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STEEL-TO-TIMBER JOINTS OF BEECH-LVL WITH VERY HIGH STRENGTH STEEL DOWELS

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ABSTRACT: Double-shear steel-to-timber joints of beech laminated veneer lumber (LVL) with slotted-in steel plates using very high strength steel (VHSS) dowels have been investigated. Tensile tests on full-scale joints with one, two, three and six dowels have been carried out, using both VHSS and mild steel dowels. The goal of the research was to investigate the mechanical behaviour of joints of beech-LVL, with regard to load-carrying capacity (LCC), ductility, stiffness; and to find out whether the current design rules of Eurocode 5 are suitable for LVL and VHSS steels. Other examined aspects were the effect of multiple fasteners in a row and the influence of fastener steel grade. Tests showed higher values of joints with VHSS dowels, characterized generally by low scatter. The prediction ability of Eurocode 5 has been found to be inadequate and too conservative. A proposal for improvement is included.

KEYWORDS: Beech LVL, Baubuche, double shear timber joint, timber connections, very high strength steel, dowels, effective number of fasteners, bending capacity, yield moment, embedment strength

1 INTRODUCTION

The development of products with higher strength is currently an important goal for structural timber. In the last decades, Laminated Veneer Lumber (LVL) assumed particular relevance in this research field, as for its reliability and mechanical properties it consistently enhances wood structural performance. An interesting development is the production of LVL made of beech: tests on the product revealed impressive mechanical characteristic values (e.g. $f_{m0k}=70\ MPa$), not reached before by any product other than dense tropical hardwoods [1], [2].

However, as connections play a key role, and govern the element dimensions of timber structures, e.g. in trusses and frames, it is relevant to optimize joints for strength, stiffness and ductility. Indeed, previous works have shown the limits of joint design according to Eurocode 5 [3, 4]: tests on timber joints of hardwood species have revealed a too conservative prediction of load-carrying capacity. It was therefore expected that the same problem would occur also for LVL and other engineered wood-based products with high density.

A further optimization of timber joints is possible through the utilization of dowels made of very high strength steels, having yield strengths of more than 1000 MPa [5]. They permit to use fewer fasteners for the same load-carrying capacity, reducing handling and drilling costs [3], besides minimising joint and element dimensions. It is important that very high strength steels not only have high yield strength, but also high plastic deformation capacity, in order to obtain connections that are ductile [5].

In this work very high strength steel dowels are used in LVL connections and their test results compared with mild steel ones. Beech-LVL members are connected through a slotted-in steel plate and smooth dowel type fasteners of VHSS and mild steel. The characteristics of the joints are listed as load carrying capacity, connection stiffness and ductility. Also the influence of number of fasteners in a row is investigated.

2 MATERIALS AND COMPONENTS

The materials used in this work are beech-LVL for timber elements, mild steel slotted-in steel plates, and mild steel, as well as very high strength steel (VHSS) dowels. In figure 1 the detail of a specimen is presented.

2.1 GLULAM FROM BEECH-LVL

The mechanical advantages of hardwood over softwood are higher tensile, flexural and compressive strength as well as higher stiffness, which permits to use more slender elements for withstand the same load. Moreover, beech

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today is almost entirely used for non-structural applications and its demand it is not significantly high [6].
The LVL production allows a more efficient wood extraction from logs, and the influence of knots and other imperfections is reduced by using thin veneers.
Beech-LVL is manufactured by bonding together, with a phenolic adhesive, thin veneer sheets with a dry thickness of 3.7 mm, a width of up to 1850 mm, and a length of 1850 mm. In the tested product, all veneers were positioned with the fibre direction parallel to the longitudinal axis.
As the production of LVL allows a maximal thickness of 40 mm, elements of larger thickness are obtained gluing together several LVL-panels, resulting in a glued laminated member of Beech-LVL. As the declared properties do not vary, usually it is not distinguished between glulam of LVL and LVL.
In this work, panels of glulam of Beech-LVL of thickness 160 mm have been used.

