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# CONNECTIONS WITH SMALL DIAMETER FASTENERS IN EUROPEAN HARDWOODS

Carmen Sandhaas[1], Jan Kipper[2], Elisabet Kuck[3]

**ABSTRACT:** In Europe, it is expected that the availability of hardwood species as construction material will increase in the coming decades due to climate change and the resulting forest conversion. When building with hardwoods, connections with relevant European hardwood species such as beech and birch are necessary, where dowel-type fasteners with small diameters play a special role, as such fasteners are usually inserted without predrilling. A feasibility study to identify suitable fasteners that can be inserted without predrilling was carried out, leading to selection criteria based on the ratio of fastener diameter to insertion length. Used fasteners were staples and nails, and used hardwood products were laminated veneer lumber made of beech and birch solid timber. For selected fasteners, input parameters needed for the design of timber connections were determined and used to calculate expected load-carrying capacities of connections between hardwood products and wood-based panels. Comparing experimental with calculated values, the applicability of the European Yield Model for connections with small diameter fasteners in European hardwoods could be confirmed.

**KEYWORDS:** connection, timber, birch, beech, staple, nail

## 1 – INTRODUCTION

In Europe, it is expected that the utilisation of hardwood species will increase in the coming decades. Hardwood products that are already available in Europe are laminated veneer lumber made of beech (beech LVL) or products made from other wood species such as birch, ash or oak [1]. With its high density, beech LVL represents an upper limit in terms of strength and stiffness properties as well as potentially achievable connection capacities. Concerning connections, dowel-type fasteners with small diameters, e.g. staples and nails, play a special role, as such fasteners are usually inserted without predrilling. This, however, is difficult to achieve due to high densities of hardwoods leading to a high insertion resistance. Nevertheless, the use of staples and nails is relevant for hardwood products, as these fasteners are used to attach sheathing materials such as OSB and gypsum fibre boards, e.g. for timber frame buildings made of hardwoods or for fire protection.

This contribution hence deals with small diameter fasteners that have been selected in a feasibility study where the limits of insertion of these fasteners without pre-drilling were investigated. Moreover, input parameters needed for existing design models developed for softwood connections, i.e. the so-called European Yield Model (EYM) [2], were determined. These include steel properties such as the yield moment and tensile capacity and system parameters such as withdrawal and head pull-through capacities. Finally, connection tests were carried out whose results are compared to expected capacities in accordance to the EYM that were calculated based on the derived input parameters. Therefore, the validity of the EYM for connections with small diameter fasteners in European hardwoods can be assessed.

## 2 – BACKGROUND

In the current European timber design standard, Eurocode 5 [2], timber connections can be designed using the EYM for which certain experimentally determined input parameters must be defined. These input parameters include for instance withdrawal capacities which are unknown for small diameter fasteners such as staples and nails in hardwoods. Furthermore, the high density of hardwoods makes the insertion without predrilling of such fasteners difficult. Finally, the EYM was developed for connections using softwood species, and its applicability to connections using hardwood species must be investigated.

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## 3 – PROJECT DESCRIPTION

A first step to enable the use of hardwood connections with small diameter fasteners is, therefore, the selection of appropriate fasteners that can be inserted at all. For this scope, a feasibility study was conceived and carried out, where different staples and nails were inserted in different substrates, directly into hardwood products and indirectly through different wood-based panels into hardwood products [3].

Used staples had diameters of 1.53, 1.80 and 2.00 mm and lengths varied between 40 and 75 mm. All staples were resin-coated. The diameters of non-smooth shank nails ranged from 2.5 up to 4.5 mm with lengths between 30 and 50 mm. Appropriate nail and staple guns were used to insert the fasteners. Used hardwood products were beech LVL with a mean density of 797 kg/m$^3$ and birch solid timber with a mean density of 624 kg/m$^3$. To investigate the influence of wood-based panels through which the fasteners are inserted, OSB and gypsum fibre boards (GFB) were used.

