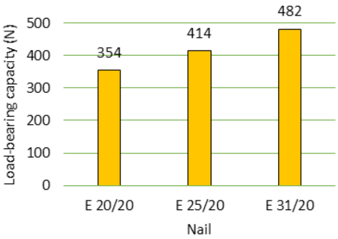

Fig. 4: Load-bearing capacity of the nails in single shear connections according to EC5.

Aside from its diameter, load-bearing capacity of the nails is also dictated by their penetration depth (*s*), which is evident from the expression for the characteristic load-bearing capacity of the fasteners in single shear steel-to-timber connections, failure mode (*A*). When considering the concept of the nail metal connectors, penetration depth of the nails is significant for two reasons:

- load-bearing capacity of the connectors is a function of nail penetration depth,
- from the stand point of the material usage, the economy of the nail metal connector.

In the nail metal connector design, the primary goal is to increase the load-bearing capacity, while the economic aspect is less important, except when the increase of the penetration depth is justified from the aspect of increasing the load-bearing capacity. A varying the penetration depth of the nails to determine their load-bearing capacity analytically while designing the metal nail connector will help to calculate the correct nail length. Tab. 2 and Fig. 5 represent the load-bearing capacity of the nails for the various penetration depths.

Based on the calculated values of the load-bearing capacities of the nails, it can be concluded that increased penetration depth of the nails will increase their load bearing capacity; however, only up to a certain point and up until the ratio of the length and the diameter of the nails is such that a failure happens in accordance with the failure mode A - nail rotation. This is especially noticeable with a smaller diameter nails, which can be seen in E 20 nails. By increasing the length of the nails, and thus their penetration depth which would result in increase steel deformations along the longitudinal line of symmetry of the nails, failure mode (*B*) becomes more relevant. Practically, this means that using nails with the diameter of d=2.0 mm that are longer than 20 mm will have no effect on a load bearing capacity, which can have a significant economic impact.

Tab. 2: Load-bearing capacity of the nails in single shear connections as a function of penetration depth (EC5).

Penetration depth s (mm)	**Fv,Rk (N)**		
	E 20	E 25	E 31
19	354	414	482
20	367	436	507
21	367	458	532
22	367	480	558
23	367	501	583
24	367	523	608

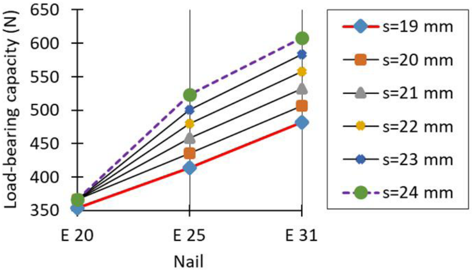

Fig. 5: Load-bearing capacity of the nails in single shear connections as a function of penetration depth (EC5).

Dimensioning of the connections formed by metal connectors

The nail metal connector plate anchorage capacity is defined on the basis of EN 1075 (1999) and EN 28970 (1991) standards, in function of the ultimate load, effective connector area and wood density:

$$f_{a,\alpha,\beta} = \frac{F_{\alpha,\beta,\max}}{2 \cdot A_{ef}} \cdot \left(\frac{\rho_k}{\rho}\right)^c, \qquad (\mathrm{N{\cdot}mm^{-2}}) \qquad (4)$$

where: $f_{a,\alpha,\beta}$ - ultimate plate anchorage capacity for given angles α and β (for one connector in connection),

α - angle between direction of force and direction of the longitudinal axis of connector, (rad)

β - angle between direction of force and direction of the longitudinal axis of timber member, (rad)

$F_{a,\alpha,\beta,max}$ - maximum load, (N)

A_{ef} - effective connector area, (mm^2)

ρ_k - characteristic density of wood, for certain class of wood, ($kg{\cdot}m^{-3}$)

ρ - density of wood, for the test sample, ($kg{\cdot}m^{-3}$)

c - dimensionless coefficient.