2.2 STEEL DOWELS

It was decided to use dowels with diameter of 10 mm made out of VHSS and mild steel, in order to analyse the different joint behaviour when using different steel grades. Dowels of S235 were ordered as mild steel specimens. As VHSS dowels are not yet available, 12.9 grade bolts were used for specimens with VHSS fasteners; the bolts length was enough to allow no contact between LVL panels and the bolt head or the threaded part of the fastener.

2.3 STEEL PLATE

Steel plates of S235 and thickness of 10 mm were slotted in the joints in order to obtain a double shear steel-to-timber connection. The steel plate was designed according to Eurocode 3 part 1-12, and in order to avoid plate failure, e.g. bearing, the end- and edge-distances of the drilled holes were chosen to be abundant.

Figure 1: *Detail of a joint specimen*

3 TESTS ON FASTENERS

3.1 FASTENER PROPERTIES

In order to better understand and analyse the mechanical properties of the joints under investigation, bending and tensile tests on the steel fasteners were carried out, respectively at the Wood Research Institute of the TU Munich (bending) and at Delft University of Technology (tension). The results have provided the tensile strength of fasteners as well as their whole moment-rotation behaviour. The test set-up for the fastener bending tests was developed and provided by the University of Trento.

3.2 TENSILE TESTS

3.2.1 Test preparation

Dog-bone shaped specimens were prepared and the tests performed according to the EN ISO 6892-1 standard for metallic tensile testing [12]. A total of 15 specimens were tested, 5 VHSS dowels and 10 mild dowels, as for the joint tests two separate shipments of mild steel dowels were needed. Therefore, 5 specimens per mild steel shipment were tested, in order to inquire eventual mechanical differences.

3.2.2 Results

Figure 2 shows test results in terms of stress-strain relationships. They are named according to the steel grade (M for mild, H for VHSS), and test order (a, b, c, etc.).

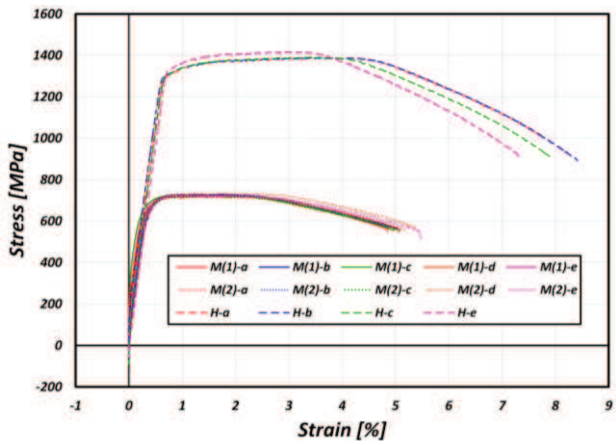

Figure 2: *Tensile test stress-strain curves*

From Figure 2 it is easily detectable that the test results show a very low scatter. Both mild and VHSS steel specimens show a mechanical behaviour characterized by a clear elastic branch up to the yield strength, followed by a plastic plateau showing no hardening up to rupture. As a consequence, yielding and tensile failure strengths are very close and also failure strains are relatively small. Surprisingly, VHSS specimens have larger maximum strains than those of mild specimens. Finally, dowels of nominally S235 grade show an unexpected high mean tensile strength of 726 MPa. The large difference between expected and measured yield strength can be problematic when structures are designed with a specific maximum load carrying capacity with respect to yielding, for instance portal frames with moment resisting connections.
Table 1 summarizes the mean values of the tensile strength and of the strain at rupture with their COVs.

Table 1: *Tensile test results*

Tensile tests	MILD		VHSS	
	mean	COV [%]	mean	COV [%]
Tensile strength [MPa]	726	0.66	1397	0.98
Strain at rupture [%]	5.1	4.05	8.0	6.21

3.3 BENDING TESTS

3.3.1 Test preparation

Bending tests allow drawing the mechanical behaviour of fasteners when submitted to bending, giving evidence of their effective maximum bending moment and ductility and consequently information on how the fasteners will behave in failure modes 2 and 3 according to the Johansen's theory [7]. The test apparatus developed at the University of Trento, allows to test fasteners in pure bending, avoiding shear stresses. Tests have been performed on fasteners with two free lengths between clamps: 3d and 6d (respectively 30 and 60 mm).

