# HEAD PULL-THROUGH PROPERTIES OF SELF-TAPPING SCREWS

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*This paper was originally published for INTER 2022*

**Keywords:** *self-tapping screw, head pull-through, timber, wood*

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## 1 INTRODUCTION

The head pull-through capacity $F_{head}$ is, together with the withdrawal capacity $F_w$, especially important for joints with screws as screws can transmit high axial forces. However, whereas $F_w$ is always relevant for design, this is not the case for $F_{head}$. If the head side member is made of e.g. steel, then – depending on the steel plate thickness – the screw head cannot be pulled through and either steel or withdrawal failure occurs. Differently to withdrawal, few publications covering head pull-through were found; these include publications dealing with the head pull-through resistance of nails and screws in plywood and OSB (Chui and Craft, 2002; Munch-Andersen and Sorensen, 2011) and investigations discussing screw-press gluing (Bratulic et al., 2019; Fürst, 2019).

Currently, characteristic head pull-through parameters $f_{head,k}$ must be taken from technical documentation of screws, hence are proprietary information given as so-called declared values by the individual screw producers. Indeed, the current Eurocode 5 (2010) states that characteristic head pull-through parameters must be determined in accordance with EN 14592 (2012). Concerning head pull-through tests, both EN 14592 and the EAD (EAD 130118-01-0603, 2019) refer to the test standard EN 1383 (2016). Whereas EN 14592 requires ten head pull-through tests to be carried out in order to establish a declared value for $f_{head,k}$, the EAD allows for the declaration of a conservative $f_{head,k}$-value of 10 MPa for timber with a characteristic density of 380 kg/m$^3$ without testing. A difficulty with EN 1383 is that not enough specifications are given concerning precise test setup and execution. It seems that historically, EN 1383 was drafted for staples, which are pulled-through (thin) wood-based panels, as the protocol for staples is rather extensively explained while imprecise specifications concern issues not relevant for staples. Particularly the prescription concerning the timber thickness t, through which fasteners with a diameter d are pulled, covers a wide range by stating that "$t \leq 7 \cdot d$". Additionally, EN 1383 only refers to "the maximum pull-through load $F_{max}$", which is then used to calculate the head pull-through parameter $f_{head}$. However, the value of $F_{max}$ will very much depend on the thickness through which the fastener is pulled resp. the deformation at which $F_{max}$ is read.

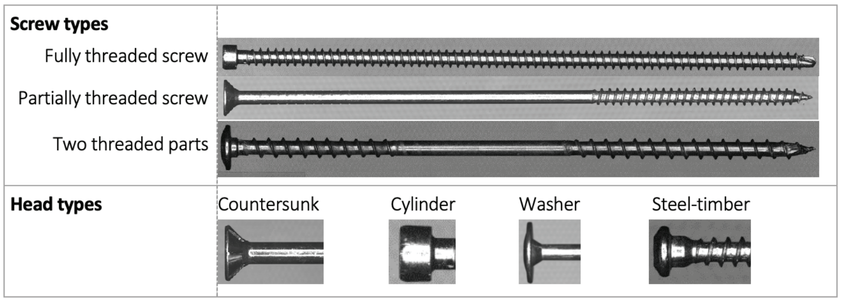
The aim of this contribution is to analyse a database containing head-pull through test results with self-tapping screws. The analyses help to understand if valid design equations can be derived that cover a whole range of screws and timber products. This could help to reduce the effort of designers that currently need to consult a large number of proprietary documents. Furthermore, additional tests were carried out in order to identify influencing factors on test results and important parameters that should be specified in a future version of EN 1383.

## 2 DATABASE

A database containing 2854 test results stemming from certification test reports was assembled, grouped in 245 series. The results contained in the database are the maximum values in kN reached until a displacement of the test machine's crosshead of 15 mm. The thickness of the timber product, through which the screws are pulled, is usually 8 times the nominal diameter $d_{nom}$, and the screws were inserted at an angle of 90° between screw axis and grain direction. The used timber products were mainly spruce (76% of all tests, not predrilled), followed by beech LVL (11%, all predrilled) oak (8%), beech (4%) and ash (1%). The predrilling diameters ranged between $0.67 \cdot d_{nom}$ and $0.8 \cdot d_{nom}$. The used timber was stored at a normal climate with 20°C and a relative humidity of 65% and the moisture content was not measured. This is important to note, as the moisture content of beech LVL usually is only around 6% to 8%, whereas that of spruce lies between 10% and 12%. The recorded density was measured as global value of one test specimen. Half of the tests per series with beech LVL were inserted in the face grain and the other half in the edge grain. All screws in oak, beech and ash solid wood specimens were oriented in radial and tangential direction with respect to the annual rings. This information is not given for all tests with spruce, where 1660 tests contain no information concerning the annual ring orientation.

Figure 1 shows a classification of the screws. These were mostly partially threaded screws (87%), 11% had two threaded parts and fully threaded screws constituted only 2% of all tests. A fundamental difference exists between screws with a partial thread and screws with a full thread or two threaded parts. The last two screw types have a thread directly underneath the head that contributes to the head pull-through resistance, whereas partially threaded screws have a smooth shank directly underneath the head. This means that a head pull-through resistance can only be determined for partially threaded screws, whereas for the other screws, it is rather the withdrawal resistance that is determined. If the smooth shank part of partially threaded screws was not long enough to protrude from the timber, i.e. that part of the thread was embedded in the timber contributing to the head pull-through resistance, the timber piece was predrilled such that the threaded part was loose inside the timber. These screws were inserted until the threaded part protruded from the timber specimen, then the specimen including screw was inserted in the testing rig and it was pulled until the screw head was flush with the timber surface. Afterwards, the specimen was unloaded. Screws with a thread directly underneath the head instead were tested subdividing the series in half of the tests pulling through only the threaded part (i.e. the screw head was protruding from the timber) and the other half was tested including screw head and thread. These screws were inserted until the screw head was flush with the timber surface (tests with head and thread), and then the specimens were inserted in the testing rig.