The same materials were used to determine input parameters for connection design, namely withdrawal and head pull-through resistance, and finally the load-deformation behaviour of connections themselves [4]. Additional information concerning all tests and calculations not mentioned here can be taken from [3] and [4].

## 4 – EXPERIMENTAL SETUP

### 4.1 FEASIBILITY STUDY

The feasibility study was iterative and consisted of inserting different fasteners directly into hardwood products and indirectly through different wood-based panels into hardwood products to investigate the influence of the additional panel, varying the pressure of the nail guns and the fasteners' lengths such that an insertion optimum could be reached. After insertion, the insertion quality was judged visually in order to identify those diameters and appropriate lengths per diameter that can be inserted successfully without predrilling.

Per fastener type, diameter, length and substrates, 20 fasteners needed to be inserted completely without buckling, but not deeper than 2 mm below the surface of the substrate, in order to have passed the test. The fasteners were inserted in rectangular blocks of substrates or combinations of substrates with fastener distances and spacing in accordance with the minimum values given in Eurocode 5 [2]. Combinations of substrates were tested because it is known that wood based panels, through which fasteners are inserted into timber, facilitate proper insertion of small diameter fasteners because they help leading the staple legs and help avoiding buckling. Figure 1 (a) shows the test setup. The total thickness $T$ amounted to penetration length plus 10 mm. Figure 1 (b) shows an exemplary photo of staples 1.80x50 inserted directly in beech LVL, which did not pass the feasibility test. Criteria for failure were for instance unsuccessful insertion due to preliminary buckling or no full finsertion (fastener protruded from the timber surface).

In total, three different staples, $d$ = 1.53, 1.8 and 2.0 mm with two different lengths were used; all inserted directly in beech LVL and birch or indirectly via an OSB panel with $t$ = 15 mm or a gypsum fibreboard (GFB) with $t$ = 12 mm. In the same substrates, also ring shanked coil nails with a diameter of 2.5 mm were inserted. Ring shanked nails with $d$ = 4.0 and 4.5 mm were inserted through predrilled steel plates ($t$ = 3 mm, $d_{predrill}$ = 3 or 5 mm). All fasteners were made of carbon steel except for the 2.5 mm coil nails which were made of stainless steel.

### 4.2 INPUT PARAMETERS

After the feasibility study, the input parameters yield moment $M_y$, tensile capacity $F_t$, withdrawal capacity $F_w$ and head pull-through capacity $F_{head}$ were determined for the selected four fasteners (three staples and one nail) applying standard test methods used in Europe [5]. Concerning withdrawal, in total 18 test series were carried out, varying fasteners, substrates and insertion direction in beech LVL (WF = wide face, SF = side face). Figure 1 (c) shows the withdrawal test setup, where the maximum force and actual penetration lengths were measured and where the penetration length was chosen such that only withdrawal failures were observed. Figure 1 (d) shows an exemplary head pull-through test of a staple through a GFB (the two staple legs are clamped in the testing machine), where also the maximum force was measured. The tests were only carried out if the fastener was inserted properly in the substrate, i.e. such that the staple crown was maximum 2 mm deeper than the substrate surface.

Table 1 lists all executed test series, where with one staple, combinations of substrates were tested to investigate if prior insertion through wood based panels affects the withdrawal properties. The used timber was stored at normal climate with 20°C and 65% r.h. prior to testing.

