Double shear timber connections with dowel type fasteners

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For the design of single fastener connections with dowel type fasteners Johansen's Yield Model [1], extended by Meyer [2] is generally adopted. However, since this model gives a poor prediction of the load carrying capacity of single fastener connections with rigid fasteners, an extension based on fracture mechanics considerations was developed [3].
The strength of multiple fastener connections does not equal the strength of the single fastener connection multiplied by the number of fasteners. Generally the connection fails at a lower load because the timber splits and/or because of softening of the wood, which can be explained by the complicated stress distribution around the fastener position.
The stiffness of multiple bolted connections is lower than the stiffness of the single bolted connection multiplied by the number of bolts, which can be explained by the individual hole clearances.
Both the strength and stiffness of multiple fastener connections and the strength of single fastener connections with dowel type fasteners were studied.

Key words: timber, connections, bolts, dowels, fracture, model

Introduction

In most countries, the reduction of the load carrying capacity of a multiple fastener connection is taken into account by introducing an effective number of fasteners (n_{ef}) which is generally smaller than the real number of fasteners (n), i.e. equation (1).

$$F_{\text{multiple}} = n_{ef} F_{\text{single}} \tag{1}$$

Where:

F_{multiple}	load carrying capacity of a multiple fastener connection
F_{single}	load carrying capacity of a single fastener connection

Figuge 1 shows an example for the effective number of fasteners according to design rules used in some different countries. From this figure it is clear that no agreement exists on the design value for n_{ef}. The differences show the necessity for fundamental research into multiple fastener connections.

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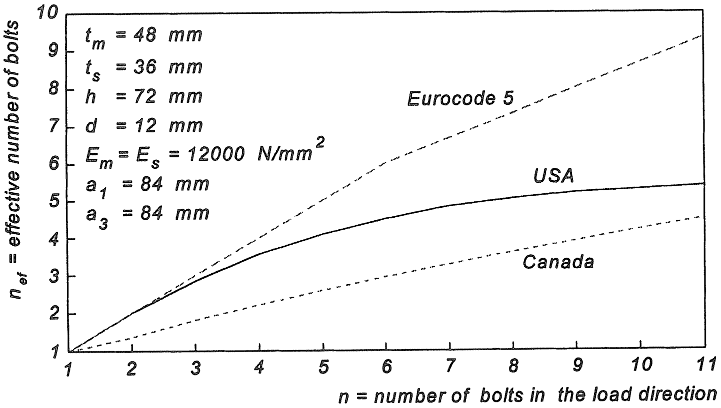


Fig. 1. *Effective number of fasteners.*

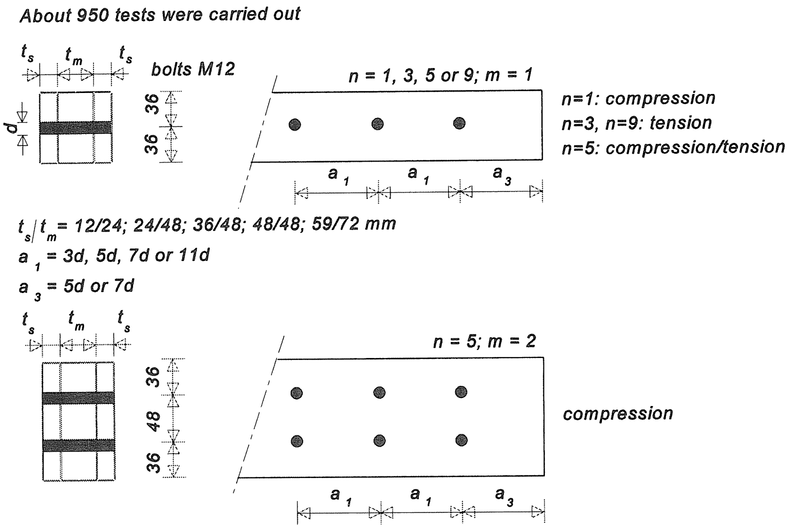


Fig. 2. *Connections studied.*

In order to determine realistic values for n_{ef}, an extensive research program was started at the Delft University of Technology, faculty of Civil Engineering, in the beginning of 1994. This research was supported by the Dutch Research Foundation STW. Main emphasis was put on the study of the short-term strength of symmetrical three-member timber-to-timber connections with dowel type fasteners loaded in tension or compression parallel to the grain. Only bolted connections were tested and generally M12 bolts ($d \approx 12$ mm) grade 4.6 were used. All specimens were made with

European spruce. About 950 tests on single and multiple bolted connections were carried out. The number of fasteners parallel to the grain (n), the spacing parallel to the grain (a_1), the number of rows (m), the slenderness ratio ($\lambda = t_m / d$) and the end distance (a_3) were varied. The slenderness ratio was varied by varying the timber thicknesses t_m and t_s.
An overview of the connections studied is given in figure 2.

It was shown that in a multiple fastener connection the stresses perpendicular to the grain and the shear stresses accumulate. This accumulation is the result of the load transferred by each fastener. For the determination of this load transfer a load distribution model was developed (based on a different non-linear load-slip curve for each fastener). A computer model was developed in which all theories were incorporated. This computer program can be downloaded for free from Internet: www.veenhoven.com (software page).

Summary of the results

It was found that the number of fasteners in the row, the spacing and the slenderness ratio are important parameters to describe the effective number of fasteners, of which the spacing is the most important one.
Furthermore, it was found that, for multiple bolted connections, individual hole clearances are not important for the connection strength. However, they affect the connection stiffness significantly. The initial slip for a multiple bolted connection is low although each bolt has a rather high hole clearance.

Single fastener connections

Theory

Since Johansen's Yield Model gives a poor prediction of the load carrying capacity of single fastener connections with rigid fasteners, an extension based on fracture mechanics consideration was developed [3]. The result is equation (2) of which some symbols are explained in Figure 3.

$$2F = 2t\sqrt{\frac{G_c E_0 d \sin(\varphi)[h - d\sin(\varphi)]}{h}} \qquad (2)$$

Where:
$2F$ = load carrying capacity; see figure 3.
G_c = fracture energy. For connections with dowel type fasteners in spruce, $G_c \approx 0.35$ Nmm/mm^2
E_0 = Young's modulus for loading parallel to the grain. For spruce, $E_0 = 12000$ N/mm^2
d, t and h: see figure 3 [mm]
φ = angle of friction ($\approx 30°$)

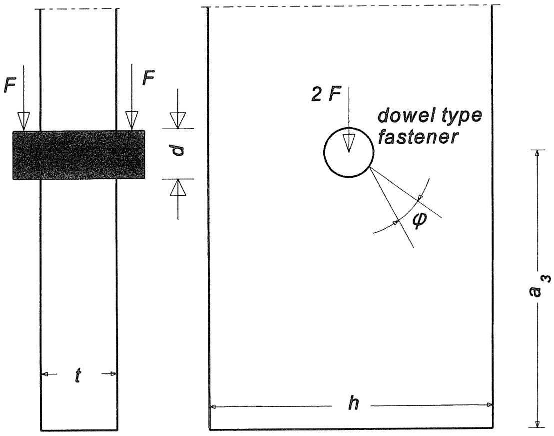


Fig. 3: Explanation of some notation in equation (2).

