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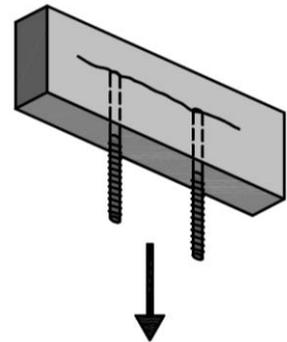
Beams loaded perpendicular to grain by connections

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1 Introduction

This contribution addresses the following issues regarding splitting:

- Is the splitting strength dependent on the connection width along the grain when laterally loaded dowel-type fasteners are applied?
- Is the Eurocode 5 model valid for axially loaded screws?
- Is the Eurocode 5 model safe for multiple connections along the span?



1 The influence of fastener spacing and number fasteners

In EN1995-1-1 (Eurocode 5) a linear elastic fracture model is implemented based on a model by Van der Put and Leijten (2000) that does not consider how the load is applied, nor the type and spacing of and number of fasteners but only what the conditions are for unstable crack growth outside the connection area. Other empirical or semi-empirical models Ehlbeck et al. (1989), Franke et al. (2012), among others, take into account the influence of the number of rows, columns and the spacing of the fasteners (nails, dowels).

A systematic and comprehensive study into the influence of rows and columns with mid span connections with 4 mm and 6mm nails was carried out by Schoenmakers (2010), Figure 1. The test results apply to mid span connections. The wood species was Spruce (C24) with a mean density of 450 kg/m³ and 12.7% m.c. The cross-sectional dimensions of the beams were 45x220mm and span 1600mm. Single shear (SS) nails and double shear (DS) nails fitted in predrilled holes. The holes in the steel side members matched the nail diameter as to prevent any clearance. The steel side plates were 15mm thick. For every connection five replicates were tested with two loaded edge distances, h_e . The load-slip curves were reported in Schoenmakers (2010). The failure mode of some tests in Figure 2 were $n =$ the number nails. It will be clear that with 5 nails plastic hinges in the nails appear.

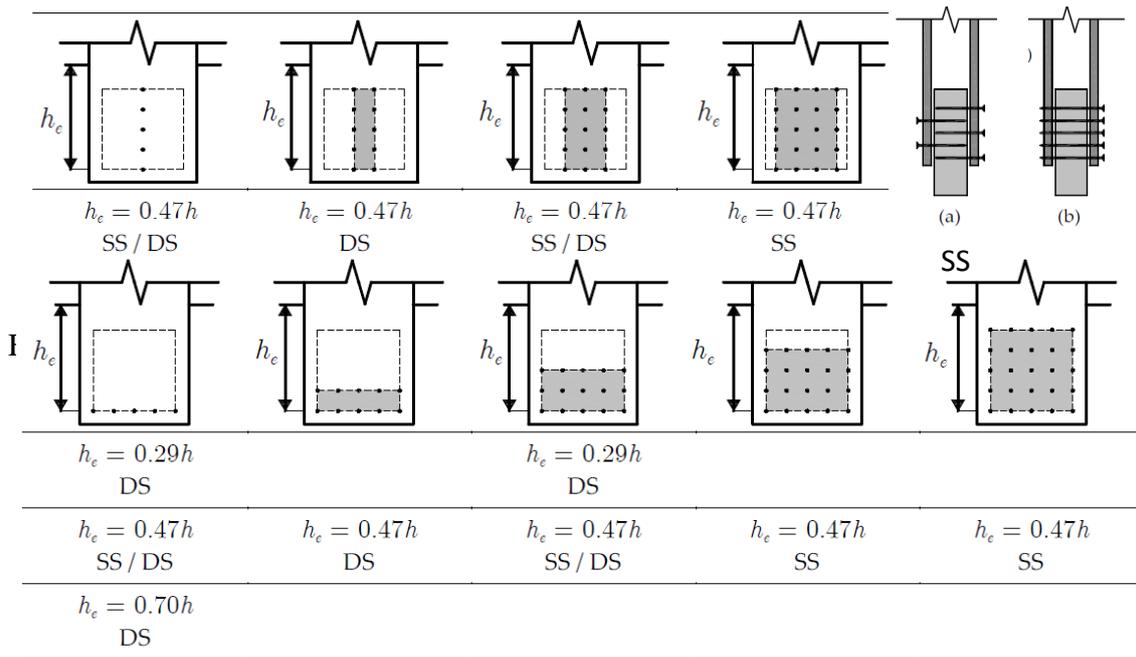


Figure 1: Connections with 4mm nails loaded in single shear (SS) and double shear (DS). For higher numbers of nails splitting occurs when the embedment stresses are still low and no plastic hinges appear.

