World Conference on
Timber Engineering
Oslo 2023

UPPER AND LOWER RESISTANCE OF SMALL STEEL-TO-TIMBER CONNECTIONS AND COMPARISON WITH REVISED EYM

Jørgen Munch-Andersen[1]

ABSTRACT: The European Yield Model for lateral resistance of connections is revised in the draft for a new Eurocode 5, EN 1995-1-1, for timber structures. In the future there will be only one formula, applying to both timber-to-timber and steel-to-timber connections as well as one or more shear planes. Results from testing of small steel-to-timber connections is compared to estimates using the revised EYM with strength parameters taken from the code as well as the actual values. There is a significant reserve that complicates the estimate of the upper value of the resistance, which is of interest for designing for robustness (against progressive collapse) and against brittle failure during earthquake. The ratio between the upper and lower characteristic resistances is investigated, and methods to reduce the ratio are discussed.

KEYWORDS: EYM, steel to timber, lateral resistance, upper characteristic resistance, lower characteristic resistance

1 INTRODUCTION

The revised version of the European Yield Model (EYM) - to appear in the coming revision of Eurocode 5 part 1-1 for timber structures [1] - is applied to laterally loaded connections with steel plates connected to structural timber using strength parameters determined for the actual timber and fasteners used.

The results are compared to the lateral resistance determined by testing according to in EN 1380 [5]. Investigations at mean value level are carried out, from which the actual rope-effect [16],[17] is determined for the various combinations of fasteners and steel plates used.

The coefficient of variation (CoV) for the different combinations is estimated, which enables to determine the 'true' lower and upper characteristic resistances. The lower value is further compared to lower value obtained using the EYM [1], [2].

The upper value is used to estimate an 'overstrength' factors as the ratio between the 'true' upper and the lower characteristic resistance obtained using the EYM in Eurocode 5.

The overstrength factor is of interest when designing for robustness using the principle of segmentation, where fuse-elements with a known upper value of resistance are needed to halt progressive collapse [1],[4]. It is also needed when designing for seismic loads to ensure the formation of hinges in the fasteners before the timber around the connection fails in a brittle manner.

2 REVISED EYM

The revised EYM is basically the traditional formula for timber-to-timber connections with one shear plane [2], having an equation for each of the six possible failure modes (a)-(f), see Figure 1.

$$F_{D,k}(\mathrm{i}) = \begin{cases} f_{h,k1}\, t_{h1}\, d & \text{(a)} \\ f_{h,k2}\, t_{h2}\, d & \text{(b)} \\ \dfrac{f_{h,k1}\, t_{h1}\, d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\dfrac{t_{h2}}{t_{h1}}+\left(\dfrac{t_{h2}}{t_{h1}}\right)^2\right]+\beta^3\left(\dfrac{t_{h2}}{t_{h1}}\right)^2}-\beta\left(1+\dfrac{t_{h2}}{t_{h1}}\right)\right] & \text{(c)} \\ 1{,}05\,\dfrac{f_{h,k1}\, t_{h1}\, d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,k}}{f_{h,k1}\, d\, t_{h1}^{\;2}}}-\beta\right] & \text{(d)} \\ 1{,}05\,\dfrac{f_{h,k1}\, t_{h2}\, d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{y,k}}{f_{hk,1}\, d\, t_{h2}^{\;2}}}-\beta\right] & \text{(e)} \\ 1{,}15\cdot 2\sqrt{\dfrac{\beta}{1+\beta}}\sqrt{M_{y,k}\, f_{h,k1}\, d} & \text{(f)} \end{cases}$$

where $\beta = f_{h,k2} / f_{h,k1}$

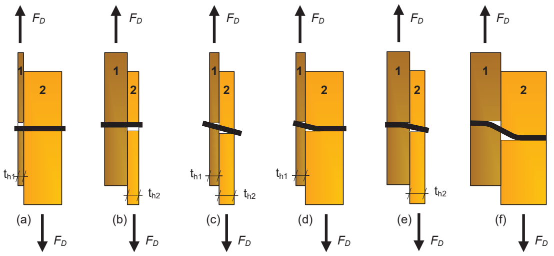

Figure 1: *The dowel contribution F_D to the lateral resistance F_v in EYM. d is the fastener diameter, M_y is the yield moment, t_{h1} and t_{h2} are the embedment depths and f_{h1} and f_{h2} the embedment strengths of member 1 and 2.*

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[1] Jørgen Munch-Andersen, BUILD, Aalborg University - Copenhagen, jcma@build.aau.dk

https://doi.org/10.52202/069179-0194

The EYM estimates the lateral resistance as

$$F_{v,k} = \text{Min}\,[F_{D,k}(i) + F_{T,k}(i)]$$

where $F_{D,k}$(i) is the dowel (or Johansen) contribution and $F_{T,,k}$(i) is the rope-effect contribution, which normally is taken as a fraction of the axial tension resistance, $F_{ax,k}$, but for failure modes (a) and (b) there is no rotation of the fastener so there is no rope-effect).

Multiple shear planes are dealt with by specifying which of the six failure modes that cannot exist and therefore shall be disregarded in the general EYM-formula. For two shear-planes that is mode (c) and (e), when member 1 is the outer members.

