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Preface

I wish to express my sincere gratitude to all delegates of CAN'2012 Eleventh AES-ATEMA International Conference for their valuable contributions which made the Conference outstandingly successful. I trust that all delegates have had a unique experience by participating in this Conference both scientifically and culturally.

The AES-ATEMA Conference Series is sponsored and administered by Advanced Engineering Solutions [AES. COM] within the mission of AES Technical Reviews International Journal Series (ISSN 1915-5409). In this regard, I wish to express my full indebtedness to Advanced Engineering Solutions International and also to the members of the International Editorial Board of AES Technical Reviews International Journal Series.

I hope that the valuable scientific and engineering contributions presented in this CD-ROM/ book proceedings will provide guidance to Science and Engineering students, educators and researchers who are working in the field. I hope also that these proceedings will be of significant value to scientists and engineers who are involved in the production, processing of engineering materials and the study of their properties in addition to all pertinent fields.

Prof. Dr. Yehia Haddad, P. Eng.
Professor of Mechanical Engineering
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T. A. C. M. van de Put, A. J. M. Leijten / Proceedings, CAN'2012 Eleventh AES-ATEMA International Conference Toronto, Canada, August 06 - 10, 2012, pp. 75 – 82.

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Explanation of the Strength of Nailed Particle Board-to-Wood Joints

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Abstract

By the earlier derived theory of the embedding strength, based on limit design, it is possible to explain the extremely high embedding strength of nailed particle board to wood joints leading to a new exact failure equation for the embedding strength as necessary correction for design and for the Codes.

Keywords

Particle board, embedding strength, limit analysis, equilibrium method, nailed board to wood joints.

1 Introduction

Our contribution is split in two parts. This article 1, is about theory of the strength of the single nailed particle board to wood joint and the second article 2, is about the spreading theory for strengths of rows of nails (with the determination of the spreading width per nail of a group of nails) and is about the consequences for other failure mechanisms. In Van de Put [1] the one dimensional stress spreading effect was discussed and the announced publication of the three-dimensional extension is discussed in this article. A new theory is able (and has) to give a theoretical explanation of strength behaviour of all previous investigations and data. Regarding the spreading theory this was discussed in van der Put [2] for the oldest investigations of nailed particle board to wood joints, explaining e.g. Larsen's data [3]. The Johansen theory of the strength of pins, bolts and pin-dowels is based on full plastic embedment behaviour of wood and on full plastic hinges in the metal pins. However the strong, not negligible deformation of the end state is not accounted and the theory thus applies for initial flow of connections at small permanent deformations. The theory for large plastic deformations, after hardening, shown in Fig. 1 and 2, is given in

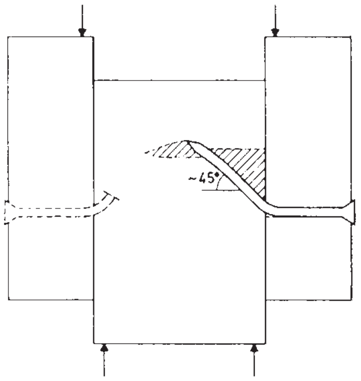

Figure 1.Failure by short nails.

Van der Put [4]. The increase of the strength with respect to the Johansen theory is not due to friction between the particle board plate and connected wood plate because at the ultimate load the gap between these connected parts opens. This is predicted by the theory of Van der Put [4] where it is shown that this point of separation of parts is the analytical condition

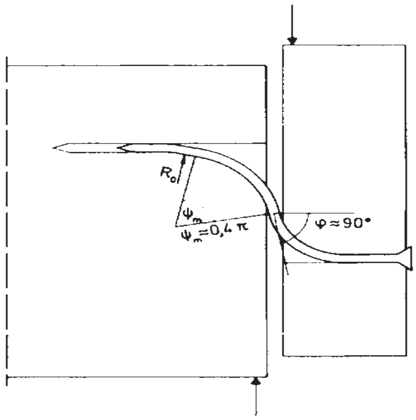

Figure 2. Failure of long nails.

for the maximal vertical loading component of the nail. Further, the increase of the bearing strength for long nails is shown to be due to the slope of the nail, having a normal force component due to the friction along the nail, causing rope action of the nail which is deformed as logarithmic spiral, shown in Fig. 2. The increase of the strength by this hardening behaviour can be given by factors with respect to the always applied Johansen strength equations for short and for long nails according to the failure modes given by Fig 1 and 2. An intermediate value can be applied for intermediate nail lengths as follows from Table 1.