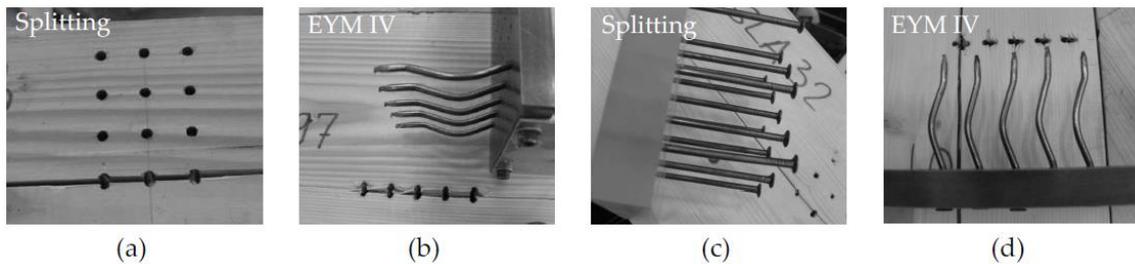


Figure 2; Typical failure modes (a) splitting $n=12$ (b) plastic hinges, $n=5$ (c) splitting $n=20$ (d) plastic hinges $n=5$; with n = number of fasteners.

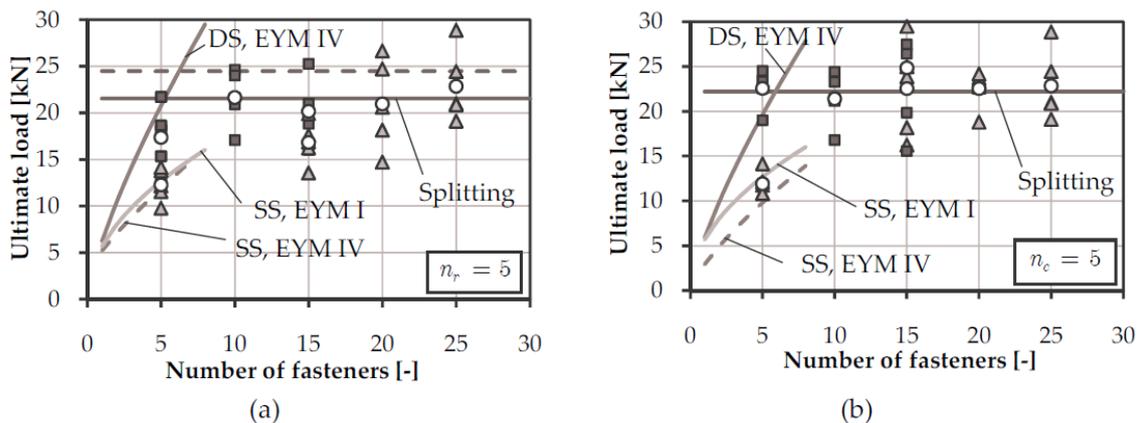


Figure 3: Results with 4mm nails: (a) top pattern Figure 1, (b) bottom pattern Figure 1.

In Figure 3 the open dots represent the mean value of each test series while the lines drawn show the predictions based on the EYM (including a number I to IV representing the governing failure modes) and the calibrated EN1995-1-1 model for splitting. It follows that when more than 10 nails are used the maximum load becomes independent of the nail

pattern for both single (SS) and double shear (DS) loaded nails. The test results with connections with 6mm nails gave similar results. Schoenmakers (2010) also reports test with high density tropical hardwoods.

In the light of these results punched metal plates (PMP) connections which can be regarded as close spaced nailed connections show comparable results. In addition to Reffold et al. (1999) Schoenmakers (2010) performed a comprehensive test program in which he varied the plate orientation as well as the loading angle (inclined load introduction).

It is concluded that for more nails than a critical number splitting governs independent of the number of fasteners as predicted by Van der Put and Leijten (2000).

3 Mid span connections with axial loaded screws

The semi-empirical models by Ehlbeck et al. (1989) and Ballerini and Rizzi (2007) do not consider connections with axial loaded screws although the same splitting phenomenon occurs. For this type of load introduction a fracture mechanical model might be applicable as this type of model does not consider how the load is introduced. To verify this point Schoenmakers (2010) carried out test using SPAX-S screws with a diameter d of 8 and 12 mm and 200 mm length, inserted in the bottom of the beam. Two basic configurations were tested: one row of 3 screws and two rows of 3 screws, respectively, Figure 4. To examine the influence of the number of screws, spacing along the grain ($s=4d$ and $8d$) and insertion depth (0.3 and 0.5 beam depth) were varied. To satisfy the edge requirements for screws the timber beams thickness was adjusted without changing the beam depth 240 and span of 1600mm. The tests comprised 16 test series of 5 replicates each.