Concerning head types, 250 screws had a cylinder head, 810 screws had a washer head, 1624 a countersunk head and 180 screws had a “steel-timber” head used to fasten steel plates to timber. The ratio of nominal diameter divided by the head diameter was 0.37 to 0.68 for screws with countersunk heads, 0.32 to 0.52 for screws with washer heads and 0.72 to 0.83 for screws with cylinder heads. No information about the angle of the countersunk heads is given, except for one series with 60° countersunk heads. Looking randomly at some photos of screws contained in the test reports, it seems that most screws had 90° countersunk heads (i.e. the “inclination” of the countersunk with respect to the screw axis was 45°). Also concerning the finishing of the side underneath the head, no information was given, e.g. concerning the presence of milling pockets or milling ribs. Furthermore, countersunk heads may need some pre-milling in order to allow for a screw insertion until the head is flush with the surface, especially for beech LVL with its high density. This information, however, is not given in the reports nor can it be retrieved retrospectively. As a rule, it can be said that in a first step, screws were inserted without pre-milling and if it was possible to fully insert these screws without any splitting, no pre-milling was carried out. This procedure is valid for all species and timber products.



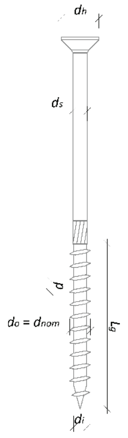


*Figure 1. Left: Classification of screws. Right: Geometrical properties with $d_h$ = head diameter, $d_s$ = diameter of smooth shank, $d_o$ = outer thread diameter = nominal diameter $d_{nom}$, $d_i$ = inner thread diameter, p = pitch, L = length = nominal length $L_{nom}$, $L_g$ = length of threaded part.*

## 3 ANALYSIS AND DISCUSSION

### 3.1 General

Observed coefficients of variation are shown in Figure 2 on the left. For beech LVL, coefficients of variation for density are low. The coefficients of variation for $F_{head}$ are high, and this high scatter is confirmed when looking at Figure 2 on the right, where the influence of the head types on the head pull-through capacity is shown. It can be seen that, obviously, for heads with large diameters, i.e. washer heads, higher $F_{head}$-values on average are reached. Particularly for beech LVL, however, results scatter considerably and screws with countersunk heads reach the highest values. As in Figure 2 on the right, the vertical axis simply shows the measured $F_{head}$-values in kN, these values must be normalised prior to any further analysis. In general, however, it can already be stated that the scatter observed for all species is surprising, as the head pull-through behaviour is thought to be similar to the behaviour of wood under a compressive load perpendicular to the grain, where the (ductile) compressive strength perpendicular to the grain together with a load distribution area governs and hence, shows rather little variation.

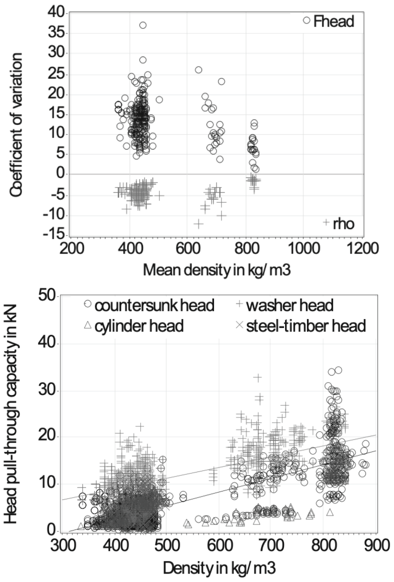


*Figure 2. Top: Observed coefficients of variation in %. Below: Head pull-through capacity $F_{head}$ in kN versus density $\rho$ in kg/m$^3$ differentiated by head types. Linear trendline is shown for screws with washer heads (red line) and countersunk heads (black line).*

The normalisation is done by dividing the head pull-through capacity $F_{head}$ through the square of the head diameter $d_h$, obtaining the head pull-through parameter $f_{head}$:

$$f_{head} = \frac{F_{head}}{d_h^2} \tag{1}$$

The "head pull-through parameter" for fully threaded screws and screws with two threaded parts, i.e. screws with a thread directly underneath the head, is instead calculated differently and in analogy to the withdrawal parameter:

$$f_{head} = \frac{F_{head}}{d_{nom} \cdot t} \tag{2}$$

where $d_{dom}$ = nominal diameter and t = thickness of the timber piece.

Figure 3 on the left shows all head pull-through parameters versus the density. The minimum value of 10 MPa of $f_{head,k}$, that can be declared without testing in accordance with the EAD, is shown. For spruce, this value of 10 MPa is obviously a good (albeit conservative) choice, whereas a stepwise or linear increase could be introduced for timber products with a density > 500 kg/m$^3$. In general, the scatter is significant, with individual $f_{head}$-values for spruce ranging between 9 MPa and 53 MPa and for beech LVL between 29 MPa and 129 MPa. This scatter is not reduced when showing mean values per series instead of individual testing values. Concerning screw types, it seems that partially threaded screws can reach higher $f_{head}$-values, which holds when considering that rather a withdrawal parameter is established when pulling through screws with a thread underneath the head. If additionally considering the head type, this seems to hold for partially threaded screws with any head type, whereas for higher densities, particularly for beech LVL, it seems to hold for partially threaded screws with countersunk heads (i.e. head types acting as wedge). Seeing the scarcity of data for species with densities > 500 kg/m$^3$, it is difficult to judge if this observed relationship is true or fictitious. However, remembering the previous statement on the need of pre-milling or not in order to fully insert screws with countersunk heads, it may well be that an insertion of screws with countersunk heads without pre-milling leads to a higher local densification underneath the head resulting in a higher head pull-through resistance. However, as no comparative testing series are available, it is difficult to draw reliable conclusions. Comparative testing series instead were carried out with solid hardwoods, where the same screws were used in different species. The results showed that oak with its lower density has lower $f_{head}$-values than beech or ash. This confirms the trend of increasing $f_{head}$-values with increasing density that can be seen for solid hardwoods in Figure 3 on the left, and which is not discernible for spruce and beech LVL.

