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SPLITTING OF BEAMS CAUSED BY MULTIPLE CONNECTIONS ALONG THE BEAM SPAN

A.J.M. Leijten[1]

ABSTRACT: In the past splitting of beams caused by connection perpendicular to grain has drawn attention. Models have mainly being developed considering one mid span connection. Some semi-empirical models assume the splitting capacity to be proportional with the number of connections when sufficiently spaced. However, recent experiments show this is not the case. Experiments show a considerable drop in splitting capacity per connection. Until now only a fracture mechanical model is able to explain the result for beams loaded by two connections. Experiments with three connections along the span of a simply supported beam show an even greater drop in splitting capacity per connection. The test results are presented and evaluated and compared to model predictions.

KEYWORDS: Timber splitting, connections, fracture models, perpendicular

1 INTRODUCTION

In recent years a topic has drawn attention of timber researchers that focus on failure of beams exposed to forces perpendicular to grain by connections, Figure 1. This type of failure is brittle and a good understanding of this phenomenon is important for save design. Since the introduction of the Eurocode for Structural Timber Design EN1995-1-1 (Eurocode 5) [1] a linear elastic fracture model is implemented based on a theoretical model by Van der Put and Leijten [2]. The model does not consider how the load is applied, nor the type and spacing of and number of fastener, but only what the conditions are for unstable crack growth outside the connection area. Other empirical and semi-empirical models by Ehlbeck and Görlacher [3], Franke et al.[4], among others, take into account the influence of the number of rows, columns and the spacing of the fasteners (nails, dowels). An excellent overview of the models available for single connections is given by Jensen et al. [5]. A systematic and comprehensive experimental en theoretical study into the influence of the fastener pattern of rows and columns at mid span connections with 4 mm and 6 mm nails was carried out by Schoenmakers [6].

2 MODELS FOR MULTIPLE CONNECTIONS

The overall majority of test so far reported in literature focus on a test configuration with a single connection at mid span with mechanical fasteners like nails, bolts or dowels. In practice more than one connection may occur

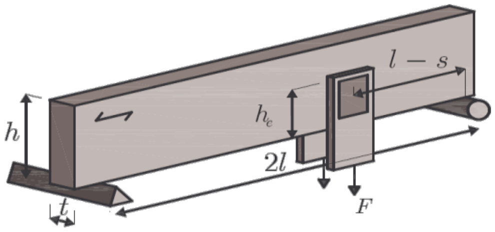

***Figure 1**: Beam loaded by single connection*

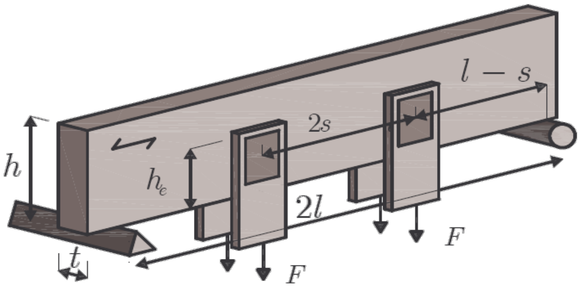

***Figure 2**: Beam with two connections*

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not even at mid span. Test results by Schoenmakers [6] and others show that out-of-mid span connections have the same splitting strength capacity as the mid span connection. This is in contrast to the design guideline by [1] that restricts the shear force on either side of the connection not to exceed the shear force of a single mid span connection. A frequent used model by Ehlbeck and Görlacher [3], assumes that tensile stresses perpendicular to grain govern the splitting capacity. This models treats multiple connections as separate independent single connections on condition they are spaced along the beam span at least twice the beam depth. When there is no interaction between connections it seems reasonable to assume the splitting capacity to be proportional with the number of connections. This assumption apparently was not sufficiently backed up by laboratory tests, as Kasim and Quenneville [5] later reported no evidence of proportionality was observed. They increasing the spacing or two groups of fastener and found the total splitting capacity did not exceed 1.4 the single connection splitting capacity, Figure 3. Since their results were published this spacing phenomenon has been left unexplained by other authors. Jensen [8] tried to explain this phenomenon using a beam-on-elastic-foundation model with a LEFM model approach with somewhat more success. The same approach using the compliance method was used as Van der Put and Leijten [2] but now for two connections symmetrically positioned along the beam span. An important assumption of this theoretical model was to assume symmetrical crack growth. This means that in Jensen's model the crack propagation direction was initiated on either side of the connection and grew at an equal rate (ie. both cracks initiated at a connection extending equally). This model considered two options of failure. If the cracks merge between the two connections prior to failure the splitting capacity would be the same as for a situation with a single connection. If the cracks didn't merge before unstable crack growth the connections failed separately and therefore the splitting capacity would be twice the single connection splitting capacity. Both options didn't match the test results of Kasim and Quenneville [5]. Applying the same compliance LEFM method Schoenmakers [6] derived a different solution. The beam was modelled as shown in Figure 4. In his approach he took account of the situation where crack growth might possibly be not symmetrical on either side of the connection. This is essentially different from the assumption made in the previous model. The results are represented by Figure 5(a). For explanation of the model result only a symmetrical part of the beam is shown in Figure 5(b), including the initial crack on either side of the connection The crack lengths were denoted by λ, and the subscripts 3 and 4 indicate the position of the crack on the