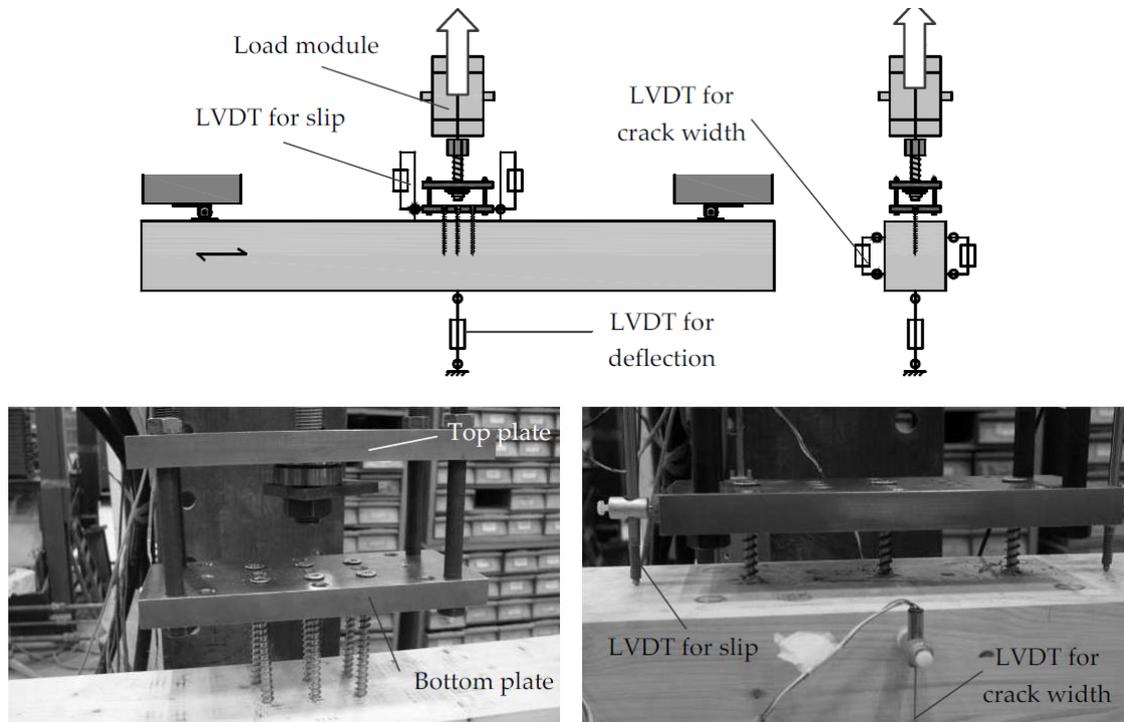
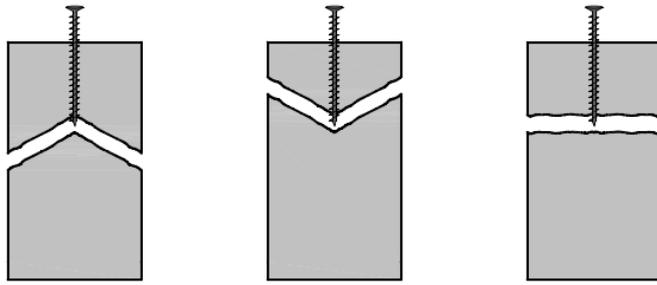


Figure 4: Test setup for bottom inserted self-tapping screws; (left) two rows of three screws; (right) one row of three screws.

Glued laminated beams of Spruce with an average density of 458 kg/m^3 at 12.2% m.c. were used. Only in the series with three 12mm screws $8d$ along the grain withdrawal was

governing while in all other cases splitting occurred. The crack planes at the screwed section of the beam are schematically drawn in Figure 5. The observed crack plane varied



at random over the test series and was either horizontal or inclined $\pm 30^\circ$ although more inclined cracks appeared for the 12 mm diameter screws than for the 8mm screws. In all cases the crack initiated approximately at the insertion depth minus 10 mm.

Figure 5: Crack orientation at the screwed section of the beam.

When the fracture parameter $(GG_c)^{0.5}$ of Eq. (3), see 4.1, was calibrated for each screw diameter, for 8mm screws the mean was $(GG_c)^{0.5} = 17.4 \text{ N/mm}^{1.5}$ for 12mm screws $(GG_c)^{0.5} = 12.6 \text{ N/mm}^{1.5}$. The predictions by Eq.(3) resulted in Figure 6(a). Schoenmakers also evaluated the test results using only one mean value of $(GG_c)^{0.5} = 14.9 \text{ N/mm}^{1.5}$ based on all his tests with glued laminated beams and dowel-type fasteners, Figure 6(b). This results in a conservative prediction for connections with $d=8\text{mm}$ screws and slightly less conservative predictions for the 12mm screws. The influence of screw diameter was left unexplained.