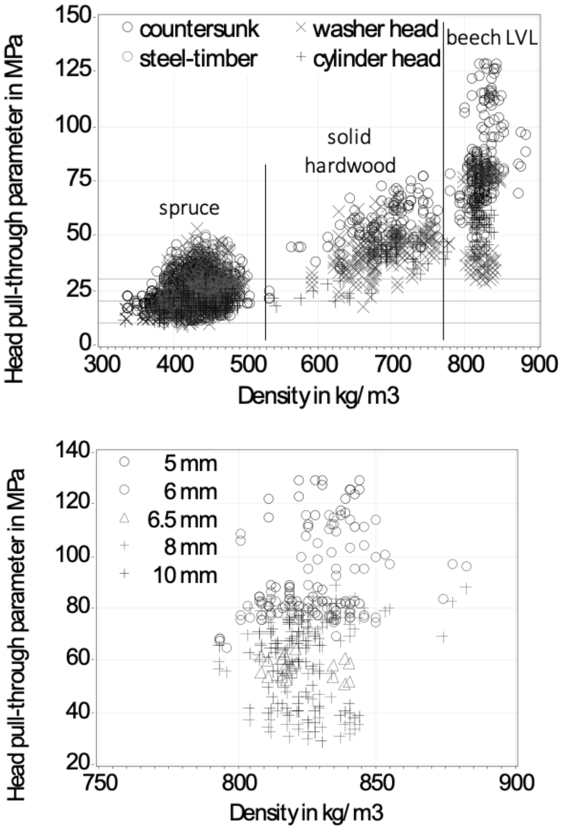


*Figure 3. Above: Head pull-though parameter $f_{head}$ versus density $\rho$, differentiated by screw types and with horizontal lines at 10, 20 and 30 MPa. Lowest $f_{head}$-value was 9.3 MPa, all other values > 10 MPa. Below: Head pull-though parameter $f_{head}$ versus density $\rho$ for beech LVL (all predrilled) and differentiated by nominal diameter.*

If giving a further look into the tests with beech LVL, further subsets can be identified. The screws in beech LVL were inserted in either the face or the edge grain, where this info is only given for partially threaded screws. However, no difference at all was observed concerning the direction of insertion (also when considering the overall database). If instead differentiating by nominal diameter as shown in Figure 3 on the right, a trend of higher $f_{head}$-values for screws with smaller nominal diameters and countersunk heads can be observed. Again recalling the statement on the need of pre-milling of countersunk heads inserted in high-density timber, a possible hypothesis arises. As the screws must be inserted until the screw head is flush with the timber surface, it may be that the countersunk heads of small diameter screws did not need pre-milling in order to ensure proper insertion. This, in turn, may have led to densification underneath the screw head with subsequent higher $f_{head}$-values.

Re-considering the analogy between head pull-though tests and compressive tests perpendicular to the grain, another approach to calculate the head pull-through capacity arises. The most simple approach is to apply a modified version of Eq. (5) given in Leijten (2009):

$$F_c = 3 \cdot f_{c,90} \cdot A_{head} = 3 \cdot f_{c,90} \cdot \pi \cdot \frac{(d_h)^2}{4} \quad (3)$$

where $F_c$ = compressive capacity in N, $f_{c,90}$ = compressive strength perpendicular to the grain in MPa, $A_{head}$ = gross area underneath the screw head in mm².

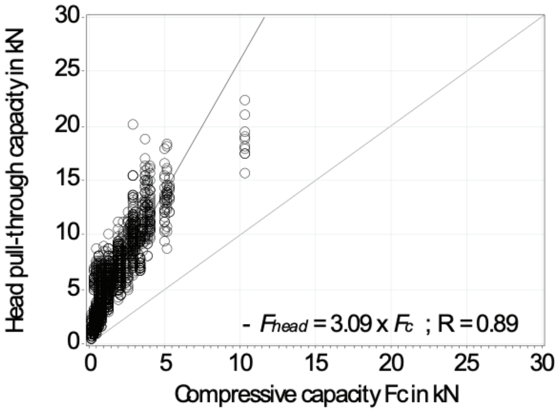


*Figure 4. Above: Head pull-through capacity versus "compressive capacity $F_c$" in accordance with Eq. (3) with $f_{c,90}$ = 2.6 MPa. Only data for spruce is considered. Bisect line is diagonal; linear regression is shown in black and regression equation is given. The values at $F_c$ > 10 kN are for screws with $d_h$ = 41 mm (12 mm screw with countersunk head and washer). Below: Shapes underneath screw heads.*

Concerning a value for $f_{c,90}$, the findings of Franke (2008) can be taken into account, who determined compressive strength values for spruce on small cubic specimens (40 x 40 x 40 mm³) with different annual ring orientation. Franke evaluated a mean compressive strength perpendicular to the grain at a strain of 1% of 3.7 MPa for tangential compression, 2.6 MPa for radial compression and 1.5 MPa for specimens with annual rings oriented at 45°. Figure 4 on the left shows the head pull-through capacities contained in the database versus the results of Eq. (3) with $f_{c,90} = 1/2 \cdot (3.7 + 2.6 + 1.5)$. Eq. (3) underestimates head pull-through capacities by a factor of three. Therefore, a simple approach as specified in Eq. (3) can only be used after further statistical calculations that establish a relationship between head pull-through capacity and compressive strength.

Differently to compressive tests, splitting underneath a screw head during insertion will influence results. The scatter observed for screws with washer heads, however, cannot be explained with this, at least not fully, because washer heads may not be even on their underside (see Figure 4 on the right) and hence still penetrate the timber and it cannot be controlled when exactly the insertion process is stopped. It must hence be questioned how valid the head pull-through capacities are, which are read at a crosshead displacement of the testing rig of 15 mm. The following questions arise:

- By how much is a screw head pulled in at 15 mm machine displacement? During testing, transducers should be used to measure deformations.
- How is the general load-displacement behaviour? Load-displacement curves are needed to assess the nonlinear shape of the curve.
- Does the thickness of the timber piece or support conditions influence test results? Here, the question is for instance if additional bending of the timber member influences head pull-through values in cases where a screw is pulled through a rather thin timber member that is supported only at a large distance from the screw.