Since it was thought that the stresses perpendicular to the grain and the shear stresses are important for finding a theoretical explanation of the reduced strength of multiple fastener connections, these stresses were also analysed for the single fastener connections. To describe these stresses, analytical models were developed.

Since the embedment stress is uniform over the timber thickness for connections with *rigid* dowel type fasteners, cracks develop over the complete timber thickness. This is not the case for connections with *non-rigid* dowel type fasteners, where the embedment strength is assumed to be uniform over a length y, see figure 4. This results in crack propagation near the shear planes over a length y_a, which is assumed to be higher than y. Only for connections with rigid dowel type fasteners it can be assumed that $y = y_a = t =$ timber thickness.

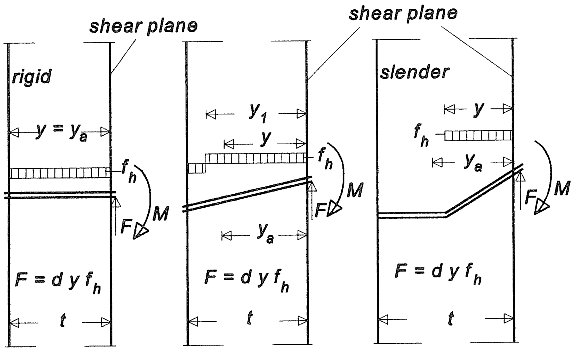


Fig. 4. The embedment stress σ_h.

The analytical model developed for the calculation of the stresses perpendicular to the grain was based on the theory of beams on an elastic foundation, in which both bending and shear deformations were considered. An example is shown in Figure 5.

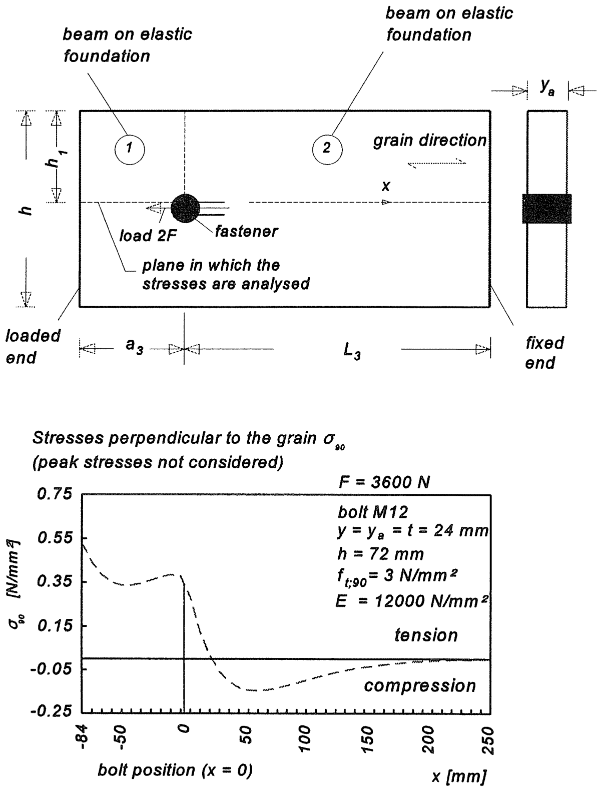


Fig. 5. Stresses perpendicular to the grain.

The peak stresses perpendicular to the grain near the fastener hole cannot be predicted with this model.

The shear stresses at failure in the loaded end were analysed with an analytical model based on the theory presented by Volkersen [4], which was extended by Gustafsson [5]. The result is equation (3), of which an example and some parameters are explained in Figure 6.

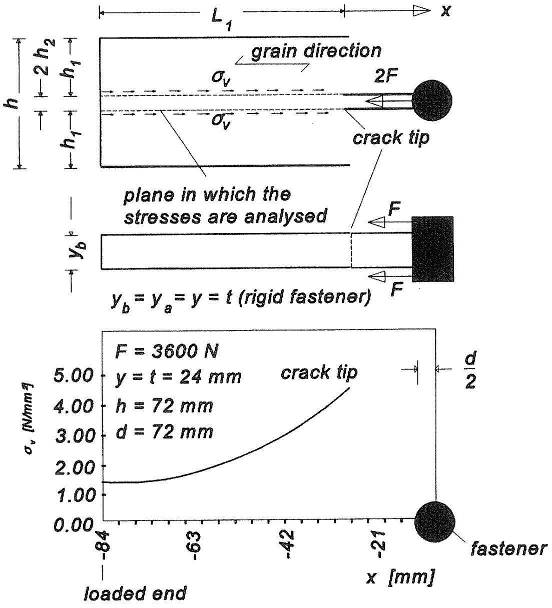


Fig. 6. Shear stresses.

Figure 6 shows two beams with width h_1 on an elastic foundation with thickness $2h_2$. The result of the analysis is equation (3).

$$
\begin{aligned}
\sigma_v &= \frac{F(h_1+h_2)f_v^2}{2\omega E_0 G_c y_b h_1 h_2}\left[\frac{\cosh(\omega L_1)}{\sinh(\omega L_1)}\cosh(\omega x)-\sinh(\omega x)\right]\\
\omega &= \sqrt{\frac{(h_1+h_2)}{2h_1h_2}\frac{f_v^2}{E_0G_c}}\\
h_2 &= \frac{d}{2}\sin(\varphi)\\
h_1 &= \frac{h-2h_2}{2}
\end{aligned}
\qquad (3)
$$

y_b: use y_a according to figure 4 for stress calculation near the fastener hole
use t, timber thickness, for stress calculation at all other positions, where it is assumed that the stresses are uniform over the timber thickness.

Experimental research

Single bolted connections were tested for two reasons:

(1) to obtain reference strength values.

(2) to study the practical individual hole clearance for each bolt in a multiple bolted connection. Therefore the single bolted connection was sawn out of multiple bolted connections, which contained five bolts. The initial position of each bolt, and therefore the hole clearance, was fixed by plywood glued on to the test specimens before cutting, see figure 7. The single bolted connections were tested in compression.