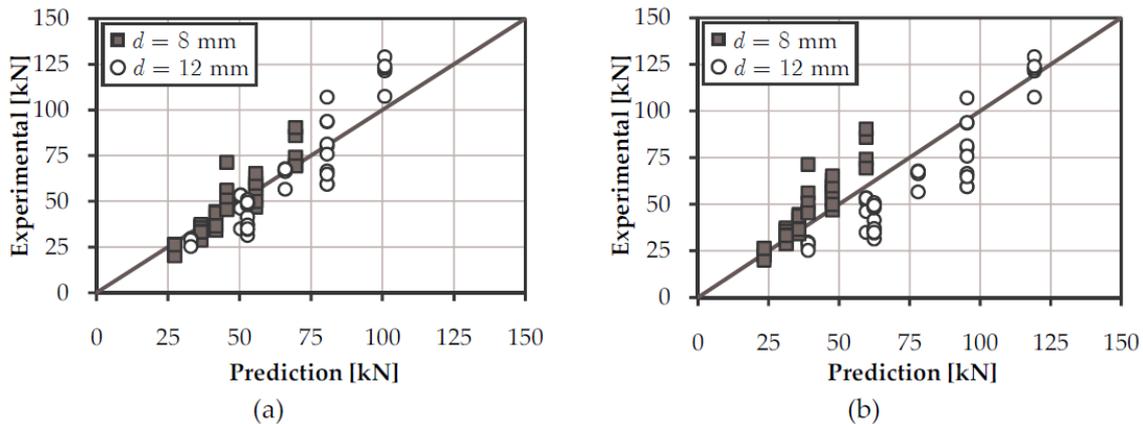


Figure 6: Eq.(3) predictions (a) calibrated per screw diameter (b) using an average calibration value.

In conclusion the fracture mechanical model of EN1995-1-1 is well able to predict the splitting capacity for axially loaded self-tapping screwed connections.

4 Multiple connections along the span

The overall majority of test so far reported in literature focus on a test configuration with a single connection at mid span. There are models that assume that when enough spaced, for instance twice the beam depth, multiple connections can be considered as individual connections and no interaction will affect the load carrying capacity. Kasim and Quenneville (2002) however, claimed that if the spacing between two connections increases the total load carrying capacity does not exceed 1.4 the single connection failure load, Figure 7. This phenomenon was left unexplained by the authors.

Jensen (2003) tried to explain this phenomenon using a beam-on-elastic-foundation-model with somewhat more success. The same compliance method as Van der Put and Leijten

(2000) was used but now for two connections symmetrically positioned along the beam span assuming symmetrical crack development, Figure 8. Main assumption in Jensen's model was crack propagation on either side of the connections at an equal rate (i.e. both cracks initiated at a connection extending equally). However, his model was unable to explain the two connection phenomenon just mentioned. Applying the same method Schoenmakers (2010) derived a different solution. The beam was modelled as shown in Figure 8 accounting for the situation where crack growth might be not symmetrical on either side of the connection. In his model crack lengths were denoted by λ , and the indices 3 and 4 indicate the beam segment the crack is attributed to (left-hand or right-hand side).

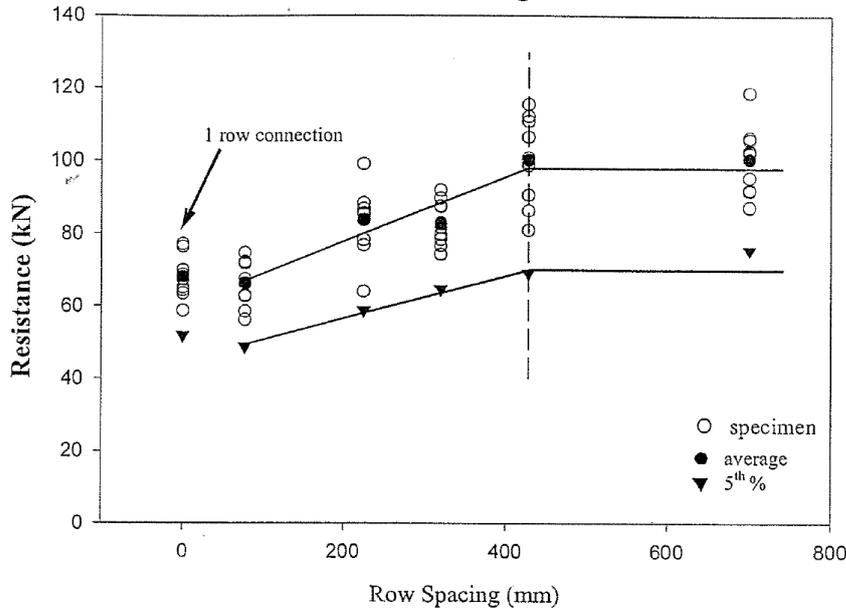


Figure 7: Result of increasing spacing between two connections (with two dowels), Kasim and Quenneville (2002).