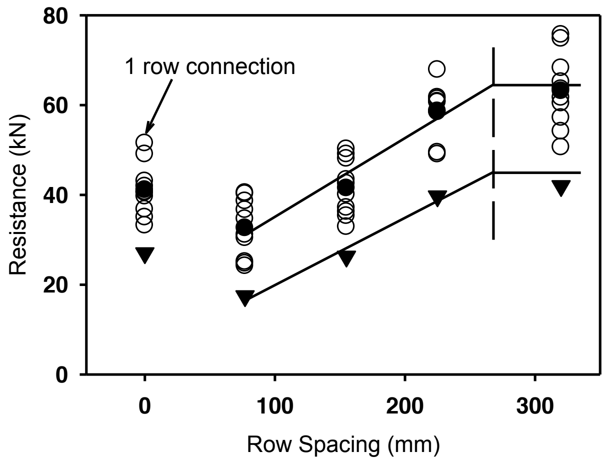

Figure 3: Splitting strength change with increasing, Kasim and Quenneville [7].

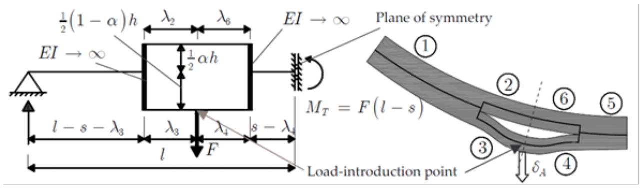

Figure 4. Model by Schoenmakers [6]

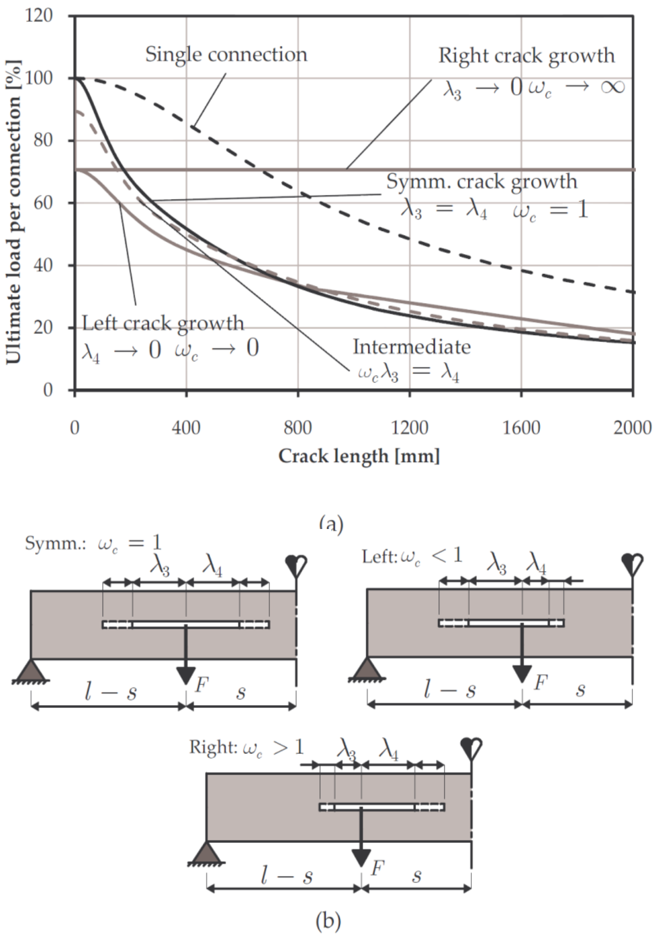

Figure 5**:** Model results by Schoenmakers [6]