Metal-to-timber connections are dealt with by using the actual embedment strength for the metal – which for e.g. steel is called the bearing strength and can be determined according to EN 1993-1-7. It is at least 600 MPa for steel plates. For e.g. aluminium, the actual value should be used, which is considerably smaller.

A further advantage of using the actual embedment strength and thickness of the metal plate is that there is no need for the definition of thick and thin steel plates in [2], the revised EYM-formula will identify the relevant failure mode just like it does for timber-to-timber connections.

It should be noted that the present formulas for steel-to-timber [2] are based on the timber-to-timber formula, just assuming infinite embedment strength and zero thickness of the steel plates. Failure modes (b), (e) and (f) are then associated with 'thick' steel plates which are defined as $d \geq t_1$ and ´thin' as $d \leq 0,5\ t_1$. For intermediate values the above-mentioned interpolation is used.

The definition of 'thick' is about the plate thickness needed to clamp a fastener that fits into the holes in a normal steel plate, if the fasteners yield stress is about 600 N/mm^2, so it was a fair approach at the time it was developed. Nowadays, it can be much higher, so the old approach is unsafe. Likewise, it is unsafe if the formula is used for aluminium plates.

'Thin' steel plates were defined as $d \leq 0,5\ t_1$, most likely as an 'engineering judgement'.

It is often forgotten that the strength of the metal plate around the fasteners should be checked according to the relevant rules (steel, aluminium, ...). In [2] the failure mode that equals (a) in Figure 1 is left out in the formulas for steel plates, so for e.g. two shear planes with a metal plate as the inner member, to the present Eurocode 5 gives no requirement to the steel plate thickness.

The corrections factors 1,15 and 1,05 in failure modes (d)-(f) partly accounts for the smaller uncertainty of the properties of steel parts than for timber, partly that k_{mod} = 1 for the metal parts. The higher factor applies to mode (f) with two hinges in the fastener and the smaller one hinges. The factors are kept in the draft [1] because the disadvantages of introducing a physically more correct methods by far outweighs the advantages, including that applying results from testing according to EN 1380 [5] is possible without special rules. (There are some mistakes in [2] regarding the use of the correction factors and where the rope-effect exists).

3 TEST PROGRAM

The test program is summarized in Table 1. Test according to EN 1380 to determine the lateral resistance F_v are carried out with four makes of ring shank nails (ID 1 to 4), one makes of smooth nail (ID 5) and two makes of screws (ID 6 and 7). The fasteners are all designed to fit into steel plates with 5 mm holes. Nominal lengths are ranging from 25 to 60 mm. Examples are shown in Figure 3. The resulting $F_{v,obs}$ for each test is taken as the smaller of the maximum load and the load at 15 mm displacement.

Table 1: *Test program, geometry, and mean values of strength parameters. The total number of tests is n = 160.*

Test		**Fastener**										**Steel plate**	
Series	n_i	**ID**	**Nominal length** L_{nom} **mm**	**Diam.** d **mm**	**Yield m.** $M_{y,mean}$ **Nmm**	**L incl head** L **mm**	**Head thic.** t_{head} **mm**	**Profiled** L_g **mm**	**Point** L_p **mm**	**Withdr.** $f_{ax,420}$ **MPa**	**Thickn.** t_1 **mm**	**Holes** ø **mm**
10	16	1	35 40 50	4,0	14300	L_{nom}+2,5	1,5	L-9,2	8,2	15,0	0,9 2,0	5,0
40	16	1	35 50	4,0	14300	L_{nom}+2,5	1,5	L-9,2	8,2	15,0	1,5 4,0	5,06,5
10	12	2	40 60	4,0	9100	L_{nom}+2,5	1,5	L-9,2	5,8	15,0	0,9 2,0	5,0
10	20	3	35 40 50 60	4,0	8600	L_{nom}+2,5	1,5	L-9,2	5,8	15,0	0,9 2,0	5,0
20	8	3	35 50	4,0	8600	L_{nom}+2,5	1,5	L-9,2	5,8	15,0	2,0	5,0
40	16	3	35 50	4,0	8600	L_{nom}+2,5	1,5	L-9,2	5,8	15,0	1,5 4,0	5,06,5
10	8	4	40	4,0	13700	L_{nom}+2,5	1,5	L-9,2	4,8	15,0	0,9 2,0	5,0
40	16	5	35 50	4,0	8700	L_{nom}+2,5	1,5	L-4.0	6,1	3,3	1,5 4,0	5,06,5
20	16	6	25 35 40 50	5,0	7200	L_{nom}+1,8	2,5	L-7,4	5,0	22,0	2,0	5,0
40	16	6	40 50	5,0	7200	L_{nom}+1,8	2,5	L-7,4	5,0	22,0	1,5 4,0	5,06,5
20	16	7	25 35 40 50	5,0	5100	L_{nom}+1,8	2,5	L-7,4	5,0	22,0	2,0	5,0
L_g is the length of the profiled (threaded) length, including the point The penetration depth for withdrawal resistance F_{ax} is $L_w = L_g - L_p$ (since the whole profiled length is embedded in the timber)								Embedment depth $t_{h2} = L - t_{head} - t_1$ For screws: d_{ef} = 1,1 d_{core} = 3,7 mm For steel plates: f_{h1} = 700 MPa				