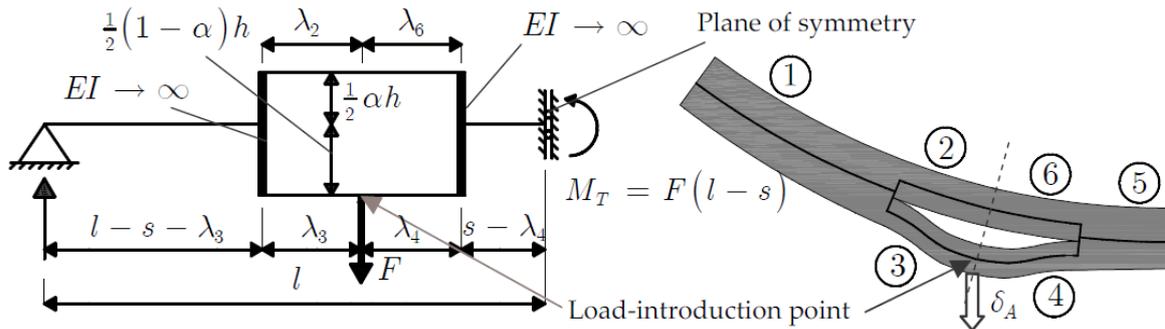


Figure 8: Modelling the symmetrical half of the beam by using only the centre lines of the deformed cracked beam (right), Schoenmakers (2010).

The compliance, $C = \delta_A/F$ in Eq. (1), contains the contribution of every (beam) element and the type of internal strain involved (normal, shear or bending) using the energy method and Mohr's Integral on each beam segment analytically as function of λ . In eq. (1), λ_3 and λ_4 correspond to both mutually independent cracks. Expressions for the internal bending moment and normal force (sectional method) used to satisfy compatibility conditions at the interface between beam segment 2 and 6, resp. were derived. The critical load per connection is obtained using the standard procedure determining the compliance change Eq. (2). Maple software was used to derive an analytical expression for the derivatives.

$$\begin{aligned}
\frac{\delta_A}{F} = & \frac{6}{5} \frac{1}{GA} \left(l - s - \lambda_3 + \frac{(1 - \xi\gamma)\lambda_3}{\alpha} \right) \\
& + \frac{1}{3EI} \left((l - s - \lambda_3)^3 + 3(l - s)^2 (s - \lambda_4) \right) \\
& + \frac{\lambda_3^2}{6E\alpha^3 I} \left((1 - \xi\gamma)(3(l - s) - \lambda_3) \right) \\
& + \frac{\left(-\frac{M_Q}{F} + \left(\xi\gamma \left(\frac{1}{2}\lambda_3 + \frac{1}{2}\lambda_4 \right) + l - s - \lambda_3 \right) + \frac{1}{2} \frac{N_Q}{F} h \right)}{E\alpha^3 I} \left((l - s)(\lambda_3 + \lambda_4) - \frac{\lambda_3^2}{2} \right) \\
& + \frac{(l - s)\lambda_3\lambda_4}{E\alpha^3 I} \left(1 - \xi\gamma \left(1 + \frac{\lambda_4}{2\lambda_3} \right) \right)
\end{aligned} \tag{1}$$

$$F_{ult} = 2F_{crit} = 2 \sqrt{\frac{2\hat{G}_c t}{\frac{\partial C}{\partial \lambda_3} d\lambda_3 + \frac{\partial C}{\partial \lambda_4} d\lambda_4}} \sqrt{d\lambda_3 + d\lambda_4} \tag{2}$$

Details can be found in Schoenmakers (2010). The results of the analysis are interesting because the conditions on either side of the connection might not be the same and crack growth either. In Figure 9 a summary of the model results is provided.