- Are there any elastic effects? Elastic effects will certainly occur, in particular for the tests in beech LVL, seeing that a screw with a Young's Modulus of 21000 GPa is pulled through a high-density product with a certain thickness. This question is in direct relation to the question before.
- Is there a difference in load-displacement behaviour between screws with countersunk heads and those with washer heads? As long as no curves are registered, this question cannot be answered.
- Does predrilling influence head pull-through values? When no predrilling is carried out, more wood material must be pushed aside when inserting a screw, which may influence the behaviour.
- Does pre-milling influence head pull-through results? This question is especially important for screws with countersunk heads inserted in high-density timber.
- Is there an influence of the insertion process? This question addresses the observation that results for screws with washer heads scatter significantly. For these screws, it is difficult to define a clear end to the insertion process. But also results for screws with other heads may be depending on how the screws are inserted and what "flush with the timber surface" means.
- Are there geometrical features of countersunk heads that influence results? This question addresses the observation that results for screws with countersunk heads scatter significantly. As no geometrical data is given for countersunk heads, e.g. the angles of the heads or if milling pockets are present, this observed scatter cannot be assessed.

To answer these questions, additional testing series must be carried out; with specified boundary conditions and well documented manufacturing and testing procedures. As a consequence, small systematic testing series presented in the next section were carried out to address some of the above-mentioned questions. Such bespoke test series will however impact on the representativeness of the data, as such series will be carried out only on very few different screws.

### 3.2 Additional testing series

Table 1 gives an overview over the additional testing series and the results. In all tests, the screw head displacement was measured using transducers, together with the machine load and displacement. Two different test rigs were used (tests with screw A on rig 1, and tests with screws B to F on rig 2), with probably individual influences on the machine displacement. The machine displacement (and not any transducer displacement) is currently considered to determine $F_{head}$-values. Consequently, it was also used to determine the test results given in Table 1, in analogy to all other data contained in the database. Figure 4 on the right shows photos of the underside head shapes of the used screws. The mean moisture content of beech LVL was 6.3% and that of spruce 11.6%. In the following, different aspects of the test results are discussed.

***Machine versus transducer displacement***

Figure 5 shows four load-displacement curves, where machine displacement and transducer displacement is differentiated. Two systematic differences can be pointed out. Firstly, load-displacement curves for screws with washer heads, upper right figure, show a steady increase until tests are stopped. This is not the case for screws with countersunk heads, which show a more pronounced nonlinear behaviour with a maximum load reached before tests are stopped. And secondly, whereas the difference in measurement method is small for tests with countersunk heads in spruce, this is not the case for screws with washer heads and in beech LVL, i.e. for tests with more rigid behaviour. It must be underlined that the four chosen curves are by no means representative for all other tests of the same series, and the qualitative load-displacement behaviour may look different from test to test, see also Figure 7 on the right. Figure 6 on the left shows opened test specimens, where the fundamental difference to compressive tests perpendicular to the grain can be seen. In the latter tests, wood fibres are not separated and can act as ropes transferring tensile loads. In head pull-through tests instead, fibres are separated and can be better compared to cantilever beams. However, these simple static models underestimate the influence of shear very considerably as was shown by Bocquet (1997, there Figure 1.22). The exemplary curves given in Figure 5 show very clearly that the current determination of $F_{head}$ at a machine displacement of 15 mm takes place when the load-displacement curves are already far in the ductile range. The permanent deformations visible in Figure 6 on the left confirm this; current values of $F_{head}$ go hand in hand with large deformations, and in the case of washer heads, $F_{max}$ is not reached at a machine displacement of 15 mm.

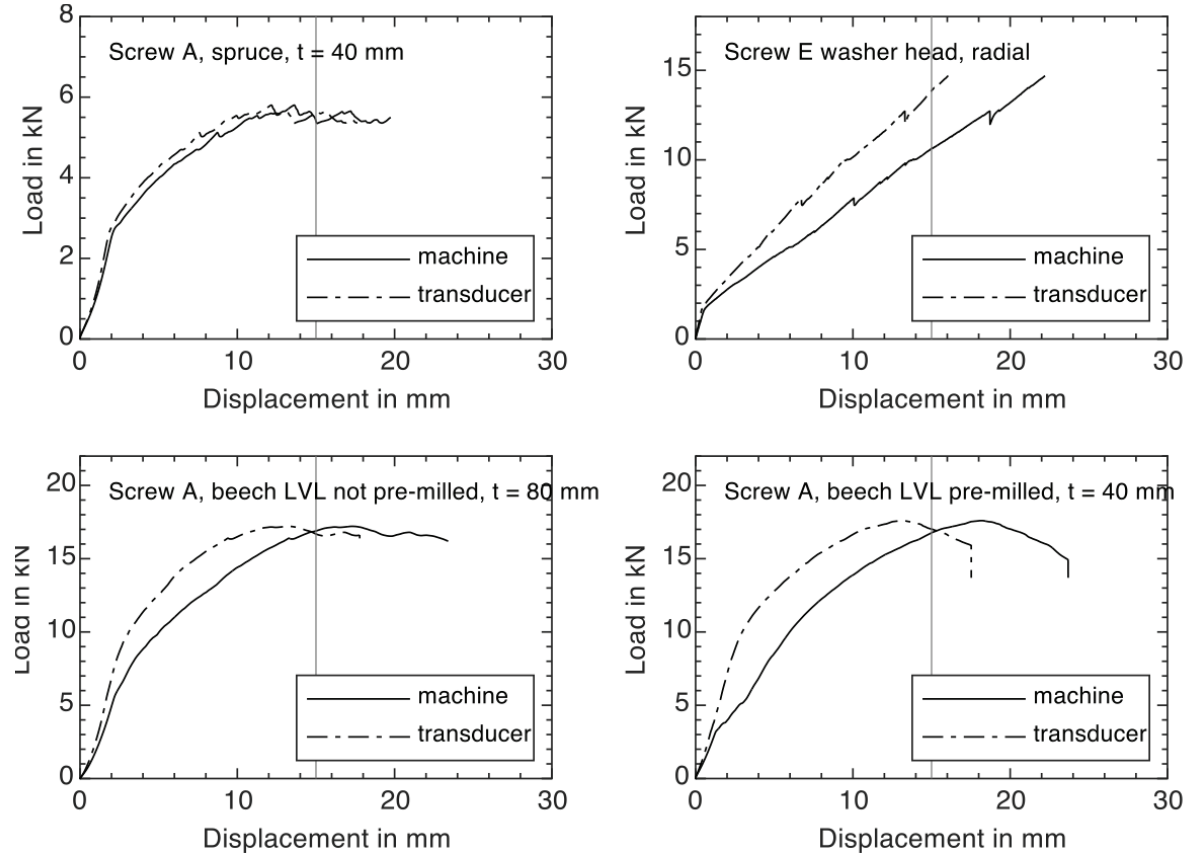


*Figure 5. Four exemplary load-displacement curves. Centre vertical line indicates 15 mm displacement.*