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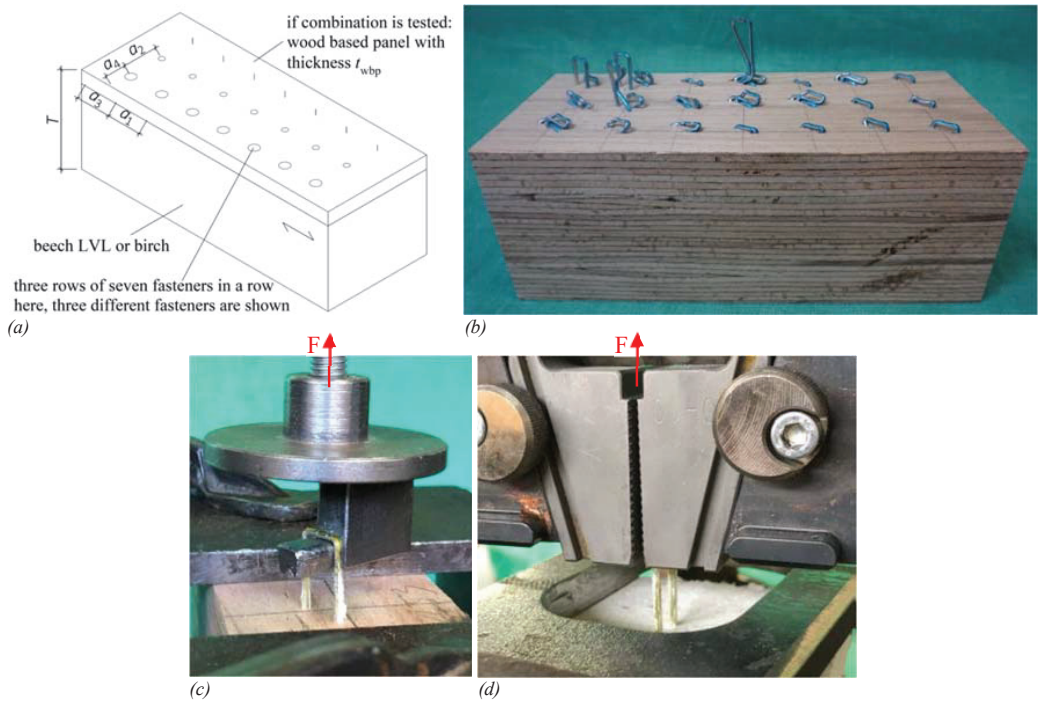


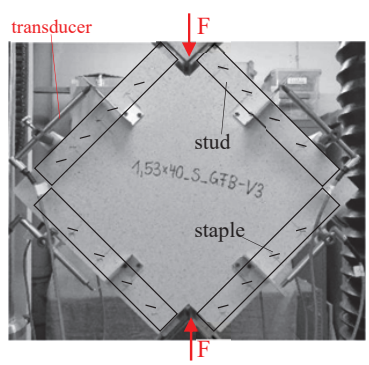

*Figure 1. (a) Setup feasibility tests. (b) Staples 1.80x50 inserted in beech LVL. (c) Withdrawal test of a staple. (d) Head pull-through test of a staple.*

*Table 1: Test series to determine input parameters.*

| | **Staple 1.53x40** | **Staple 1.8x60** | **Staple 2.0x50** | **Nail 2.5x35** |
|---|---|---|---|---|
| Yield moment $M_y$ | 10 | 10 | 10 | 10 |
| Tensile capacity $F_t$ | 10 | 10 | 10 | 10 |
| Withdrawal capacity $F_w$ | | | | |
| Beech LVL WF | 10 | 9 | 10 | 10 |
| Beech LVL SF | 10 | 9 | 9 | 10 |
| Birch | 20 | 20 | 20 | 20 |
| Head pull-through capacity $F_{head}$ | | | | |
| OSB | 10 | 10 | 10 | 10 |
| GFB | 10 | 9 | 9 | 10 |
| Withdrawal capacity $F_w$ | **OSB+ beech LVL** | **GFB+ beech LVL** | **OSB+ birch** | **GFB+ birch** |
| Staple 1.53x40 | 20 | 20 | 20 | 20 |

## 4.3 CONNECTION TESTS

33 connection tests using test specimens mimicking a timber frame shear wall with sheathing and studs were carried out. The principle of the test setup is shown in Figure 2, where also the tested combinations and used distances and spacing are given (for definitions, see also Figure 1 (a)). Per combination, four fasteners in a row were used and the specimens were symmetric, i.e. the sheathing was present on the front and rear of the specimens. This means that per test, 32 fasteners were used with a single shear plane. The staples were inserted at 30°, see also Figure 2. between fibre direction an staple crown. Eight transducers were used to measure the relative deformation between studs and sheathing. The tests were carried out with an unloading loop in accordance with EN 26891 [6] and up until a displacement of 15 mm.




