Properties of single fasteners

FP 1402 “Basis of structural timber design - from research to standards”

Short-Term Scientific Missions

Final Report

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Table des matières

Objectives

This Short Term Scientific Mission takes place in COST action FP1402 – "Basis of structural timber design - from research to standards", in Working Group 3 – "Connections". The purpose of this action is to bring scientific results and the specific information needed by designers, industry, authorities and code committees together. The main task of the Working Group 3 (Connections) is the collection and harmonization of methods and parameters to determine the load-carrying of dowel-type fasteners.

Karlsruhe University of Technology is a leading lab in the field of timber engineering. Under the supervision of Prof. Hans Blass, many tests have been done to characterize the properties of single fasteners. In the context of the forthcoming revision of EC5, this Short Term Scientific Mission at Karlsruhe University of Technology is divided in two main parts:

- The first one is based on the collect and classification of all experimental results about the characterization of fastener with nails (development of a database).
- In the second part, we look how a property may be correlated to another one in an attempt to explain one from the other.

Figure 1 – Different nails

Development of a database

The first part of the work consisted in creating a database that brings experimental results together. There are only fasteners with nails (most of them are threaded nails). Currently, the database includes results of 96 reports and approaches the following fastener and system parameters:

- Geometrical parameters of nails
  - Nominal diameter d [mm] (diameter given by the industry)
  - Nominal diameter d_n [mm] (diameter after measurement in lab)
  - Head diameter D [mm]
  - Inner diameter d_k [mm]
  - Outer diameter d_1 [mm]
  - Nominal length l [mm] (length given by industry)
  - Nominal length l_n [mm] (length after measurement in lab)
  - Peak length l_p [mm]
  - Threaded length l_g [mm]
  - Ring length t [mm]
  - Head thickness s [mm]

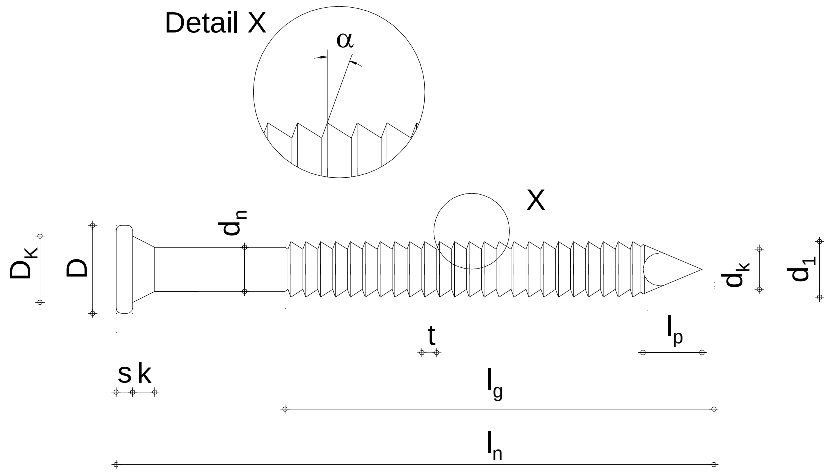


Figure 2 - Nail

- Tensile test parameters
  - Tensile strength of wire f_u [MPa]
  - Tensile capacity (of the nail) F_t [kN]
- Bending test parameters
  - Yield moment M_y [kNm]
- Withdrawal test parameters
  - Density ρ [kg/m²]
  - Effective length t_{pen} [mm]
  - Axial force F_{ax} [kN]
  - Withdrawal strength $f_{ax} = \frac{F_{ax}}{d \times t_{pen}}$ [MPa]
- Head pull-through test parameters
  - Density ρ [kg/m²]
  - Axial force F_{ax} [kN]
  - Head pull-through strength $f_{head} = \frac{F_{head}}{D^2}$ [MPa]
- Other: stainless steel, galvanized or not, fire protection or not, etc.
- Embedment strength was not considered in this mission.

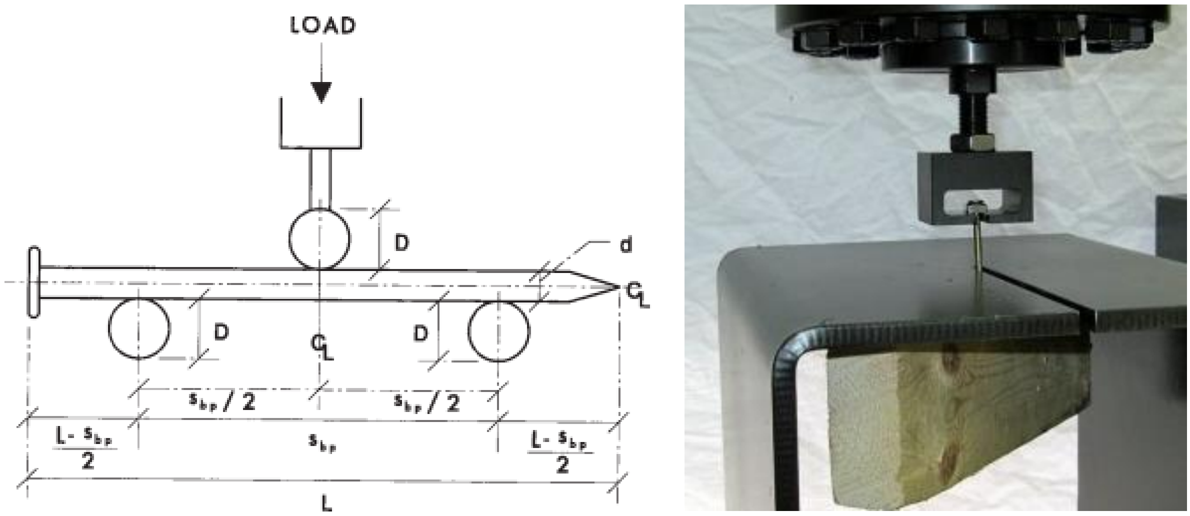


Figure 3 – Bending test and withdrawal test

The structure of the database is summarized on Table 1. The number of data for each parameter is given on Table 2.

Table 1 – Summary of the database

N° of report	Type of nail	Parameters				Geometry				Other		
		f_u [MPa]	F_t [kN]	M_y [kNm]	…	D [mm]	d_n [mm]	d_k [mm]	…	Stainless steel Y/N	Galv. Y/N	…

Table 2 – Number of data for each parameter

Geometry D, d_n, d_k, d_1 l_n, l_g, l_p, t [mm]	f_u [MPa]	F_t [kN]	M_y [kNm]	Withdrawal parameter		Head pull-through parameter	
				ρ [kg/m³]	Rax [kN]	ρ [kg/m³]	Rax [kN]
7000-8250	1082	1066	2981	3561		940	

Data analysis

The second part of the work aimed to analyse the assembled data and see where we can simplify/unify design rules, etc. Stainless steel nails were not considered.

1 Laterally loaded connections: tensile strength of wire, tensile capacity and yield moment

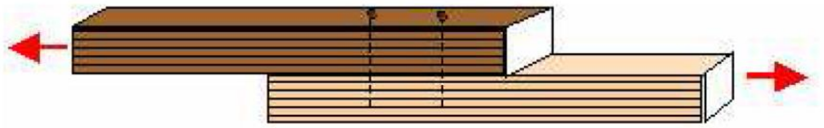


Figure 4 - Laterally loaded connections[1]

In mechanics, the yield moment is the moment taken at the elastic limit and is expressed as follow:

$$M_y = \frac{d^3 \times f_y}{6} \quad \text{1-1}$$

Where f_y is the yield strength and d the diameter of the nail. The characteristic yield moment $M_{y,Rk}$ for the different fasteners with nails in Eurocode 5 (EC5) is summarized in Table 3, where f_u is the tensile strength of wire and d the diameter of the nail.