This is a very unsatisfying situation, considering the vague prescriptions in EN 1383 (2016) and the effect this may have on results from different testing institutions. Clear prescriptions are needed at which deformation limit head pull-through capacities should be read. These deformation limits may vary depending on the application, similar to the proposal for compression perpendicular to the grain by Windeck and Blass (2017). Further prescriptions are required as to how deformations shall be measured, in particular for rigid systems, i.e. with high-density timbers and large washer heads, where larger differences between machine and transducer displacement can be observed. Quantitative differences between machine and transducer displacement are given in Table 1, where differences of up to 5 mm at a machine displacement of 15 mm were observed. This means, screw heads are pulled in by a maximum of 10 mm at a crosshead displacement of 15 mm. These 10 mm consist of an elastic and a plastic part, as can be seen in Figure 6 on the left, where the permanent deformation is less than the maximum (machine) displacement of ca. 20 to 25 mm during the test.

### *Timber thickness*

The test specimens were supported such that no bending deformation could occur, i.e. with a steel plate with an opening of 80 x 80 mm$^2$ to support the tip side timber surface (as prescribed in EN 1383) and a clear distance of 15 to 20 cm between two anchorings fastening the test specimen and steel plate to the test rig. When looking at the results with screw A in Table 1, no difference can be observed for the tests with spruce with a thickness of

40 and 80 mm. The same holds for the tests with beech LVL, where, however, the series with 40 mm thick beech LVL and screws inserted in the face grain had higher densities than all other series, obfuscating results.

*Table 1. Test results in terms of mean values with coefficients of variation, thickness t in mm, N = number of tests, displacement u of transducer when machine displacement is 15 mm. All partially threaded screws, and underside head shapes are shown in Figure 4 on the bottom.*

|  | $t$ | $N$ | Variation | $\rho$ in kg/m$^3$ | $u$ in mm | $f_{head}$ in MPa |  |
|---|---|---|---|---|---|---|---|
| Screw A, countersunk, $d_h$ = 14.8 mm, $d_{nom}$ = 8 mm, $d_{predrill}$ = 6 mm in beech LVL, not predrilled in spruce |  |  |  |  |  |  |  |
| Beech LVL, pre-milled (14 mm) | 40 | 5 | Face grain | 835 \| 0.5% | 10.1 \| 9.2% | 90.7 \| 4.8% |  |
|  |  | 5 | Edge grain | 806 \| 1.1% | 9.9 \| 5,7% | 79.2 \| 5.9% |  |
|  | 80 | 5 | Face grain | 807 \| 0.9% | 10.3 \| 14.5% | 71.2 \| 9.3% |  |
|  |  | 5 | Edge grain | 802 \| 0.3% | 10.4 \| 4.5% | 82.9 \| 2.9% | 81.0 \| 10.5% |
| Beech LVL, not pre-milled | 40 | 5 | Face grain | 835 \| 0.5% | 12.2 \| 2.4% | 94.1 \| 3.2% |  |
|  |  | 5 | Edge grain | 806 \| 1.1% | 10.8 \| 11.1% | 85.5 \| 4.0% |  |
|  | 80 | 5 | Face grain | 806 \| 1.0% | 11.7 \| 3.7% | 81.9 \| 6.9% |  |
|  |  | 5 | Edge grain | 804 \| 0.4% | 11.4 \| 4.1% | 82.8 \| 6.3% | 86.1 \| 7.7% |
| Spruce | 40 | 10 |  | 460 \| 3.6% | 12.9 \| 5.8% | 24.0 \| 9.4% |  |
|  | 80 | 10 |  | 460 \| 3.8% | 13.1 \| 3.9% | 24.4 \| 5.8% | 24.2 \| 7.9% |
| Screw B, countersunk with milling pockets, $d_h$ = 11.7 mm, $d_{nom}$ = 6 mm, not predrilled |  |  |  |  |  |  |  |
| Spruce | 60 | 10 | Radial | 466 \| 3.7% | 13.0 \| 4.2% | 31.6 \| 13.3% |  |
|  |  | 10 | Tangential | 466 \| 3.7% | 13.0 \| 4.5% | 28.7 \| 11.7% | 30.1 \| 13.5% |
| Screw C, countersunk, $d_h$ = 11.4 mm, $d_{nom}$ = 6 mm, not predrilled |  |  |  |  |  |  |  |
| Spruce | 60 | 10 | Radial | 472 \| 3.3% | 12.8 \| 3.5% | 36.2 \| 17.8% |  |
|  |  | 10 | Tangential | 472 \| 3.3% | 13.6 \| 3.3% | 30.2 \| 21.9% | 33.2 \| 21.6% |
| Screw D, washer head, $d_h$ = 13.6 mm, $d_{nom}$ = 6 mm, not predrilled |  |  |  |  |  |  |  |
| Spruce | 60 | 10 | Radial | 469 \| 3.0% | 11.6 \| 4.9% | 36.4 \| 17.2% |  |
|  |  | 10 | Tangential | 469 \| 3.0% | 12.4 \| 2.2% | 29.4 \| 10.1% | 32.9 \| 18.3% |
| Screw E, washer head, $d_h$ = 21.4 mm, $d_{nom}$ = 8 mm, not predrilled |  |  |  |  |  |  |  |
| Spruce | 80 | 10 | Radial | 457 \| 3.5% | 11.1 \| 7.4% | 23.5 \| 7.4% |  |
|  |  | 10 | Tangential | 457 \| 3.5% | 11.4 \| 6.7% | 20.8 \| 11.2% | 22.2 \| 11.2% |
| Screw F, washer head, $d_h$ = 22.4 mm, $d_{nom}$ = 10 mm, not predrilled |  |  |  |  |  |  |  |
| Spruce | 100 | 10 | Radial | 388 \| 3.1% | 12.0 \| 3.5% | 19.6 \| 13.3% |  |
|  |  | 10 | Tangential | 388 \| 3.1% | 12.0 \| 2.0% | 17.3 \| 11.1% | 18.4 \| 13.9% |

### ***Pre-milling versus not pre-milling in beech LVL***

As expected, no pre-milling to facilitate the insertion of countersunk heads leads to higher $f_{head}$-values, see Table 1 (and Figure 7 on the left). However, this trend is only weak and cannot explain the large scatter observed in the database. The weak trend is confirmed when looking at the load-displacement curves of all tests with beech LVL given in Figure 6 on the right.