| | **Staple 1.53x40** | **Staple 1.8x60** | **Staple 2.0x50** | **Nail 2.5x35** |
|---|---|---|---|---|
| OSB+beech LVL SF | 3 | 3 | 3 | 3 |
| OSB+birch | 3 | 3 | 3 | 3 |
| OSB+beech LVL WF | 3 | | | |
| GFB+beech LVL SF | 3 | | | |
| GFB+birch | 3 | | | |

Minimum distances and spacing

| **Sheathing** | $a_1$ | $a_3$ | $a_4$ |
|---|---|---|---|
| OSB | 15·$d$ | 20·$d$ | 20 mm |
| GFB | 45·$d$ | 30·$d$ | 20 mm |

*Figure 2. Connection tests: Tested combinations, distances and setup.*

# 5 – RESULTS

## 5.1 FEASIBILITY STUDY

### Nail gun pressure

All fasteners were inserted using pneumatic machines, where specific guns must be used per fastener type. The 4.0 and 4.5 mm ring shanked nails were also inserted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manually using a hammer. Per gun and fastener type, different optimum pressures were needed, which were not correlated among each other, meaning that one cannot say that larger diameter fasteners need higher pressures. The optimum pressures per gun need to be determined individually. A correlation instead exists between type of substrate and pressure. Each gun and fastener type needed the highest pressure to insert the fastener in beech LVL ($\rho_{mean}$ = 797 kg/m$^3$) alone, less pressure when inserting through a wood-based panel (OSB with $\rho_{mean}$ = 678 kg/m$^3$, GFB with $\rho_{mean}$ = 1442 kg/m$^3$) into beech LVL and lowest pressure when inserting into birch ($\rho_{mean}$ = 624 kg/m$^3$) alone or first through a wood-based panel and then into birch. To find the optimum of other gun-fastener combinations than those tested, it seems to be sufficient to determine the pressure for insertion into beech LVL alone and then reduce the pressures by 0.5 bar for each other insertion variant.

**Fastener length**

Different lengths of the same fasteners did not require adaption of gun pressure (under the prerequisite that the fasteners passed the feasibility test). Apart from the nail gun pressure, the fastener length or better, the slenderness ratio of the fasteners is a governing factor for successful insertion. Concerning the substrate, beech LVL is the upper bound – if fasteners can be inserted successfully in beech LVL alone, they can be inserted in all other substrates with lower densities as long as no major defects are present, e.g. large knots that can deviate staple legs. External wood-based panels facilitate insertion.

Maximum possible lengths for insertion in beech LVL were 40 mm for 1.53 mm staples and 60 mm for 1.8 mm staples. The 2.0 mm staples were tested only with a length of 50 mm. The 2.5 mm coil nails could be inserted up to a length of 50 mm, which, however, may not be the upper bound; longer nails were not tested. Concerning the ring shanked nails with diameters of 4 mm inserted through predrilled steel plates, these could be inserted with either a hammer or a pneumatic machine up to a maximum length of 35 mm. The ring shanked nails with a diameter of 4.5 mm could be inserted up to a length of 50 mm using a gun with a pressure of 14 bar.

Also the influence of specific nail tips was investigated. Already in 1979, Ehlbeck observed that sharp nail tips facilitate splitting [7]. This observation could be confirmed. Nails with blunt tips rather compress the wood fibres they are inserted into whereas nails with sharp tips rather penetrate in between fibres leading to premature splitting. All following tests were carried out with staples 1.53x40, 1.8x60, 2.0x50 and coil nails 2.5x35.