3.3.2 Results

Figure 3 shows the bending moment-rotation curves. The specimen are named according to their steel grade (H or M), their free length (3d or 6d) and their order (1, 2, 3). The upper curves represent the VHSS specimens i.e. H-series. Table 2 contains the mean values in terms of bending moment for each series.

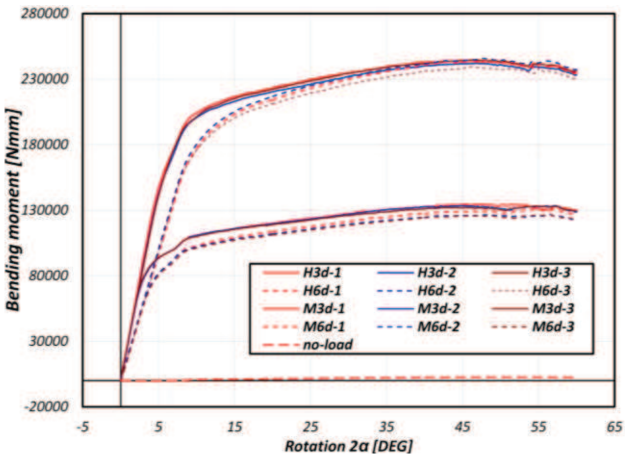

Figure 3: Bending test moment-rotation curves

While the steel grade has great influence on the maximum bending moment, free length influences only the linear part of the curve but not its maximum value. All the specimens reach a rotation of 60° (maximum machine bending angle) without showing brittle failure or decreasing significantly their bending moment.

Table 2: Bending test results

Bending tests	MILD		VHSS	
	M3d	M6d	H3d	H6d
Average maximum bending moment [Nmm]	133700	128240	243560	243090
COV [%]	0.47	1.81	0.54	1.32

4 JOINT EXPERIMENTAL PROGRAMME

4.1 JOINT DESIGN

Joint were designed according to Eurocode 5 [11]. The timber element dimensions are shown in figure 4: timber thickness t_1=74 mm, plate cut of 12 mm, resulting in a total thickness of 160 mm, equal to the timber member width. According to the Johansen's theory [7], joints with mild dowels should fail with formation of three plastic hinges (failure mode – FM – h in Eurocode 5) while joints with VHSS dowels should fail with one plastic hinge (FM g).

Timber element shape was designed and verified paying attention to the distances and to the clamps of the tensile test machine at the HFM Munich, where the tests were performed. The tapering was required to allow the positioning of the specimen. The total length was 1000 mm. The minimum spacing, end and edge distances according to Eurocode 5 were adopted as well.

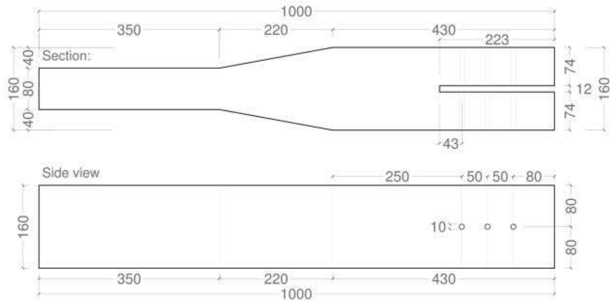

Figure 4: Joint design of the three-dowels specimen (mm).

As the beech veneers are compressed at high temperature during manufacturing of the LVL in the press, there is a risk of increased brittleness of the material. Therefore, all layers had their fibre direction parallel to the load direction, to allow specimens to fail also with brittle failure modes, such as splitting, shear out, block-shear or tension. Moreover, as observed in previously works [8], joints when loaded in tension seem to have lower LCC. Furthermore, tensile tests are less susceptible to geometric imperfection such as non-perfect alignment of members, contrary to compressive tests.

4.2 TEST SET-UP

Tests have been carried out in accordance to the EN 26891 [13]. In accordance with the standard, the loading procedure has to make a loop, in order to settle the joint and attain two different stiffness values. The test is performed in force-control up to 70% of the estimated F_{max}, then in displacement-control up to failure.