Table 1. Strength F_n in N per nail depending on the penetration length l_a.

l_a / d	8 F_n	12 F_n	15.5 F_n	profiled F_n
mean	1046	1190	1256	2556
end defor-mation	~ 15 mm	~ 18 mm	~ 28 mm	~ 16 mm

It can be seen in Fig. 1 of short nail failure that the nail bends close to the edge of the particle board showing an extremely high embedding strength of particle board although the compression strength is much lower than that of wood. This is explained by theory van der Put [2] and it thus is necessary to extend the Maier-Johansen theory for this high embedding strength. The preliminary derivation of this embedding strength is given in Van der Put [2] and Van der Put [5] in addition with the analytical models for other failure modes of the board as by the local tension strength, shear strength and splitting, The complete rigorous derivation of the embedding strength, (applicable to all materials), is given in Van der Put [6] applied to wood loaded perpendicular to grain and applied to particle board in [1] and in this article. The high embedding strength is due to confined dilatation of the board under the local nail-loading and the magnitude thus depends on the possibility of spreading of the nail force in the board. The required theoretical derivation in van der Put [6] is based on the exact boundary value analysis equivalent to limit design of a construction of an equilibrium system of the ultimate state of the wood matrix which satisfies the boundary conditions and nowhere violates strength conditions. The power representation of this stress spreading model of confined dilatation provides a simple design method which precisely matches to the data and is able to explain e.g. the data depending on the different parameters of the extended investigation on the embedding strength of Budianto et. al [7] as was already shown in [2]. The predictions of the theory for other parameters and other dimensions of the specimens are confirmed by additional tests, reported in Van der Put [1], [2], [5], and in this article. The influence of the Weibull effect Van der Put [1], [8], of small dowel diameter failure is not discussed because it is regarded separately in the Eurocode.

2 Embedding Strength of Particle Board in a Nailed Joint

2.1 Iterative calculation method

According to the theory Van de Put [1], the particle board embedding strength for nails with a limited bearing length l_b due to 3-dimensional spreading is:

$$f_{h,p} = f_{c,p} \cdot \sqrt{\frac{b \cdot t}{d \cdot l_b}} \qquad (1)$$

where:

$f_{c,p}$ = compression strength of particle board

d = diameter of the nail

t = plate thickness

b = working width of the plate per nail (acting as stress spreading width)

l_b = bearing length of the nail, about (1 to 2)·d, according to:

$$l_b = d \cdot \sqrt{\frac{f_a}{3 \cdot f_{h,p}} \cdot \frac{2}{1 + f_{h.p} / f_h}} \qquad (2)$$

for the failure mechanism III of the nail with two plastic hinges according to the Johansen-Maier theory. Thus in eq.(1), the concentrated load on the area $d.l_b$ spreads to the maximal available area $b \cdot t$. In eq.(2) is f_α the flow stress for full plastic bending of the nail and f_h the embedding strength of the adjacent wood of the particle board to wood joint. The bearing force F of a nail in a symmetrical particle board-to-wood joint is:

$$F = f_{h,p} \cdot d \cdot l_b \qquad (3)$$

For a rigid pin, remaining straight at loading, as in the standard embedding strength test is: $l_b = t$ and according to eq.(1) is:

$$F = f_{c,p} \cdot \sqrt{\frac{b}{d}} \cdot d \cdot t \qquad (4)$$

as shown to apply for the embedding strength test discussed in Van de Put [1]. For the mechanism with two plastic hinges in the nail, $f_{h,p}$ and l_b can be found by a trial iteration from eq.(1) and eq.(2). Assume a value of l_b and calculate $f_{h,p}$ by eq.(1). Then find a new value of l_b with eq.(2), which normally will be different from the initial assumed value and thus an intermediate value has to inserted again in eq.(1) until the right value is found. For instance for the specimen according to Fig. 3, $l_b/d \approx 0.66$ is found by trial giving:

$$f_{h,p} = f_{c,p}\sqrt{\frac{(42/4)18}{(2.1)^2 0.66}} = f_{c,p}8.06$$

and thus

$$\frac{l_b}{d} = \sqrt{\frac{720}{8.06\cdot 24.9}\cdot\frac{2/3}{1+8.06\cdot 24.9/45}} = 0.66$$

and

Then: F= 8.06 ·24.9· $(2.1)^2$ 0.66 = 584 N (Measured is 595 N at high testing speed but small ultimate strain) In these equations is 24.9 N/mm^2 the compression strength of the particle board, and 18 mm the plate thickness. The spreading width per nail of the pattern of 4 nails is: 20d/4 = 42/4, For the 6 nail pattern of d = 3.3 mm nails is:

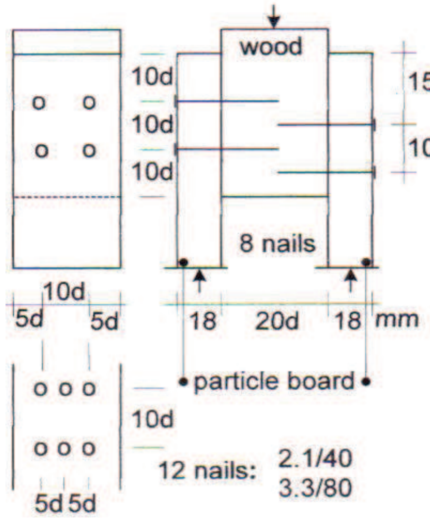

Figure 3. Nailed particle board-to-wood connection.