Table 3 - Characteristic yield moment for nails fasteners (EC5)

Nails	
Smooth round nails (EC5 equation 8.14)	$M_{y,Rk} = 0{,}3\ d^{2{,}6} f_u$
Smooth square and grooved nails (EC5 equation 8.14)	$M_{y,Rk} = 0{,}45\ d^{2{,}6} f_u$
Threaded nails	As stated in BS EN 14592, by testing in accordance with BS EN 409

It is interesting to notice that most nails of the database are round threaded nails. It could be relevant to see if a relationship can be found as for smooth round nails. In this section, each parameter (tensile strength of wire, tensile capacity and yield moment) is analysed with general comments and we try to answer the following questions:

- Can we obtain yield strength f_y from tensile strength of wire f_u ?
- Can we obtain tensile capacity (of the nail) F_t from tensile strength of wire f_u ?
- Can we obtain yield moment M_y from the other parameters ?

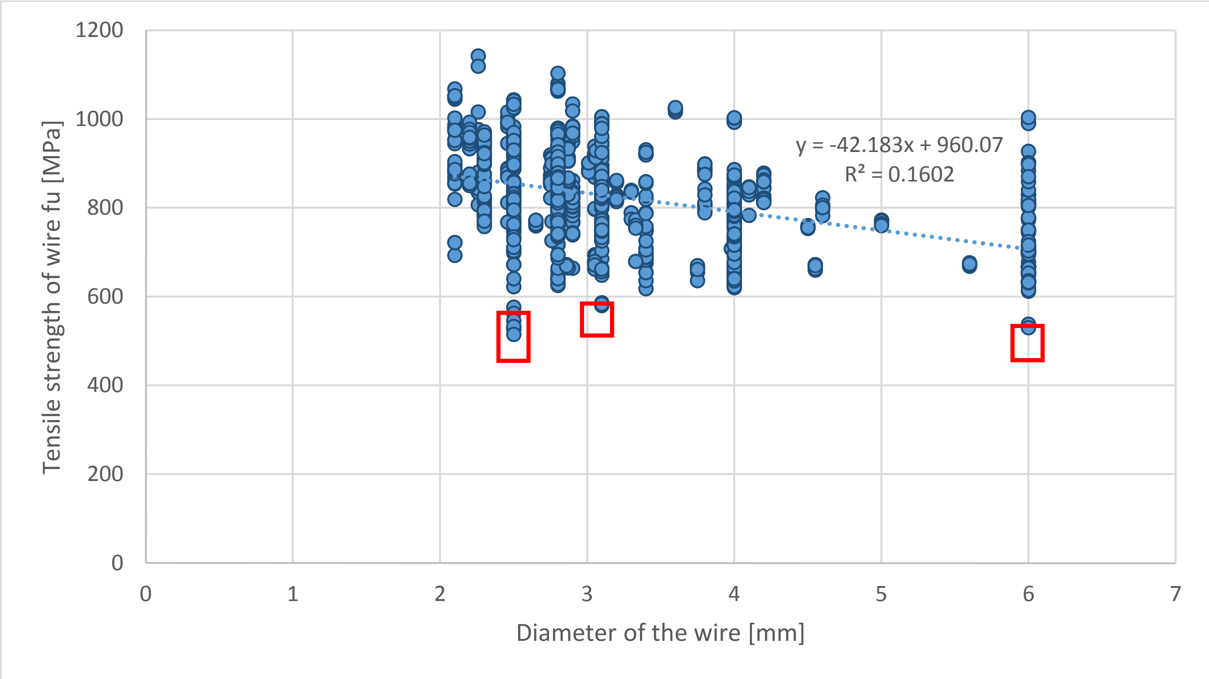
A detailed analysis (regression and calculation of R^2[2]) is performed for yield moment.

[1] Source: « Timber Connections », Ad Leijten
http://eurocodes.jrc.ec.europa.eu/doc/WS2008/EN1995_5_Leijten.pdf

[2] In statistics, the coefficient of determination, denoted R² or r² and pronounced R², is a number that indicates how well data fit a statistical model – sometimes simply a line or a curve. An R² of 1 indicates that the regression

1.1 Tensile strength of wire f_u [MPa]

We can see on Graph 1 that the tensile strength ranges from 515 [MPa] to 1142 [MPa] and seems to slowly decrease with the diameter of the wire. However, the low value of R² (R²=0.1602) shows that data don't fit very well. We notice that some values are under 600 MPa (highlighted in red).



Graph 1

Something interesting we can try with the data is to see if a relationship can be found between the yield strength f_y and the tensile strength f_u. The yield strength was not measured in the reports of the KIT but we can calculate, using the yield moment equation 1-1.

$$M_y = \frac{d^3 \times f_y}{6} \rightarrow f_y = \frac{M_y \times 6}{d^3} \qquad \text{1-2}$$

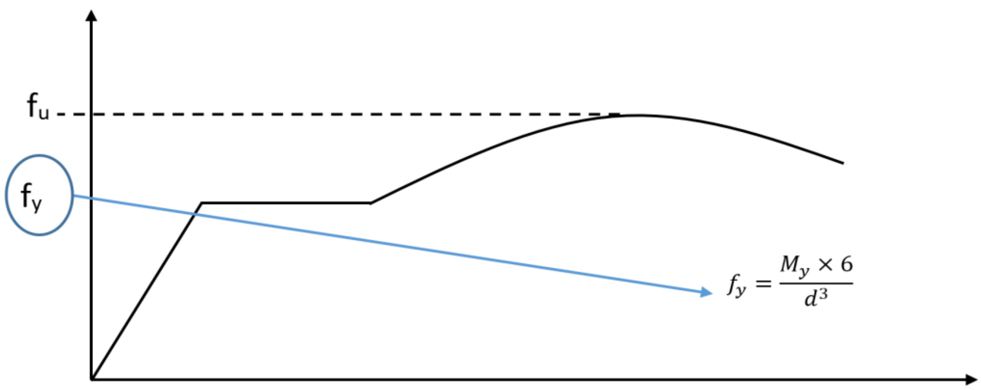


Figure 5 - Yield strength f_y and the tensile strength f_u

A handling of the data is necessary. For one report, the mean value of tensile strength was associated to nail diameter d. Graph 2 shows that there is no obvious relationship.

