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INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION IN BUILDING AND CONSTRUCTION

WORKING COMMISSION W18 - TIMBER STRUCTURES

DESIGN APPROACH FOR THE SPLITTING FAILURE OF DOWEL-TYPE CONNECTIONS LOADED PERPENDICULAR TO GRAIN

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Presented by P Quenneville

C Sigrist asked for clarification of how the loads in the dowels were monitored. P Quenneville stated the Plexiglas plate was strain gauged and calibrated, and even though the method was not precise, it gave a good indication. C Sigrist further asked whether optical method could be used. P Quenneville stated yes although the method was considered outdated.

S Aicher commented that the numerical solution depended on fracture energy normalized to available tested material. He asked to what extent these numerical models could be extended to other material. P Quenneville agreed with the comments and was not sure if the models could be extended to other material.

A Leijten commented that in slide 15 two cracks existed. With reference to the test results at Delft he questioned whether it was possible that gaps between the bolt and the bolt hole existed might have an influence on the results. He further questioned the validity of the unit of Ge' being N/mm^2. P Quenneville did not believe the units were wrong but will check and could provide example calculations. S Aicher confirmed the correctness of the units in the paper. A Leijten further commented that the spacing of dowels was increased for scientific interest but in practice one would want to have minimal spacing. P Quenneville responded that the spacing was kept the same in the study and the information was used for model.

A Frangi discussed existing rules for loaded edge distance and in European technical approval database splitting was observed even though the rules were followed. P Quenneville stated that if you have very big bolts one should check carefully as mixed mode of failure could happen.

A Frangi asked if one could have a ductile failure, would the Johansen approach be still correct for this type of connection given the stress variation between bolts. P Quenneville stated that the Johansen approach would be valid as there is redistribution of loads once plasticity was reached in one of the bolts.

C Sigrist discussed the choice of slenderness of dowel which was chosen to check splitting failure mode. He commented that it would not be possible to check the issue of ductile behaviour raised by A Frangi.

Design approach for the splitting failure of dowel-type connections loaded perpendicular to grain

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1 Introduction

For the prediction of the splitting failure of dowel-type connections loaded perpendicular to grain (as shown in Figure 1), different design equations are available in publication or various international standards. Depending on the size, layout as well as the loading situation, the connection behaves in brittle or ductile failure. The ductile failure depends on the embedment strength of the wood and the bending capacity of the dowel. For the prediction of the ductile failure, the established European Yield Model (EYM) is used in international standards. The brittle failure of connections occurs due to the exceeding of tension or shear stress in the wood member. Based on the anisotropy of wood, the tension stress perpendicular to grain leads to very brittle failure behaviour and it is the most critical case for the failure of connections.

For the splitting failure of double shear connections loaded perpendicular, the design standards can be mainly distinguished between a strength criterion which was introduced by Ehlbeck, Görlacher & Werner (1989) and a fracture mechanic model introduced by v. d. Put & Leijten (1990). Current research results and publications show that there are disagreements between the experimental results and the design values, which result in uncertain predictions or in conservative values, Ballerini (2004), Jensen (2005), Schoenmakers (2010), and Franke & Quenneville (2010).

The splitting failure behaviour of double shear dowel-type connections loaded perpendicular to grain were investigated in experimental test series and using a numerical model. The failure behaviour was analyzed by fracture mechanic methods. The fracture mechanic is a recent design method compared to the established strength criteria which provides the assessment of the stress singularities like in connection, notches or holes.