## 5.2 INPUT PARAMETERS

The results of the test determining the yield moment and tensile capacity are given in Table 2. The withdrawal parameter $f_w$ given in Table 3 was calculated by dividing the withdrawal capacity $F_w$ ($F_w$ corresponds to the maximum force measured during the test) by the diameter $d$ of the fastener and the penetration length $L_{pen}$, where, in the case of the 2.5 mm nail, the nail tip length of 3.3 mm was subtracted. $L_{pen}$ was measured after insertion.

The fasteners cannot be inserted in the timber specimens without using additional spruce blocks through which the fasteners are pneumatically inserted. These blocks were then removed prior to testing. To additionally investigate the influence of wood-based panels on withdrawal properties, also realistic insertion processes were tested; i.e. the fasteners were inserted through wood-based panels which were then removed in order to be able to pull out the fasteners. The results are given in Table 4. In terms of withdrawal parameters, no difference could be observed where a hypothesis was that insertion through wood-based panels may lead to abrasion of the resin coating with subsequent lower $f_w$-values.

Finally, Table 5 gives the results of the head pull-through tests, where the head pull-through parameter $f_{head}$ was calculated by dividing the head pull-through capacity $F_{head}$ ($F_{head}$ corresponds to the maximum force measured until a displacement of 15 mm of the testing machine's crosshead) by the square of the head diameter $d_{head}$ in the case of nails or the product of the width of staple leg $b$ and staple crown $b_r$ in the case of staples.

*Table 2: Steel properties (staple: per leg).*

| | **Staple 1.53x40** | **Staple 1.8x60** | **Staple 2.0x50** | **Nail 2.5x35** |
|---|---|---|---|---|
| Yield moment $M_y$ in Nmm (at bending angle $\alpha$ = 45°), $N$ = 10 | | | | |
| Mean value | 665 | 966 | 1376 | 2641 |
| COV in % | 4.84 | 2.13 | 1.72 | 5.51 |
| 5$^{th}$ percentile (EN 14358) | 598 | 869 | 1239 | 2346 |
| Tensile capacity $F_t$ in kN, $N$ = 10 | | | | |
| Mean value | 2.90 | 3.55 | 4.58 | 4.23 |
| COV in % | 2.53 | 1.71 | 1.61 | 2.88 |
| 5$^{th}$ percentile (EN 14358) | 2.61 | 3.19 | 4.12 | 3.81 |

*Table 3: Withdrawal parameter $f_w$ in MPa (staple: per leg).*

| $f_w$ in MPa | **Staple 1.53x40** | | **Staple 1.8x60** | | **Staple 2.0x50** | | **Nail 2.5x35** | |
|---|---|---|---|---|---|---|---|---|
| *Beech LVL* | SF | WF | SF | WF | SF | WF | SF | WF |
| N | 10 | 10 | 9 | 9 | 9 | 10 | 10 | 10 |
| Mean value | 28.8 | 35.2 | 26.9 | 26.0 | 27.1 | 25.6 | 48.0 | 56.4 |
| COV in % | 16.8 | 11.0 | 8.66 | 11.0 | 16.9 | 16.0 | 21.6 | 19.7 |
| 5$^{th}$ percentile | 19.6 | 27.7 | 22.4 | 20.1 | 18.2 | 18.0 | 29.1 | 36.5 |
| $\rho_{mean}$ in kg/m$^3$ | 807 | 807 | 805 | 810 | 809 | 807 | 807 | 807 |
| *Birch* N | 20 | | 20 | | 20 | | 20 | |
| Mean value | 16.6 | | 17.8 | | 14.9 | | 25.7 | |
| COV in % | 18.6 | | 12.7 | | 17.3 | | 21.8 | |
| 5$^{th}$ percentile | 11.2 | | 13.8 | | 10.5 | | 16.8 | |
| $\rho_{mean}$ in kg/m$^3$ | 585 | | 585 | | 585 | | 585 | |