The specimens were equipped with two LVDTs, one per each side, non-aligned positioned in order to detect possible rotations during the tests.

4.3 TEST PROGRAMME

Four joint configurations have been selected in order to investigate the effective number of fasteners in a row, group behaviour and ductility. Tests on joints with following number of dowels were carried out:

- with 1 dowel;
- with 2 dowels;
- with 3 dowels;
- with 6 dowels, in two rows of 3 dowels each.

For all joint configurations, specimens with dowels of both mild steel and VHSS were tested. Each series was composed by 5 tests, for a total of 40 experiments.

Specimens were named according to dowels steel grade (H or M respectively for specimens with VHSS or with mild steel dowels), the number of fasteners (1, 2, 3 and 6), and an alphabetic order letter to identify each test of the same series (a, b, c, etc).

5 TEST RESULTS

5.1 GENERAL RESULTS

5.1.1 Load–slip curves

In figure 5 the load-slip curves of all tests are summarized. Each graph presents the curves of series with the same number of fasteners. Red lines indicates H-series (with VHSS dowels), blue lines M-series (with mild steel dowels). The deformation scale remains equal in all graphs, whereas the force scale changes between upper and lower graphs in order better to observe the curves. The joints always show considerable ductile behaviour.

H-series have always higher load-carrying capacity and almost always smaller ductility, except from 1-dowel series (first graph). The joint ductility, on average, decreases with increasing number of fasteners, even if the most substantial reduction occurs between 1-dowel and multiple-dowels series.

5.1.2 Mean values

Mean LCC and joint stiffness are reported in table 3. The LCC have a low scatter (2-6%), confirming the reliability of the material. Specimens with VHSS dowels (H-series) reach higher LCC with an increase of about 16 and 22% with respect to LCC of M-series.

Two stiffness values are presented: K_{ser} representing the initial stiffness before the load-loop; and K_{el} the elastic stiffness, which represents the stiffness once the joint has settled, always larger than the previous. The COVs of K_{ser} are generally larger than those of K_{el} probably due to a larger influence of initial setting.

5.1.3 Failure modes

In figure 6, the observed failure modes (FM) of the eight joint configurations are presented. The observed FMs are almost always in line with Johansen's equation predictions.

Exceptions are joints with a single dowel. H1-series specimens show the formation of three plastic hinges (FM h), two of which not fully developed; while according to theory only one plastic hinge should occur.

Interesting is the FM of M1-series specimens: the steel dowel fails in shear and is responsible for the less ductile behaviour and the abrupt decrease of the load at 7-9 mm displacement (See fig. 5). The formation of three fully developed plastic hinges was avoided by the shear failure of the dowel.

On the contrary, all other specimens present FM g for H-series, with formation of one plastic hinge, and FM h for M-series, with formation of three hinges. M3-specimens external plastic hinges were not always fully developed and M6-specimens present combined FM: three-hinges FMs for dowels placed in the upper row; one-hinge FM for the other dowels. The maximum fastener bending angle, registered in H1-series, was estimated to be about 42°.