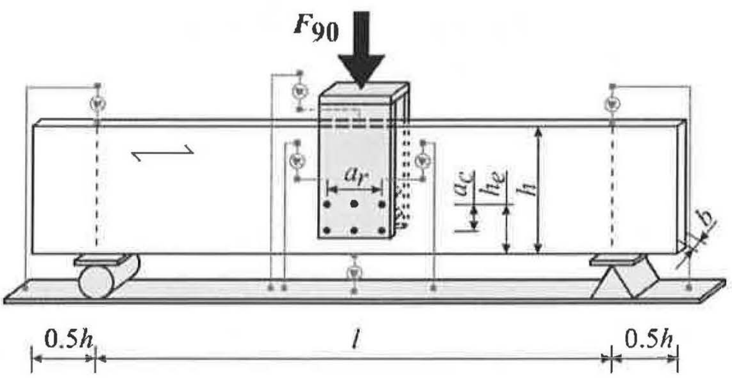

Figure 1: Test setup and connection layout defined

2 Material and Method

2.1 Test program

Experimental and numerical test series are used for the analyses of the failure behaviour. The experimental test series with multiple dowel-type connections and different loaded edged distances were conducted in Laminated Veneer Lumber of Radiata Pine (LVL). The test specimens were in large scale format to provide comparable results to practical construction details. Parallel to the load displacement curves in the test series, the distribution of the load over the number of dowels at the connection and the crack initiation as well as crack propagation were measured, as described in Franke et al. (2012) and shown in Figure 1 and Figure 2.

In addition, various numerical test series with single or multiple dowel-type connections with different loaded edge distances, positions, different number of dowels per row or column as well as different spacing within the connection are simulated. The numerical model used is defined as a 2-dimensional model based on the purpose to especially investigate the splitting of the wood and is presented in Franke & Quenneville (2011b). The numerical model simulates the splitting failure of wood under tension perpendicular to grain and shear as well as the ductile failure of wood due to compression. However, since the focus is to investigate the brittle failure mechanism, the bending of the dowel is not included in the numerical model and the influence is neglected. This is acceptable if the dowel slenderness ratio is small and ductile behaviour due to dowel bending is minimized. The capabilities of the numerical model were verified on comprehensive experimental test series done in Canadian spruce glulam and also with the experimental test series done in LVL. The correlation reached is shown in Figure 3.

The complete experimental and numerical test programme is summarized in Table 1. In each test series, the dowel diameter d was 20 mm.

Table 1: Experimental and numerical test program

			Connection Layout			
Material	**Test setup**	**Sizes b / h / l [mm]**	**Dowel m x n**	**Loaded edge distance h_e/h**	**Connection width a_r**	**Connection height a_c**
LVL	exp.	63/400/1600	3x1	0.2/ 0.4/ 0.6	8d	-
LVL	exp.	63/600/2400	3x1	0.13/ 0.4/ 0.6	8d	-
LVL	exp.	63/400/1600	3x2	0.4/ 0.6	8d	4d
LVL	exp.	63/400/2400	3x2	0.4/ 0.6	8d	4d
LVL	exp.	63/400/2400	3x2	0.4/ 0.6	8d	4d
LVL	exp.	63/400/2400	3x2	0.4	8d	4d
LVL	exp.	63/600/2400	5x2	0.4	16d	4d
LVL	num.	63/(200, 400, 600)/4h	2x2	0.2/ 0.4/ 0.6/ 0.8	3d/ 6d/ 10d/15d/20d/25d	-
GL	num.	80/(190, 300, 400, 600, 800)/610	1x1	0.2/ 0.3/ 0.4/ 0.5/ 0.6/ 0.7/ 0.8	-	-
GL	num.	80/190/4h+ar	2x1	0.2/ 0.3/ 0.4/ 0.5/ 0.6/ 0.7/ 0.8	3d/ 4d/ 6d/ 8d/ 10d/ 15d/ 20d/ 25d	-
GL	num.	80/(300, 400, 600, 800)/(4h+ar)	2x1	0.3/ 0.5/ 0.7	3d/ 6d/ 8d/ 10d/ 20d	-
GL	num.	80/190/610	1-6x1	0.4/ 0.6	(n - 1) 3d	-
GL	num.	80/304/1320	1-4x1-3	0.44/ 0.7	16.8d	(m-1) 3d
GL	num.	80/304/1320	2-3x2	0.44/ 0.7	16.8d	3d, 4.5d, 6d