$$f_{h,p} = f_{c,p}\sqrt{\frac{(62/6)18}{(3.3)^2 1.4}} = f_{c,p}3.5$$

and thus:

$$\frac{l_b}{d} = \sqrt{\frac{720}{3.5\cdot 24.9}\cdot\frac{2/3}{1+3.5\cdot 24.9/45}} = 1.4$$

Thus F=3.5·24.9·$(3.3)^2$1.3 = 1330 N (Measured is 1580N thus 1.19 times higher by the string action of the long nail 3.3-80. In the same way is for 4 nails of d = 3.3 mm pattern l_b/d = 1, and is F= 126 · $(3.3)^2$ = 1372N (Measured is 1550 N thus 1.13 times higher by string action of longer nails. According to the theory of [4] this factor should be: 1.27/1.13 = 1.12. For the 2.1 mm 6 nail pattern F = 562 N (measured 574 N). The results are summarized in Table 2. The same applies for other tested

Table 2 – Evaluation of strength data of Fig. 3 specimens.

Num of nails	nail diameter in [mm]	test data per nail in [N]	theory per nail in [N]	cord action factor
8	2.1	595	584	(1.02)
8	3.3	1550	1372	1.13
12	2.1	574	562	(1.02)
12	3.3	1580	1330	1.19
data from relatively high strain rate testing by TNO and a low allowed permanent strain (lower string action by lower hardening).				

nail patterns, and it follows that a precise description is possible based on the mean possible spreading width per nail. The proposed design formulas contain implicitly the influence of a row effect for rows of 2 nails.

2.2 Direct calculation method

For a direct solution of the embedding strength equation l_b/d has to be eliminated from eq.(1) and eq.(2). Then, by eq.(1):

$$f_{h,p}\cdot\sqrt{\frac{l_b}{d}} = f_{c,p}\cdot\sqrt{\frac{b\cdot t}{d^2}} = f_{hm} \qquad (5)$$

and by eq.(2):

$$\left(\frac{f_{h,p}}{f_{hm}}\right)^4=\left(\frac{d}{l_b}\right)^2=\frac{1.5\cdot f_{h,p}}{f_a}\cdot\left(1+\frac{f_{h,p}}{f_h}\right) \quad (6)$$

or:

$$\left(\frac{f_{h,p}}{f_{hm}}\right)^3-\frac{f_{h,p}}{f_{hm}}\cdot\frac{1.5\cdot f_{hm}}{f_a}\cdot\frac{f_{hm}}{f_h}-\frac{1.5\cdot f_{hm}}{f_a}=0 \quad (7)$$

This has the form of:

$$z^3-z\cdot p\cdot q-p=0 \quad (8)$$

The solution of this equation is if:

$$-\left(\frac{p\cdot q}{3}\right)^3+\left(\frac{p}{2}\right)^2\geq 0:$$

$$z_1=u+v;$$

$$z_2=(-1-i\sqrt{3})u+0.5(-1+i\sqrt{3})v;$$

$$z_3=0.5(-1+i\sqrt{3})u+(-1-i\sqrt{3})v$$

with:

$$u=\sqrt[3]{\frac{p}{2}+\sqrt{\frac{p^2}{4}-\left(\frac{p\cdot q}{3}\right)^3}} \text{ and}$$

$$v=\sqrt[3]{\frac{p}{2}-\sqrt{\frac{p^2}{4}-\left(\frac{p\cdot q}{3}\right)^3}}$$

Only the real solution should apply. Thus:

$$z=u+v=\sqrt[3]{\frac{p}{2}}\cdot\left(\sqrt[3]{1+\sqrt{1-\frac{4}{27}\cdot p\cdot q^3}}\right)+$$

$$+\sqrt[3]{\frac{p}{2}}\cdot\left(\sqrt[3]{1-\sqrt{1-\frac{4}{27}\cdot p\cdot q^3}}\right) \quad (9)$$

or as row-expansion:

$$z=\sqrt[3]{\frac{p}{2}}\cdot\left(1+S-\cdots+1-S+\cdots\right)$$

With $S=\frac{1}{3}\cdot\sqrt{1-\frac{4}{27}\cdot p\cdot q^3}$ giving

$$z\approx 2\cdot\sqrt[3]{p/2}=\sqrt[3]{4\cdot p} \quad (10)$$

Thus: $$f_{h,p}\approx f_{hm}\cdot\sqrt[3]{\frac{6\cdot f_{hm}}{f_a}}=f_{hl} \quad (11)$$

with: $\frac{f_{hm}}{f_h}\leq\sqrt[4]{\frac{9}{2}\cdot\frac{f_a}{f_h}}$ or: $f_{h,p}=f_{hl}\leq 3\cdot f_h$