*Table 4: Withdrawal parameter $f_w$ in MPa per leg of staple 1.53x40.*

| $f_w$ in MPa | Beech LVL | | | | Birch | |
|---|---|---|---|---|---|---|
| | OSB | | GFB | | OSB | GFB |
| | SF | WF | SF | WF | | |
| N | 10 | 10 | 10 | 10 | 20 | 20 |
| Mean value | 28.4 | 28.9 | 30.5 | 32.5 | 14.3 | 17.8 |
| COV in % | 17.0 | 16.3 | 9.4 | 9.8 | 21.7 | 14.4 |
| 5th percentile | 19.6 | 20.2 | 24.8 | 26.4 | 9.1 | 13.1 |
| $\rho_{mean}$ in kg/m³ | 807 | 807 | 807 | 807 | 585 | 585 |

*Table 5: Head pull-through parameter $f_{head}$ in MPa.*

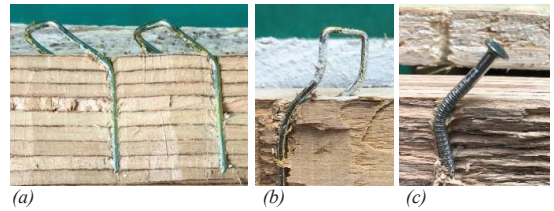
| $f_{head}$ in MPa | | 1.53x40 | 1.8x60 | 2.0x50 | 2.5x35 |
|---|---|---|---|---|---|
| *OSB* | N | 10 | 10 | 10 | 10 |
| Mean value | | 58.35 | 37.73 | 46.80 | 42.21 |
| COV in % | | 30.45 | 28.20 | 27.69 | 22.18 |
| 5th percentile | | 29.66 | 19.76 | 25.41 | 26.41 |
| $\rho_{mean}$ in kg/m³ | | 602 | 612 | 685 | 623 |
| *GFB* | N | 10 | 9 | 9 | 10 |
| Mean value | | 34.43 | 33.79 | 19.30 | 24.99 |
| COV in % | | 20.93 | 10.22 | 17.30 | 5.28 |
| 5th percentile | | 21.32 | 27.18 | 12.89 | 22.32 |
| $\rho_{mean}$ in kg/m³ | | 1200 | 1200 | 1200 | 1200 |

1.53x40: $b$ = 1.6 mm, $b_r$ = 11 mm. 1.8x60: $b$ = 1.81 mm, $b_r$ = 11.1 mm. 2.0x50: $b$ = 2.03 mm, $b_r$ = 11.6 mm. 2.5x35: $d_{head}$ = 5.63 mm.

## 5.3 CONNECTION TESTS

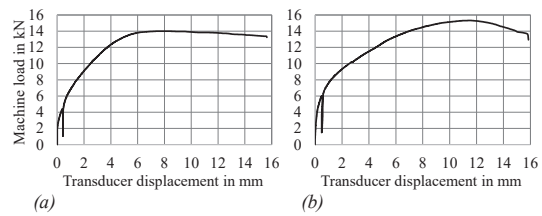
With the same fasteners as those used to determine the input parameters, connection tests were carried out, where the layout and test procedure were given in section 4.3. All specimens reached 15 mm transducer displacement, i.e. a relative displacement between sheathing and studs of 15 mm was reached, with exception of one specimen. This specimen with staples 1.53x40 in beech LVL (SF) and GFB sheathing failed at a maximum relative displacement of 9.4 mm due to failure of the GFB (splitting). In all other specimens instead, failure modes as shown exemplarily in Figure 3 were reached.

Two typical load-displacement curves are shown in Figure 4. Table 6 lists the test results in terms of density $\rho$ of the studs, maximum machine load $F_{max}$ and displacement $v_{Fmax}$ at $F_{max}$. The given values for $\rho$ and $F_{max}$ are mean values (mean of three tests) and $v_{Fmax}$ is the mean value of the three maximum $v_{Fmax}$-values per test (eight displacements were measured per test, four connections with four fasteners on front and rear, see also Figure 2).