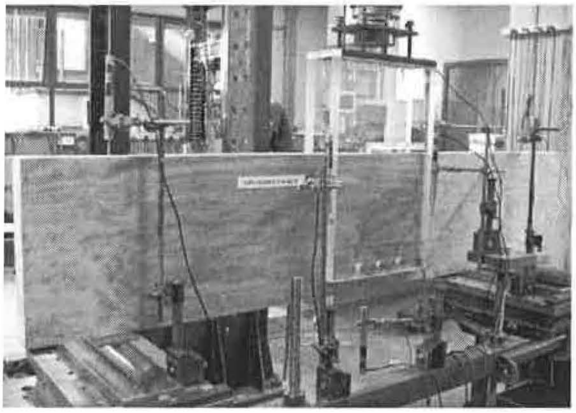

Figure 2: Test setup of LVL test series

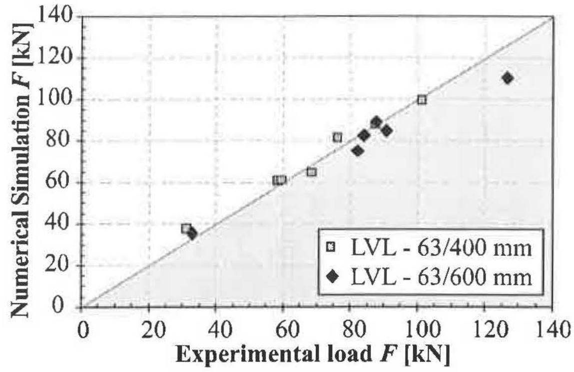

Figure 3: Correlation of the numerical model to test results in LVL

2.2 Splitting failure behaviour

For the characterization of the brittle failure behaviour of double shear connections investigated, the energy balance method together with crack resistance curves were used as one of the fracture mechanic methods. The crack resistance curves evaluated for double shear connections show a nonlinear material behaviour. The crack grows stable as long as the crack resistance increases more than the crack extension force under a constant load during crack propagation. If the crack resistance exceeds the critical value, the crack will grow in an unstable manner and the system fails. The fracture energies determined were split into the fracture mode I and mode II using the method of Ishikawa et al. (1979). The critical fracture energies determined are not comparable with the fracture energies known for different materials for the pure fracture modes I or II because they are caused by a stress situation related to one connection layout and do not relate to test setups for the investigation of a single fracture mode. Therefore, in this paper, the fracture energies determined for dowel-type connections are called specific critical fracture energies, $\mathcal{G}^{I,II}_{spec,c}$.

The splitting failure of the double shear dowel-type connections is classified by the fracture mode I (transverse tension) and mode II (in plane shear). The fracture values reached show that the connection layout and the depth of the beam influence the ratio between these two fracture modes. Figure 4 shows as an example the numerical solution for a 3 by 2 dowel type connection and Figure 5 the corresponding crack resistance curve for the dowel at the edge with the largest loaded edge distance. In the case shown, the failure load is 60 kN.

The analysis of the single crack resistance curves of each dowel of a connection shows that the outside dowels with the largest loaded edge distances of the connection trigger the

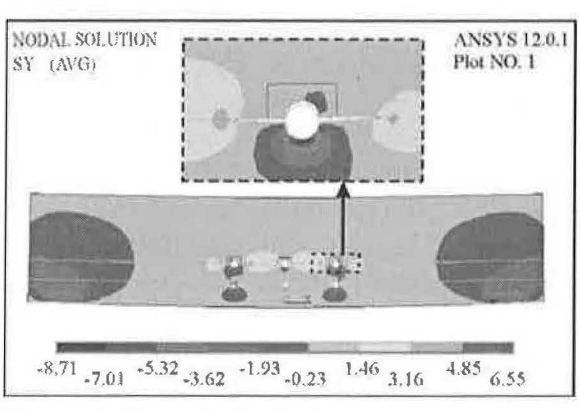

Figure 4: Numerical solution - transverse stress for 3 x 2 dowel type connection

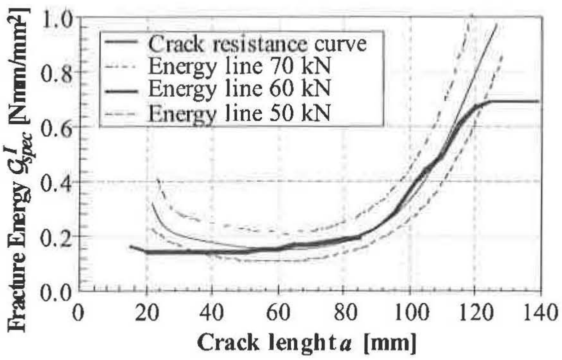

Figure 5: Crack resistance curve for mode I with energy lines for the outside side of the dowel marked in Figure 4