For strong plates it is possible that:
$f_{h,p}>3f_h$

Then it is possible that

$$-\left(\frac{p\cdot q}{3}\right)^3+\left(\frac{p}{2}\right)^2<0$$

The solution of eq.(7) then is:

$$z=\frac{f_{h,p}}{f_{hm}}=\sqrt{\frac{4pq}{3}}\cos\left(\frac{1}{3}\arccos\left(\sqrt{\frac{27}{4pq^3}}\right)\right)=$$

$$=\sqrt{\frac{2f_{hm}^2}{f_af_h}}\cos\left(\frac{1}{3}\arccos\left(\sqrt{\frac{9f_af_h^3}{\sigma_{hm}^4}}\right)\right)$$

or: $$f_{h,p}\approx f_{hm}\cdot\sqrt{\frac{2f_{hm}^2}{f_af_h}}=f_{hh}$$

(12)

with: $\frac{f_{hm}}{f_h}\geq\sqrt[4]{\frac{9}{2}\cdot\frac{f_a}{f_h}}$

or $f_{h,p}=f_{hh}\geq 3\cdot f_h$

By this high strength $f_{h,p}=f_{hh}$ according to eq.(12), the working bearing length of the nail l_b is very small, a fraction of the diameter d (what is physically improbable) and the stress also is always close to the upper value following from the local failure mechanism according to Fig.4. Design thus always can be based on eq.(11). Expressed in f_{hh} of eq.(12) is:

$$f_{hl} = f_{hh} \cdot \sqrt[3]{\frac{3f_h}{f_{hh}}} \leq f_{hh} \qquad (13)$$

Because $f_{hh} \leq 3 \cdot f_h$, thus showing strength safely can be based on f_{hl} of eq.(11) alone.
The upper value of the embedding strength

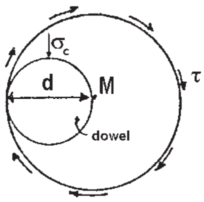

Figure 4. Local failure mechanism of the dowel

follows from the local failure mechanism of Fig.4 which, by the circular ultimate shear plane gives an upper. From the moment equilibrium around point M follows:

$$f_{h,p} d \cdot d / 2 = f_{v,p} \cdot 2\pi \cdot d \cdot d \text{ or}$$

$$f_{h,p} = f_{v,p} \cdot 4\pi = (f_{c,p} / 2) \cdot \pi 4 = 2\pi \cdot f_{c,p} \approx 6 f_{c,p}$$

Because the strength of the boundary layer is 1.7 times higher than the mean strength, thus is $1.7 f_{h,p}$ for structural particle board plates, the maximal value of the embedding strength is:

$$f_{h,p} \leq 1.7 \cdot 6 = 10 f_{c,p} \qquad (14)$$

for thin nails by this local failure mechanism at the outer plate boundary. This explains the possibility of the high value $f_{h,p} = 8.06\ f_{c,p}$ found in Section 2.1.

3 Hardening (nail string action) by influence of the effective nail penetration length

The specimens of Fig. 5 are used to determine the failure mechanisms depending on the length of the nail. Chosen are series with nails 2.8/65; 2.8/55; 2.8/45 and profiled nails 3.4/65.

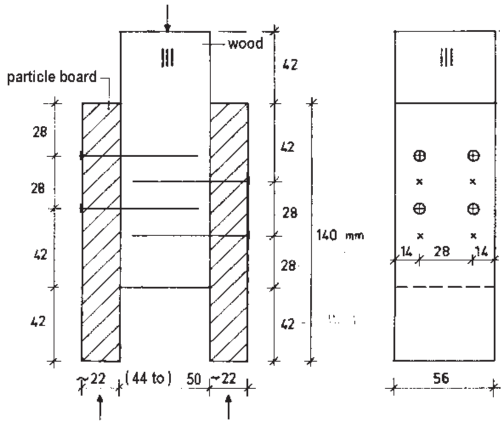

Figure 5. Test-specimens for the influence of the nail lengths on hardening.

The relative penetration lengths of the nails in the wood thus are:

$$\frac{l_a}{d} = \frac{(65 - 22)}{2.8} = 15.4$$

$$\frac{l_a}{d} = \frac{(55 - 22)}{2.8} = 11.8$$

$$\frac{l_a}{d} = \frac{(45 - 22)}{2.8} = 8.2$$

The theory of failure and hardening behaviour is derived and discussed in [4]. It was shown that the hardening of the strength of the specimens with short nails is a factor 1.13, while this is 1.27 for the long nails. An estimate of first flow according to nail mechanism III with two plastic hinges, thus is about 1046/1.1 = 950 N or 1256/1.3 = 965 N or 958 N as mean value. The working length of the nail then is:

$$\frac{l_b}{d}=\frac{F}{f_{h,p}d^2}=\frac{F}{f_{c,p}d^2}\cdot\sqrt{\frac{dl_b}{tb_t/n}} \quad \text{or:}$$

$$\frac{l_b}{d}=\frac{F^2}{\left(f_{h,p}d^2\right)^2}\cdot\frac{d^2}{tb_t/n}=\frac{958^2}{\left(16\cdot 2.8^2\right)^2}\frac{2.8^2}{22\cdot 56/4}=1.48$$