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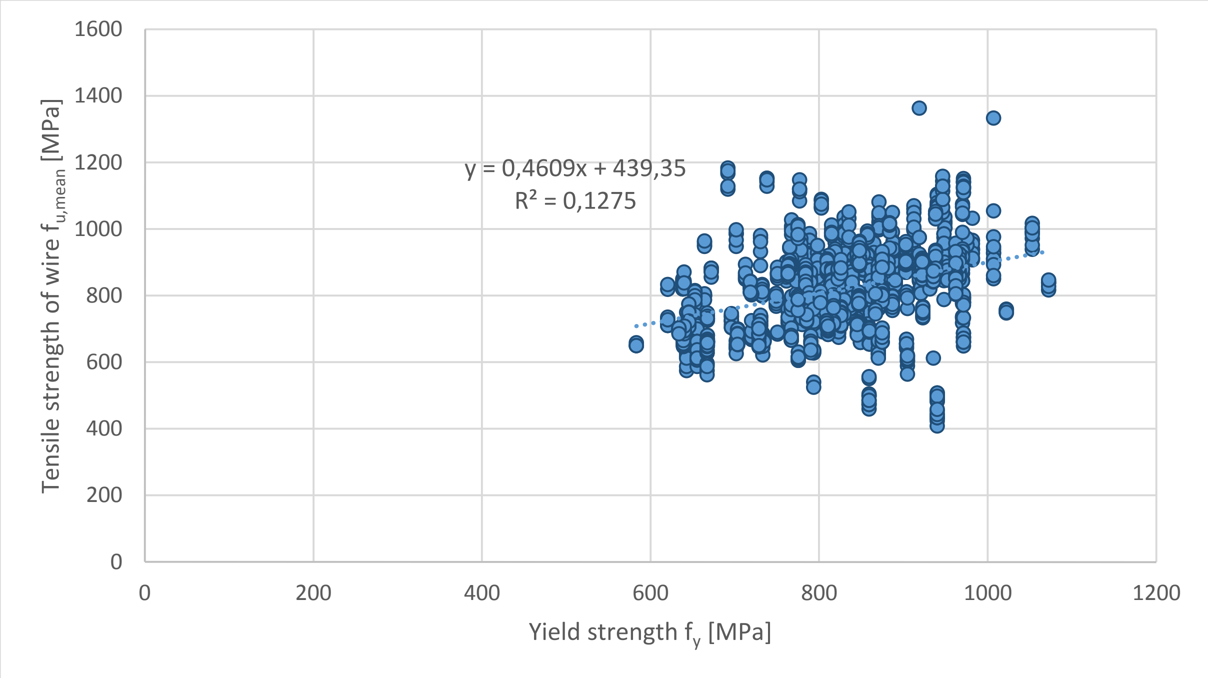
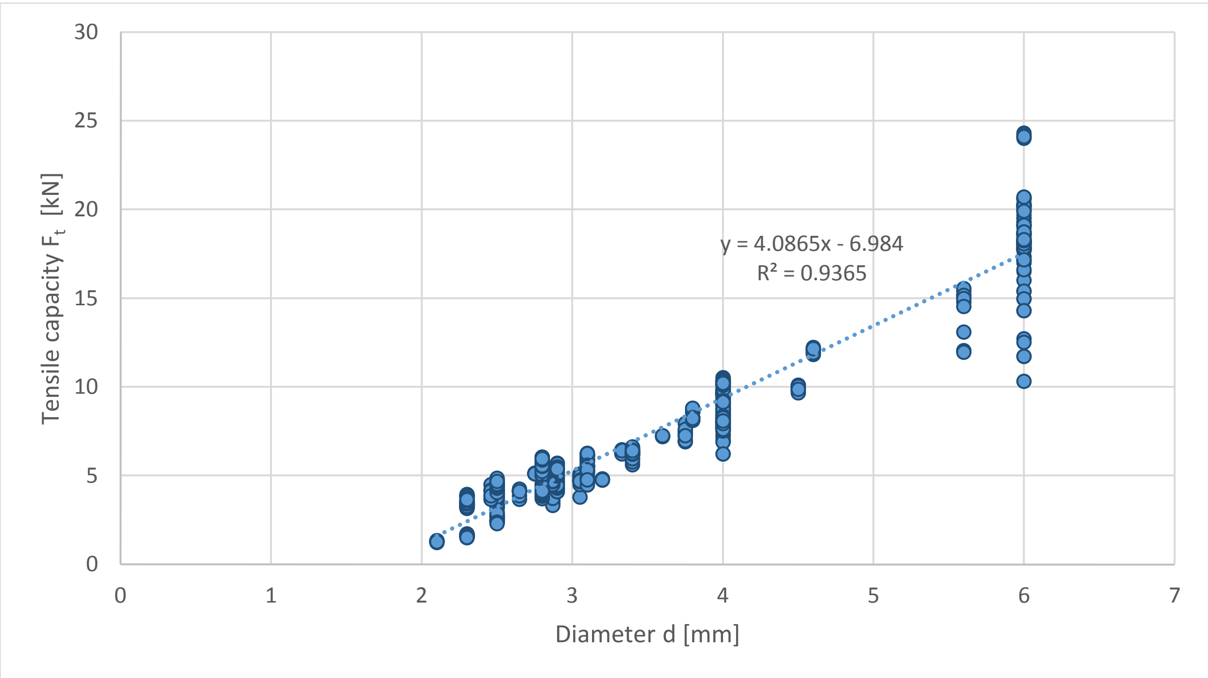
line perfectly fits the data, while an R² of 0 indicates that the line does not fit the data at all. This latter can be because the data is more non-linear than the curve allows, or because it is random.



Graph 2

1.2 Tensile capacity (of the nail) F_t [kN]

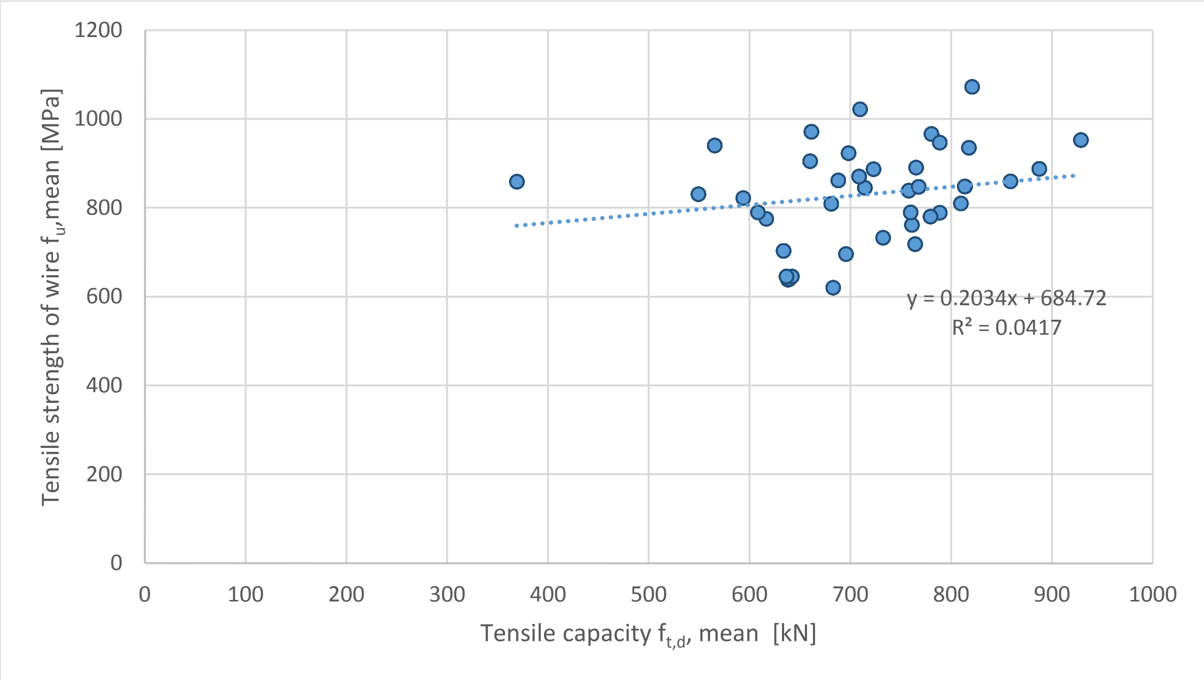
The tensile capacity F_t ranges from 1.23 [kN] (d=2.1 mm) and 35.5 [kN] (d=6 mm). According to the hereunder chart, the relation between tensile capacity F_t and the diameter d of the nail is obvious and seems linear.