right or left hand side of the connection. The horizontal axis of Figure 5(a) denotes the crack length. When a (dominant) crack grows usually other cracks grow simultaneously but not at the same rate necessarily. Plausible situations were investigated and evaluated. What Figure 5(a) shows is the following. The critical splitting load of a single mid span connection is taken as reference (100%), represented by the top curve in Figure 5(a). This curve goes down with increasing symmetrical crack growth which is likely to occur. Now two connections are considered. To account for different crack growths rates on either side of the connection the parameter ω_c is introduced. This parameter represents the ratio of the length of two cracks on either side of the connection, for instance $\omega_c = \lambda_4/\lambda_3$ including the increments, Figure 5(b). For a symmetrical crack growth, $\lambda_4 = \lambda_3$ this parameter become $\omega_c = 1$, Figure 5 (b) top. This behaviour is indicated by a line in the graph that starts at 100% like the single connection but it drops more rapidly, Figure 5(a). Starting at 100% meaning the splitting strength with two connections is twice the single connection strength; this agrees with Jensen's [8] model. If however, the crack growth towards to support is dominant compared to the crack growth towards mid span it means that $\omega_c \rightarrow 0$ and this behaviour is represented by the lowest curve in Figure 5(a). The critical splitting load per connection will not exceed about 0.71 times the single connection critical splitting load. In total the splitting capacity would be about 1.4 the single connection splitting capacity. This is in agreement with the experimental results by Kasim and Quenneville [7], Figure 3. If on the other hand, the crack growth towards mid span is dominant while the crack growth towards the support is very small, the parameter ω_c becomes $\omega_c \gg 1$. As shown again by the appropriate curve in Figure 5(a), the critical splitting load per connection will not exceed 0.71 times the single connection critical splitting load. Again in total the failure load would be 1.4 the single connection splitting capacity. For intermediate situations of crack growth the failure load can go up to about 0.9 time the single connection splitting capacity. However, nature will usually choose the situation with the lowest resistance and for this reason splitting will usually happen at about 1.4 times the single load splitting capacity.

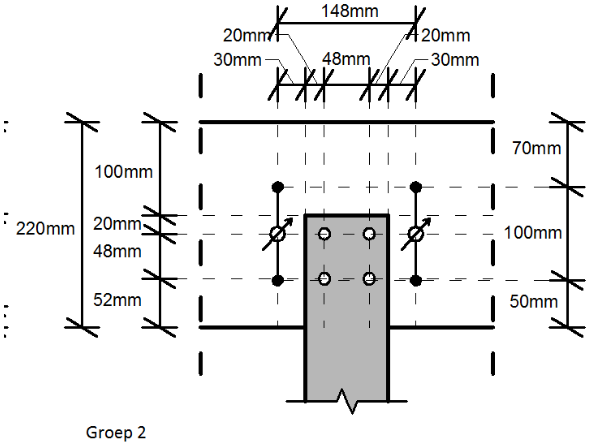

Figure 6: *Connection with steel side plates on either side*

3 EXPERIMENTAL VERIFICATION

Apart from the theoretical model development Schoenmakers [6] performed many tests some of which were conducted to verify his two connection model. Later tests by Leijten, used three equally spaced connections using dowels and steel plates, Figure 6, 7 en 8. The latter tests were carried out in 2013 and used timber from the same batch of Spruce beams as Schoenmakers [6], strength class C24 (5 % characteristic bending strength is 24 N/mm^2). Test by Schoenmakers [6] used glued laminated beams with a mean density of 450 kg/m^3 and moisture content of 12.7 % as well as sawn timber. The cross-section varied from 45x300 for the glued laminated beams to 40x220 mm^2 for the sawn timber beams. Nailed connections had 5 rows of 5 nails= 25 nails in a square pattern. For 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 (4*d*) 12mm diameter dowels were used set in a square pattern. The steel side plates were of 15 mm thick mild steel, Figure 6. All beams failed brittle by splitting. In addition Schoenmakers [6] also tested cantilevered beams with connections at the end and half way the cantilever length which are left out here. The test Series comprising three connections were equally spaced at two times the beam depth, 2*h* along the span. All three connections were loaded by separate hydraulic actuators each having a load cell to check for any differences, which appeared to be insignificant. Crack initiation and growth direction were studied with special