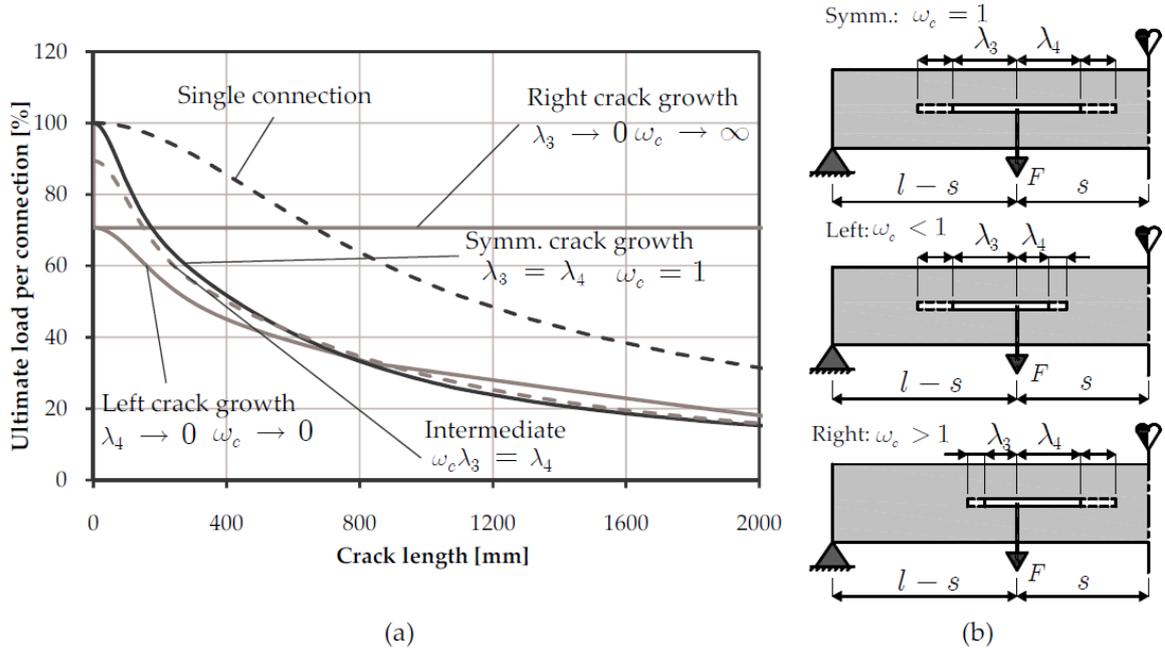


Figure 9: Critical load per connection as function of the crack length. (a) Comparison to the critical load corresponding to the beam with a single mid span connection. (b) Three cases of dominant crack propagation direction.

When a (dominant) crack grows usually other cracks also grow simultaneously but may be at a different rate. Plausible situations were investigated and evaluated. The critical failure load of one mid span connection is taken as a reference (100%), top curve in Figure 9. This curve goes down with increasing symmetrical crack growth. To consider different crack growths on either side of the connection ω_c is introduced. This parameter represents the ratio of the length of two growing cracks, for instance $\omega_c = \lambda_4/\lambda_3$ including the increments,

Figure 9b. In case of symmetrical crack growth, $\lambda_4 = \lambda_3$ and so $\omega_c=1$, the splitting strength of two connections is double the single connection; agrees with Jensen's (2003) model. However, the lowest curve associated with a dominant crack growth towards the support while the crack growth towards mid span is very small, the critical load per connection will become $0.5(2)^{0.5}=0.71$ times the single mid span critical load. This explains the results of Kasim and Quenneville (2002). However, if the crack growth is neither symmetrical nor dominating towards the support an intermediate situation occurs with a critical load per connection between 0.71 and 1.0 time the critical load of a single mid span connection.

4.1 Experimental verification

Apart from the theoretical model development Schoenmakers (2010) performed many tests some of which were conducted to verify his two connection model. Later tests by Leijten, used three equally spaced connections along the span, Figure 10. The latter tests were carried out in 2013 and used the timber from the same batch of Spruce beams as Schoenmakers, strength class C24.

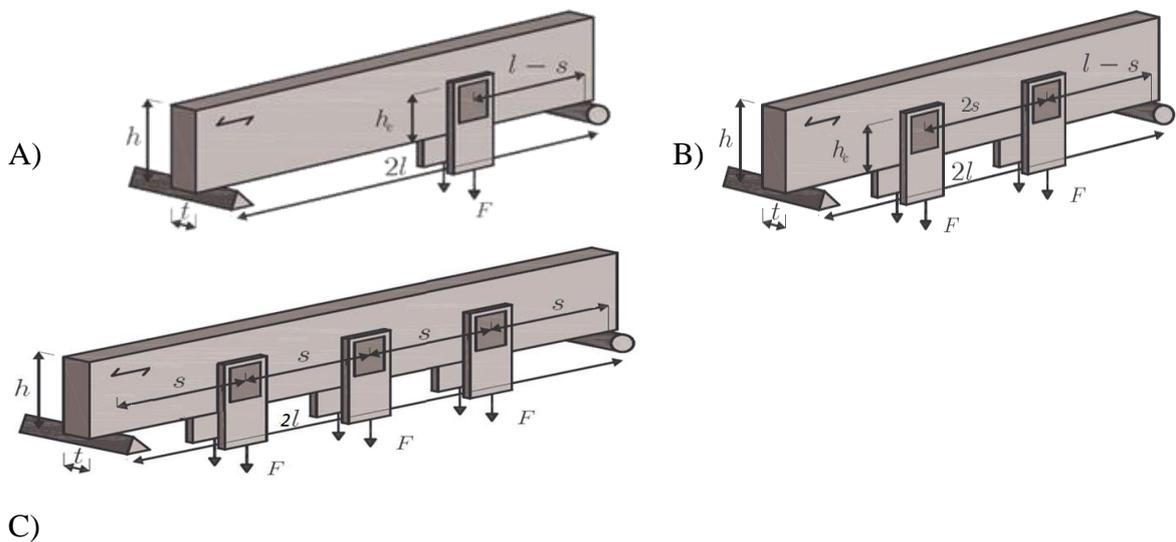


Figure 10: Overview of Table 1 test series

A) Test Series 1 to 8. B) Series 9&10 and 14&15. C) Series 16 and 17.