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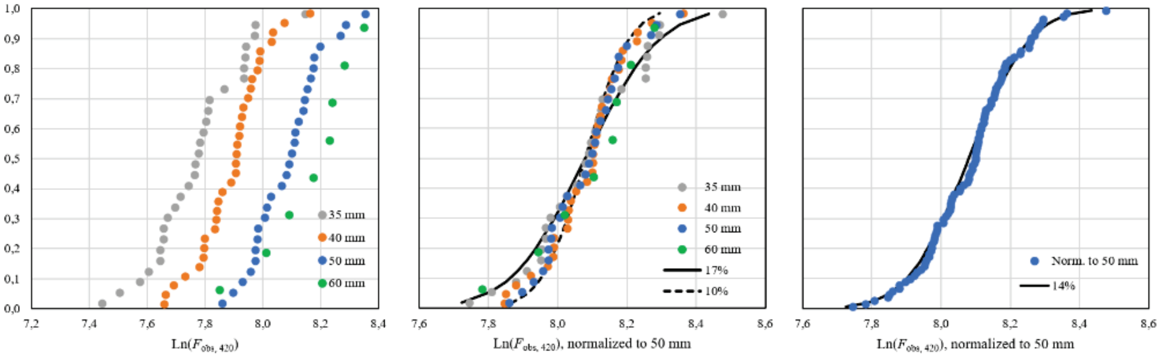


a. b. c.

Figure 2: *The distribution function for ln($F_{v,420}$) for all four makes of ring shank nails.*
a. Per length. b. Normalized to the mean value for length 50 mm. c. All lengths considered as one population.

Figure 3: *Examples of fasteners used.*

Tests are carried out in three series named 10, 20 and 40. Test results for Series 10 and 20 originates from[10], for Series 40 from [11]. The timber batches are different for each series. Tests to determine the withdrawal strength f_{ax} for each fastener and batch are also carried out, the results are shown in Table 1.

For Series 10 is used timber with densities fulfilling the requirements to both methods given in EN ISO 8970:2010 [8], where the focus was on limiting the density variation, see [19].

For Series 20 and 40 is used timber with 'low' and 'high' density centred around 350 kg/m^3 and 500 kg/m^3 respectively, representing the extreme values for structural soft wood timber of European strength class C24 with characteristic density 350 kg/m^3 and mean density 420 kg/m^3. The mean density in all series is close to 420 kg/m^3.

The latest edition, EN ISO 8970:2020 [9], focuses on a natural variation of the density of the test specimens and includes methods to correct available data to the natural density variation. Where relevant, all test results are normalized to represent the density 420 kg/m^3 using these methods.

Actual values of yield moments and withdrawal strengths are determined according to EN 409 [6] and 1382 [7] Steel plates with four different thicknesses ranging from 0,9 mm to 4,0 mm has been used. For some thicknesses also test with 6,5 mm holes was carried out as a supplement to the normal 5,0 mm.

4 ACTUAL DISTRIBUTION

In this section only the influence of the nominal length and the density is considered, the rest is considered as residuals. Apart from the yield moment there is little difference between the four makes of ring shank nails (ID 1 to 4). A study of the observed values of F_v does not reveal any dependency on the hole diameter and only a very limited dependency on the yield moment and the steel plate thickness. This is further discussed in section 5.

Since the density distribution is not fulfilling the requirement to a natural variation in the new EN/ISO 8970 [9], i.e. a normal distribution with a coefficient of variation, CoV ~ 10 %, it is necessary to normalize the observations to a reference density, here taken as 420 kg/m^3. The contribution from the density variation to the total CoV is then added as defined in [9].

The observed values are normalized to $F_{v,420}$ by multiplying by $(420/\rho)^c$, where ρ is the actual density. It is found that $c = 1{,}3$ ensures a good fit to the expected LogN-distribution. This value of c is within the expected range, but estimation of c according to Annex B in [9] is not possible since the densities does not follow the normal distribution.

In the following is used ln($F_{v,420}$) as the dependent variable since it is expected to be normally distributed, as al resistances are. Table 2 shows the statistical characteristics of ln($F_{v,420}$) for each nail length and Figure 2a the corresponding distribution functions. Note that e.g. $F = 2000$ N => ln(F) = 7,6 and $F = 4000$ N => ln(F) = 8,3.