MATERIAL AND METHODS

Experimental testing was conducted by loading of multiple samples up to the ultimate bearing capacity of connection realized by nail metal connector plate, in accordance with the provisions of Eurocode 5. Before the formation of the test samples nail metal connectors were made, with disposition of nails on the plate in accordance with the adopted concept, within which the nails form a network of equilateral triangles whose edges are equal to the fivefold value of nail diameter (Fig. 6). Nails which have been used for the production of connectors have been made according to standard SRPS EN 10230-1 (2010), with a flat circular head and labels E 20/20, E 25/20 and E 31/20 (diameter 2.0 mm, 2.5 mm, 3.1 mm and length 20 mm). The nails have been embedded into the connector's plate in the pre-drilled holes, whose diameter was 70% of the diameter of the nails.

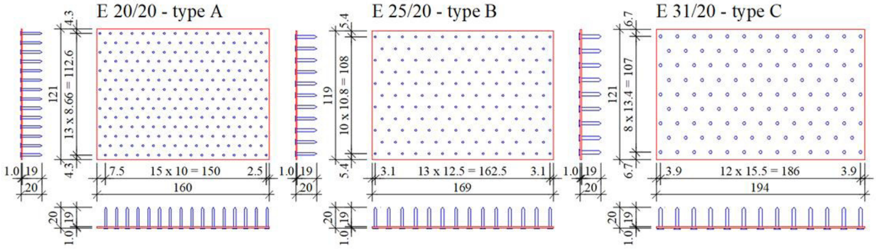

Fig. 6: Geometry of the nail metal connector plates.

The thickness of the steel plate which has been used for the production of connectors is d=1.0 mm, with the quality of the material in accordance with EN 10025 (2011). Solid spruce wood of class C24 has been used for the test samples, according to EN 338 (2003), with humidity of 15%, and a bulk density ρ=350 kg·m^{-3}, according to EN 408 (2010). Experimental determination of the anchorage capacity of connection for three samples in one test group, whose geometry has been realized in accordance with EN 1075 (1999) has been conducted, and the value of angle β=0° has been adopted (Fig. 7). Dimensions of the cross-section of timber members subjected to tension were 44/140 mm.

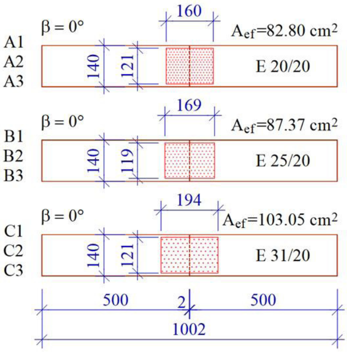

Fig. 7: Types of samples for testing.

The width of the cross-section of a timber element of 44 mm makes it possible, after the installation of nail connectors into the wood, not to overlap the two opposite nails, that is, that the tips of the nails are at a certain distance from each other, which is important for the bearing capacity of the connection. By choosing the mentioned parameters, as well as on the basis of previous experiences, it can be concluded that the failure will not occur on the plate of the connector, which is certainly important, because the goal is to determine the load-bearing capacity of the steel-to-timber connection in this experiment.

The forming of samples was conducted in production facility of LKV Center from Belgrade. The embedding of the nail metal connector plates into the wood was performed by hydraulic press with the capacity of 240 kN. First, the connector plate was embedded on one side of the sample, and then on the other side of the sample.

Experimental testing procedure

Experimental testing of samples was preceded by conditioning of timber elements, that is, conditioning of samples as a whole, after the installation of nail connectors into the two timber elements, all in accordance with ISO 554 (1976) standard (the air temperature of 20°C and moisture content of 65%). Testing of the load-bearing capacity of realized connections was performed on the hydraulic tensile testing machine, made by Amsler. The deformations of the connections were registered with mechanical deformation indicators, with 0.01 mm accuracy; which were positioned on the both sides of the sample (Fig. 8).

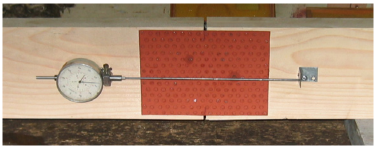

Fig. 8: Samples for testing.

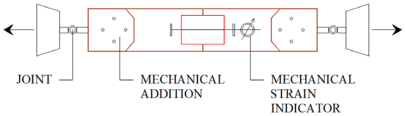

Fig. 9: Application of tensile force.