### *Density*

Figure 7 on the left shows $f_{head}$-values versus density of the tests with screw A in beech LVL, including the trendlines. The trend based on the in total 40 tests is clear; $f_{head}$-values are increasing with increasing density. Such a clear trend, however, cannot be observed when looking at the database, see Figure 3 on the right. The general issue of discernible trends within bespoke series that vanish when looking at more representative data can be underlined.

### ***Insertion direction***

Concerning insertion in edge or face grain of beech LVL (screw A), the picture is blurry when looking at Table 1, The test results for 40 mm thick beech LVL cannot be interpreted due to the difference in density. The test results for 80 mm thick beech LVL instead show a larger difference between edge and face grain for the pre-milled specimens, and no difference for the not pre-milled specimens. Concerning the tests with spruce, tests with screws inserted in radial direction lead to higher $f_{head}$-values, which can be explained with homogenisation effects when inserting screws in radial direction. It is, however, contradictory to the already cited findings from Franke (2008), who evaluated higher compressive strength values in tangential direction in comparison to the radial direction.

***Influence of shapes underneath screw heads***

Figure 7 shows the load-displacement curves for the tests with screws B and C, which had different shapes underneath their countersunk heads, see Figure 4. The scatter is significant, also when looking at the coefficients of variation given in Table 1, and this scatter cannot be explained when giving a closer look to the test specimen, production and execution. No conclusive statement can be made based on these few tests. For screws with washer heads, $f_{head}$-values seem to decrease with larger screw diameters (with consequentially larger head diameters); a trend that can be confirmed considering the whole database.

### 3.1 Characteristic values

Irrespective of the observed scatter and the resulting challenges in finding meaningful relationships, characteristic values are needed for design. Therefore, conventional characteristic values are calculated applying EN 14358 (2016) and prEN 14592 (2017). In a first step, a nonlinear regression using 2854 individual

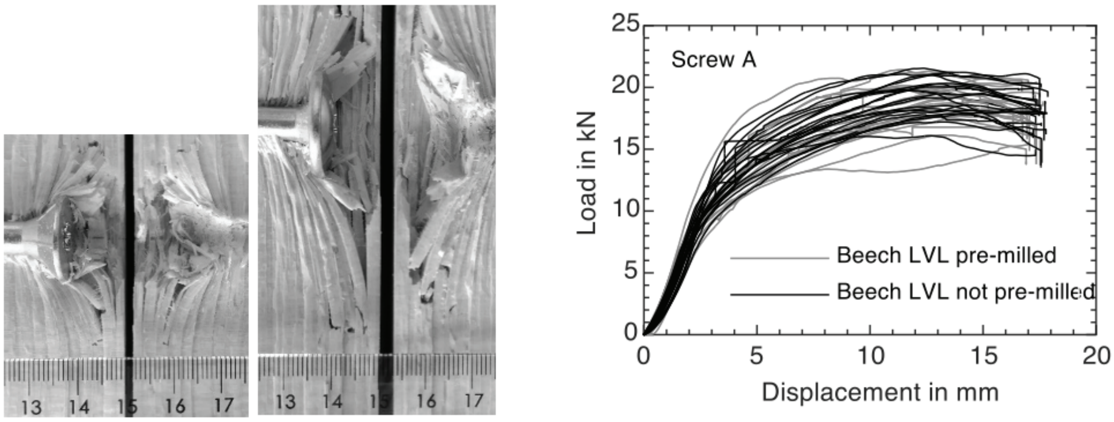


*Figure 6. Top: Opened test specimens (not predrilled). Bottom: Load-displacement curves of head pull-through tests showing transducer displacement. Results screw A in beech LVL.*

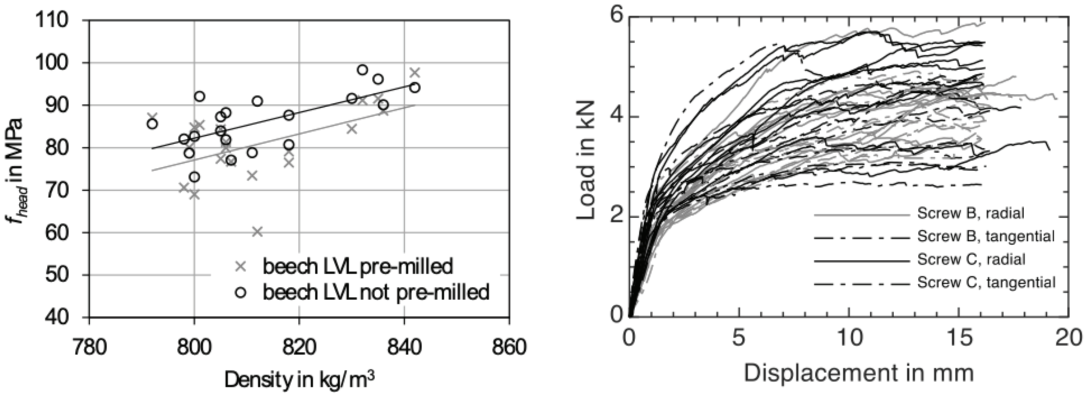


*Figure 7. Top: $f_{head}$-values versus density. Results for screws A in beech LVL with trendlines for pre-milled and not pre-milled specimens. Bottom: Load-displacement curves of head pull-through tests showing transducer displacement. Results for screws B and C.*

test results was carried out in order to determine a correction factor, the exponent in Eq. (4) ($R^2 = 0.7$):

$$f_{head} = 9.5 \cdot 10^{-4} \cdot \rho^{1.67} \qquad (4)$$

where $f_{head}$ = head pull-through parameter, $\rho$ = density.