Table 2: *Statistical characteristics of ln($F_{v,420}$)* ***for nails,*** *which is assumed to be normally distributed.*

Nail length	35 mm	40 mm	50 mm	60 mm	All
Mean ln(F_v)	7,77	7,89	8,08	8,15	8,08
Std.dev.	0,16	0,10	0,12	0,16	0,13

When adjusting so the mean value for each length becomes equal to the mean value for 50 mm length, the curves shift as shown in Figure 2b, where normal distributions with std.dev. 10% and 17% are seen to include most of the observations. When all date after the shifting are considered as one population the distribution becomes the one shown in Figure 2c, closely following a standard distribution with std.dev. 14 % (meaning that $F_{v,420}$ has CoV_{420} = 14%, see e.g. Annex D.7 in Eurocode 0, [3]). According to e.g. [9] the contribution from the natural density variation, which for strength class C24 is CoV_ρ = 10%, increases the total variation to

$$\text{CoV}_{tot} = \sqrt{\text{CoV}_{420}{}^2 + \text{CoV}_\rho{}^2} = \sqrt{0{,}14^2 + 0{,}10^2} = 17\%$$

The lower characteristic value then becomes

$$F_{v,0,05} = \exp(\text{mean}\ \ln(F_{v,420}) - 1{,}65 \cdot 0{,}17)$$
$$= \exp(7{,}80) = 2440\ \text{N}$$

and the upper

$$F_{v,0,95} = \exp(\text{mean}\ \ln(F_{v,420}) + 1{,}65 \cdot 0{,}17)$$
$$= \exp(8{,}36) = 4280\ \text{N}$$

The ratio is then 4280/2440 = 1,75. This can be generalized to the values in Table 3.

Table 3: *Ratio between upper and lower characteristic value of a LogN-distributed variable X as function of the standard deviation of ln(X).)*

	Characteristic /mean value		
Std.dev.	Low (5%)	High (95%)	Ratio
5%	0,921	1,086	1,18
8%	0,876	1,141	1,30
11 %	0,834	1,199	1,44
14 %	0,794	1,260	1,59
17 %	0,755	1,324	1,75
20 %	0,719	1,391	1,93
23 %	0,684	1,462	2,14
26 %	0,651	1,536	2,36
29 %	0,620	1,614	2,60
32 %	0,590	1,696	2,87
35 %	0,561	1,782	3,17
38 %	0,534	1,872	3,50

For the two makes of screws the same procedure leads to the final distribution for length 50 mm shown in Figure 4, with the mean value ln($F_{v,420}$) = 8,17 and std.dev. = 11 %. According to Table 3 this gives a ratio of 1,44. The total variation for screws becomes CoV_{tot} = 15%.

There are too few observations for smooth nails to make a meaningful analysis for these on their own. Further, the influence of the conditioning is severe [15], so many more tests are required.

5 OBSERVATIONS COMPARED TO EYM USING MEAN VALUES

In this section the observed lateral resistances F_v are compared to an estimate based on EYM, replacing the characteristic values of the strength parameters with the best available estimate for their mean values.

The EYM is used for estimating the mean lateral resistance in the form

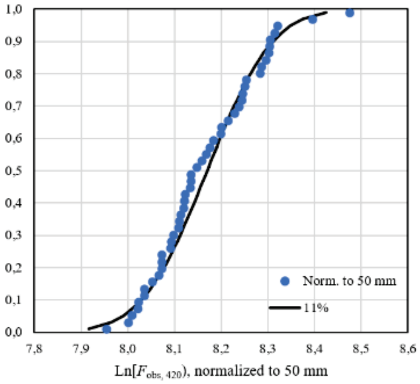


Figure 4: *The distribution function for ln(F_v) for the two makes of screws when normalized to the mean value for length 50 mm and all lengths then considered as one population.*

$$F_v = F_D + F_T \ \text{with}\ \ F_T = \alpha\, F_{ax} \qquad (1)$$

For F_D is used the formula in Figure 1 setting the correction factors 1,05 and 1,15 equal to 1 because there are no partial factors and k_{mod} adjustment involved.

The measured mean values for the yield moments M_y are given in Table 1. The CoV is about 5%.

For the embedment strength the formula in Eurocode 5 (without predrilling) is used, just replacing the characteristic density by the actual density, thus using

$$f_h = 0{,}082\, \rho\, d^{-0{,}3} \qquad (2)$$

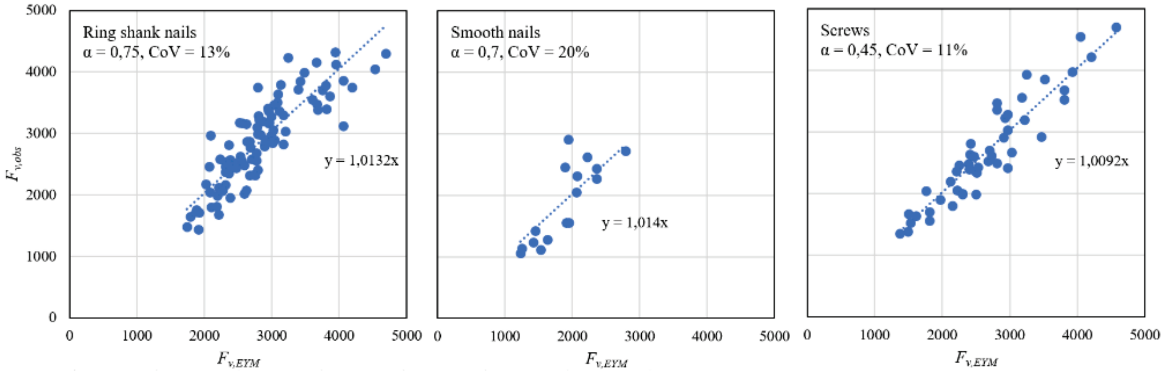
The embedment depth t_{h2} is taken as L_g, Table 1. This length includes the point length because the range of lengths used for the tests clearly shows this to be the best estimate. This is demonstrated below, compare Figure 6a and Figure 7.