In Table 1 the test series are grouped according to the type of fasteners, the dimensions of the beams and other parameters are indicated in column (2) to (9). The glued laminated beams used had a mean density of 450 kg/m^3 and moisture content of 12.7%. Nailed connections had 5 rows of 5 nails= 25 nails in a square pattern. For the other tests sawn timber beams was used with a mean density of 455 kg/m^3 and 12.9% m.c. For the sawn wood beams four close spaced ($4d$) 12mm diameter dowels were used set in a square pattern. All beams failed brittle by splitting. In addition Schoenmakers (2010) also tested cantilevered beams with connections at the end and half way the cantilever length but left out here. Series 16 and 17 beams comprised of three connections equally spaced at two times the beam depth, $2h$ along the span. All three connections were loaded by separate hydraulic actuators each having a load cell to check for any differences, which were insignificant. Crack initiation and growth direction were studied with special LVDT's mounted at close distance on either side of each connection. In addition a high speed camera was used to observe the crack growth visually. In 70% of the tests the crack initiation started at the connections near the support. A dominant crack growth direction

was difficult to determine. In 30% of tests a symmetric crack growth could be determined. In 50% of the cases a leading crack direction could not be established.

The number of connections along the span is given in column (5), Table 1. The critical load, F_{crit} is the load per connection, column (10). To allow comparison between test series using different cross-sections, distance from the support, number and type of fasteners the mean apparent fracture parameter $(GG_c)^{0.5}$ was calculated per test series with Eq.(3).

$$F_{ult} = 2F_{crit} = 2t \sqrt{\frac{GG_c h \alpha}{\frac{3}{5}(1 - \alpha)}} \quad (3)$$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) |
|----------------|----------------------|-----------------|------------|------------|-------------------------------|------------------|------------------------------|------------|--|--|-------|
| Test series no | cross section bxh | no of test n | span 2l | num of con | distance from support [mm] | num of fast n | loaded edge distance he/h | diam, d | mean max load per connection Fcrit [kN] | adjusted calibration (GGc) ^{0,5} mean | mean |
| | [mm ²] | - | [mm] | | [mm] | - | [%] | [mm] | [kN] | [N/mm ^{1,5}] | |
| 1 | 45x300 | 5 | 2600 | 1 | 650 | 25 | 47 | 4 | 27,78 | 13,19 | |
| 2 | 45x300 | 5 | 2600 | 1 | 900 | 25 | 47 | 4 | 29,41 | 13,97 | |
| 3 | 45x220 | 5 | 1600 | 1 | 800 | 25 | 47 | 4 | 22,79 | 14,04 | |
| 4 | 45x220 | 5 | 1600 | 1 | 800 | 20 | 47 | 4 | 22,54 | 13,89 | |
| 5* | 45x220 | 5 | 1600 | 1 | 800 | 20 | 47 | 4 | 22,52 | 13,88 | 13,35 |
| 6 | 45x220 | 5 | 1400 | 1 | 700 | 15 | 47 | 4 | 21,82 | 13,45 | |
| 7 | 45x220 | 5 | 1200 | 1 | 600 | 15 | 47 | 4 | 20,11 | 12,39 | |
| 8 | 45x220 | 5 | 1000 | 1 | 500 | 15 | 47 | 4 | 19,43 | 11,97 | |
| 9 | 45x300 | 5 | 2600 | 2 | 900 | 25 | 47 | 4 | 19,68 | 9,35 | 9,38 |
| 10 | 45x300 | 5 | 2600 | 2 | 650 | 25 | 47 | 4 | 19,83 | 9,42 | |
| 11 | 45x220 | 3 | 1400 | 1 | 700 | 4 | 44 | 12 | 17,91 | 11,72 | |
| 12 | 45x220 | 5 | 1200 | 1 | 600 | 4 | 44 | 12 | 18,76 | 12,28 | 11,97 |
| 13 | 45x220 | 5 | 1000 | 1 | 500 | 4 | 44 | 12 | 18,17 | 11,90 | |
| 14 | 45x220 | 5 | 1600 | 2 | 400 | 4 | 44 | 12 | 16,68 | 10,92 | 11,21 |
| 15 | 45x220 | 5 | 1600 | 2 | 200 | 4 | 44 | 12 | 17,56 | 11,50 | |
| 16 | 45x220 | 10 | 2000 | 3 | 440 | 4 | 46 | 12 | 11,68 | 7,34 | 7,71 |
| 17 | 40x220 | 10 | 2000 | 3 | 440 | 4 | 33 | 12 | 8,68 | 8,07 | |

)* one extreem low left out

Table 1: Test results of beam with multiple connections.

This fracture parameter was adjusted for the following reasons:

- From evaluation of his total data base Schoenmakers (2010) found a 10% higher value with glued laminated beams. This takes 10% off for test series 1, 2 and 9 & 10.
- When two or three connections are tested simultaneously the weakest will always fail first and distorts comparison of the mean between series. Therefore the average values of the fracture parameter of these test series were adjusted using established statistical procedures, Douwen et al. (1982). It assumes that the results are normally distributed which results in a rise of the mean fracture parameter of approximately 10%.