This nonlinear regression did not comprise a thorough residual analysis with corresponding deletion of outliers with studentised residuals larger than |3|. Moreover, no differentiation, e.g. with respect to different wood species, was made. Further nonlinear regressions revealed an exponent of 1.00 for all tests with spruce, 1.61 for the tests with solid hardwoods, and no convergence was possible for the tests with beech LVL. The exponent of 1.67 is used to correct the head pull-through parameters of each test series, hence also of the series with spruce, using reference densities $\rho_{ref}$ that correspond to the mean densities of all series per wood type.

$$f_{head,corr} = f_{head} \cdot \left( \frac{\rho_{ref}}{\rho_{mean}} \right)^{1.67} \qquad (5)$$

where $f_{head,corr}$ = corrected head pull-through parameter, $\rho_{ref}$ = mean density of all series per wood type: spruce $\rho_{ref,spruce}$ = 433 kg/m$^3$, solid hardwood $\rho_{ref,solidHW}$ = 690 kg/m$^3$, beech LVL $\rho_{ref,beechLVL}$ = 826 kg/m$^3$, $\rho_{mean}$ = mean density of each test series.

The corrected head pull-through parameters $f_{head,corr}$ are assumed to have a lognormal distribution and the logarithm is taken. A normal distribution is assumed for the density. Figure 8 shows the histograms of both values for all tests with spruce, confirming the distribution assumptions taken. Using the approach given in Annex D of prEN 14592 (2017), the standard deviations of the corrected head pull-through parameter can now be adjusted so that they reflect the timber population:

$$std_{fhead,corr} = \sqrt{std_{fhead}^2 + 1.67^2 \cdot \left(0.10^2 - COV_\rho^2\right)} \qquad (6)$$

where $std_{fhead,corr}$= corrected standard deviation of head pull-through parameter, $std_{fhead}$ = observed standard deviation of head pull-through parameter, 1.67 = correction factor, see Eq.(5), 0.10 = target COV of density of timber population, $COV_\rho$ = observed COV of density, per test series, see Figure 2 on the left.

Finally, in accordance with EN 14358 (2016), 5th percentiles for $f_{head,corr}$ were estimated using the corrected standard deviations $std_{fhead,corr}$. The limited amount of test results per test series was considered applying the $k_s$-factor given in EN 14358.

The calculated characteristic $f_{head,k}$-values are shown in Figure 9, where in total 14 $f_{head,k}$-values were smaller than 10 MPa, although only one original $f_{head}$-value was smaller than 10 MPa (the lower bound value defined in the EAD), see Figure 3 on the left. This, however, is a consequence of the corrections in accordance with Eqs. (5) and (6). Scatter is, again, persistent. Higher $f_{head,k}$-values can be reached for smaller diameters (Figure 9 on the left), which may be an effect of data scarcity for larger diameters. However, a similar trend was observed for nails (Sandhaas and Görlacher, 2018). This, together with the similarity to head pull-through behaviour of nails, leads to the obvious step of combining databases as is done in Figure 10. In general, data clouds for nails and screws look similar, although nails can reach higher values, where the underside shape of nail heads in general is even (nails with trumpet heads were not pulled through). The data discussed here confirms the lower bound constant of $f_{head,k}$ = 10 MPa for screws pulled through spruce given in the EAD (2019), whereas for nails, a lower bound constant of $f_{head,k}$ = 15 MPa was found by Sandhaas and Görlacher. However, data for other species than spruce are missing for nails. If it is now postulated that nails pulled through higher density timber behave similar to screws, then a lower bound equation encompassing a correction of density for both fastener types is possible. As exponential approaches are very sensitive at their boundaries, the exponent of 1.67 found in Eq. (4) should not be considered. This exponent is furthermore deemed to be too high due to the large scatter of data for beech LVL. Instead, the exponent of 1.25 found for nails could be applied, leading to the following equation shown also in Figure 10:

$$f_{head,k} = 10 \cdot \left( \frac{\rho_k}{350} \right)^{1.25} \qquad (7)$$

where 10 = constant value of $f_{head}$ of 10 MPa, adjustment of $f_{head,k}$ for density with reference density of 350 kg/m$^3$ = $\rho_k$ of C24, EN 338 (2016), and the exponent of 1.25 for nails taken from Sandhaas and Görlacher (2018).

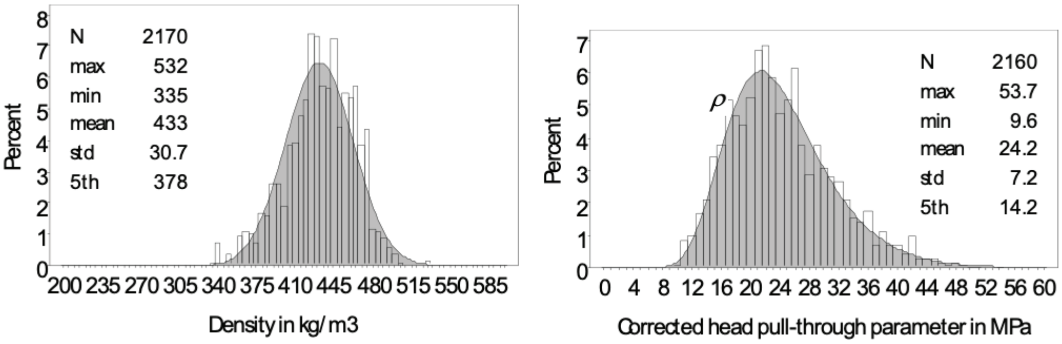


*Figure 8. Head pull-through tests with spruce. Left: Histogram of density with fitted normal dis-tribution. Right: Histogram of $f_{head,corr}$-values with fitted lognormal distribution (for one series of 10 tests, $d_h$ was not recorded and hence, $f_{head}$ could not be calculated).*