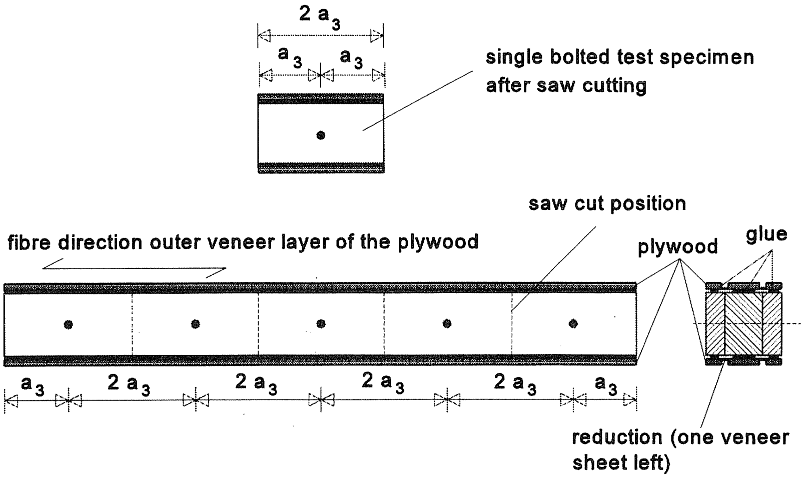
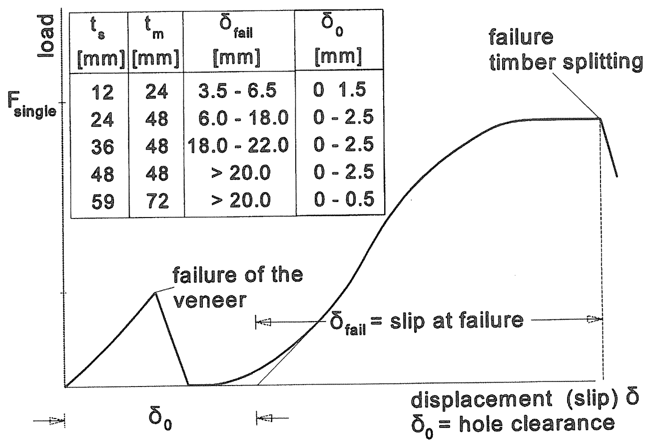


Fig. 7. Manufacturing of the test specimens for the single bolted connections.

Since the only objective of the plywood was fixing the initial bolt position and not strengthening the connection, the thickness of the plywood was reduced to one single veneer sheet of which the fibre direction was parallel to the direction of the applied load.

The tests were displacement controlled. The load increased until the plywood failed. Then the bolt slipped over the hole clearance and the load dropped. This slip, and by this the hole clearance, was recorded. After the bolt slip the displacement was increased until the connection failed.

When the plywood failed, the bolt slipped over the hole clearance. This slip, and thus the hole clearance, was recorded, see figure 8.



t_s [mm]	t_m [mm]	δ_{fail} [mm]	δ_0 [mm]
12	24	3.5 - 6.5	0 1.5
24	48	6.0 - 18.0	0 - 2.5
36	48	18.0 - 22.0	0 - 2.5
48	48	> 20.0	0 - 2.5
59	72	> 20.0	0 - 0.5

Fig. 8. Load-slip curves for the single fastener connections.

Usually the diameter of the drill was 1 mm larger than the nominal bolt diameter. This was done for a large number of test specimens, which resulted in a hole clearance between 0 and 2.5 mm (i.e. the bolt may slip over 2.5 mm without carrying load). Since the actual shank diameter of M12 bolts was significantly smaller than 12 mm, it was decided to reduce the nominal hole diameter to the nominal bolt diameter (= 12 mm), which resulted in smaller hole clearances (between 0 and 0.5 mm).

The strength of the connections with rigid bolt was significantly lower than the strength obtained with Johansen's Yield Model. Therefore these results were simulated with equation (2), based on fracture mechanics considerations, which was found to be better in predicting the test results than Johansen's Yield Model.

Multiple fastener connections

Theory

Four models, which were incorporated into the computer program mentioned before, were developed:

- A load distribution model for simulating the load distribution over the various fasteners.
- A model for the stresses perpendicular to the grain.
- A model for the shear stresses.
- A failure model.

The models for the stresses perpendicular to the grain and the shear stresses are both extensions of the models described in the section about the single fastener connections.

The load distribution model, being a spring model, was based on the following assumptions:

- Linear elastic behaviour of the timber between the fasteners.

- Uniform stresses across the timber cross section.
- Different non-linear load-slip behaviour for all fasteners according to figure 9 and equation (4).

$$F = [F_0 + k_1(\delta - \delta_0)]\left(1 - e^{-\frac{k_0(\delta - \delta_0)}{F_0}}\right) \le F_{\text{single}} \tag{4}$$

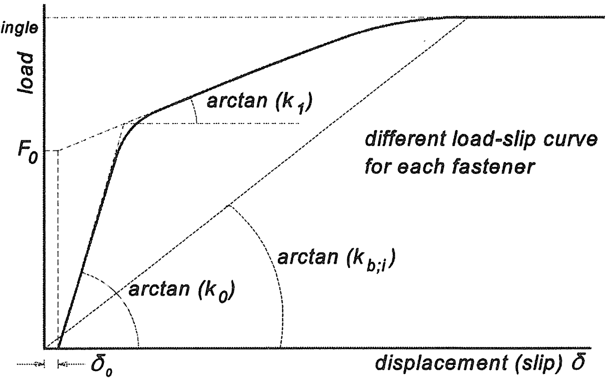


Fig. 9. Load-slip curve (plot of equation 4).

The spring model shown in Figure 10 was analysed. It was assumed that the fastener slip, being the result of wood compression and dowel bending, can be described by the load-slip curve presented in figure 9.

The result of the analysis is equations (5); see also Figure 10.

$$\Delta_i = \Delta_{i-1} + \frac{\sum_{k=1}^{i-1} F_k}{k_{m;i-1}} = \sum_{j=2}^{i}\left(\frac{\sum_{k=j}^{n} F_k}{k_{s;j-1}}\right) + \delta_i \tag{5}$$

$$\delta_i = \frac{F_i}{k_{b;i}}$$

Where:

Δ_i = the connection slip at fastener i with respect to the reference slip at fastener 1, where $\Delta = 0$.

δ_i = the fastener slip shown in figure 9.

$k_{b;i}$ = stiffness value defined in figure 9 [N/mm].

F_i = the load transferred by fastener *i* [N].

The axial stiffness of the timber side members between fastener (*i*) and (*i*+1) is called $k_{s;i}$ [N/mm]. In analogy, the axial stiffness of the middle member is called $k_{m;i}$ [N/mm]. With $k_{s;i}$ and $k_{m;i}$ a linear elastic behaviour of the timber between the fasteners was simulated.