Testing procedure was conducted according to EN 26891 (1991). Load was applied in the value of 40% of the estimated maximum load and retained for 30 seconds. Then the load was reduced to a value of 10% of the estimated maximum load and retained for 30 seconds. The load was then raised until ultimate load or displacement was attained. Total test time of one sample was about 15 minutes. Application of tensile force was carried out through certain mechanical additions (Fig. 9). The tensile force was applied with an increment of 4.0 kN. Failure of connections occurred only due to overdrawn allowable displacements of the connection. The testing of each sample was discontinued after the destruction of connection, when the beginning of nails pulling out of wood was visually ascertained, during the displacement of the connection within the limits between 2.0 and 4.0 mm.

RESULTS

Results of the experimental testing have been shown on the force-displacement diagrams, which present the individual values of connection displacement and the mean values (Fig. 10, 11, 12, 13, 14 and 15).

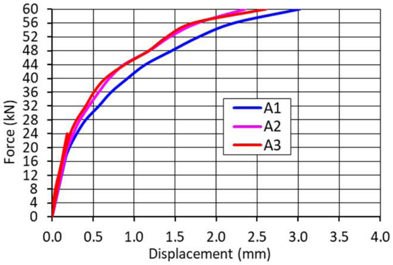

Fig. 10: Force-displacement diagram (individual values).

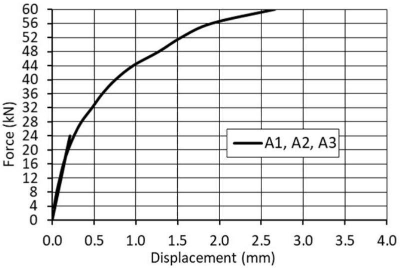

Fig. 11: Force-displacement diagram (mean value).

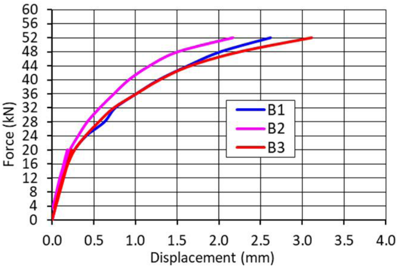

Fig. 12: Force-displacement diagram (individual values).

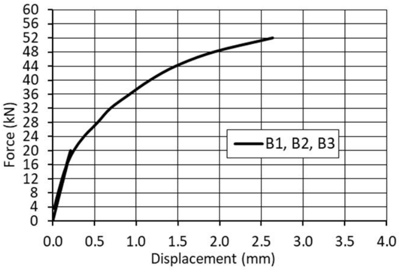

Fig. 13: Force-displacement diagram (mean value).

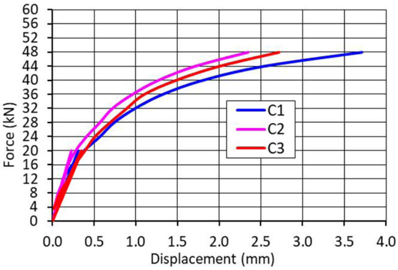

Fig. 14: Force-displacement diagram (individual values).

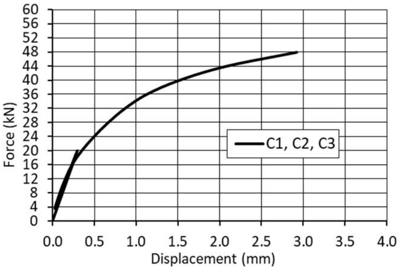

Fig. 15: Force-displacement diagram (mean value).

Characteristic parameters in accordance with EN 26891 (1991) are shown in Tab. 3 (Fest - estimated maximum load, F_{max} - maximum load for the adopted allowable displacements of connection, v01 - displacement for the value of 10% of estimated maximal load, v_{04} - displacement for the value of 40% of estimated maximum load, v_{06} - displacement for the value of 60% of estimated maximum load, v08 - displacement for the value of 80% of estimated maximum load and v_{max} - maximum displacement). Load F_{est} has been estimated to amount to 60 kN for test group (A) and 50 kN for test groups (B) and (C), based on the results of previous experimental testing, for the displacement of connection in limits between 2.0 mm and 3.0 mm. In the discussion of the test results, the ultimate load-bearing capacity of connection for the different values of the shown displacements of connection has been determined.

Tab. 3: Test results.