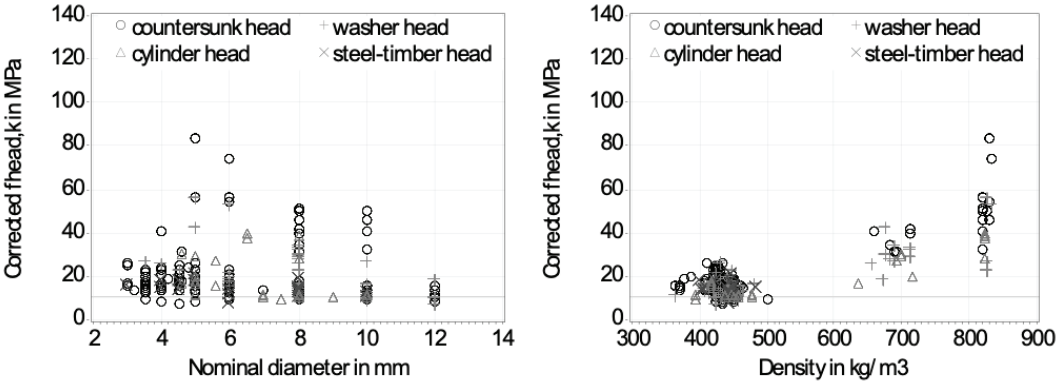


*Figure 9. Characteristic values of the head pull-through parameter $f_{head,k}$ based on corrected standard deviations. 14 of 245 $f_{head,k}$-values < 10 MPa (only spruce).*

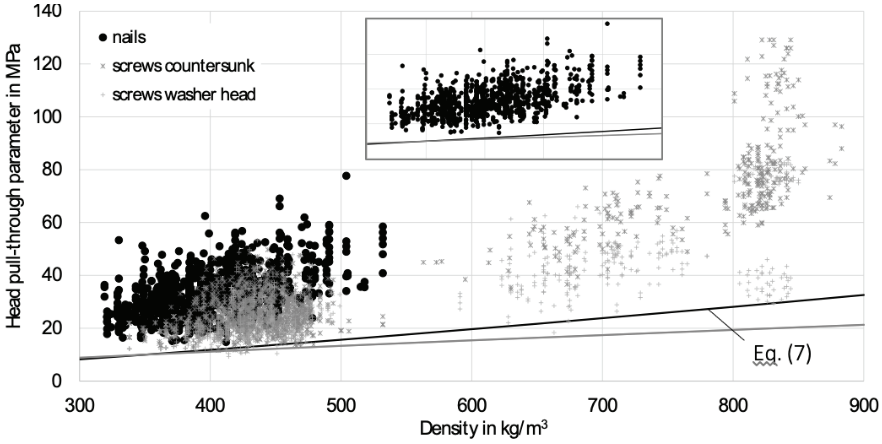


*Figure 10. Individual $f_{head}$-values versus density for nails, screws with countersunk heads and screws with washer heads. The box inset shows only data for nails together with Eq. (7) for better identification of data cloud position with respect to Eq. (7). The red line corresponds to Eq. (7), but with an exponent of 0.8 as in the current Eurocode 5 (2010).*

Eq. (7) obviously delivers conservative values for the head pull-through parameter, and it is not derived by applying accepted statistical procedures. However, the persistent large scatter, in particular for beech LVL, does not allow for any meaningful, more sophisticated regressions. Moreover, considering the load-displacement behaviour shown e.g. in Figure 5, remaining conservative may be a good choice as $f_{head}$-values are currently determined at rather large displacements, and hence represent upper bound values (except for screws with washer heads). Finally, a lack of understanding of the source of the observed scatter, even after having analysed the additional tests discussed in section 3.2, makes further analyses rather pointless. Within a wood type, i.e. spruce, solid hardwood and beech LVL, no or only a weak trend of higher $f_{head}$-values at higher densities can be observed. An alternative scenario to Eq. (7) could be to keep the lower bound value of 10 MPa for screws pulled through softwood. Similar, for timber with 500 kg/m$^3$ < $\rho$ < 900 kg/m$^3$, a constant minimum value could be used, without considering any differences in density. Such minimum values for $f_{head,k}$ could be 20 MPa for solid hardwoods, and 30 MPa for beech LVL, see Figure 3 on the left.

## 4 CONCLUSIONS

In general, the observed scatter of the assembled representative database is large, and neither analyses of potential influence factors nor additional tests clarified the source of this scatter. However, the tests indicated that features not reported up to now may impact on results and should be recorded in future. Such features are e.g. more exact geometrical definitions of the screws and of the timber specimens. Above all, the lack of definition at which deformation level head pull-through capacities should be determined, is a major omission. Furthermore, also the insertion process should be more precisely prescribed, including information on predrilling and pre-milling. All this should be part of a future version of EN 1383. Concerning the source of the large observed scatter, further possible hypotheses are the impact of other wood characteristics than the density (or insertion direction) alone, e.g. local properties of the wood directly underneath resp. closely around the screw, together with certain features of the individual screws, e.g. underside head shapes. In particular for beech LVL, a highly homogenised product, the scatter is significant and does not allow for meaningful regressions. Currently, in accordance with the EAD, a minimum characteristic value of the head pull-through parameter $f_{head,k}$ of 10 MPa for softwood can be declared. This value could be confirmed. Analogously, lower bound constants could be defined also for higher-density timber products. Nevertheless, all these approaches remain conservative. To sum up, different scenarios are possible how $f_{head,k}$-values needed for design could be defined as long as no further investigations are available that help understanding the source of the observed scatter with subsequent tailor-made solutions for design. These scenarios encompass e.g. (i) maintenance of the state-of-the-art, i.e. $f_{head,k}$-values can be declared as proprietary properties by the individual screw producers, (ii) the definition of lower bound values or equations that will not allow for higher $f_{head,k}$-values and that potentially lead to wrong predictions of the failure modes, or (iii) technical classes are defined to keep simple constant values or equations whilst allowing for higher $f_{head,k}$-values.

## 5 ACKNOWLEDGEMENTS

This work has been carried out within the project hardwood_joint, which is supported under the umbrella of ERA-NET Cofund ForestValue by BMLFUW (AT), ADEME (FR), FNR (DE) and Vinnova, Swedish Energy Agency and Formas (SE). ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773324.

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