Having taken these factors into account the corrected apparent fracture parameter is given column (11). Column (12) shows the mean of the test series grouped by fastener type and number of connections.

For the nailed connections there is a distinct difference in strength between tests with one and two connections. The strength ratio $9.38/13.35=0.70$ which is close to Schoenmakers (2010) lower bound prediction of 0.71. For connections with dowels the situation is different because no significant difference is found between the corrected fracture parameter of one and two connections, i.e. 11.97 and 11.21 respectively. However, three connections apparently have a very significant effect, with a drop in strength to $7.71/11.97=0.64$ per connection. No model is yet able to explain this behaviour. However, Schoenmakers model might be a good candidate when extended to three connections.

The consequences of these test results are considerable if one understands that in a number of semi-empirical and empirical models connections are considered as separate connections when spaced more than twice the beam depth. In Figure 11 the total load on the beam is presented as ratio of the single connection strength. The two dots for beams with two connections represent the connections with nails and the other one for dowels. The predictions by EN1995-1-1 are indicated as well as the lower bound prediction by Schoenmakers for two connections. As shown the EN1995-1-1 prediction is conservative.

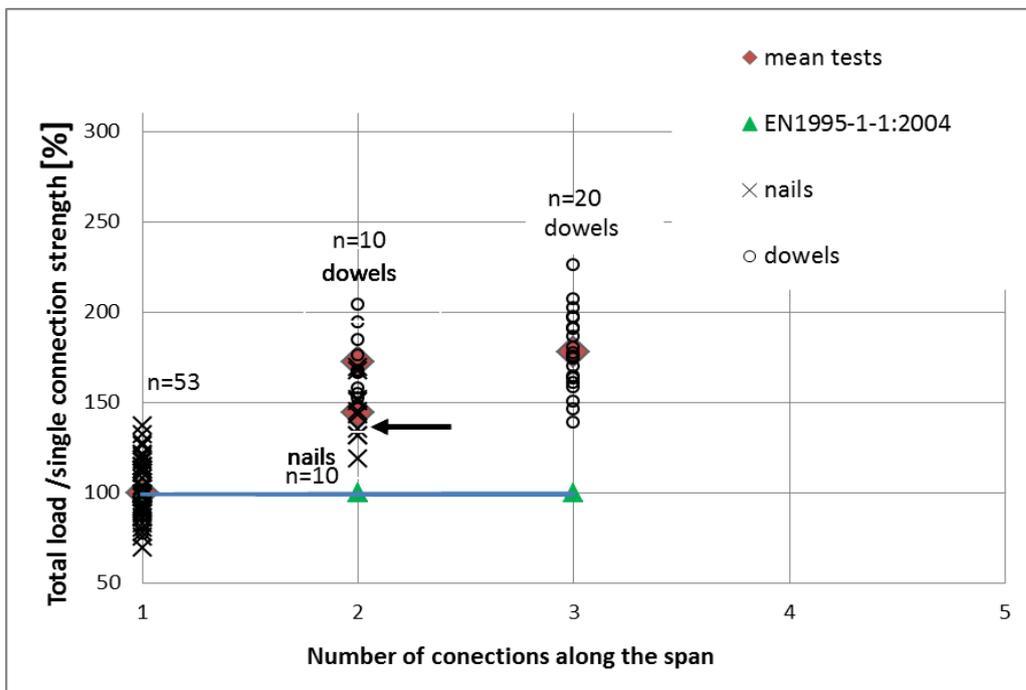


Figure 11: Code predictions and test results: ← = mean lower boundary by Schoenmakers (2010) for two connection.

5 Proposed revision for Eurocode 5:2004 (EN1995-1-1)

Test results with multiple connections show Eurocode 5 provisions to be conservative. This is caused by the shear force criterion. Because the effect of multiple connections is not yet fully understood and theoretical models are lacking the proposal is not to change the shear force criterion for beams with multiple connections. For one connection placed anywhere along the span however, this shear strength criterion is too restrictive and be deleted or exchanged by a more appropriate criterion, Jensen et al. (2013). The tentative suggestion for beams with connections at the end face is to regard them as notched beams.

6 Conclusions

- splitting as governing failure mode is independent of the number of fasteners when a certain critical number is exceeded.
- models based on fracture mechanics have the ability to predict splitting of beams loaded by axial loaded screwed connections.
- multiple connections spaced along the span of a simply supported beam significantly affect the total load bearing capacity. The fracture model by Schoenmakers (2012) for two connections is able to predict a lower boundary. This model is a good candidate to be extended to more than two connections. Current Eurocode 5 splitting provisions are conservative and therefore safe.

7 Acknowledgment

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