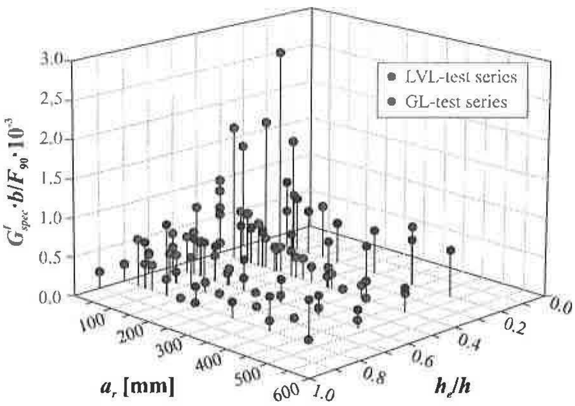

Figure 6: Distribution of fracture energies for mode I for Glulam and LVL

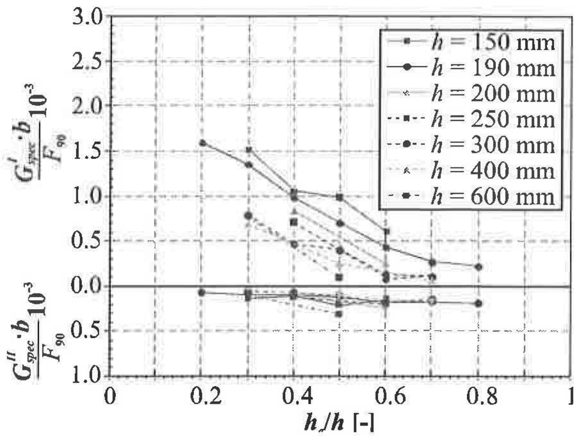

Figure 7: Dependency of fracture energies on depth of the member for Glulam

unstable failure of the connection, Franke & Quenneville (2011a). The cracks between the outer dowels (inner part of the connection) become also unstable and the wood between these dowels is then completely separated.

For each dowel of every connection layout investigated, the crack resistance curves as well as the critical specific fracture energies were determined, as described above. The distribution of these fracture energies of the outside dowel with largest edge distance shows a dependency on the loaded edge distance h_e/h, the connection width parallel to grain a_r and the depth of the member h, as shown in Figure 6 and Figure 7. In general, the normalized fracture energies for solid wood, including glulam, show a different behaviour than LVL. Due to the multi-layered cross section of the engineered wood product LVL being more homogeneous, the brittle failure behaviour is different from the solid wood one.

The distribution of the specific critical fracture energies in relation to the member depth shows an influence on the fracture mode I but not on mode II, as shown as example for single dowel-type connections in Figure 7. The test programme considers member depths from 150 mm up to 600 mm. The increase of the member depth results in a decreasing of the normalized specific critical fracture energy for fracture mode I. Whereas the values respectively the corresponding curves are all close together for the fracture mode II.

2.3 Failure criteria

The splitting failure of dowel-type connections can be summarized using a common failure criteria. The failure criteria describes the interaction between the fracture modes I and II. The distribution of the numerical test series investigated are compared with the linear-, quadratic- and Wu-failure criterion (1967), as shown in Figure 8. The assessment of the distribution of the specific critical fracture energies for the test programme shows that the quadratic failure criterion mostly encloses all failure cases for Glulam and LVL test series. The quadratic failure criterion will be used for the prediction of the splitting failure behaviour of dowel-type connections. The quadratic failure criterion takes into account the important parameters of the connection layout of single and multiple dowel type connections as well as the ratio between the fracture modes I and II.