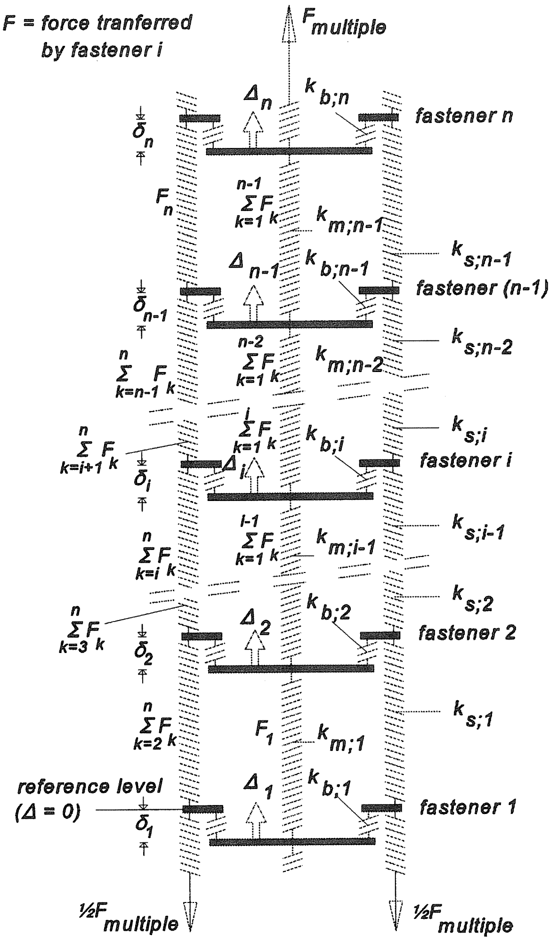


Fig. 10. Spring model.

For a connection load at serviceability limit state level, the load distribution model results in non-uniform load distribution over the fasteners and, since the individual hole clearance δ_0 (see figure 9) is one of the input parameters, the load distribution model was very useful for the analysis of the connection stiffness. The results for a connection with four (rigid) bolts obtained with the spring model are plotted in figure 11.

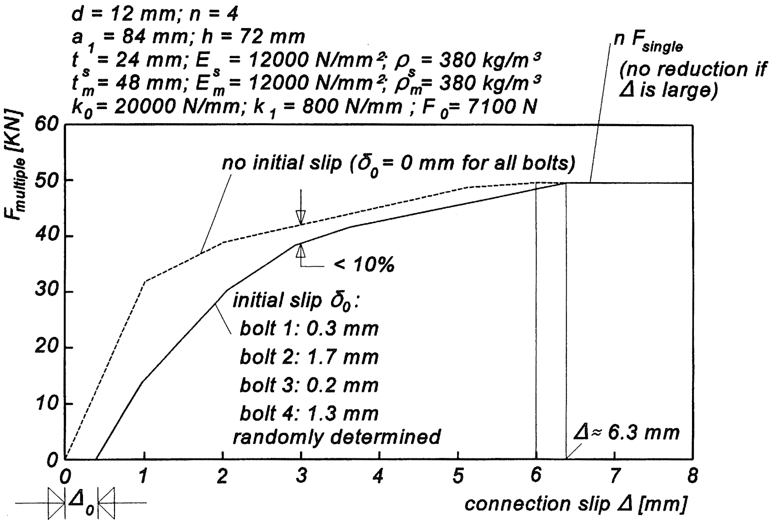


Fig. 11. Calculated load-slip curves.

Only the initial slip (the hole clearance) was varied. Figure 11 shows that, in this case, the influence of the hole clearances on the load carrying capacity is less than 10% if the connection slip at failure load is larger than three mm ($\Delta \geq 3$ mm). Similar calculations with other connection geometry showed in principle the same result. This indicates that the influence of the hole clearances (fabrication tolerances) on the load carrying capacity is of minor importance. This was also confirmed by the experimental results.

However, since the load at serviceability limit state level is not uniform distributed over the fasteners, the hole clearances have a large influence on the connection stiffness. It may be that, at low load level, some fasteners do not transfer load at all and, consequently, do not contribute to the connection stiffness.

Generally, connections with dowel type fasteners fail due to crack propagation at the fastener hole(s). Since these cracks develop due to stresses perpendicular to the grain and shear stresses, analytical models for determining these stresses were developed.

For the single fastener connections these models were already discussed. For multiple fastener connections it was shown that the stresses accumulate, see figure 12, which explains crack propagation and/or softening at a rather low load level.

In figure 12 three distinct points can be considered.

(a) The tension stress perpendicular to the grain and the shear stress at bolt position 1 due to the load transferred by bolt 1.

(b) The tension stress perpendicular to the grain and the shear stress at bolt position 1 due to the load transferred by bolt 2 at a spacing of 84 mm (a_1 = 84 mm). Figure 12[I] shows for th stresses perpendicular to the grain that the value of (b) is about half the value of (a); for a smaller spacing the value of (b) is even larger.

(c) The tension stress perpendicular to the grain and the shear stress at bolt position 1 due to the load transferred by bolt 3 at a spacing of 168 mm (a_1 = 168 mm).

As shown in figure 12 the stresses at bolt position 1 are considerably increased by bolt 2, which has the smallest distance to bolt 1.

Conclusion: the stresses at bolt position 1 are enlarged due to the presence of bolts at other positions. This stress accumulation depends strongly on the spacing: the stress accumulation is large for connections with small spacings, which explains the low load carrying capacity of those connections.

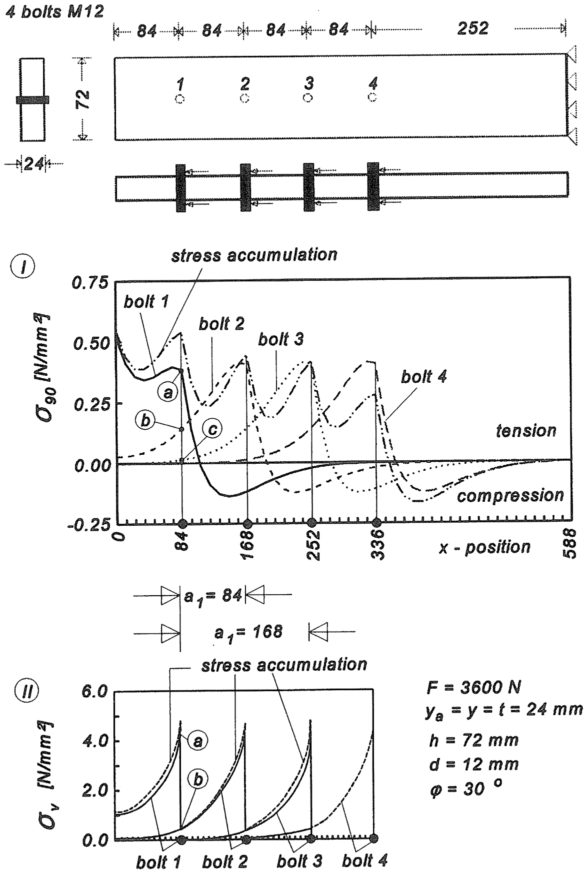


Fig. 12. Accumulation of the stresses perpendicular to the grain (I) and the shear stresses (II) (example).