thus:

$$f_{h,p}=16\sqrt{\frac{22\cdot 56/4}{2.8^2\cdot 1.48}}=16\cdot 5.14=82.3\ \text{N/mm}^2$$

and $F= 82.3 \cdot (2.8)^2\, 1.48 = 958$ N

This does agree with:

$$F=82.3\cdot 2.8^2\cdot\sqrt{\frac{740}{82.3}\cdot\frac{2/3}{1+82.3/45}}=939\,\text{N},$$

close to 958N

The direct calculation of $f_{h,p}$ gives:

$$f_{hm}=f_{c,p}\sqrt{\frac{t\cdot b_t/n}{d^2}}=16\cdot\sqrt{\frac{22\cdot 56/4}{2.8^2}}=100.3\ \text{MPa}$$

$$f_{h,p}\approx f_{hm}\cdot\sqrt[3]{\frac{6\cdot f_{hm}}{f_a}}=100.3\sqrt[3]{\frac{602}{740}}=93 > 82.3$$

or: $$F=93\cdot 2.8^2\cdot\sqrt{\frac{740}{93}\cdot\frac{2/3}{1+93/45}}=959\,\text{N}$$

the right measured value, showing F to be not sensitive for estimate difference of $f_{h,p}$. It now thus is shown that eq.(11) gives an excellent estimate for design.

4 Conclusions

- The stress spreading theory explains the high embedding strength for nails with a limited working length due to 3-dimensional spreading. Test-results confirm this behaviour.
- The nail head reaction is important for spreading in thickness direction of the nailed particle board to wood plate. Stress spreading in thickness direction of the particle board plate should not be accounted for head-less nails.
- To account for this very high embedding strength of nailed particle board to wood joints, an iterative adaption for the spreading strength is derived, verified by test data.
- Also the derivation for a direct analytical estimation method of this high embedding strength is given with the simplification of the formula and the very good fit to data is shown.
- Based on the local mechanism of fig. 4, the derivation is given of the highest possible ultimate embedding strength of particle board, which is verified by the discussed tests.

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Estimation of the Influence of Rows of Nails in Particle Board-to-Wood Joints

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Abstract

The exact spreading theory, provides in our other contribution, the universal law of embedding strength of nailed particle board to wood joints and even in the simplified power law form, this law is very precise. The consequence of the theory is that it also provides the right row factor for rows of nails, as is discussed in this article 2, leading to a necessary application for design and for the Building Codes.

Keywords

Particle board, embedding strength, limit analysis, equilibrium method, nailed board to wood joints, row effect.

Introduction

Our contribution is split in two parts. One article 1, is about theory of the strength of single nailed particle board to wood connection and this article 2, is about consequences of the theory for the strength of rows of nails where also the determination of the spreading width per nail of a group of nails is discussed and the consequences for other failure mechanisms.

The power representation of the stress spreading model of confined dilatation provides a simple design method which precisely matches to the data and is able to explain e.g. the measured data depending on the different parameters of the extended investigation on the embedding strength of Budianto et al. [1] as was already shown in Van der Put [2]. The predictions of the theory for other parameters and other dimensions of the specimens are confirmed by additional tests, reported in van der Put [2], [3], [4] and in this article. The influence of the Weibull effect, van der Put [3], [5], of small dowel diameter failure is not discussed because it is regarded separately in the Eurocode. The stress spreading embedding strength theory thus is necessary to extend the Maier-Johansen theory and to explain failure behaviour of nailed particle board to wood joints.

2 Rows of Nails in Nailed Particle Board to Wood Joints

The stress spreading theory applies generally e.g. for particle board and for wood loaded perpendicular to the grain. As example of a connection by a group of nails, Fig. 1 shows a hanger connection loading a beam perpendicular to the grain. In this case maximal spreading of the nail forces is possible

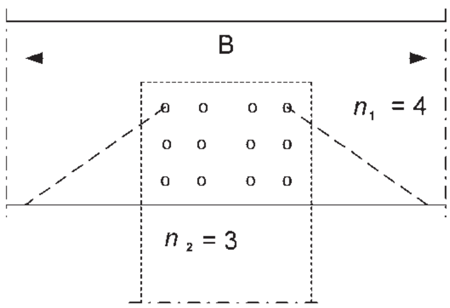

Figure 1. Connection by a group of nails.

There are n_1 rows of n_2 nails per row. Total number of nails thus is: $n=n_1 \cdot n_2$. The spreading width per row now is: $b_r = B/n_1$ and the spreading width per nail then is:

$$b = B/(n_1 \cdot n_2) = B/n \tag{1}$$

The working spreading width b per nail thus follows from the maximal spreading width divided by the total number of nails of the nail pattern. This follows from the highest lower bound solution when all nails have the same strength by a same spreading lengths b. This is shown empirically to be right in e.g. in van der Put [5] based on data of CIB-W18/32-7-2. For limited spreading possibility in long rows, as given in Fig. 2, the stress in the board becomes high and the influence of this stress on spreading possibility and thus on strengths, has to be accounted as follows:

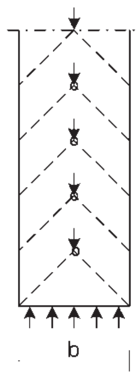

Figure 2. Row of nails connection.