Graph 3

It is possible to express this tensile capacity F_t as a stress $f_{t,d}$ with equation 1-3. and compare it with the tensile strength of wire f_u (see Graph 4). It seems that there is again no relationship.

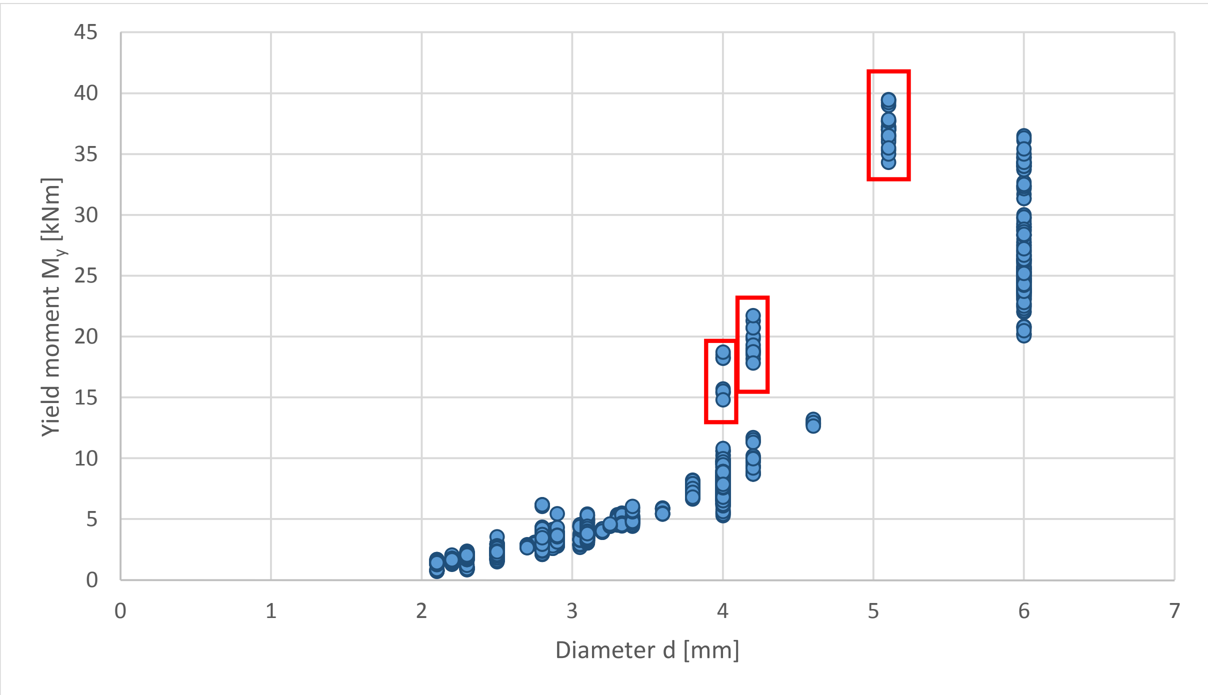
$$f_{t,d} = \frac{F_t}{\frac{d\pi}{4}} \tag{1-3}$$



Graph 4

1.3 Yield moment M_y [kNm]

As expected, Graph 5 shows that yield moment M_y and diameter d fit quite well. However, some data seem to be outside the trend (highlighted in red). They are summarized in Table 4. It is important to notice that for these data, no tensile tests were performed.



Graph 5

Table 4 – Data outside the trend

d [mm]	My [kNm]
4	15.4
4	15.4
4	15.7
4	15.5
4	14.8
4	18.2
4	18.3
4	18.5
4	18.2
4	18.7
4.2	18.5
4.2	18.67
4.2	18.17
4.2	18.75
4.2	17.83
4.2	19.3
4.2	20.7
4.2	21.3
4.2	20.7
4.2	21.7
4.2	19.8
4.2	20
4.2	18.8
4.2	19
4.2	18.8

d [mm]	My [kNm]
5.1	37.25
5.1	36.98
5.1	37.05
5.1	36.97
5.1	36.4
5.1	39.38
5.1	39
5.1	39.23
5.1	39.45
5.1	39.44
5.1	37.2
5.1	36.6
5.1	37.7
5.1	37.2
5.1	36.2
5.1	37.7
5.1	35.3
5.1	34.3
5.1	36
5.1	35
5.1	37
5.1	36.5
5.1	35.5
5.1	37.67
5.1	37.83

We can find two relationships from two different sources that define the yield moment according to other parameters:

- In Eurocode 5 (equation 8.14) for round smooth nails:

$$M_{y,k} = 0{,}3d^{2,6}f_u \tag{1-4}$$

- In mechanics:

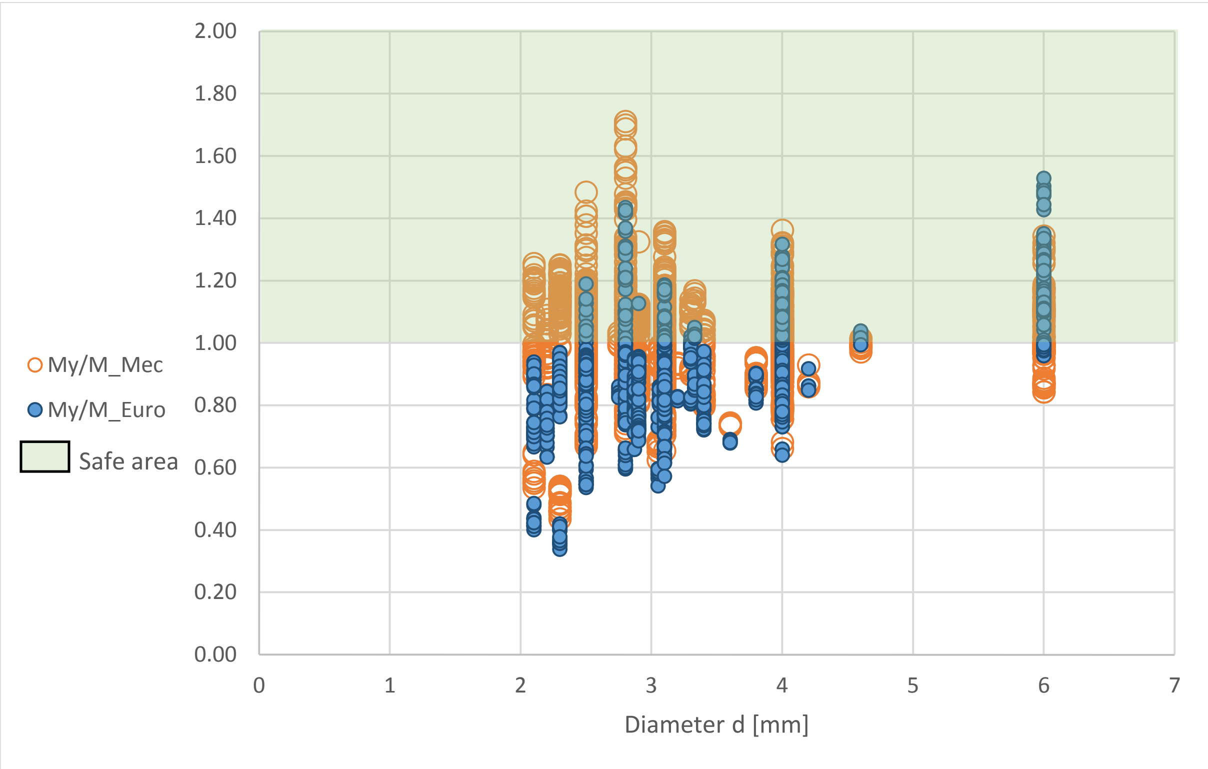
$$M_y = \frac{d^3 f_y}{6} \tag{1-5}$$

The yield strength f_y is not calculated and consequently, we will replace it by the tensile strength of wire f_u. Another assumption is that we only use mean values. As a result, equations 1-4 and 1-5 becomes:

$$M_{Euro} = 0{,}3d^{2{,}6} f_{u,mean} \tag{1-6}$$

$$M_{mec} = \frac{d^3 f_{u,mean}}{6} \tag{1-7}$$

Graph 6 shows the ratio M_y/M_{Euro} and M_y/M_{mec} (M_y is the Yield moment coming from the experimental tests). The safe area is highlighted is green. The two distributions are quite different for small diameters but are closer for large diameters (especially $d = 4\ [mm]$ and $d = 6\ [mm]$). It is interesting to notice that M_y/M_{Euro} gives a lot a results in the unsafe area for small diameters of nails.



Graph 6

1.4 My, fu, Ft + Geometry (d, d_n, d_1, d_k)

With the software SAS (statistical analysis software), we try in this section to find relationships between the following parameters:

- Diameter d [mm] (diameter given by industry)
- Nominal diameter d_n [mm] (diameter after measurement)
- Inner diameter d_k [mm]
- Outer diameter d_1 [mm]
- Tensile strength of wire f_u [MPa]
- Tensile capacity (of the nail) F_t [kN]
- Four stress forms of the tensile capacity [MPa] :

$$f_{t,d} = \frac{F_t}{\frac{\pi^2 d}{4}}, f_{t,d_n} = \frac{F_t}{\frac{\pi^2 d_n}{4}}, f_{t,d_1} = \frac{F_t}{\frac{\pi^2 d_1}{4}}, f_{t,d_k} = \frac{F_t}{\frac{\pi^2 d_k}{4}} \tag{1-8}$$

- Yield moment M_y [kNm]

We calculate mean values for f_u and F_t (and consequently for $f_{t,d}$, f_{t,d_n}, f_{t,d_1} and f_{t,d_k}). Two type of regressions are explored:

- Linear regression $a = bx + c$
- Linear regression with logarithmic transformations $\ln a = \ln b\, x + \ln c$

1.4.1 Linear regression $a = bx + c$

The hereunder table shows R² values. The highest values are highlighted in red. As expected, we find strong links between the different types of diameters, yield moment and tensile capacity.

Table 5 - R² for Linear regression a=bx+c

	d	d_n	d_k	d_1	M_y	f_u	F_t	$f_{t,d}$	f_{t,d_n}	f_{t,d_k}	f_{t,d_1}
d		0.989	0.974	0.986	0.926	0.289	0.960	0.002	0.005	0	0.006
d_n			0.982	0.986	0.914	0.304	0.955	0.002	0.011	0.001	0.009
d_k				0.964	0.88	0.267	0.933	0.003	0.014	0.009	0.007
d_1					0.925	0.288	0.956	0.003	0.011	0	0.018
M_y						0.245	0.943	0.004	0.012	0	0.014
f_u							0.227	0.042	0.069	0.014	0.045

Table 6 gives the R² value for the relationship between M_y/f_u ($M_y/f_{t,d}$) and the different types of diameters. The values are high but can be improved.

Table 6 - R² for Linear regression a=bx+c

	d	d_n	d_k	d_1
M_y/f_u	0.882	0.887	0.843	0.895
$M_y/f_{t,d}$	0.887			

1.4.2 Linear regression with logarithmic transformations $\ln(a) = \ln(b)x + \ln(c)$

It seems relevant to approach the following relationship:

$$\ln(a) = \ln(b)\, x + \ln(c) \;\rightarrow a = \exp(c)\, b^x \qquad \text{1-9}$$

Table 7 gives R² values but for the logarithm of the variable. The highest values are highlighted in red.

Table 7- R² for linear regression of the logarithm ln a=ln (b) x+ln (c) or a=exp(c) b^x

	$\ln(d_n)$	$\ln(d_k)$	$\ln(d_1)$	$\ln(M_y)$	$\ln(f_u)$	$\ln(F_t)$	$\ln(f_{t,d})$	$\ln(f_{t,d_n})$	$\ln(f_{t,d_k})$	$\ln(f_{t,d_1})$
$\ln(d)$	0.986	0.968	0.982	0.941	0.289	0.911	0.005	0.002	0.011	0.003
$\ln(d_n)$		0.979	0.984	0.926	0.011	0.903	0.006	0	0.006	0.002
$\ln(d_k)$			0.959	0.894	0.263	0.869	0.002	0	0	0.001
$\ln(d_1)$				0.912	0.294	0.881	0.002	0	0.005	0
$\ln(M_y)$					0.260	0.940	0.045	0.034	0.061	0.041
$\ln(f_u)$						0.204	0.028	0.052	0.005	0.029

Table 8 gives the R² values for the relationship between M_y/f_u ($M_y/f_{t,d}$) and the different types of diameters. The most relevant relationship involves the same parameters than the ones given by EC 5 and is highlighted in red.

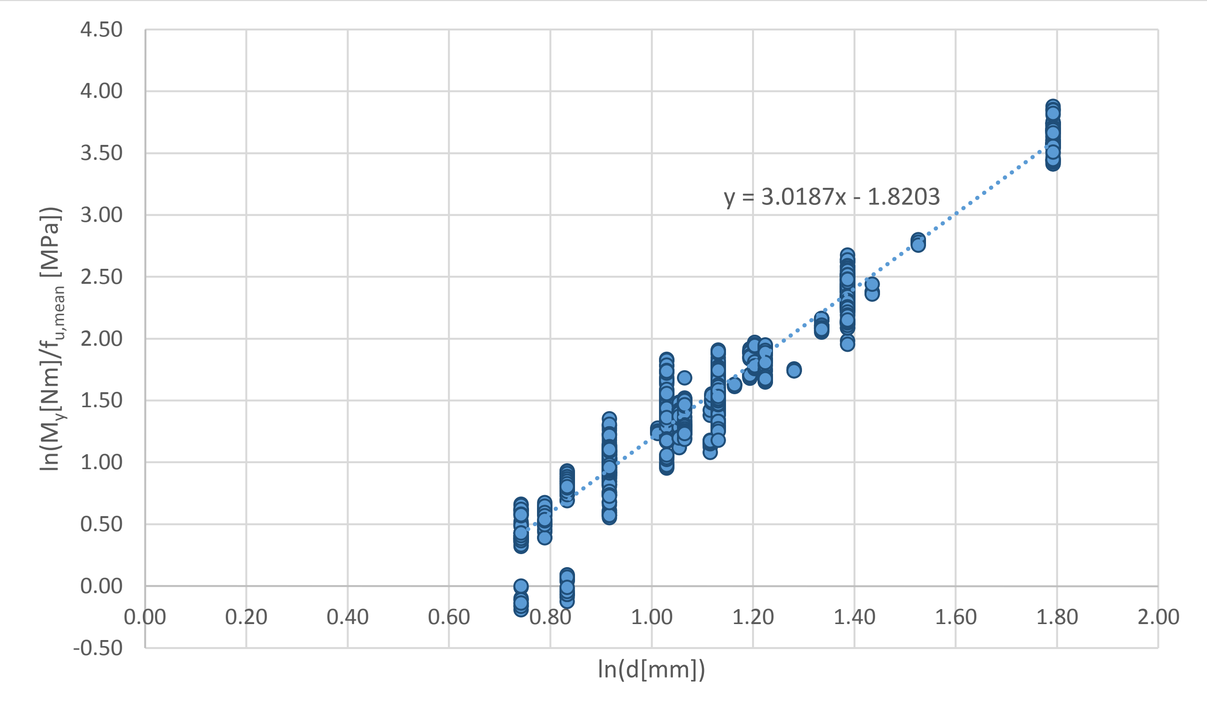
Table 8 - R² for linear regression of the logarithm ln a=ln (b) x+ln (c) or a=exp(c) bˣ