*(a) (b) (c)*

*Figure 3. Observed failure modes. (a) 1.53x40 in beech LVL (WF) with OSB. (b) 1.53x40 in birch with GFB. (c) 2.5x35 in birch with OSB.*




*(a) (b)*

*Figure 4. Exemplary load-displacement curves. (a) birch-OSB connection with 1.53x40. (b) beech LVL (SF) -OSB connection with 2.5x35.*

## 6 – COMPARISON WITH EYM

The capacities of the tested connections were finally predicted using the EYM (see equations given in Eurocode 5 [2], but without the correction factors 1.05 and 1.15). The expected values given in Table 7 were calculated using the experimentally determined input parameters (section 5.2). However, the embedment strength $f_h$ was not experimentally determined. For this, the equations from Eurocode 5 were considered using measured densities instead of characteristic values in the case of the studs.

Concerning embedment strength of wood-based panels, the following equations were used. These two equations give characteristic values. Therefore, these characteristic values were transformed into mean values by assuming a normal distribution and an coefficient of variation (COV) of 20% in the case of OSB and of 10% in the case of GFB (characteristic values were divided by (1-1.64 · COV)).

*Table 6: Results of connection tests; second number in percentage is COV. $F_{max}$ is per specimen, i.e. for 32 fasteners, see also Figure 2. N = 3.*

| | OSB sheathing | | | | | | | | | GFB sheathing | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.53 x40 | | | 1.8x60 | | 2.0x50 | | 2.5x35 | | 1.53x40 | |
| | Beech LVL | | Birch | Beech LVL | Birch | Beech LVL | Birch | Beech LVL | Birch | Beech LVL | Birch |
| Mean values | WF | SF | | SF | | SF | | SF | | SF | |
| $\rho$ in kg/m³ | 805 / 0.9% | 825 / 1.8% | 589 / 3.2% | 824 / 2.5% | 631 / 8.1% | 785 / 2.9% | 628 / 6.6% | 795 / 1.7% | 565 / 6.6% | 805 / 3.5% | 616 / 4.6% |
| $F_{max}$ in kN | 15.7 / 4.8% | 17.5 / 6.1% | 13.7 / 1.7% | 17.4 / 3.7% | 16.2 / 4.8% | 21.5 / 4.9% | 20.1 / 5.6% | 16.0 / 4.1% | 13.2 / 7.3% | 18.1 / 2.9% | 16.1 / 5.9% |
| $v_{Fmax}$ in mm | 8.4 / 9.7% | 9.5 / 14.3% | 8.3 / 13.2% | 8.9 / 14.9% | 10.2 / 4.1% | 7.5 / 6.3% | 9.8 / 18.8% | 10.4 / 11.0% | 11.6 / 14.6% | 4.5 / 9.7% | 5.2 / 11.1% |

*Table 7: Observed capacities $F_{max}$ and expected capacities $F_{exp}$.*

| | OSB sheathing | | | | | | | | | GFB sheathing | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.53 x40 | | | 1.8x60 | | 2.0x50 | | 2.5x35 | | 1.53x40 | |
| | Beech LVL | | Birch | Beech LVL | Birch | Beech LVL | Birch | Beech LVL | Birch | Beech LVL | Birch |
| | WF | SF | | SF | | SF | | SF | | SF | |
| $F_{max}$ in kN | 15.7 | 17.5 | 13.7 | 17.4 | 16.2 | 21.5 | 20.1 | 16.0 | 13.2 | 18.1 | 16.1 |
| $F_{exp}$ in kN | 15.5 | 15.6 | 13.4 | 19.8 | 17.4 | 24.1 | 21.2 | 19.6 | 17.1 | 14.0 | 12.6 |
| $F_{exp}$ / $F_{max}$ | 0.99 | 0.89 | 0.98 | 1.14 | 1.08 | 1.12 | 1.05 | 1.23 | 1.29 | 0.77 | 0.78 |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OSB (Eurocode 5): $f_{h,k} = 65 \cdot d^{-0.7} \cdot t^{0.1}$ (1)