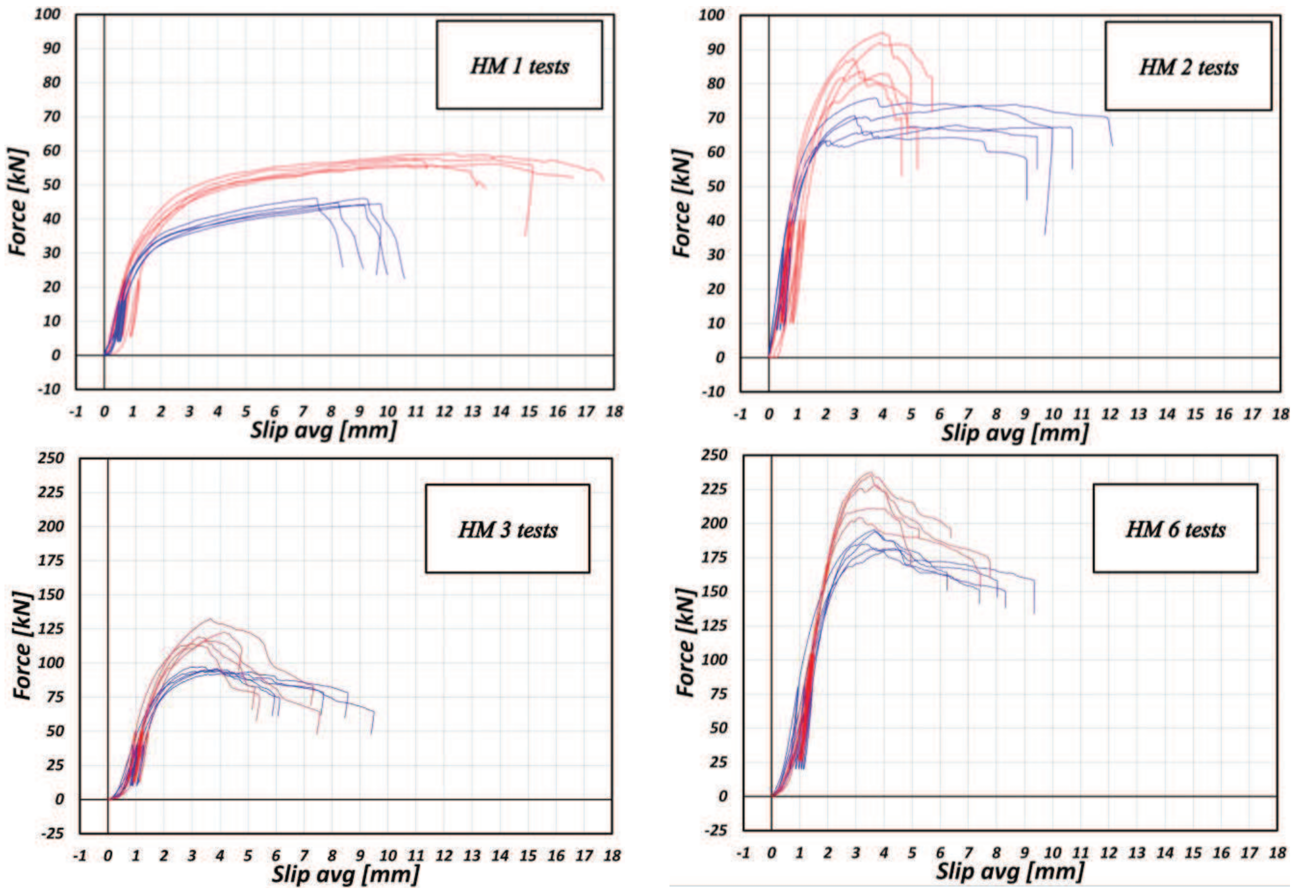

Figure 5: *Load-slip curves of M-series joints (blue lines) and of H-series joints (red lines).*

Table 3: *Mean joint test results*

Mean joint test results	F_{max} Mean [KN]	F_{max} COV [%]	K_{ser} Mean [KN/mm]	K_{ser} COV [%]	K_{el} Mean [KN/mm]	K_{el} COV [%]	Failure modes EC 5
H1	57.44	2.33	39.89	5.64	61.40	7.11	G/H
M1	45.08	2.07	39.98	28.84	67.53	8.59	H/shear
H2	88.13	5.52	60.98	13.89	86.02	9.05	G
M2	70.54	6.53	58.24	11.56	102.51	6.02	H
H3	120.83	6.07	77.36	9.79	124.33	7.31	G
M3	95.17	1.62	63.03	11.52	122.71	7.45	G/H
H6	223.21	6.42	124.48	10.55	180.80	5.36	G
M6	187.19	4.01	109.28	20.26	194.99	3.00	H

Figure 6: *Typical failure modes of each joint configuration*

5.2 ANALYSIS PER FASTENER

5.2.1 LCC per fastener

Figure 7 reports the average LCC of each dowel in the joint for each joint configuration. In this way it is possible to observe the mean load carried by each fastener. Their fastener number orders the values.

The LCC decreases with increasing number of fasteners, both for joints with VHSS and for those with mild dowels, confirming the reduction in LCC for multiple dowels.