	d	d_n	d_k	d_1
M_y/f_u	0.937	0.928	0.887	0.911
$M_y/f_{t,d}$	0.956			

Graph 7 shows that $\ln\left(\frac{M_y}{f_u}\right)$ fit quite well with $\ln(d)$. Considering that $f_u = f_{u,mean}$, we obtain the following regression:

$$M_y = 0.162\, d^{3.02} f_{u,mean} \quad (1\text{-}10)$$

The equation 1-11 seems close to equation 1-7 (given by mechanics).



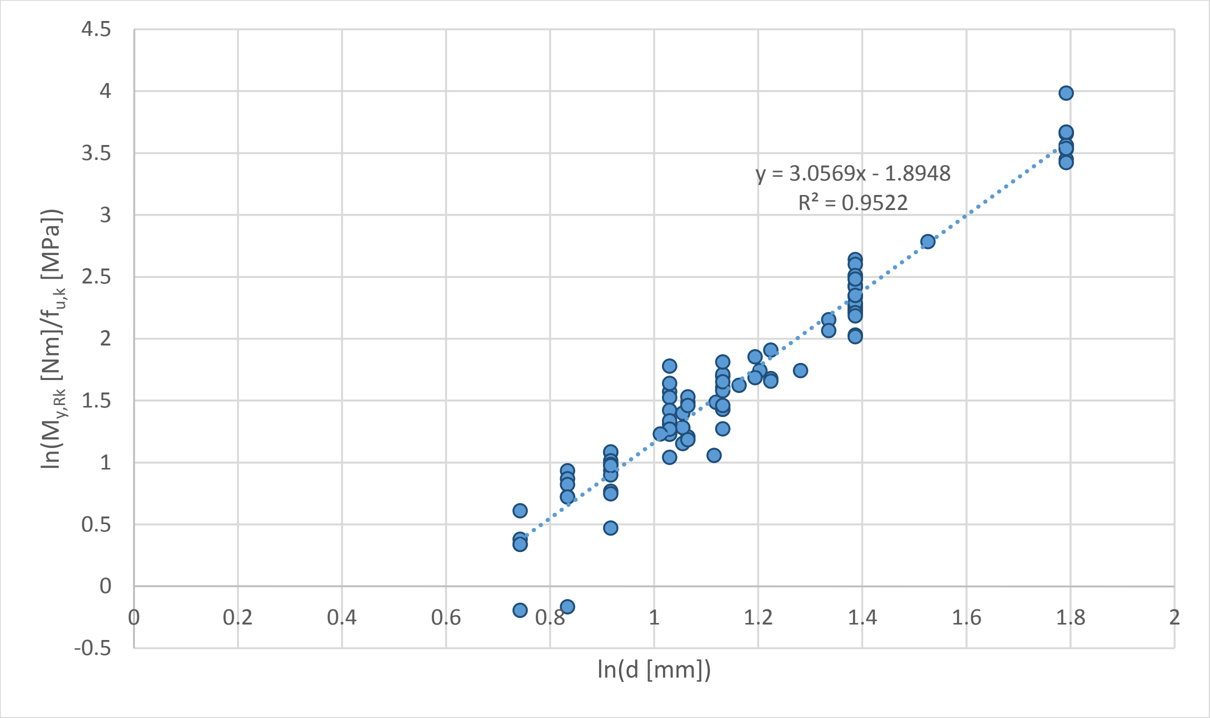
Graph 7

Another analysis is made with characteristic values calculated in each report (with a log-normal distribution):

$$\ln(M_{y,Rk}) = \overline{\ln(M_y)} - k\sigma_{\ln(M_y)} \quad (1\text{-}11)$$

Where $\overline{\ln(M_y)}$ is the mean, $\sigma_{\ln(M_y)}$ the standard deviation and k a coefficient that depends on the fixed probability (here, 5% and so $k = 1.64$). We obtain a similar regression than before as showed in Graph 8. The equation of the regression is similar to equation 1-11:

$$M_{y,Rk} = 0.15\, d^{3.06} f_{uk} \quad (1\text{-}12)$$



Graph 8

2 Axially loaded connections

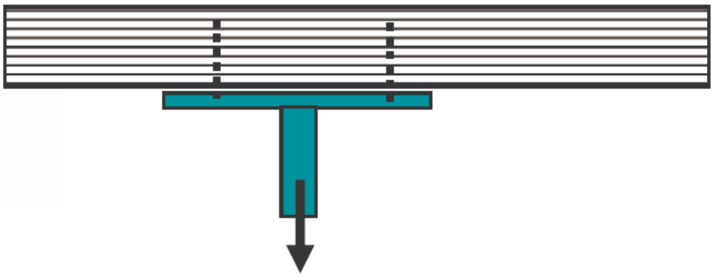


Figure 6 - Axially loaded connections [3]

The value of the axial strength of connections with nails is defined as follow in EC 5:

Table 9 - Axially loaded connections in EC 5

Nails	
Smooth round nails (EC5 equation 8.24)	$F_{ax,Rk} = \begin{cases} f_{ax,k} d t_{pen} \\ f_{ax,k} d t + f_{head,k} D^2 \end{cases}$
Other nails (EC5 equation 8.23)	$F_{ax,Rk} = \begin{cases} f_{ax,k} d t_{pen} \\ f_{head,k} D^2 \end{cases}$

[3] Source: « Timber Connections », Ad Leijten
http://eurocodes.jrc.ec.europa.eu/doc/WS2008/EN1995_5_Leijten.pdf

$f_{ax,k}$ and $f_{head,k}$ are respectively withdrawal strength and head pull-through strength and are defined in Table 10.