The failure model was based on the following considerations.
The magnitude of the stresses perpendicular to the grain and the shear stresses depend on the load transferred by each fastener. The strength values for tension perpendicular to the grain and shear are not independent. Therefore, a combination of strength values obtained by tests on specimens simultaneously loaded in tension perpendicular and shear were chosen. These strength values were presented by van der Put [7]. Since the cracks also develop at failure load for single fastener connections it has been assumed that the perpendicular to the grain tensile strength and the shear strength are also reached in a single fastener connection. Since these stresses accumulate in a multiple fastener connection and the stress values cannot exceed the strength values, the load per fastener must be reduced in a multiple fastener connection (softening).

As mentioned before, the spring model, the stress models and the failure model were incorporated in a computer program. As an example the multiple bolted connection with four bolts shown in figure 12 was analysed. The (calculated) result is plotted in figure 13, in which it is shown that, despite of the different individual hole clearances, almost uniform load distribution is reached at failure. The load-slip curves for the individual bolts are also shown in figure 13. In this example the initial slip δ_0 is the only difference between these four curves.

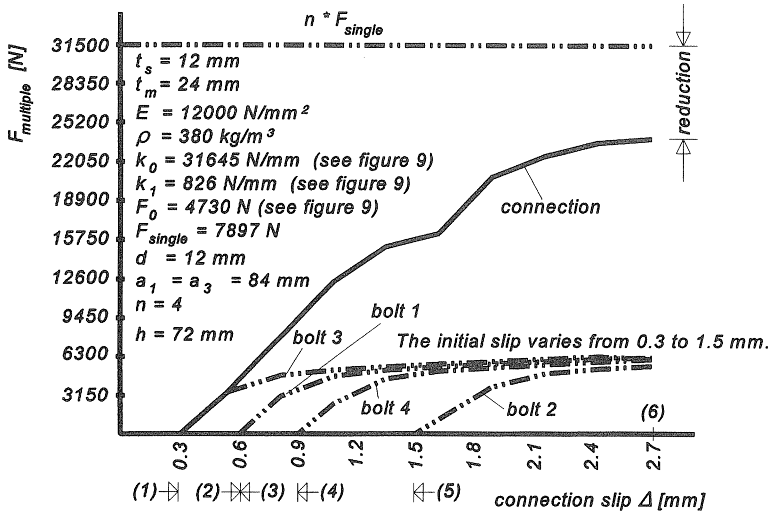


Fig. 13. Load carrying capacity of the multiple bolted connection shown in figure 12.

Experimental research

To determine the short term strength, about 850 tests on multiple bolted connections and about 100 tests on single bolted connections were carried out. The specimens tested are shown in figure 2. The single bolted connections were all tested in compression. The multiple bolted connections with three and nine bolts in line were all tested in tension. Half of the connections with five bolts in line were tested in compression, the other half was tested in tension. All results were presented in [3]. Generally, one of the failure modes shown in figure 14 can be expected.

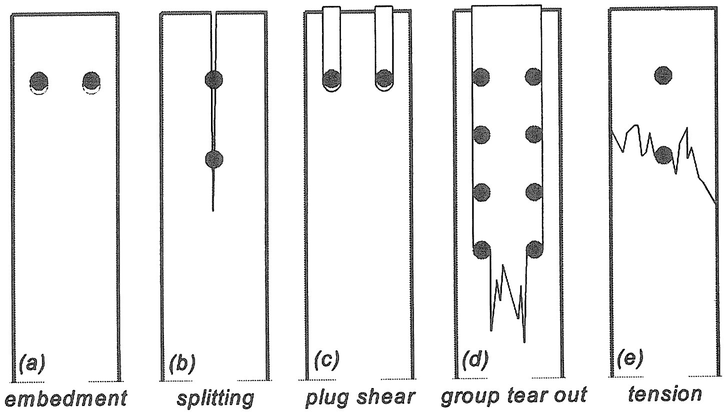


Fig. 14. Failure modes for bolted connections.

During the testsdiscussed in this section, failure mode (d), group tear out, was never observed. In this section the multiple fastener connection strength is discussed depending on:

A) the hole clearances
B) the number of bolts in the load direction (n)
C) the spacing in the load direction (a_1)
D) the number of rows (m)
E) the slenderness ratio
F) the loaded end distance (a_3)
F) the timber density (ρ)

The influence of all parameters mentioned, except the number of rows, can be explained by the results of the discussed theoretical analyses.

The results are presented with so called BOX PLOTS, provided by the statistical package (SPSS). An example is shown in figure 15: the box contains 50% of all strength values: 25% of the tests show lower strength values than the lower box border (B), 25% show higher values than the upper box border (A).

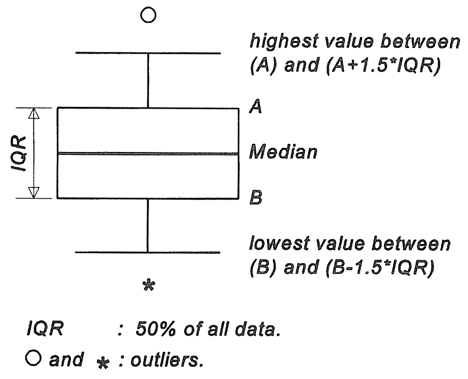


Fig. 15. Box plot.

The distance between the box borders is called IQR (interquartile range). The thick line in the box represents the median (≈ average value in most cases). The upper horizontal line outside the box represents the highest strength value between the upper box border and 1.5*IQR above the box. The lower horizontal line outside the box represents the lowest strength value between the lower box border and 1.5*IQR below the box. None of the values in between the range 1.5*IQR below and above the box are shown. All values outside this range are shown, i.e. the values indicated (*) or (o). Thus: the box seize and the horizontal lines outside the box indicate the scatter in the test results. The box seize (50%) and 1.5*IQR are arbitrarily chosen (fixed by SPSS). There is no significance to the width of the BOX PLOT.

A) The hole clearances

It was thought that the hole clearances (fabrication tolerances) would affect the load carrying capacity of a multiple bolted connection significantly. In the section on the theoretical developments for multiple fastener connections it was discussed that this only is the case if the connection slip at failure is low (< 3 mm); see figure 11. To study the effect of fabrication tolerances experimentally, two series of test specimens were manufactured in two different ways.

For the first series the holes in the side and middle members were clamped and drilled simultaneously and the fasteners could be put into position immediately. A prefabricated timber structure was simulated, resulting in negligible differences in hole clearances between the individual bolts.

For the second series the holes in the side members and middle member were drilled seperately, after which the timber members were assembled randomly to form connections. An erected timber structure at the building site was simulated, which, most likely, resulted in different hole clearances for the individual bolts (the exact position of the bolts could not be determined).