The withdrawal strength f_{ax} is used for estimating the rope-effect contribution F_T. The rope-effect is taken as a fraction α of the tension resistance F_{ax}. The 'best' value of α is discussed below.

$f_{ax,420}$ given in Table 1 is the withdrawal strength for density 420 kg/m^3 and is determined to apply to the profiled length excluding the point length. The value for the different makes of ring shank nails respectively screws are very similar, so the same values are assumed as seen in Table 1. The withdrawal strength used in the EYM is adjusted to the actual density as

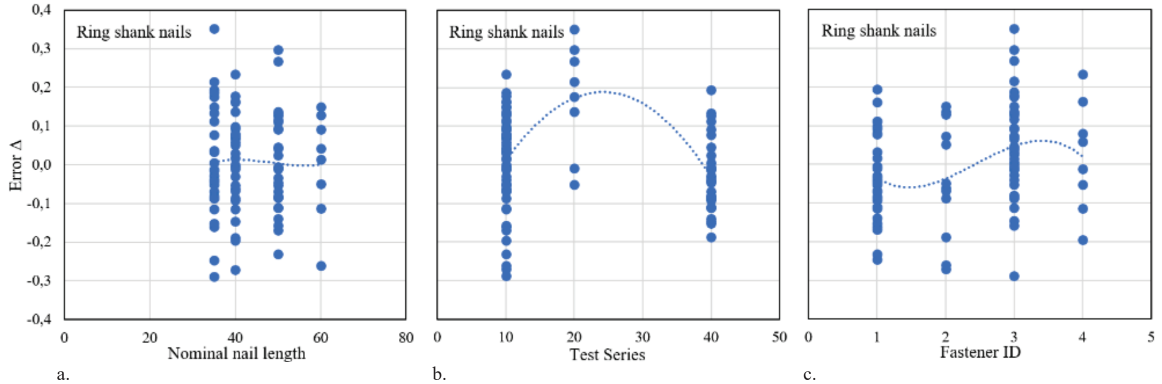
$$f_{ax} = f_{ax,420}\ (\rho/420)^{c\_ax} \qquad (3)$$

where ρ is the actual density and c_{ax} is the exponent that gives the best estimate (smallest CoV) when estimating $f_{ax,420}$. The value of the exponent might be different for the



a. b. c.

Figure 5: *Observed lateral resistance versus estimate using EYM with mean value of strength parameters. α is the rope-effect factor that ensure a slope just above 1. CoV is the variance of EYM regarded as a model of the resistance in accordance with Annex D.7 in EN 1990 [3].*



a. b. c.

Figure 6: *The error Δ as dependent on the nail length, test series and fastener ID, see Table 1.*

different fastener types. For ring shank nails it was 1,5 and for smooth nails 2,0. For screws any value between 1,0 and 1,5 was about equally good. Henceforth, 1,5 is used for ring shank nails and screws, but the influence is small. For screws is used the effective diameter $d_{ef} = 1{,}1d_{core}$, where d_{core} is the diameter of the core of the thread, both for estimating f_{h2} and in the formula for F_D in Figure 1. For the withdrawal resistance F_{ax} is used the outer thread diameter. These definitions are in accordance with amendment A2 to EN 1995-1-1 [2].

Figure 5 shows plots for each type of fastener of the observed values of F_v against the estimated value using EYM with mean values of strength parameters. The rope-effect factor α given is the one that ensure a slope of the trend line slightly above 1. A slope above 1 means that the mean value model is conservative.

Assuming again that F_v is logN-distributed the CoV of the EYM-model can be estimated from annex D.7 i EN 1990 [3] as the standard deviation of the error Δ, where

$$\Delta = \ln(F_{v,obs}/F_{v,EYM})$$

The CoV's in Figure 5 are determined this way. If a change to the model reduces this CoV, the model is better. A tool to get ideas on how to improve a model is to plot the relation between the error Δ and one of the input parameters.

As an example, Figure 6 shows such plots for the error versus the length of ring shank nails, the test series, and the fastener ID. A polynomial trend line is shown, which has sufficient terms to pass through the weighted average for each variation, so attention should only be made to where the trend line crosses the vertical lines with the determined errors.

Figure 6a illustrates that the influence of the nail length seems to be modelled very well. Figure 6b indicates that the observations in Series 20 are higher than expected from the strength parameters, about 20 %. It is not unexpected that other properties of the timber than the density influences the resistance, see e.g. [18], so the 'error' is in part caused by the natural variation. Finally, Figure 6c indicates that faster ID 2 causes somewhat smaller resistance than average and ID 3 higher, but it is hardly significant, less than 5%. Further, it is part of the natural variation of fastener properties.

Figure 7 is similar to Figure 6a, except that the embedment depth t_{h2} is reduced by the point length. It is obvious that this introduces a systematic error in the model, even the CoV is hardly increased.