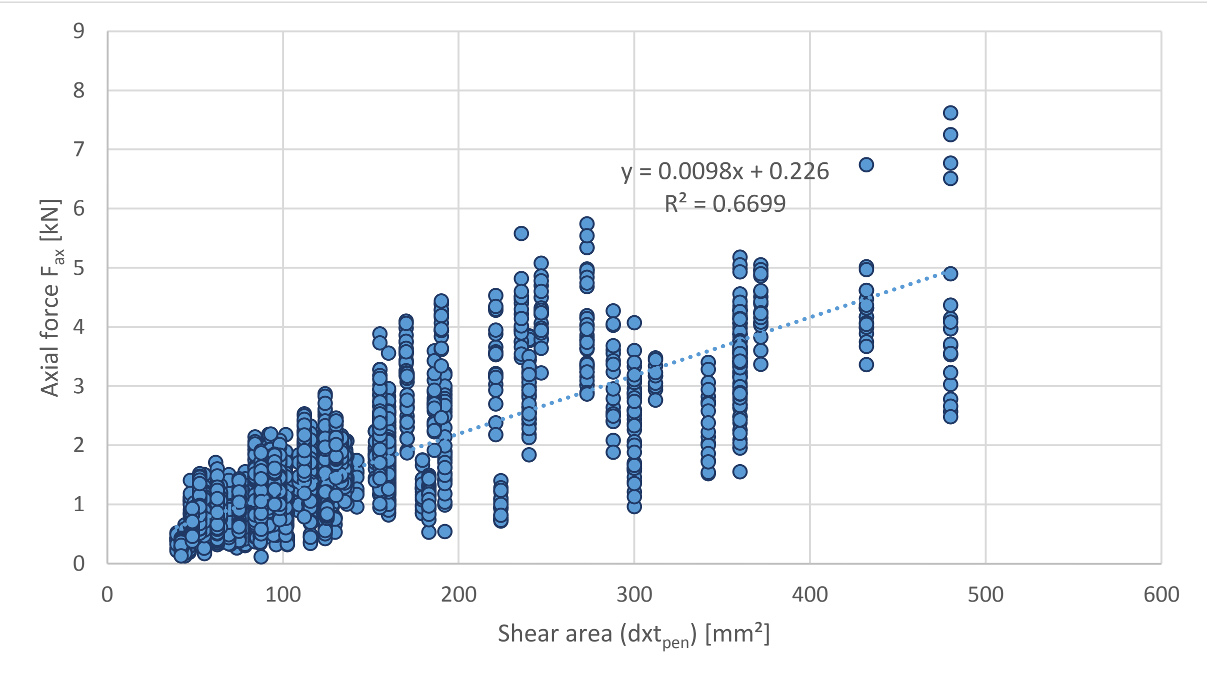
Table 10 - Withdrawal strength and head pull-through strength in EC 5

Nails	
Smooth round nails (EC5 equation 8.25-26) with an efficient length higher than $12d$	$f_{ax,k} = 20 \times 10^{-6}\rho_k^2$ $f_{head,k} = 70 \times 10^{-6}\rho_k^2$
Other nails (EC5 equation 8.14)	By testing in accordance with EN 1382, EN 1383 and EN 14358.

In this section, we will see if it is possible to calculate for threated nails F_{ax}, f_{ax} and f_{head} from geometrical parameters and wood density and have an equation similar to equation 8.25-26 in Eurocode 5.

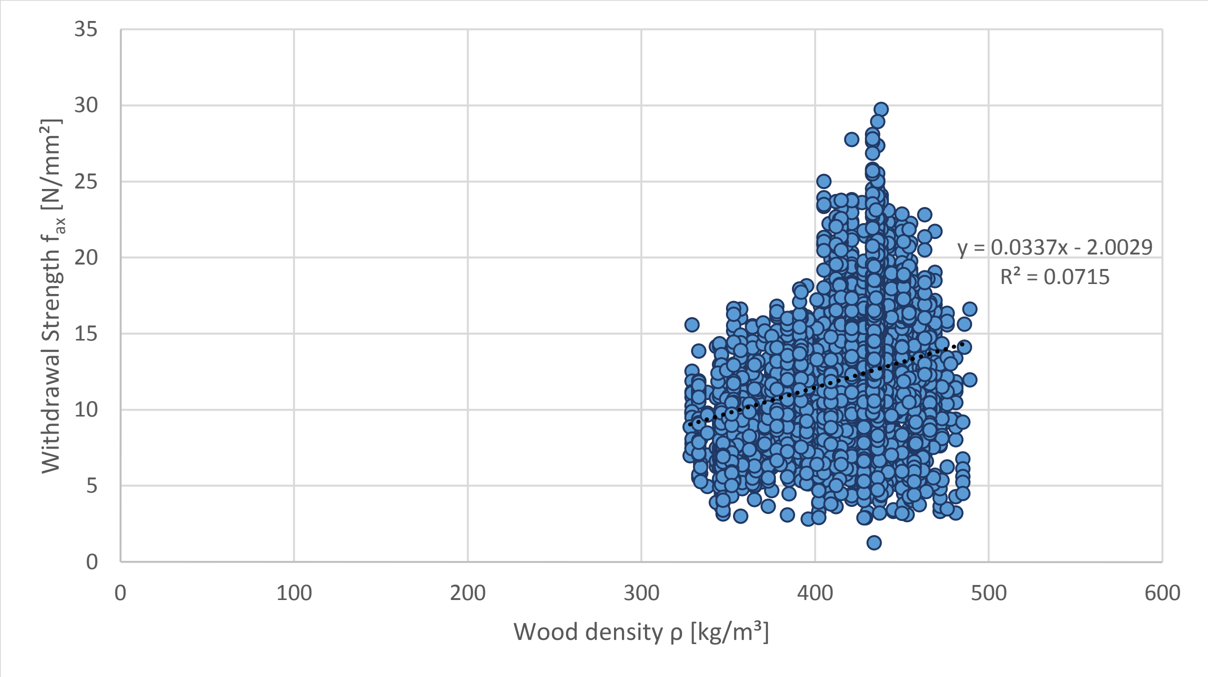
2.1 Withdrawal strength

Graph 9 shows the relationship between the axial force and the shear area ($t_{pen} \times d$). It seems linear (it not surprising: if t_{pen} increases, F_{ax} increases) but R² is not so high because of the scattering of the data.



Graph 9

However, Graph 9 is not very relevant because an important parameter is missing: the density ρ of the wood. It could be interesting to see if a relationship similar to equation in Table 10 can be found for non-smoothed nail. Nonetheless, Graph 10 shows that withdrawal strength f_{ax} doesn't fit with the density ρ.



Graph 10

A similar analysis than for the yield moment in section 1.4 was led in order to show if it exists a relationship between various geometrical parameters that can influence the axial strength. However, the calculation of the R^2 doesn't give more information than before. Highest values are highlighted in red.