GFB (ETA-03/0050): $f_{h,k} = 7 \cdot d^{-0.7} \cdot t^{0.9}$ (2)

The predicted failure modes were failure mode f with two plastic hinges per shear plane for all connections. This was indeed how the stapled connections failed, see Figure 3. The nailed connections, however, showed only one plastic hinge per shear plane, see Figure 3. Figure 5 shows the comparison of expected with observed values in terms of connection capacities, where individual test

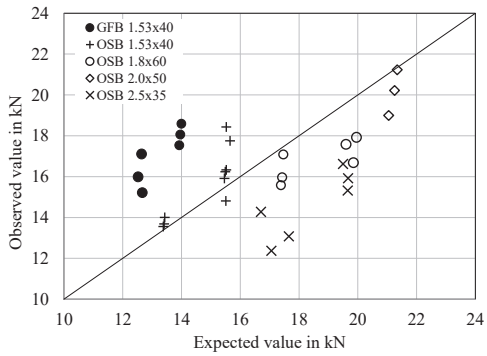


*Figure 5. Comparison of expected with observed values.*

results and individual expected values (differences due to different densities of studs) are shown. The results scatter around the bisect line, confirming the applicability of the EYM also to connections with small diameter fasteners in hardwoods. Looking at the different connection groups, however, differences get evident.

With one exception, all results for connections with 1.53 mm staples are on the safe side, with expected values lower than observed values. All other results show higher expected than experimental values. A reason for this could be rather unprecise equations to calculate the embedment strength in wood-based panels, see Equations (1) and (2). Indeed, if characteristic instead of mean values are used, the results for 1.8 mm and 2.0 mm staples scatter around the bisect line as expected. The expected results for nails instead are still higher than experimental results, but the prediction of the failure mode is correct, i.e. one plastic hinge per shear plane.

Also for the embedment strength of the studs, existing equations and no experimental results were considered. Meyer [8] showed that the current equations from Eurocode 5 (on the base of mean densities) are no good predictor of embedment strength. Hence, uncertainties exist concerning the used embedment strength values, which impact on the prediction quality of the EYM.

## 7 – CONCLUSION

Connections with small diameter fasteners inserted in European hardwoods without predrilling were investigated. The chosen hardwood products relevant for the building sector were beech LVL and birch, where beech LVL represents an upper bound in terms of feasibility and capacity due to its high density. Due to the high densities of hardwoods, these fasteners are difficult to insert and therefore, suitable fasteners must be identified in a first step. For this, an easy and pragmatic method was applied with which a maximum possible insertion length can be determined. For instance, staples with a maximum slenderness between 25 and 30 (length divided by diameter) could be inserted, where, however, a broader study based on more staples (made of different steel grades) must be carried out in order to provide generally valid results. Apart from the feasibility of inserting different fasteners, also other factors limiting insertion length exist. Above all, there is a limit of insertion length after which the load-bearing capacity of connections cannot be increased any more, making the use of longer fasteners pointless.

For suitable fasteners, yield moment, tensile capacity, withdrawal and head pull-through capacity were determined, which can be readily used for connection design in accordance with the EYM. Only the embedment strength as important input parameter of the EYM was not determined experimentally. In the case of staples, no test method exists with which their embedment strength can be determined, which is due to their very small diameter making it impossible to apply standard test methods.

Concerning connections and their design in accordance with the EYM, the comparison of experimental with expected results showed the applicability of the EYM, where the determined input parameters were used to calculate the expected values. The investigated connection typologies were beech LVL and birch in combination with OSB and GFB panels. Observed differences between experimental and expected values of up to 29% could be due to inexact embedment strength values, as these were calculated based on current equations and not based on test values. In order to improve the prediction capability of the EYM, embedment tests should be done, where in the case of staples, a test method should be developed first.

Generally, it can be concluded that always all input parameters needed for design of connections should be determined experimentally when doing connection tests in order to validate the design models of the connections.

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