The maximal spreading and thus the maximal embedment strength σ_1 is according to Fig. 3:

$$\sigma_{1,0} = \sigma_c \sqrt{A_3 / A_1} \tag{2}$$

where $\sigma_c \geq f_{c,p}$ by a factor ≥ 1 depending on the type of compression strength test. When there already is stress in the specimen by the other nails of a row, the spreading possibility is diminished what can be represented by a diminished possible spreading area A_2 instead of total A_3 as schematically given in Fig. 3.

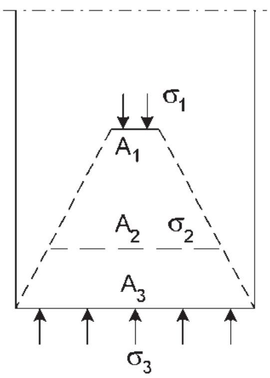

Figure 3. Reduced spreading area

Then, due to stress in the board, is:

$$\sigma_1 = \sigma_c \sqrt{\frac{A_2}{A_1}} = \sigma_c \sqrt{\frac{A_2 \sigma_2}{A_1 \sigma_2}} =$$

$$= \sigma_c \sqrt{\frac{A_3 \sigma_3}{A_1 \sigma_2}} = \sigma_{1,0} \sqrt{\frac{\sigma_3}{\sigma_2}} \qquad (3)$$

The reduction factor of the embedding strength per nail due to a row thus is:

$$\rho = \sqrt{\frac{\sigma_3}{\sigma_2}} = \sqrt{\frac{\sigma_3 A_3}{\sigma_2 A_2} \cdot \frac{A_2}{A_3}} = \sqrt{\frac{A_2}{A_3}} \qquad (4)$$

The reduction of adjacent spreading areas of adjacent nails of the row is small. Thus A_2 can be given as: $A_2 = A_3 - \Delta A$, where ΔA is small. Thus:

$$\rho = \sqrt{\frac{A_2}{A_3}} = \sqrt{\frac{A_3 - \Delta A}{A_3}} = \sqrt{1 - \frac{\Delta A}{A_3}} \approx 1 - \frac{\Delta A}{2 A_3} \qquad (5)$$

as first terms of a row expansion. The approximate linearity of ρ along the row shows that the total mean value of the reduction factor for the total row can be based on the mean value of ρ, thus also on the mean values of the all stresses σ_2 and σ_3 in the plate. Then:

$$\sigma_3 = \frac{1}{2}\left(\frac{p}{A_2} + \frac{np}{A_2}\right) = \frac{n+1}{2} \cdot \frac{p}{A_2} =$$

$$= \frac{n+1}{2} \sigma_1 \sqrt{\frac{\sigma_2}{\sigma_3}} \cdot \frac{A_1}{A_2} = \frac{n+1}{2} \sqrt{\frac{\sigma_2}{\sigma_3}} \sigma_2 \qquad (6)$$

where p is the (by plasticity determined) load per nail and n the number of nails in the row. Thus:

$$\left(\frac{\sigma_2}{\sigma_3}\right)^{3/2} = \frac{2}{n+1} \quad \text{or:}$$

$$\sqrt{\frac{\sigma_2}{\sigma_3}} = \left(\frac{2}{n+1}\right)^{1/3} = \sqrt{\frac{A_2}{A_1}} = \rho \qquad (7)$$

Because a minimum of four nails per joint are required, no reduction factor should be used for rows of two nails and the row-factor becomes:

$$\rho = \left(\frac{3}{n+1}\right)^{1/3} \leq 1 \quad (\text{when } n \geq 2) \qquad (8)$$

For long rows, according to Fig. 4, the upper n_1 nails have full spreading with spreading width $2a_1$, thus $\rho = 1$ for $n_1 = b/(2a_1)$. For the lower $n_2 = n - b/2a_1$ nails is $\rho = \left(\frac{2}{n_2+1}\right)^{1/3}$

Thus the total reduction factor of the row is:

$$\rho_t = \frac{n_1 \cdot 1 + n_2 \left(\frac{2}{n_2+1}\right)^{1/3}}{n} =$$

$$= \frac{b}{2a_1 n} + \left(1 - \frac{b}{2a_1 n}\right)\left(\frac{2}{n+1-\frac{d}{2a_1}}\right)^{1/3} \qquad (9)$$

The longest row, tested and analytically verified in literature, is a row of 9 nails of Larsen (1974). The specimen width was $b = 46.7d$ and $a_1 = 7d$. Thus $b/a_1 = 6.67$ and

$$\rho_t = \left(1 - \frac{6.67}{2 \cdot 9}\right)\left(\frac{2}{9+1-\frac{6.67}{2}}\right)^{1/3} + \frac{6.67}{2 \cdot 9} = 0.79 \qquad (10)$$