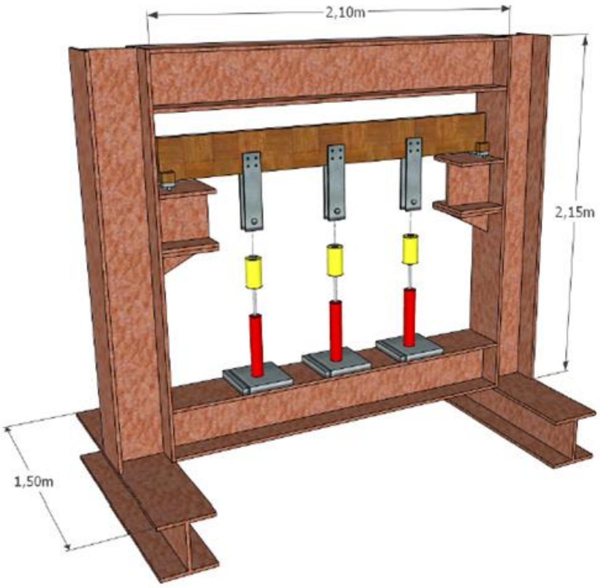

Figure 7: *Arrangement with three connections*

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. If the leading crack resulting in progressive splitting failure would start from the connection closest to the support it would validate the starting points of the theory of Van der Put and Leijten [2] assuming dominant failure is caused by shear, a starting point of their model. After evaluation of the results it was found that in 70% of the tests a stable crack initiation appeared at the connections near the support first. However, despite of the LVDT mounted on both sides of each connection, Figure 6, a dominant crack growth direction reading was very difficult to establish. Splitting failure occurred in 3 to 5 thousands of a second. Figure 9 shows the LVDT readings in time. In 30% of tests a symmetric crack growth could be determined. In 50% of the cases a leading crack growth direction could not be established. For this reason no conclusive and supporting evidence could be given for the theoretical starting point of the theory by Van de Put and Leijten [2]. 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 equation [1] taken from Van der Put and Leijten [2].

Figure 8: *Test beam after failure with three connections*

$$F_{crit} = b \cdot \sqrt{G \cdot G_c} \cdot \sqrt{\frac{h_e}{\frac{3}{5}(1-\alpha)}} \qquad (1)$$

where:

F_{ult}	max shear force on either side of the connection
b	beam width
G	shear modulus
G_c	material parameter by calibration to tests
h	beam depth
α	ratio of loaded edge distance and beam depth

This fracture parameter GG_c resulting from Eq.(1) had to be adjusted for the following reasons:

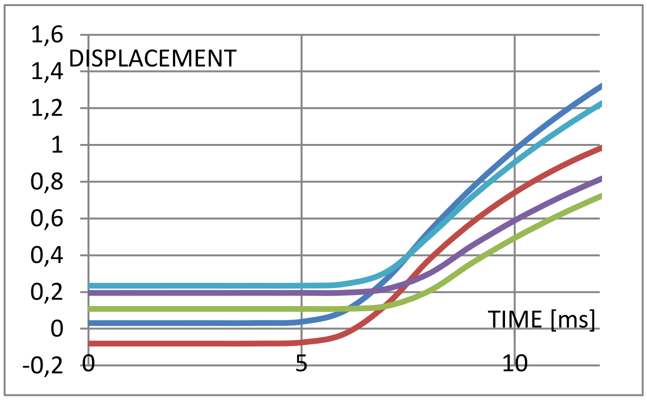

Figure 9: *Measurements of LVD'S to detect leading crack direction*

- From evaluation of his total data base Schoenmakers [5] found on average a 10% higher value with glued laminated beams compared to sawn timber beams. For this reason 10% was taken off for test series 1, 2 and 9 & 10.

- When beams with two or three connections are tested the weakest will always fail first and distorts comparison of the mean value between other series with different number of connections. Therefore, the average values of the fracture parameter of these test series were adjusted using established statistical procedures, Douwen et al. [9]. It assumes that the results are normally distributed which results in a rise of the mean fracture parameter of approximately 10%.