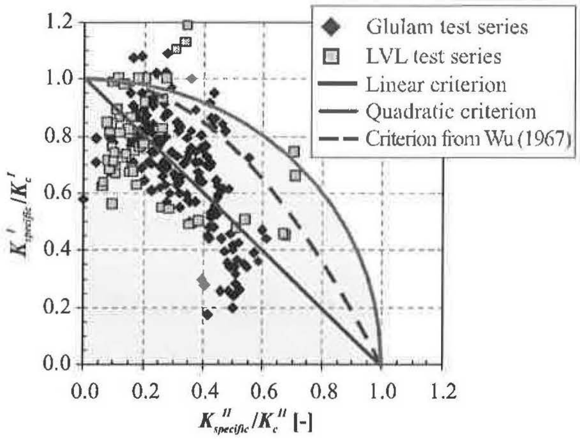

Figure 8: Failure criteria for dowel-type connections loaded perpendicular to grain for Glulam and LVL test series

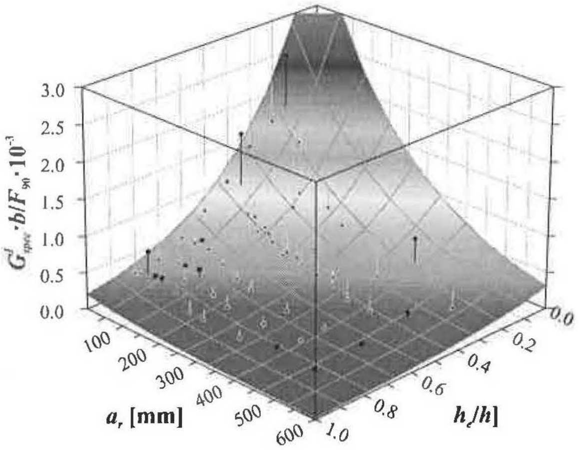

Figure 9: 3-dim. curve of the normalized fracture energies for mode I compared to the individual test results for solid wood/glulam

3 Design approach

Depending on the connection layout and its position over the member depth, double shear dowel type connections fail either in a ductile manner such as bending of the dowel or the embedment failure of the wood or in splitting of the wood. Therefore the design for double shear connections loaded perpendicular to grain has to be used in combination with the European Yield Model (EYM) for the prediction of the ductile failure behaviour as given in Eq. (1).

$$F_{connection} = \min\begin{cases} F_{ductile}(\text{EYM}) \\ F_{splitting} = F_{90} \end{cases} \tag{1}$$

For the design proposal for predicting the splitting failure, the quadratic failure criterion will be used to consider the interaction between the transverse tension and shear failure. Substituting the individual critical specific fracture energies with the distribution of the normalized fracture energies $\mathcal{G}^{I,II}_{norm}$, the splitting load F_{90} for dowel-type connections in timber becomes:

$$F_{90} = \frac{b}{\left(\frac{\mathcal{G}^{I}_{norm}(h_e/h, a_r, h)}{\mathcal{G}^{I}_{c}} + \frac{\mathcal{G}^{II}_{norm}(h_e/h, a_r, h)}{\mathcal{G}^{II}_{c}}\right)} k_r \tag{2}$$

Where F_{90} in [N] is the load capacity depending on the splitting failure of the wood. $\mathcal{G}^{I}_{c}$ and $\mathcal{G}^{II}_{c}$ [Nmm/mm²] are the critical material fracture energies for the fracture mode I or II and b [mm] is the width of the member. The normalized fracture energies $\mathcal{G}^{I,II}_{norm}$ enclose all individual critical specific fracture energies of the various connection layouts considered. Therefore, the critical specific fracture energy of each connection layout investigated was normalized with the specimen width b and the splitting load F_{90}, see Eq. (3).

$$\mathcal{G}^{I,II}_{norm} = \frac{\mathcal{G}^{I,II}_{spec}\cdot b}{F_{90}} \tag{3}$$

The distribution of all values for solid wood and glulam test series were expressed with a 3-dimensional group of curves, which depends on the loaded edge distance ratio h_e/h, the connection width a_r [mm] and the member depth h, as shown in Eq. (4) and Eq. (6) and for LVL as in Eq. (5) and Eq. (6). Figure 9 shows as example the 3-dimensional curve for the member depth $h = 190$ mm compared to the individual values of the test series. The empirically determined Eq. (4), Eq. (5) and Eq. (6) are based on more than 200 different connection layouts investigated in solid wood, glulam or LVL.