Please note that the last series, i.e. joints with six dowels positioned in two rows of three dowels, shows lower values than 3-dowels series, even if the effective number calculated according to Eurocode 5 is the same, and block shear failure was not observed. This finding suggests an influence of the distance between the rows of fasteners on the LCC.

5.2.2 Effective number of fasteners

In figure 8, the observed effective number of fasteners is derived and compared to Eurocode 5 calculation. In the graph, values of tested joints with 1, 2, and 3 dowels are presented; 6-dowels-series are not displayed since Eurocode 5 does not consider any influences of number of rows perpendicular to grain direction.

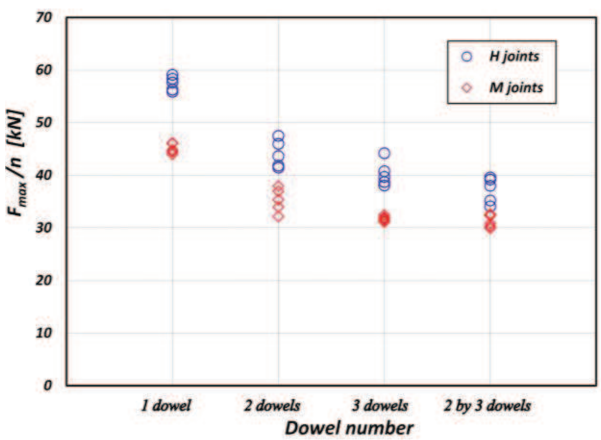

Figure 7: *LCC per fastener*

Contrary to what was observed in [5], no correlation between fastener steel grade and effective number of fasteners has been detected, possibly because of the high yield strength of the mild steel fasteners. The tests show a decrease in terms of LCC per fastener with increasing number of dowels. The effective number according to Eurocode 5 well describes the experimental results trend.

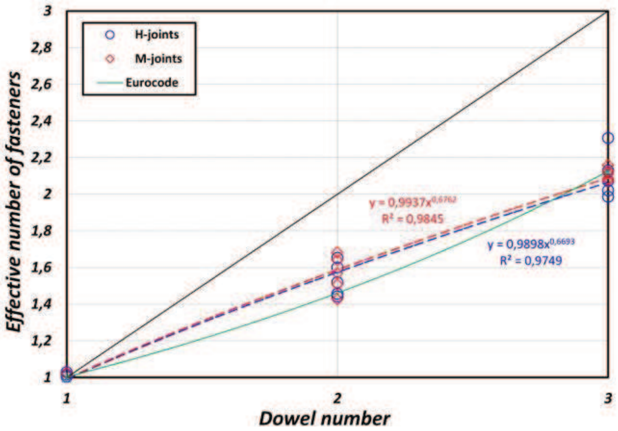

Figure 8: *Effective number of fasteners from test results*

5.2.3 Stiffness

In figure 9, the value of K_{ser} divided by the number of fasteners is reported. According to Eurocode 5, stiffness should have a linear relation with number of fasteners, and consequently in the graph the test results should be horizontally aligned. However, test results show clearly a decrease in terms of stiffness per fastener, as found also in other tests by Sandhaas [4], suggesting that an effective number should be used also in stiffness calculation. The scatter in stiffness per fastener decreases with increasing number of fasteners.

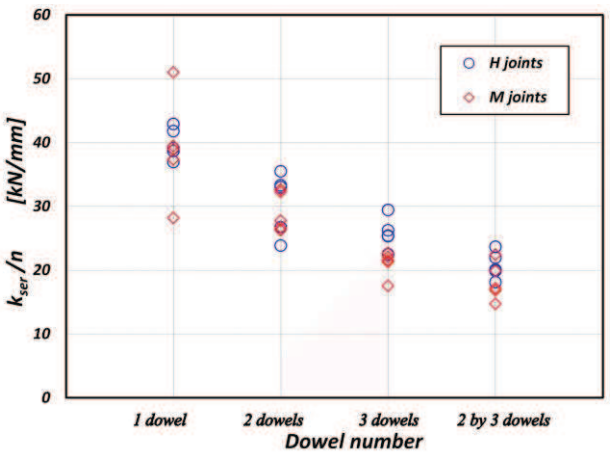

Figure 9: *Stiffness per fastener*

5.2.4 Influence of steel grade

In order to evaluate the influence of the fastener steel grade on the joint behaviour, table 4 reports the ratio between mean values of series with VHSS dowels (H-series) and mild steel dowels (M-series).