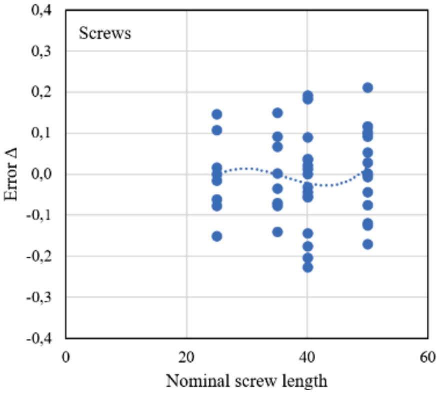


Figure 8 is equal to Figure 6a, but for screws. Again, the influence of the nail length seems to be modelled very well. The dependency on test series and fastener ID is not shown, it is at the same level as for ring shank nails.

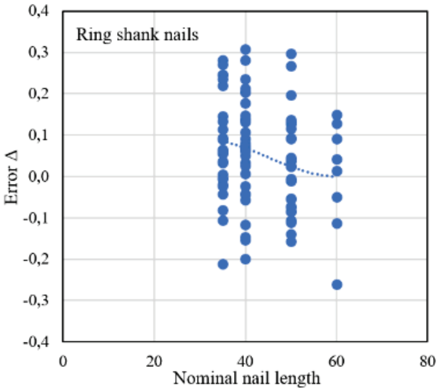


Figure 7: *The error Δ as dependent on the nail length when* t_{h2} *is reduced by the point length.*

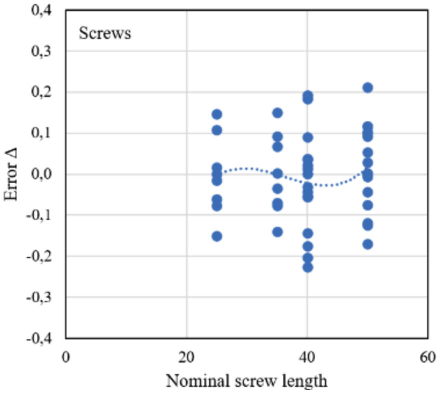


Figure 8: *The error Δ as dependent on the screw length.*

Similar plots for the steel plate thickness and the oversized holes compared to the normal 5 mm holes shows no trends that cannot be attributed to the general variation, mostly related to those combinations tested in Series 20.

As stated above, the rope-effect factor α given in Figure 5 was just chosen to make the EYM fit to the observed resistances. It could be that the dowel contribution F_D was under- or overestimated, e.g. if the formula for the embedment strength is incorrect. This can be investigated by using

$$F_v = \delta\, F_D + \alpha\, F_{ax} \tag{4}$$

and then find the combination of δ and α that minimize the CoV of the model keeping the slope just above 1, see Table 4. The values in bold are those used for Figure 5a and c. The table shows that by decreasing δ from 1 to 0,8 or 0,9 the CoV is slightly reduced, but it is a very flat minimum, so there is no evidence for not using $\delta = 1$. The flat minimum is of course related to the fact that the density is decisive for both F_D and F_{ax}.

In the next section it is shown that the sensitivity to the value of M_y is much smaller than to the density. Due to the limited amount of data, it should be regarded as a coincidence that the optimal value for δ seems to be 0,85 for both nails and screws.

Table 4: *Weighing of dowel contribution* F_D *by* δ *and axial resistance* F_{ax} *by* α *to minimise the CoV of the estimated lateral resistance* F_v*. The bold values are used in Figure 5 and henceforth.*

δ	0,7	0,8	0,9	**1,0**	1,1
Ring shank nails					
α	0,99	0,91	0,83	**0,75**	0,67
CoV	0,129	0,127	0,127	0,129	0,132
Screws					
α	0,56	0,52	0,48	**0,45**	0,41
CoV	0,106	0,105	0,105	0,107	0,111

It can be deducted from the estimated CoV's that the additional parameters taken into account in EYM do not really improve the accuracy because the CoV's found in Figure 2 for nails and Figure 4 for screws are almost identical to those given in Figure 5. In Figure 4 only a simple adjustment for density and the length of the fastener is applied, whereas in Figure 5 also the influence of the actual values of the yield moment and the steel plate thickness are taken into account by the EYM. So, the CoV should be smaller, but it is 11% for screws in both cases and only drops from 14 % to 13 % for nails. This means that other circumstances than those included in the EYM has a significant influence.

6 CHARACTERISTIC RESISTANCE FROM TESTS AND EYM

The mean value model for the lateral resistance F_v represented by Formula (1) appears from Figure 5 to be a reasonable model for the real resistance when using the strength parameters given in Table 1 and the rope-effect factor α given in Figure 5, i.e. 0,75 for ring shank nails and 0,45 for screws.

The CoV of the model is in section 4 estimated as 17 % for ring shank nails and 15 % for screws for connections using timber C24. According to Table 3, the lover characteristic resistance should then be 0,76 respectively 0,78 of the mean measured value for a certain set of conditions.

https://doi.org/10.52202/069179-0194

6.1 EVM ESTIMATE OF RESISTANCE

In this section mean values of $F_{v,EYM}$ has been estimated for a range of parameters representing the conditions for the tests where F_v were observed. The geometry and properties of the fasteners used is generally as in Table 1. All steel plate thicknesses 0,9, 1,5, 2,0 and 4,0 mm are used for all parameter combinations.