4 RESULTS

Having taken these factors into account the nailed connections showed a distinct difference in strength between tests with one and two connections. The strength ratio of 0.70, which is close to the predicted value by Schoenmakers [5] of 0.71, agrees well with Kasim and Quenneville [7]. 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, Figure 10. However, three connections apparently have a very significant effect, with a drop in strength to 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 the connections are considered as separate connections when spaced more than twice the beam depth. In Figure 11 the summation of the strength of all connections of a tested beam is related to the strength of a beam with a single connection expressed as a ratio set on the vertical axis. The number of connections is shown on the horizontal axis. The two dots for beams with two connections represent the mean splitting strength ratio for connections with nails and the other one for dowels. Figure 11 also shows the prediction by EN1995-1-1 when calibrated to the test results of beams with one connection. Because of the shear force restriction the splitting strength capacity prediction for multiple connections is the same as for a beam with one connection at mid span. It is shown by the straight horizontal line in Figure 11. As such the EN1995-1-1 prediction is conservative and safe. There is one curve in Figure 11 that assumes a proportional increase of the splitting strength capacity with the number connections. This curve is based on Ehlbeck and Görlacher [3] which forms the backbone of the current German DIN 1052 standard and clearly overestimates the strength and therefore is regarded as non-conservative. Schoenmakers model predicts 1.4 for two connections as lower boundary which seems to be closer to the reality than the other models. The Schoenmakers model would be a good candidate to model the situation for three and more connections in future.

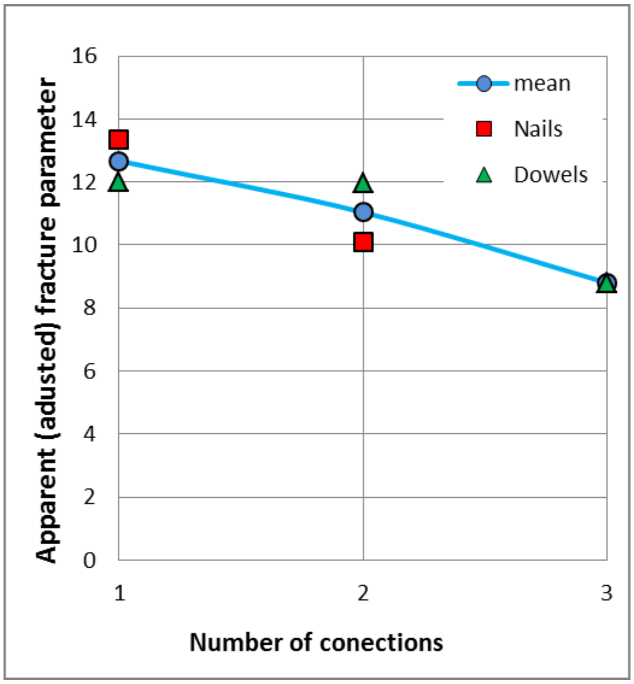

Figure 10: *Decrease in fracture parameter*

5 CONCLUSIONS

Multiple connections spaced along the span of a simply supported beam significantly affect the total load bearing capacity compared to one connection. None of the empirical or semi-empirical models are able to predict the correct splitting capacity. Only the fracture model by Schoenmakers [5] for two connections is able to provide a satisfactory prediction of the splitting capacity and promising candidate for the explanation of the splitting strength with three connections. The theoretical starting point of the theory by Van de Put and Leijten [2], is that the dominating failure mode is governed by shear (fracture Mode II) and not by perpendicular to grain stresses (fracture Mode I). An effort was made to detect the leading crack in the experiments with two and three connections. Therefore LVDT's were mounted on either side of the connections but after evaluation of the findings no conclusive evidence was obtained. Nevertheless in the majority of tests the first cracks initiated ate the closest to the support connections. Evaluation of the splitting capacity of beams, with one, two and three connections revealed and compared to the design guidelines in European Codes proved current Eurocode 5 splitting provisions to be conservative while the DIN 1052 model grossly overestimates the splitting strength and there is non-conservative.

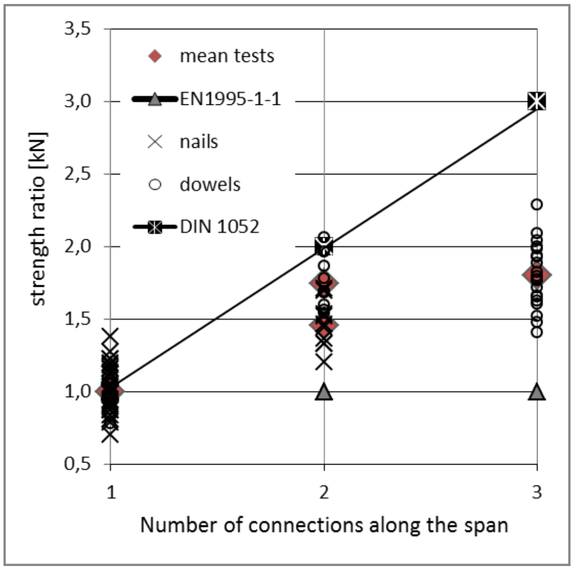

Figure 11: *Strength ratio using multiple connections*

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