In terms of LCC, VHSS dowels increase the joint strength by about 19-27% with respect to mild steel fasteners.

The effective number of VHSS joints is lower or equal to those of the mild steel ones; however the difference is very small and considered to be irrelevant.

Both stiffness values (K_{ser} and K_{el}) seem very little influenced by fastener steel grade.

Table 4: *Steel grade – ratio between H- and M-series values*

H/M	F_{max}	K_{ser}	K_{el}	n_{ef}
1 dowel	1.27	1.02	0.91	1.00
2 dowels	1.25	1.05	0.84	0.98
3 dowels	1.27	1.23	1.01	1.00
2 by 3 d	1.19	1.14	0.93	0.94

5.3 COMPARISON WITH EUROCODE 5

5.3.1 Load carrying capacity

Eurocode 5 adopts Johansen's equations for designing connections. In order to calculate the joint LCC, two parameters are required: embedment strength in timber members and fastener yield moment. The parameters depend on geometric quantities, such as timber member thickness and fastener diameter; and mechanical properties, such as timber density and steel strength. The equations given in Eurocode for calculating these parameters are the following:

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

$$M_{y,Rk} = 0.3 f_{u,k} d^{2.6} \tag{2}$$

The embedment equation (1), of experimental derivation, had been discussed by many authors and many other formulae had been derived from other embedment tests [4, 9]. The common features are: smaller dependence on fastener diameter and larger dependence on timber density. A proposed equation, which better suits for wood and timber products with higher density values, is the following:

$$f_{h,o,k} = 0.082\rho_k \tag{3}$$

The yield moment equation (2) is a regression equation derived by Blass et al [10]. The equation was proposed as argued that joint maximum LCCs are attained before fasteners could reach bending angles of 45°. Therefore, the activated bending moment would not reach the theoretical yield moment given by equation (4):

$$M_{y,Rk} = f_{y,k} d^3 / 6 \tag{4}$$

On the other hand, equation (2) is punishing for dowels made out of steel with high strength or with large diameters [4]. The reasons are: firstly, that with increasing strength, the strain hardening ratio of steel decreases, and in equation (2) the yield strength $f_{y,k}$ is replaced by a ratio on ultimate strength $f_{u,k}$, calibrated from mild steel. Secondly, the difference between the values from equations (2) and (4) grows with increasing diameter.

A more suitable approach would be based on a fully developed yield moment in the fastener and compare the test results with the theoretically correct yield moment:

$$M_{y,Rk} = f_{u,k} d^3 / 6 \qquad (5)$$

In formula (5) the yield strength has been replaced by the ultimate strength.

In table 5 mean test values are compared with the results from Eurocode 5 and with the proposed equations applying declared by producer mean timber density (declaration of performance) and observed mean steel ultimate strength from tensile tests. Table 6 shows the prediction capacity of the two formulations.

From the tables, it can be seen that values obtained using the proposed equations better suit the experimental results than Eurocode 5 equations, but both the formulations are conservative. Observing the ratios of table 6, it can be seen that Eurocode predictions are 25-35% lower than test results.

On the other hand, the prediction ability enhances to an underestimation of around 20% for H-series and 10% for M-series using the proposed equations. The joint design of Eurocode 5 seems to be too conservative.