$$\mathcal{G}^{I}_{norm} = e^{\left(h^{-1}\left(200-10h_e \cdot h^{-0.25}-a_r\right)\right)} \text{ for solid wood and glulam} \tag{4}$$

$$\mathcal{G}^{I}_{norm} = e^{\left(0.8-1.6h_e h^{-1}-1\cdot 10^{-3}a_r\right)} \text{ for LVL} \tag{5}$$

$$\mathcal{G}^{II}_{norm} = \left(0.05+0.12\frac{h_e}{h}+1\cdot 10^{-3}a_r\right) \text{ for solid wood, glulam and LVL} \tag{6}$$

The approach given in Eq. (2) considers the dependency on the geometry parameters of single and multiple dowel-type connections as well as on the member's cross section. The influence on the position of the connection along the span of the beam could not be observed and is therefore not considered in the design approach, Franke & Quenneville (2010).

The analysis of the test results shows that the load capacity as well as the stress situation beside the outside dowel with the largest loaded edge distance increases with increasing the number of rows and becomes constant for a higher number of rows, as shown in Figure 10, Franke & Quenneville (2012). This behaviour could be summarized using the quadratic interaction of the areas of the tension stress perpendicular to grain and the shear stress besides the dowels at the corner of the top row, Franke & Quenneville (2011a). The effect of the number of rows n is described with the following factor k_r:

$$k_r = \begin{cases} 1 & \text{for} \quad n = 1 \\ 0.1+\left(\arctan(n)\right)^{0.6} & \text{for} \quad n > 1 \end{cases} \tag{7}$$

It was observed that the load capacity does not increase for connections with constant loaded edged distance but different spacing between the rows, Franke & Quenneville (2011a). Therefore a dependency on the spacing between the rows is not included in the factor k_r.

For wider connections with more than two columns, e.g. nail plate connections, as shown in Figure 8, the splitting load has to be determined as either for the whole connection with the complete connection width a_r or as for single connections with the individual connection widths $a_{r,i}$. The minimum of the load capacities of Eq. (8) is the governing splitting load capacity of the connection.

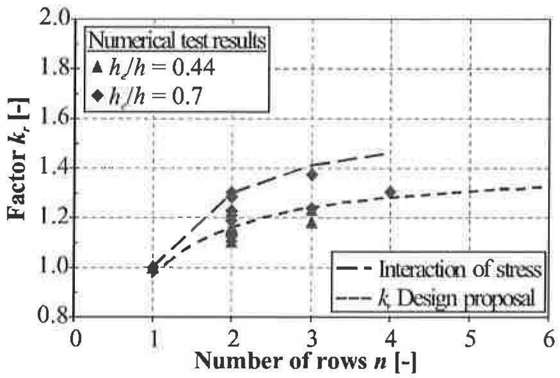

Figure 10: Factor k_r, depending on the numerical load capacities and stress situations determined

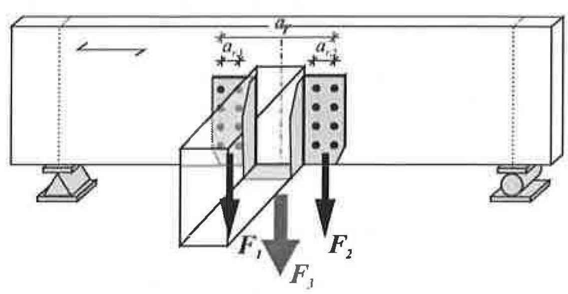

Figure 11: Design characteristics for nail plates or double dowel-type connections

$$F_{90} = \min \begin{cases} F_1(a_{r,1}) + F_2(a_{r,2}) \\ F_3(a_r) \end{cases} \tag{8}$$