This reduction factor is a reduction on the embedding strength and should be applied in the iteration procedure of our other contribution. Depending on the nail failure mechanism the row factor of the strength will be above 0.8, comparable with Larsen's measurements. The given analysis shows a simple Code embedment-stress reduction rule to be possible: ρ_1=1 for the nails with full $2a_1$ spreading possibility over b (n_1 nails of Fig.4) and:

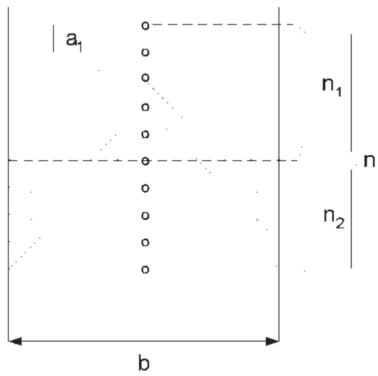

Figure 4. Row spreading possibility.

$$\rho = \left(\frac{2}{n+1}\right)^{1/3} \leq 1 \text{ or:}$$

$$f_{h,p} = f_{hm} \cdot \left(\frac{6f_{hm}}{f_a} \cdot \frac{2}{n+1}\right)^{1/3} \tag{11}$$

as found by our article 1, for reduced spreading widths (the lower $n = n_2$ nails of Fig. 4).

3 Critical Specimen Dimensions for Interaction of All Failure Mechanisms

Design should be based on equal characteristic strengths of nail and particle board plate. Then only nail failure will be detected and is only determining for the strength of the connection. In the past this plastic end-stage of nailed connections was a demand and it still applies for staple connections. Now design in practice is based on empirical minimal nail- row- end- and edge distances giving rise to many possibilities of combined failure of nail and particle board plate. According to the reliability demand it is necessary for an empiric approach to run at least an enormous extended testing program with all thinkable failure mode interactions of all thinkable specimen dimensions and conditions. Because this testing never gives a guaranty of finding the worst case, this has to be found by theory, the universal law of nature. Based on theory, design is possible of a test specimen with equal strength for all possible types of failure at the same time. This specimen is given by Fig. 5 of

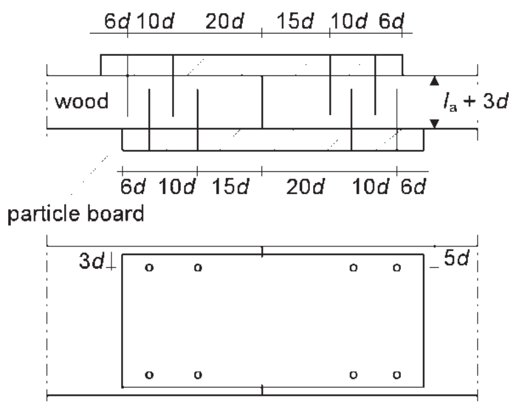

Figure 5. Tensile test string of four nailed critical connections.

the nailed particle board to wood tension joint of van der Put [6]. The row length of 2 nails is chosen because the nail withdrawal force is the highest and the highest plate loading is possible by bending and tension at the upper and lower weakest cross sections. High stress in the particle board plate not only reduces the spreading effect but also embedding strength by a high eccentricity moment of the nail force.

Applying for that case the failure criterion for combined tension and bending van der Put [2], it follows that the width b' of the tested plates per row (row distance) should be:

$$b' = 5.5 \cdot d + F_r / (f_{p,t} \cdot t) \geq 8 \cdot d \qquad (12)$$

where F_r is the ultimate tensile load per row in the plate with $f_{p,t}$ as tensile strength. $B \geq 8d$ is required for the plate strength at the end nail of the row. The chosen values for t/d, (board thickness-nail diameter ratio) was 4.5 to 10.5 as applied in panels. The penetration length of the nail was $12d$ to have always influence of nail withdrawal at the ultimate state. All possible plate failure mechanisms did occur at testing as e.g. panel shear failure at small end-distances of the nails; in plane shear failure in the weakest plane and splitting; tension failure perpendicular to the plate surface and rolling shear. There was no indication of strength reduction due to interaction of these local failure mechanisms, which could be avoided by sufficient end- edge- and row distances.

The explanation of no combined failure influence is given by the theory in Van der Put [7]. In the end state embedding compression and friction along the nail are determining for the strength. This means that at the same nail deformation the spreading effect can be diminished at weak spots and increased at strong spots causing stress redistribution and the optimum is reached when the ultimate values of all mechanisms are reached at the same time showing the occurrence of any of all possible single failure modes in the end state. Also creep tests during about a half year, done at a high loading level (0.7 times the short term strength) on the multiple critical joints of Fig. 5 did not show a decrease of the long term strength by interaction of failure mechanisms The predicted long-term strength is above 0.55 (for 50 years). Nail head pull through tests and analysis of the determining spreading stress in Van der Put [2] shows the pull through of the common nail is not determining in practice. The reaction by the nail head is important for the possibility of stress spreading in the thickness direction. At the application of head-less nails, only spreading in one direction (i.e. the plate direction) and not in thickness direction of the particle board plate has to be accounted. The analysis showed that for the one plastic hinge nail failure case, the contribution of nail head rotation on the bearing strength is small and can be accounted by a factor in the Johansen equations (see Section 4).