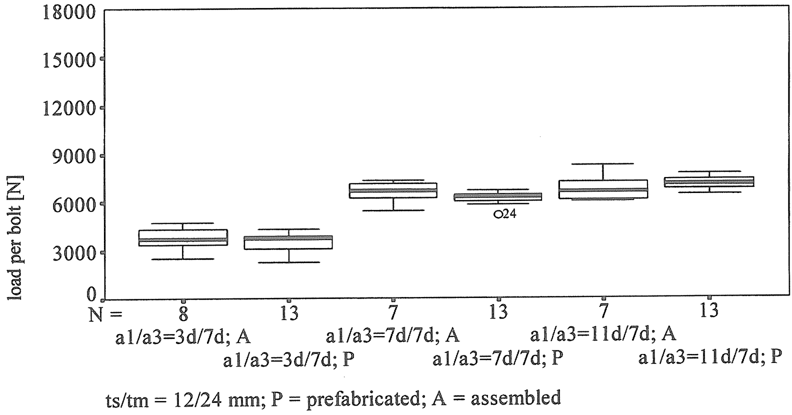


Fig. 16. Test results for specimens with different manufacturing methods.

The results for the tests with t_s / t_m = 12/24 mm (rigid bolts) given in figure 16 show that no significant difference in the median of the load carrying capacity was found for the different manufacturing methods. However, figure 15 also shows that the variation in the results for prefabricated connections is smaller than for the assembled connections, which may result in a lower characteristic strength for connections in the assembled structure.
However, from the results it can be concluded that the hole clearances do hardly affect the average load carrying capacity of multiple bolted connection, which can also be shown by calculations carried out with the load distribution model, see figure 11.
However, a large influence of the hole clearances on the stiffness of multiple bolted connections was shown. Conform the theoretical results discussed before, the experimental results showed a much lower connection stiffness compared to the situation where it was assumed that the stiffness was linear to the number of bolts. Based on the test results, equation (6) was proposed for predicting the stiffness parameter per shear plane for multiple **bolted** connections.

$$k_{\text{ser}} = k_{\text{bolt}} \frac{\rho^{1.5} d}{20} = 0.3 \, \frac{\rho^{1.5} d}{20} \qquad (6)$$

Where:
k_{ser} = stiffness per shear plane according to Eurocode 5 [6] in N/mm.
ρ = density in kg/m^3 (The actual density, not the characteristic density.

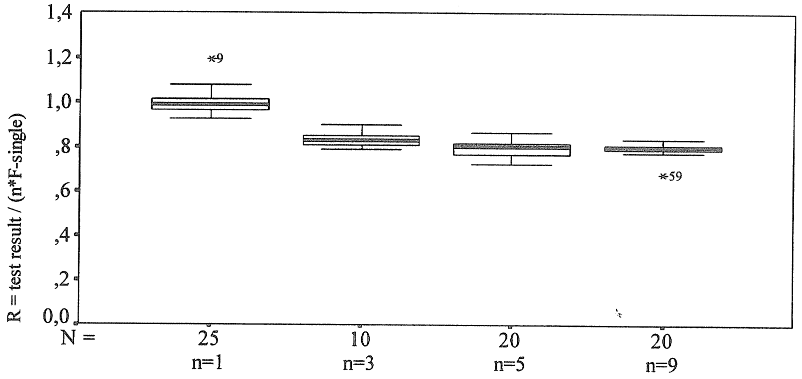
Note: Since the actual density was used for the determination of k_{bolt}, equation (6) results in the average value for k_{ser}. According to Eurocode 5 the characteristic value for the density should be substituted to obtain the average value for k_{ser}. In that case k_{bolt} = 0.4.

Furthermore, the load-slip relation of a **multiple** bolted connection showed little initial slip even if the initial slip of the individual bolts was rather large.

B) The number of bolts parallel to the load direction (n)

Generally the load carrying capacity depends on the number of bolts. However, figure 17 shows that this dependence reduces with increasing number of fasteners, which agrees with the result of the theoretical analyses already discussed.

Note: F_{single} = load carrying capacity of a single bolted connection.



ts/tm = 24/48 mm; a1 = a3 = 7d; bolts M12.

Fig. 17. Influence of the number of bolts (n) on the load carrying capacity.

Note: F_{single} = load carrying capacity of a single bolted connection.

The theoretical analyses show that the strength reduction per bolt is relatively largest for a multiple bolted connection with two bolts in the row and that the reduction factor R should be equal for a connection with five bolts and one with nine bolts. This is supported by the results given in figure 17. However, in some cases the strength per bolt was a bit lower for a connection with nine than with five bolts in the row. This can be explained by size effects, i.e. the probability that asteners are situated in weak timber is increased if the length of the connection is increased.

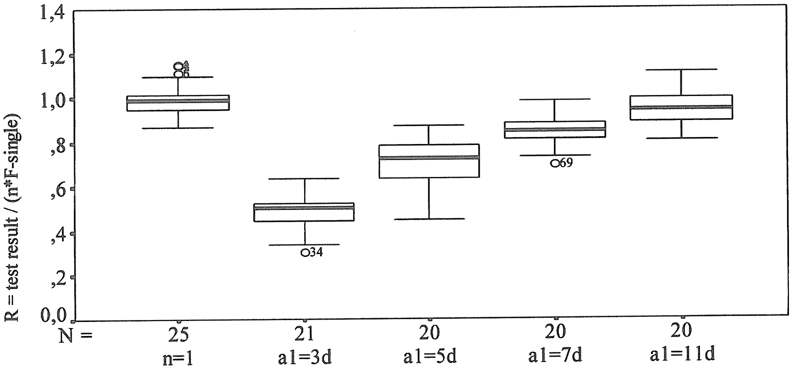
The connection strength is not greatly influenced by the number of bolts parallel to the load direction (n).

C) The spacing in the load direction (a_1)

Figures 18 shows that the load carrying capacity depends considerably on the spacing (a_1), i.e for small spacings the reduction in load carrying capacity is rather high (the reduction factor is rather low).

The influence of the spacing is more or less equal for all slenderness ratios used and seems to be the most important parameter for the connection strength.

Figure 18 also shows that the spacing did not influence the scatterband of the load carrying capacity significantly.



ts/tm = 12/24 mm; n = 5; a3 = 7d; bolts M12.

Fig. 18. Influence of the spacing (a_1) on the load carrying capacity.

D) The number of rows (m)

The tests series with two rows of fasteners were all tested in compression. All specimens contained five bolts in the row and were tested in compression which explains why none of the test specimens failed due to "group tear out", see figure 14. "Group tear out" may occur in connections which are loaded in tension with small row spacing a_2.

For the connections described here the row spacing was kept constant at a_2 = 4d. See figure 2 for further information on the test specimens.

The median of the load carrying capacity of multiple fastener connections with two rows of five bolts was generally slightly lower than those with one row of five bolts and equal spacing (a_1), end distance (a_3) and bolt slenderness ration (λ), see figure 19, i.e. the strength of multiple fastener connections with two rows of fasteners was on average about 90% of the strength of multiple fastener connections with one row of fasteners.