	Load		Displacement				
Sample	**F_{est} (kN)**	**F_{max} (kN)**	**v_{01} (mm)**	**v_{04} (mm)**	**v_{06} (mm)**	**v_{08} (mm)**	**v_{max} (mm)**
A1	60	57.40	0.03	0.23	0.72	1.46	3.02
A2	60	60.00	0.02	0.22	0.57	1.19	2.36
A3	60	59.51	0.02	0.19	0.51	1.18	2.61
The average values							
A	60	58.97	0.027	0.213	0.600	1.277	2.663
B1	50	51.20	0.02	0.12	0.69	1.28	2.62
B2	50	52.00	0.01	0.18	0.49	0.92	2.17
B3	50	49.16	0.04	0.23	0.65	1.29	3.11
The average values							
B	50	50.79	0.023	0.210	0.613	1.163	2.633
C1	50	43.90	0.05	0.31	0.86	1.81	3.71
C2	50	48.00	0.03	0.23	0.64	1.27	2.35
C3	50	46.78	0.03	0.35	0.79	1.48	2.72
The average values							
C	50	46.23	0.037	0.297	0.767	1.517	2.927

DISCUSSION

Based on the given diagrams, the differences in displacements of the connections in test groups *(A), (B)* and *(C)*, for the same values of the applied load can be noted. For all connections, minor differences in displacements to the extent of 0.4.Fest can be noted, whereupon the increase of deformation is higher for the connections in test groups *(B)* and *(C)*, relative to the connections in test group *(A)*, for the same value of applied load. The experiment showed that in all test groups failure occurs according to failure mode A, and not by failure mode B, which can be regarded as the expected failure in connection with thin plates and nails of smaller lengths, which excludes the possibility of the formation of a plastic joint (Johnsson 2004). The used thickness of the plates, as well as the penetration depth of the nails, showed that in this case, the most ductile failure (failure mode F) cannot be achieved (Blass and Ehlbeck 1998). Also, the higher load-bearing capacity and ductility of the connection could be achieved by further optimization of the penetration depth of the nails (Bruehl et al. 2011), which implies a larger width of the cross-section of the timber member, compared to the adopted value of 44 mm.

The effective connector area for all test groups is different, therefore, for the same value of displacement, a higher load-bearing capacity per unit area of the connector in test group *(A)*, compared to the test groups *(B)* and *(C)*, can be noted. If the load-bearing capacities are observed, and the values of displacements are considered in steps of 0.5 mm, the differences in ultimate load-bearing capacities of these three test groups of connectors can be stated (Fig. 16). For displacement of connections of 2.5 mm, the bearing capacity of connectors in test group B was 83% of bearing capacity of connectors in test group *(A)*, while the bearing capacity of connectors in test group C was 63% of bearing capacity of connectors in test group *(A)* (Fig. 17).

Having in mind that the same class of wood, with the same density, for all test samples was used, and the fact that testing in accordance with the conditions defined by the standard ISO 554 (1976) was conducted, a value of c = 0 for dimensionless coefficient (c) in accordance with EN 1075 (1999) and EN 28970 (1991) is taken. In this way the effect of ratio of characteristic and real wood density on the load-bearing capacity of connection is excluded. Accordingly, ultimate plate anchorage capacities, for the displacements of connection in steps of 0.5 mm (Fig. 16) are determined, as well as the ratio between the ultimate load-bearing capacities of connectors for test groups (A), (B) and (C), for given displacements (Fig. 17).

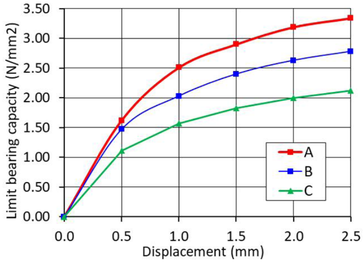

Fig. 16: Ultimate load-bearing capacity of load-bearing capacities.

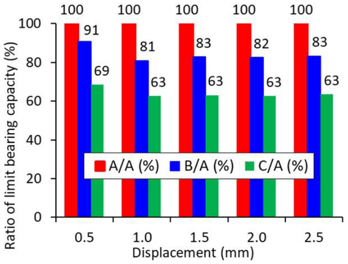

Fig. 17: Ratio between ultimate connections.