4 Extension and Simplification of the Lower Bound Johansen Equations.

Although much simpler design equations are possible based on the real occurring failure mode van der Put [7], it is necessary to adapt to for EC 5 accepted Johansen equations of initial flow. In Van der Put [2] the extension of the Johansen equations is given for the spreading effect, the varying compression strength over the thickness of the plate and the bearing influence of the nail-head with the necessary simplification of the equations by straight lines. By this simplification the one hinge nail failure load per nail F_2 is:

$$F_2 = 0.85 F_1 \frac{t_3 - t}{t_3 - 0.85 t_1} + F_3 \frac{t - 0.85 t_1}{t_3 - 0.85 t_1} \geq F_1 \quad (13)$$

This equation (13) applies for head-less nails and for plates having no strong dense boundary layers as e.g. flax plates by the minor bearing effect by nail head rotation. For particle board plates the clamping effect by nail head rotation leads to:

$$F_2 = F_1 \frac{t_3 - t}{t_3 - t_1} + F_3 \frac{t - t_1}{t_3 - t_1} \geq \frac{F_1}{0.85} \qquad (14)$$

as extended Johansen equation where F_1, F_3, t_1, t_3 are given in Fig. 6. $F_1$is the maximal possible bearing force of a straight remaining nail at the maximal possible plate thickness t_1 for this failure case and F_3 the ultimate nail force for two plastic hinge nail failure at the minimal possible plate thickness t_3 for this failure case.

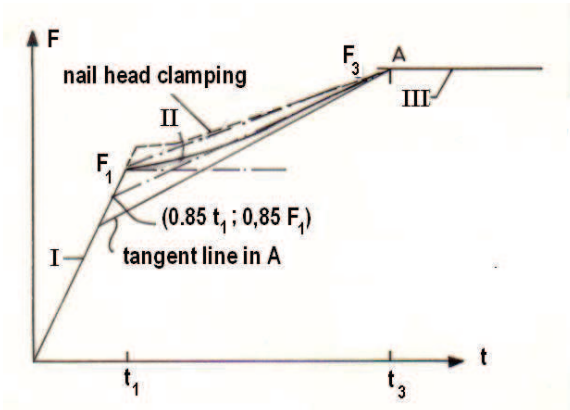

Figure 6. Extended Johansen lines of nailed connections.

$$F_1 = f_{c,p} t_1 d \sqrt{\frac{b'}{d}}$$

with:

$$\frac{t_1}{d} = 0.71 \sqrt{\frac{f_a}{f_{h,p,1}} \cdot \frac{2/3}{1 + f_{h,p,1} / f_h}}$$

where:

$$f_{h,p,1} = f_{c,p} \cdot \sqrt{\frac{b'}{d}} \qquad (15)$$

according to eq.(4), where $f_{c,p}$ is the mean compression strength of the whole plate.

$$F_3 = f_{h,p,3} d^2 \cdot \sqrt{\frac{f_a}{3 \cdot f_{h,p,3}} \cdot \frac{2}{1 + f_{h.p,3} / f_h}}$$

with:

$$\frac{t_3}{d} = \left(1 + \sqrt{1 + \frac{f_{h,p,3}}{f_h}}\right) \sqrt{\left(\frac{f_a}{f_{h,p,3}} \cdot \frac{2/3}{1 + f_{h,p,3} / f_h}\right)} \qquad (16)$$

and $f_{h,p,3} \approx f_{hm} \cdot \left(\frac{6 f_{hm}}{f_a} \cdot \frac{2}{n+1}\right)^{1/3}$

with $f_{hm} = f_{c,p} \cdot \sqrt{\frac{b' \cdot t}{d^2}}$

according to our article 1: eq.(2), eq.(3), eq.(5) for $f_{h,p,3}$ and eq.(11) of this article 2 because of any row factor.

5 Conclusions

- The stress spreading theory explains the high embedding strength for nails and the row factor for rows of nails. Test-results confirm this behaviour.
- The test result of the designed critical specimen, which is critical for all different failure mechanisms (as combined bending-tension and shear failure of the plate with nail withdrawal) at the same time did indeed show the equal possibility of occurrence of all these mechanisms indicating the possibility of stress redistribution of the spreading stress and therefore no interaction of the failure mechanisms occurred (being all critical at about the same time).
- The derivation of the row factor is given verified by data and a simplification for the Regulations is proposed.
- The necessary extension of the Johansen equation for nail head clamping and for stress spreading effect is given with the simplification of the formulas.

Correction factors of the strength for shorter nails are necessary.

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