For nails the point length is taken as 6,0 mm in all cases and all the nominal lengths 35, 40, 50 and 60 mm are included. Two yield moments are used, 7500 Nmm and 15000 Nmm.

For screws all the nominal lengths 25, 35, 40 and 50 mm are included. Two yield moments are used, 5000 Nmm and 7500 Nmm.

These 128 estimates are compared to estimates using the same geometries, but inserting characteristic values of the strength parameters M_y, f_h, and f_{ax} in the model, as intended in Eurocode 5.

The characteristic yield moment is determined assuming a CoV of 5%, which means that the characteristic value is 92% of the mean value. For f_h, and f_{ax} is simply used the mean density ρ_m = 420 kg/m^3 for determining the mean value and ρ_k = 350 kg/m^3 for determining the characteristic value in Formula (2) and (3). The aforementioned factors 1,05 and 1,15 are also applied as they are meaningful for the characteristic values.

Hereby is determined pairs of $F_{v\text{,EYM,mean}}$ and $F_{v\text{,EYM,charac}}$, the relation for ring shank nails is shown in Figure 9 as the blue points. Not surprisingly, the ratio is fairly constant. For screws the relation is shown as the blue point in Figure 10, the slope is seen to be the same as for nails. The slope 0,83 for both nails and screws reflects mainly the ratio between the characteristic and mean value of the density which is 350/420 = 0,833, see 6.4.

6.2 LIMITS TO ROPE-EFFECT

Eurocode 5 has some limitations on the rope-effect, which reduce the characteristic resistance significantly. In the present issue [2] the rope-effect factor, here called α, is limited to 0,25, in the draft it is increased to 0,4 for nails. In both versions, the rope effect contribution F_T is limited to 0,5 F_D for nails and 1,0 F_D for screws, where F_D is the dowel contribution given in Figure 1. The latter limit is thought to prevent the need for large displacements to reach the estimated resistance but appears rather conservative here since the observed values of F_v used are already limited to 15 mm displacement.

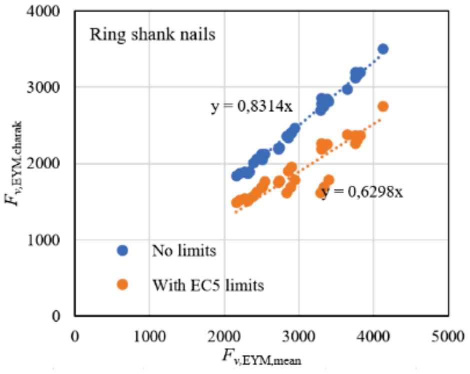


Figure 9: *The characteristic lateral load resistance for nails versus the mean resistance, without and with limits given in Eurocode 5 [2].*

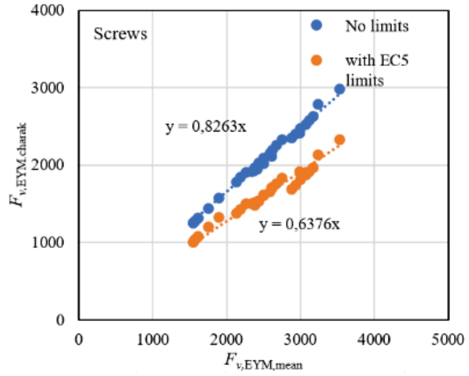


Figure 10: *The characteristic lateral load resistance for screws versus the mean resistance, without and with limits given in Eurocode 5 [2].*

Applying the limitations given in [2]causes a drop as illustrated by the orange points in Figure 9 and Figure 10. The characteristic resistance obtained from Eurocode 5 is seen to end up around 63 % of the mean value.

6.3 OVERSTRENGTH

By overstrength is as stated above understood the factor to arrive from the lower characteristic resistance determined from Eurocode 5 to the real upper characteristic resistance.

In 6.2 is found a factor of 1/0,63 = 1,58 from the characteristic resistance determined form Eurocode 5 to the real mean value and from Table 3 is found that the upper characteristic value is 1,39 times the mean value for a connection if the resistance has a real CoV of up to 20 %. An basic overstrength factor of about 1,58 · 1,39 = 2,2 should therefore be assumed in design.

It is obvious that if the EYM in Eurocode 5 estimate a more accurate (higher) characteristic resistance, the overstrength factor will be smaller.

6.4 SENSITIVITY TO PARAMETERS

The significance of an accurate value of the strength parameters is investigated, assuming the EYM is 'correct'.

For the yield moment the significance is limited. Comparing the EYM results for the two values used for nails, 7500 Nmm and 15000 Nmm, shows that this halving of the yield moment only reduced $F_{v,EYM}$ by 10%. The steel plate thicknesses ranges from 0,9 mm to 4 mm. The thicker one increases $F_{v,EYM}$ by 7 % compared to the thinner, so again a limited significance.

But if the density is changed by 10%, $F_{v,EYM}$ also change by about 10 %. This is mainly because f_h, is assumed proportional to the density in (2) and f_{ax} is increasing a little more than proportional when $c_{ax} > 1$, see (3).

https://doi.org/10.52202/069179-0194

The low sensitivity to the yield moment and the plate thickness contributes to explains why the CoV in Section 5 does not decrease when using the EYM rather than just correcting for density and length as in Section 4.