Table 11 - R^2 for Linear regression a=bx+c

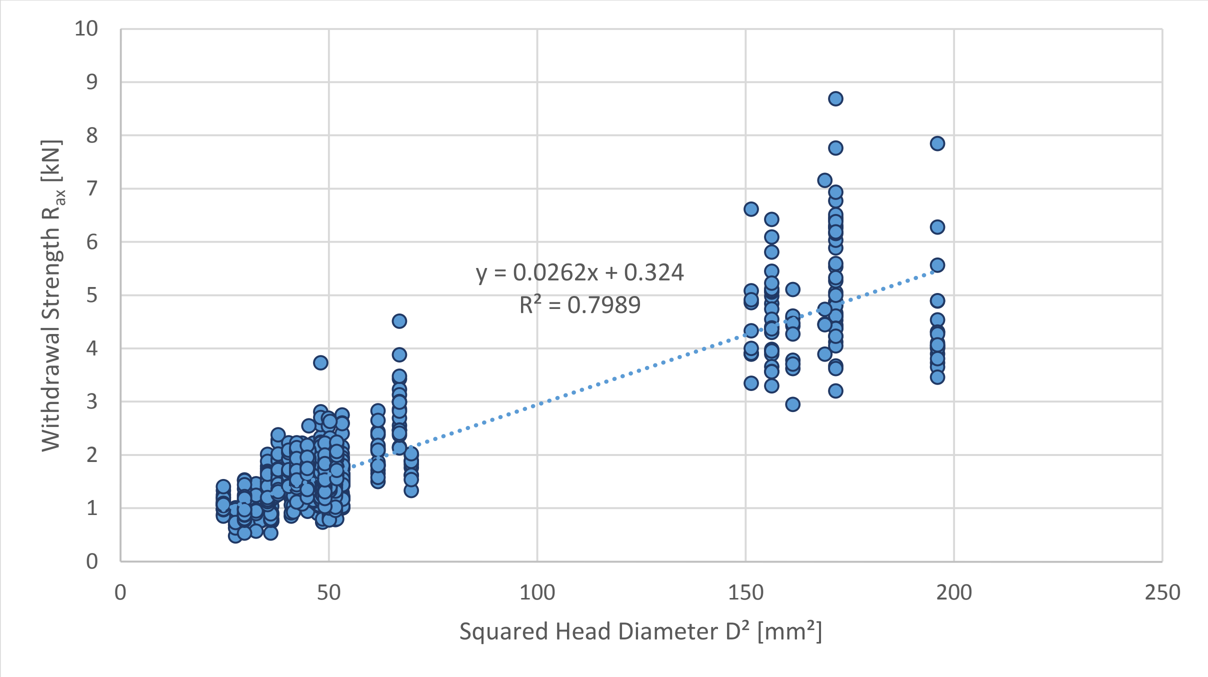
	ρ	t_{pen}	d	d_n	d_k	d_1	$d_1 - d_k$	l_g	t
F_{ax}	0.01	0.647	0.471	0.472	0.458	0.472	0.235	0.375	0.118
F_{ax}/ρ		0.623	0.487	0.487	0.470	0.488	0.256	0.374	0.145
f_{ax}	0.052	0.002	0.038	0.033	0.035	0.032	0.006	0.001	0.020
f_{ax}/ρ		0.003	0.033	0.029	0.033	0.028	0.002	0.001	0.008

Table 12 - R^2 for linear regression of the logarithm ln a=ln (b) x+ln (c) or a=exp(c) b^x

	$\ln(\rho)$	$\ln(t_{pen})$	$\ln(d)$	$\ln(d_n)$	$\ln(d_k)$	$\ln(d_1)$	$\ln(d_1 - d_k)$	$\ln(l_g)$	$\ln(t)$
$\ln(F_{ax})$	0.018	0.653	0.493	0.499	0.484	0.499	0.182	0.350	0.331
$\ln\left(\frac{F_{ax}}{\rho}\right)$		0.652	0.517	0.519	0.500	0.521	0.200	0.355	0.154
$\ln(f_{ax})$	0.052	0.002	0.030	0.024	0.027	0.024	0	0	0.012
$\ln\left(\frac{f_{ax}}{\rho}\right)$		0.004	0.026	0.022	0.025	0.02	0.001	0	0.003

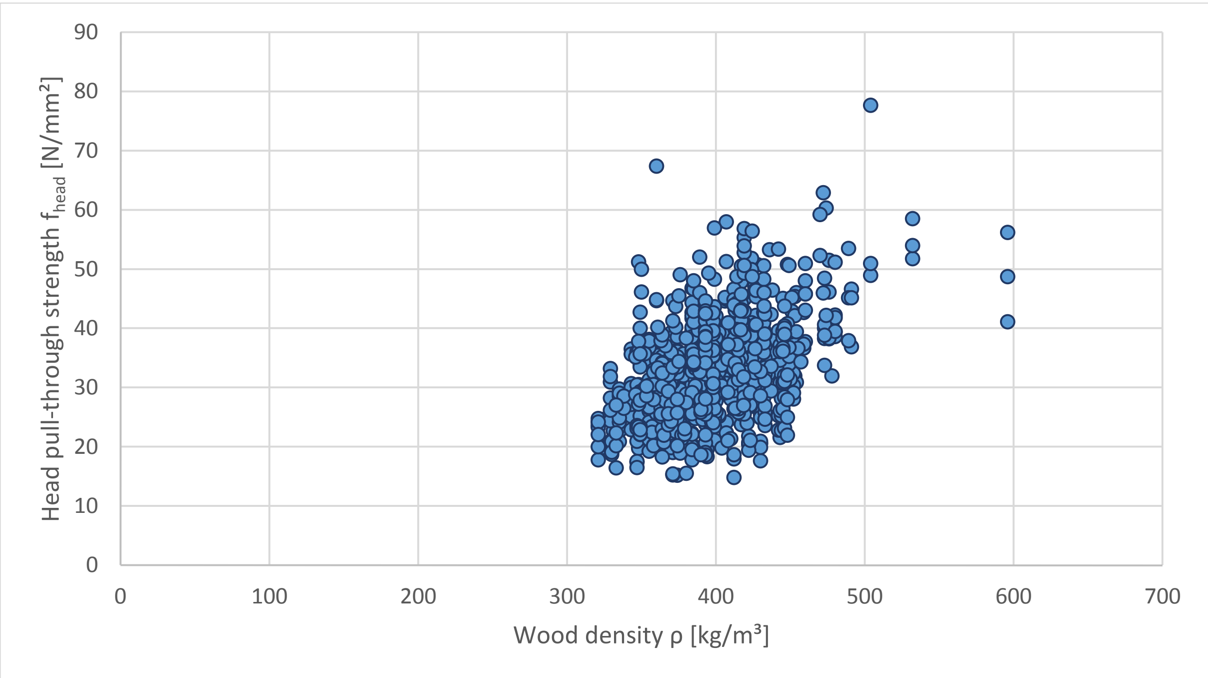
2.2 Head pull-through strength

The analysis for the head-pull test parameters is similar to section 2.1. Graph 11 shows the relationship between the axial force and the squared head diameter D^2. It seems linear (it not surprising, if D increases, F_{ax} increases). R^2 quite is high.



Graph 11

As far as Graph 12 is concerned, observations are similar to Graph 10.



Graph 12

The calculation of R^2 doesn't give more information than before.

Table 13 - R^2 for Linear regression a=bx+c

	ρ	d	D
F_{ax}	0.151	0.794	0.795
F_{ax}/ρ	0.067	0.824	0.81
f_{ax}	0.243	0.038	0.062
f_{ax}/ρ	0.022	0.783	0.817

Table 14 - R^2 for linear regression of the logarithm ln a=ln (b) x+ln (c) or a=exp(c) b^x

	$\ln(\rho)$	$\ln(d)$	$\ln(D)$
$\ln(F_{ax})$	0.208	0.722	0.723
$\ln\left(\frac{F_{ax}}{\rho}\right)$	0.077	0.771	0.767
$\ln(f_{ax})$	0.232	0.044	0.071
$\ln\left(\frac{f_{ax}}{\rho}\right)$	0.037	0.940	

Conclusion and further work

The objective of the work was firstly to develop a database for nails. It will be filled during further works and a similar work will be done for screws.

As far as the second point of the mission is concerned, the main conclusion for data analysis can be summarized in two points:

1. Laterally loaded connections: it seems that the yield moment of threaded round nails can be calculated from tensile strength of the wire and diameter of the nail, as it is done in EC5 for smooth nails. However, the relationship seems closer to equation given by mechanics.
2. Axially loaded connections: Head pull-through and withdrawal strength can't be obtained from other parameters.

Results will be presented at the COST conference held at the KTH, Stockholm (Sweden) in March 2016 (10^{th} -11^{th} March) and hosted by Dr. Andreas Falk.

Figures

Graphs

References

1. EN 1995-1-1 Common rules and rules for building, section 8 “Connections”, Comité Européen de Normalisation
2. Structural Timber Design to Eurocode 5, 2nd Edition, Jack Porteous, Abdy Kermani, Wiley-Blackwell, May 2013, pp 395-410