4 Discussion

The design proposal is compared with experimental test series in solid wood, glulam and LVL. Figure 12 includes the correlation with the experimental test series in Canadian spruce glulam done by Reshke (1999), Kasim (2002) & Lehoux (2004). The test series cover single and multiple dowel-type connections. Furthermore, the design proposal are also compared with the experimental test series from: Ballerini (2004, 2003, 1999) who investigated mainly different depths of the member and different loaded edge distances; Möhler & Lautenschläger (1989) who observed different numbers of rows, connection widths and loaded edge distances; Ehlbeck & Görlacher (1989) who did tests with nailed steel-to-wood connections; and Schoenmaker (2010) where test series encloses various double-shear connections in European spruce. The comparisons are always related to Eq. (1), because for all cases of the experimental test results published, the differentiation between the ultimate or splitting load capacities is not given.The material values used for Canadian spruce glulam and European spruce are $\mathcal{G}_c^I = 0.225\,\text{Nmm/mm}^2$ and $\mathcal{G}_c^{II} = 0.650\,\text{Nmm/mm}^2$, as referenced in Vasic (2000) and Larsen & Gustafsson (1990). Figure 12 always shows a close correlation in the comparison of the experimental test series and the design proposal.

Figure 13 shows the comparison of the splitting load capacity and the design load F_{90} for the experimental and numerical test series in LVL. In this case the splitting load is known and the direct correlation to the new design approach can be shown. The material values used for LVL are $\mathcal{G}_c^I = 1.0\ \text{Nmm/mm}^2$ and $\mathcal{G}_c^{II} = 6.0\ \text{Nmm/mm}^2$, as referenced in Franke & Quenneville (2012), Ardalany et al. (2012). The design approach for LVL also shows a very good correlation to the experimental results.

For the comparison of the design proposal with the current two main international design standards, the same experimental and numerical test series were used. For the comparisons with solid wood and glulam, the 5% percentile values of the material parameters, as given in CSA O86-09, DIN 1052:2008, EN 1995-1-1:2004 and experimental results are used. In the experimental test series, where the values are unknown, the average values were reduced by about 15%. For the comparison with the average values of the test series in LVL, the tension strength of 1.4 N/mm² was used for the DIN 1052:2008 equations and the value $C_I = 22.9\ \text{N/mm}^{1.5}$ found by Jensen & Quenneville (2011) for LVL was used for the EN 1955-1-1:2004 equations instead of $C_I = 14\ \text{N/mm}^{1.5}$.

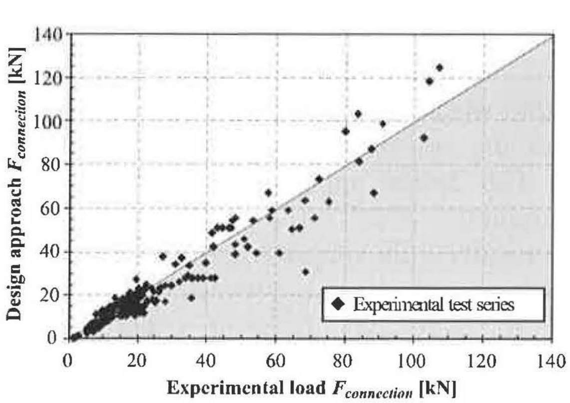

Figure 12: Comparison of design proposal and experimental test series published for European spruce or Canadian spruce

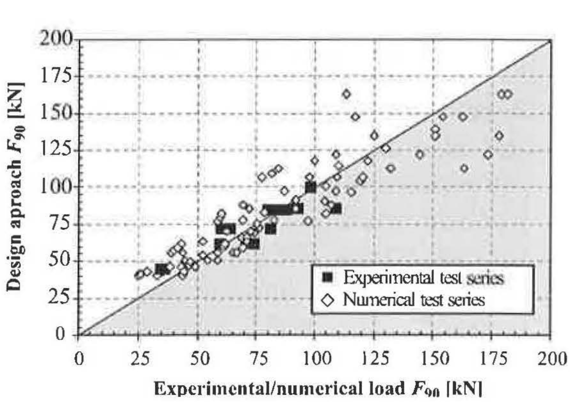

Figure 13: Comparison of design proposal and experimental as well as numerical test series for LVL

From Figures 14, 15, 16 and 17, one can observe that both the DIN 1052:2008 and the EN 1955-1-1:2004 design equations result in more inconsistent predictions of the failure strength and show also generally a wider variation. Whereas the predictions using the DIN 1052:2008 equations for solid wood show mostly conservative results, they are mostly unconservative for LVL. The opposite can be seen for the predictions using the EN 1995-1-1:2004 equations. Many predictions for solid wood are overestimated whereas almost all predictions for LVL are underestimated. The differences clearly reflect the nonconsideration of the effect of important connection configuration parameters.