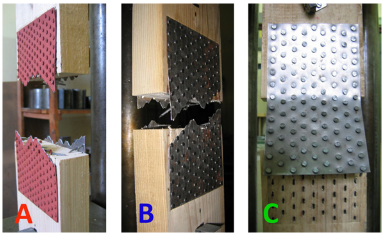

Fig. 18: Failure of tested connections (test groups A, B and C).

Therefore, it may be presumed with great certainty, which has proven by this experiment, that the connections will achieve deformation up to 2.5 mm before the failure of any element in connection occurs, that is, before it comes to the decline of the force on the force-displacement diagram. Failure modes, shown in Fig. 18, were registered after the removal of the instruments for measuring the deformation (because of their safety), and indicate that the choice of steel plate thickness for the connector was justified because the failure of the steel plate cross-section occurred in the deformation of the connection significantly larger than the one that is valid for defining the ultimate load-bearing capacity of nail-to-timber connection.

CONCLUSIONS

The aim of the conducted experimental tests was to determine the extent to which the geometry of the nails - diameter and length of the nails, affect the load-bearing capacity of the nail metal connector plates. In this paper, the behavior of the connections in the nonlinear part of the force-displacement diagram, at a displacement from 0.5 mm to 2.5 mm, with a step of

0.5 mm, was analyzed, and the ratio between ultimate load-bearing capacities for all test groups was determined. For all test groups (*A, B* and *C*) small differences in load-bearing capacity of the connection in the elastic region for values of displacement up to 0.2 mm were observed, whereas the connectors in test group A proved to be of higher quality in the plastic deformation zone. The connectors in test group (*A*) have a higher load-bearing capacity compared to the connectors in test groups (*B*) and (*C*) for all measured deformation from 0.5 mm to 2.5 mm. The load-bearing capacity of the connectors in test groups (*B*) and (*C*) is lower in relation to the capacity of the connectors in test group (*A*), considering the smaller number of nails per unit area of the nail metal connecter. The corresponding surface of one nail per unit area of the metal plate is 86.6 mm^2 for the nail E 20/20, 135.3 mm^2 for the nail E 25/20 and 208.0 mm^2 for the nail E 31/20.

The calculated value of the characteristic load-bearing capacity of one nail E 25/20, determined in accordance with the regulations of EC5, is 17% higher than the load-bearing capacity of the nail E 20/20 (414/354=1.17, Fig. 4). However, the experimentally determined load-bearing capacity of the connectors in test group (*B*) (E 25/20) is less than the load-bearing capacity of the connectors in test group (*A*) (E 20/20) and values 83% of the load-bearing capacity of the connectors in test group (*A*). This can be justified by the fact that the corresponding surface of one nail in the test group (*B*) is 56% higher than the one for the test group (*A*) (135.3/86.6=1.56), that is, a smaller number of nails participate in the acceptance and transmission of loads in the (*B*) type connectors compared to the connectors in test group (*A*).

Differences in load-bearing capacity for the connectors in test group (*C*) compared to the connectors in test group (*A*) are even more pronounced. The calculated value of the characteristic load-bearing capacity of one nail E 31/20, determined in accordance with the EC5 regulations, is 36% higher than the load bearing capacity of the nail E 20/20 (482/354=1.36, Fig. 4). However, the experimentally determined load-bearing capacity of the connectors in test group (*C*) (E 31/20) is less than the capacity of the connectors in test group (*A*) (E 20/20) and values 63% of the load capacity of the connectors in test group (*A*). This can be justified by the fact that the corresponding surface of one nail in the test group C is 140% higher than the one for the test group (*A*) (208.0/86.6=2.40), that is, a smaller number of nails participate in the acceptance and transmission of loads in the (*C*) type connectors compared to the connectors in the test group (*A*).

The results of the research are applicable only to the tested types of nail metal connectors, with the adopted position and the geometry of the nails, therefore the next step in this research is to consider some other combinations of positions, diameters and lengths of the nails that can form a nail metal connector in order to improve the load-bearing capacity of this mechanical fastener. For the final assessment of the quality of the nail metal connectors, as a new mechanical fastener in timber structures, further research in accordance with the previous conclusions is needed, i.e. the experimental testing of new series of samples.

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