6.5 IMPROVEMENT OF THE EYM

Any good model should give a close estimate of the mean value and have a low CoV. The EYM is giving a too low estimate for the mean value and there might be physical phenomenon not taken into account, resulting in a high CoV.

It is obvious that an increase of the rope-effect factor α, will improve the estimate of the mean value, but at the same time a likely source to variability not accounted for by the EYM, is the rope-effect factor α, which might depend on other properties in a more complicated way than assumed now. This is important to understand before the full rope-effect contribution should be used for design. There might also be time dependent issues, even these are more prone to significant impact for larger fasteners.

It is likely that the rope-effect factor will depend on the yield moment and the thickness of the steel plate and the ratios between fastener og plate properties. The rope-effect could, e.g., be higher for thin steel plates than for thick, so the small gain from a thick plate in the dowel contribution is lost again in the rope-effect contribution.

Sørensen [11] noted that the rope-effect consists of two contributions, the component of the axial load in the fastener in the direction of the external load and the friction between the members as they are pressed together by the axial load. The photos in Figure 11 illustrates that the withdrawal resistance might not be the correct measure for the axial load in the fastener when approaching the ultimate load since there are gaps between the fastener and the timber. Sørensen suggested that the axial load could depend on friction between the fastener and the timber rather than the withdrawal resistance. These phenomena were dealt with already by Johansen [12] and Meyer [13], and further by Svensson & Munch-Andersen [16], [17].

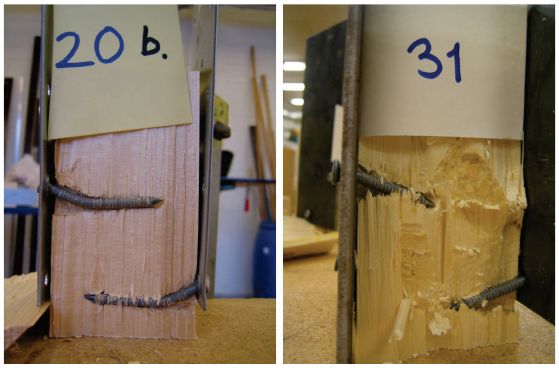


Figure 11: *Observed failure modes. Left, a normal nail, where a hinge is formed in the timber. Right, a hardened nail, where no hinges are formed, even the steel plate is 4 mm thick. [11].*

7 CONCLUSIONS AND FUTURE WORK

The EYM (Euorpean Yield Model) as intended in Eurocode 5 [1] seems to give a good estimate for the dowel-effect contribution F_D to the lateral resistance F_v, but there is a significant reserve when estimating the characteristic lateral load resistance $F_{v,k}$ using the EYM (European Yield Model) as intended in Eurocode 5 [1], [2]. The main reason is that the rope-effect contribution revealed by tests is significantly higher than considered in the code, also in the draft for a new Eurocode 5 [1].

This reserve is to some extent needed to account for e.g. shrinkage and to limit displacements, but it seems larger than necessary. Besides the unnecessary costs and uses of resources it complicates the design when the upper value of the resistance is needed for design, typically when designing for earthquake, where failure need to occur as hinges in the fasteners, and for robustness when the segmentation principle is used and the connection should act as a fuse, halting the collapse.

The overstrength factor – the gap from the lower characteristic resistance estimated from Eurocode and up to the real upper characteristic resistance determined from tests – is estimated to be about 2,2 for the investigated steel to timber connections with small diameter fasteners. This provides that the timber used is not stronger than anticipated. If, e.g., the densities are as for C30 and not as for C24 as assumed in the design, the overstrength factor will increase about 8 % to 2,4. A general factor probably needs to take such a possibility into account.

The rope-effect contribution is limited by fractions of both axial tension resistance and the dowel resistance, see 6.2. Both limits need to be increased if a higher utility of the real resistance of should be allowed. As mentioned, a purpose of the limit seems to be to limit the deformations, which might be reasonable, but the observed resistances used for this study is already limited to 15 mm in accordance with EN 1380 [5], so further limitations should not be necessary to ensure an acceptable deformation at the characteristic resistance.

It should also be noted that when using tests according to EN 1380, e.g. via an EAD and ETA, the 15 mm limit is the only one applying, thus making it quite unattractive to uses the EYM compared to testing.

In further studies focus should be on correct estimate for the rope-effect. One tool would be to examine the displacements during loading more closely – data are available for the tests this study is based on, but not yet used. For Series 40 [11] the actual failure mode is also registered, which should be compared to the prediction from the EYM. Figure 11 might indicate that a fastener with a high yield moment (so it does not form hinges) might need larger displacement to reach its maximum resistance than if the yield moment is lower.

https://doi.org/10.52202/069179-0194

ACKNOWLEDGEMENT

This paper is based on the MSc-thesis by Ane Louise Sørensen[11], who did an outstanding job (which I had the pleasure to co-supervise together with Sigurdur Ormarsson), and test reports from VHT [10], kindly made available by ITW Construction Products, Middelfart, Denmark.

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https://doi.org/10.52202/069179-0194