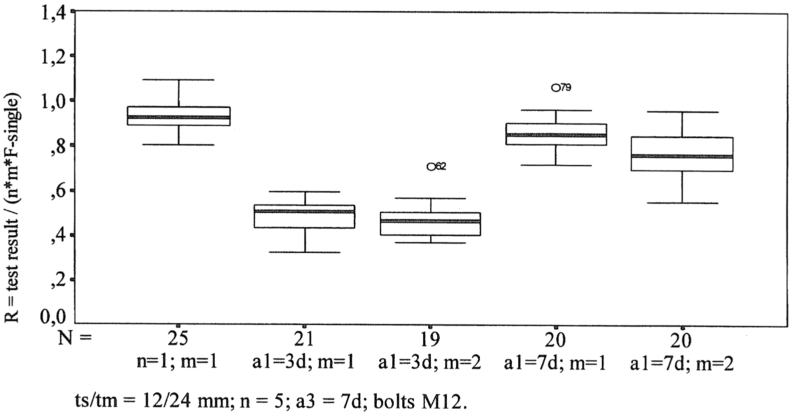


Fig. 19. The number of rows (m) affects the load carrying capacity. All tests were carried out in compression.

E) The slenderness ratio (λ)

The load carrying capacity of the single fastener F_{single}, calculated according to Johansen's Yield Model [1], depends on the fastener slenderness ratio λ ($\lambda = t_m / d$).

Figure 20 shows almost equal influence of the slenderness ratio on the normalised load carrying capacity of multiple fastener connections F_{multiple} (average values) for the three slenderness ratios used, which can be explained by the stresses in the middle member and the type of failure (splitting).

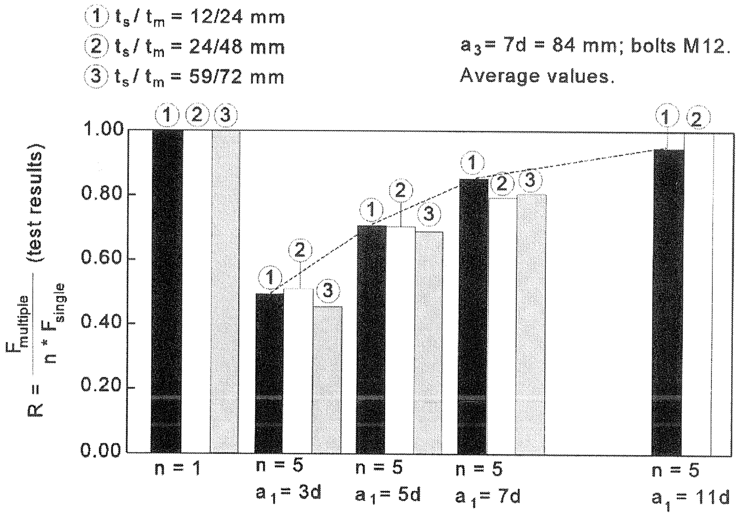


Fig. 20. Influence of the slenderness ratio (and spacing a_1).

Even for failure mode III according to Johansen's Yield Model, see figure 21, the embedment stress is more or less uniform over the thickness of the middle member even if the slenderness ratio is higher than λ_{gr} (but not too high).

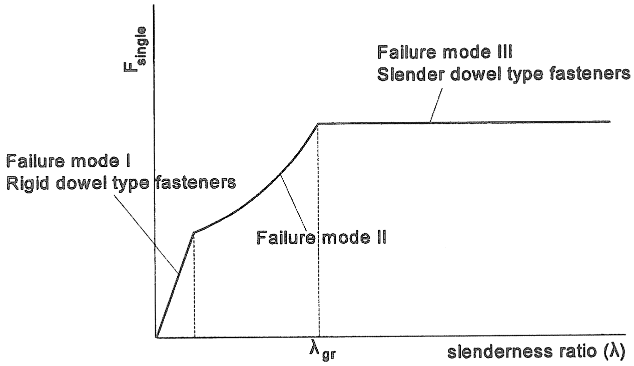
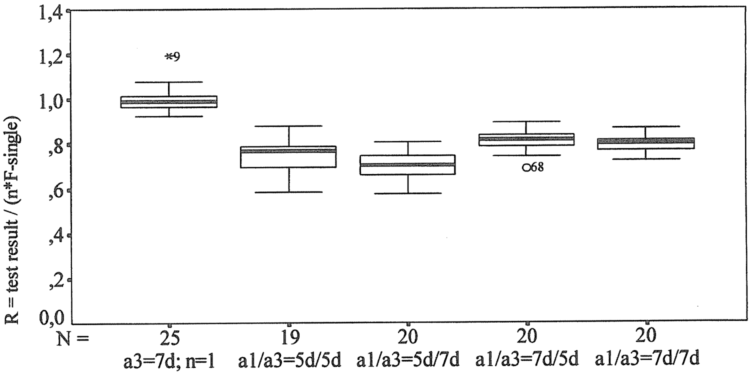


Fig. 21. Failure modes according to Johansen's Yield Model.

This uniform stress distribution results in crack developing over the complete cross section and the middle member will fail due to splitting. Consequently, independently of the slenderness ratio, most tests failed due to splitting of the middle member. An influence of the slenderness ratio on the load carrying capacity can only be expected for large slenderness ratios ($\lambda >> \lambda_{gr}$). Then it can be expected that the effective number of bolts increases if the slenderness ratio increases. Tests on specimens with $\lambda >> \lambda_g$ were, however, not carried out.

F) Loaded end distance (a_3).

The loaded end distance (a_3) was chosen a_3 = 5d and a_3 = 7d. Figure 22 shows that this variation hardly affects the short term strength of the multiple bolted connections.



ts/tm = 24/48 mm; n=5; bolts M12.

Fig. 22. Influence of the end distance (a_3) on the load carrying capacity.

However, it is known that the influence on the load carrying capacity is significant for smaller end distances (smaller than 5d). This can be explained by the stresses perpendicular to the grain at the loaded end, which, theoretically, increase exponentionally if the loaded end distance is reduced, see figure 5 and 23, and result in timber splitting due to tension perpendicular to the grain at the loaded end.

The failure mode for end distances of 5d and more is, however, completely different: the connection fails due to timber splitting near the bolt hole.

It was shown that the stresses perpendicular to the grain at the loaded end are much higher for a_3 = 5d than for a_3 = 7d, see figure 23. It is known that the load duration effect on tension perpendicular to the grain is high. Therefore, for long term loading and a_3 = 5d, the connection most likely fails due to timber splitting at the loaded end, and an end distance of 5d should not be considered, although the short term strength does not give any indication for that.