Table 5: *LCC from tests, EC5 and proposed equations (3) and (5) with mean density and mean ultimate steel strength*

Mean	F_{max} [KN]		
results	Test	EC5	Proposed
H1	57.44	39.66	45.76
M1	45.08	31.52	39.25
H2	88.13	58.28	67.25
M2	70.54	46.32	57.68
H3	120.83	83.94	96.87
M3	95.17	66.73	83.09
H6	223.21	167.89	193.74
M6	187.19	133.45	166.18

Table 6: *LCC ratio of EC5 and prop equations on test results*

F_{max} ratio	EC5 / Test	Proposed / Test
H1	0.69	0.80
M1	0.70	0.87
H2	0.66	0.76
M2	0.66	0.82
H3	0.69	0.80
M3	0.70	0.87
H6	0.75	0.87
M6	0.71	0.89

5.3.2 Stiffness and effective number

In order to investigate how well the Eurocode 5 joint design predicts the mechanical behaviour of the tested joints, also stiffness and effective number are compared using mean test results. The results are summarized in table 7: for each joint configuration the ratio between observed average stiffness (K_{ser} and K_{el}), and Eurocode 5 one (K_{ser}) is presented, as well as the ratio between observed effective number (which is obviously equal to 1 for H1 and M1 series) and that predicted by Eurocode 5.

Table 7 shows that Eurocode does not well-predict the observed stiffness values. For joints with multiple fasteners, it seems that the stiffness should be calculated with an effective number of fasteners, similarly to what is needed for the calculation of the load carrying capacity. With reference to the effective number, Eurocode 5 equation well-matches observed experimental values, showing prediction errors which do not exceed 6%.

Table 7: *Ratio of stiffness and effective number with EC5*

EC5/Test	K_{ser}	K_{el}	n_{ef}
H1	0.88	0.57	1.00
M1	0.90	0.52	1.00
H2	1.15	0.81	0.96
M2	1.20	0.68	0.94
H3	1.36	0.84	1.01
M3	1.67	0.86	1.00
H6	1.69	1.16	1.09
M6	1.92	1.08	1.02

6 CONCLUSIONS

The purpose of the experimental investigation was to analyse double-shear steel to timber joints of beech-LVL with slotted-in steel plates. Mild steel and VHSS dowels as fasteners have been applied, enquiring whether VHSS dowels can enhance timber joint performances.

Focusing on the mechanical performance, the load carrying capacity of beech-LVL joints is high. The joints show ductile behaviour, also with VHSS and multiple fasteners. The scatter is small, pointing out the material reliability. Observed FMs are generally in line with Johansen's equations predictions; an exceptional result was FM of joints with one mild dowel, as the joints failed with steel shear failure of the fastener.

Concerning the potential of very high strength steel, joints with VHSS dowels show LCC 20-30% larger than with mild dowels. This increase must be put in perspective and is related to the ratio of the steel strengths applied. The VHSS and mild steel had failure strengths of 1397 MPa and 725 MPa respectively. Consequently, differences will be greater if mild steel is applied with lower yield strength.

Tensile and bending fastener tests show comparable ductile behaviour of both VHSS and mild steel dowels; all the bending specimens reached a bending angle of 60° without significantly decreasing their bending moment; moreover, VHSS dowels had larger strain than mild dowels in tensile tests. Unexpectedly, mild dowels of ordered S235 showed far larger mechanical properties than expected. This could be unfavourable in terms of joint dissipation capacity, as for instance in seismic structures. After the joint tests, maximum bending angles of around 42° were reached.

The difference in terms of joint ductility when using different steel dowels is evident but not crucial: M-series have generally larger deformation capacity, but in one-dowel-joints H-series exceed M-series ductility. No differences in terms of effective number between H- and M-series were found.

Eurocode 5 joint design equations have been found too conservative for the observed strength of beech-LVL joints. The predictions are 30-50% smaller than observed results. Proposed improvements for fastener bending capacity and

timber member embedment strength are better predicting the test results, especially when using VHSS dowels in the connections. Theoretical yield moment with steel ultimate strength (5) visibly enhances the prediction capacity of Eurocode formulation.
On the other side, the effective number of fasteners in a row according to Eurocode 5 is well describing the LCC trend of joints with multiple dowels.
Eurocode stiffness calculation has been found also quite inadequate, not taking into account an evident relationship between stiffness and number of fasteners. The observed results suggest that an effective number of fasteners should be adopted also for stiffness.
To conclude, very high strength steel fasteners are considered to be suitable in timber joints, permitting an optimisation especially when timber species or engineered wood products with high strengths are used.

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