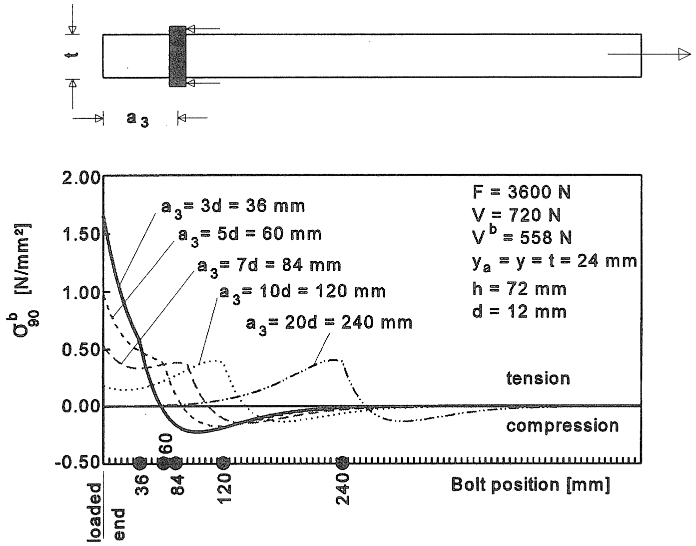


Fig. 23. Influence of the loaded end distance a_3 on the stresses perpendicular to the grain.

G) The timber density (ρ)

The densities measured at a timber moisture content of 12% varied between 320 kg/m^3 and 580 kg/m^3 with an average of 450 kg/m^3 and a variation of 44 kg/m^3 (≈ 10%).

The embedment strength, and consequently the load carrying capacity calculated according to Johansen's Yield Model [1], is strongly correlated to the timber density. However, it was shown by calculation that the densities of the three members may vary from 320 kg/m^3 to 580 kg/m^3 without influencing the theoretical load carrying capacity [3]. Consequently, no significant correlation can be expected between the densities and the load carrying capacity for timber to timber connections.

Design equations

Regression analysis was used to derive design equations. Among others, regression equation (7), was chosen for further analyses, because the correlation was the highest when using this equation. The relations taken into account were already discussed. It was shown that the short term connection strength F_{multiple} depends on the number of fasteners parallel to the load direction (n), the spacing (a_1), the number of rows (m) and the slenderness ratio (λ). It was assumed that these geometrical properties determine the effective number of fasteners n_{ef}. The number of rows tested was limited to $m = 1$ and $m = 2$ and it was suggested to take the row influence into account introducing a factor k_{m} ($k_{\text{m}} = 1.0$ for $m = 1$ and $k_{\text{m}} = 0.9$ for $m = 2$). No k_{m}value was suggested for $m > 2$.
The loaded end distance (a_3) was found not to be important for the short term strength ($a_3 \geq 5d$).
All tests were carried out on connections of which the thickness of the middle member was equal or less than the total thickness of the side members ($t_{\text{m}} \leq 2t_{\text{s}}$). Therefore the slenderness ratio was defined as t_{m}/d ($\lambda = t_{\text{m}}/d$). If t_{m} is larger than $2t_{\text{s}}$, it is suggested that the slenderness ratio is $2t_{\text{s}}/d$ ($\lambda = 2t_{\text{s}}/d$).
Regression equation (7), was chosen for further analyses.

$$F_{\text{multiple}} = k_{\text{m}} C_1 n^{C_2} \left(\frac{a_1}{d}\right)^{C_3} \lambda^{C_4} F_{\text{single}} \tag{7}$$

Notes: – F_{single} is the load carrying capacity according to Johansen's Yield Model [1].
– $n > 1$.

Since a spacing of 3d (a_1 =3d) is not practical (brittle failure modes) and the regression coefficients for $a_1 \geq 3$d were different from those obtained for $a_1 \geq 5$d and $a_1 \geq 7$d, which were by and large the same, the test with a spacing of 3d were not considered. All the other test results and some results obtained with the computer program, referred to in the introduction, were considered.
The regression analysis resulted in an equation with which the average strength can be predicted. These values are not appropriate for the limit state design, which requires characteristic values. The transformation of the average values to characteristic values resulted in equation (8).

$$F_{\text{multiple}} = k_{\text{m}} 0.43 n^{0.9} \left(\frac{a_1}{d}\right)^{0.30} \lambda^{0.30} F_{\text{single}} \tag{8}$$

Note: $\lambda \geq 3$ (bolted connections with $\lambda < 3$ should not be considered). If $\lambda < 3$, F_{single} should be calculated according to equation (2) in stead of according to Johansen's Yield Model. If the result according to equation (2) is taken into account, equation (8) can also be applied.

The load carrying capacity of multiple fastener connections depends mostly on the fastener diameter, the number of fasteners, the slenderness ratio and the spacing . The spacing (a_1) is most determining and the slenderness ratio is the least determining. Therefore an additional regression analysis was carried out resulting in equation (9).

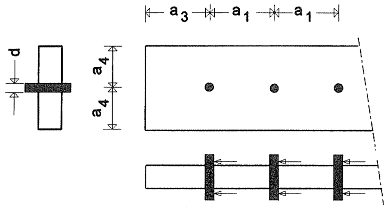
$$n_{\text{ef}} = k_{\text{m}} n^{0.9} \left(\frac{a_1}{10d} \right)^{0.25} \qquad (9)$$

Notes:– $n > 1$.

– $\lambda \geq 3$ (bolted connections with $\lambda < 3$ should not be considered, see the note below equation (8)).

A summary with the range of validity is given in table 1.

Table 1. Summary and range of validity.

Connection	Range of validity
	$n \geq 2$ $a_1 \geq 5d$ $a_3 \geq 7d$ $a_4 \geq 3d$ reduction factor for two rows of bolts for $a_2 \geq 4d$: $m > 2$: not tested; no k_m value given $m = 2$: $k_m = 0.90$ For $m = 1$, $k_m = 1.00$ slenderness ratio: $\lambda = t_m/d$ or $2t_s/d$, whichever is the lesser. $\lambda \geq 3$. the density $\rho = 380$ kg/m^3 (spruce; characteristic value). hole clearances < 1.5 mm.
Design rule	
$F_{multiple} = k_m \, n^{0.90} \left(\frac{a_1}{10d} \right)^{0.25} F_{single} \leq n \, F_{single}$ (9)	

Summary

The strength of multiple fastener connections in general and multiple bolted connections in detail were discussed. The influence of the number of bolts in the row, the number of rows, the spacing, the loaded end distance and the bolt slenderness were described based on a theoretical and experimental research carried out at the Delft University of Technology in the years 1994 to 1998. A load distribution model, models for predicting the stresses perpendicular to the grain and shear stresses and a failure model were developed and discussed. All models were incorporated into a computer model, which can be downloaded from Internet as described in the introduction.

About 950 short term tests on single and multiple bolted connections loaded parallel to the grain were carried out. In most cases M12 bolts grade 4.6 were used. An overview of the connections studied is given in figure 2.

It was found that the spacing between the bolts has the largest influence of all on the connection strength. The influence of the number of fasteners, the number of rows, the bolt slenderness and the loaded end distance is less pronounced.

The research resulted in design equations of which the one given in table 1 is most practical.

Acknowledgements

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