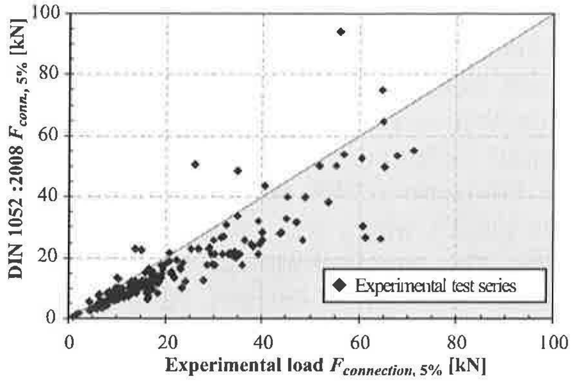

Figure 14: Comparison of DIN 1052:2008 and experimental test series published for European spruce or Canadian spruce

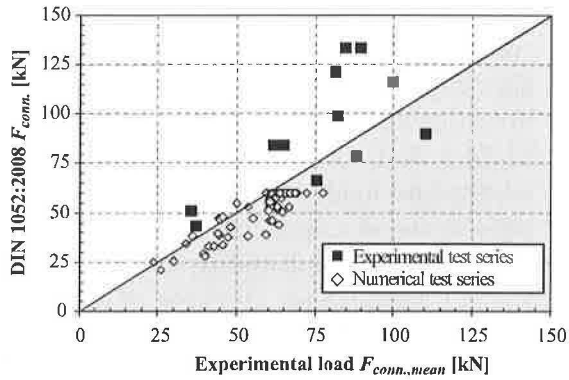

Figure 15: Comparison of DIN 1052:2008 and experimental as well as numerical test series for LVL

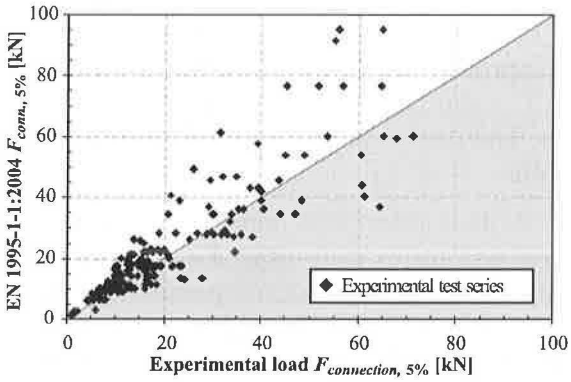

Figure 16: Comparison of EN 1995-1-1:2004 and experimental test series published for European spruce or Canadian spruce

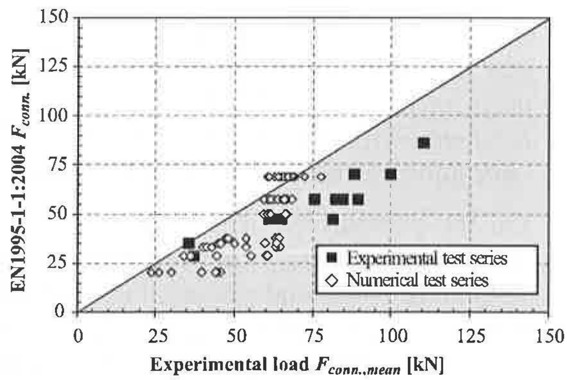

Figure 17: Comparison of EN 1995-1-1:2004 and experimental as well as numerical test series for LVL

5 Conclusion and view

A new design proposal is presented for double shear connections in solid wood, glulam and also LVL which allows one to predict the splitting failure of the wood due to connections loaded perpendicular to grain. The design approach is based on fracture mechanic methods including the important parameters which influence the load capacity of the connection. The comparison of the design results with comprehensive experimental test series done in Canadian and European spruce confirms the procedure of the design proposal. The good agreement is based on over 200 different experimental test configurations and 600 numerical test results.

The correlation between the new design proposal for double shear dowel-type connections loaded perpendicular to grain and the experimental test results confirms the methods used and the failure criteria determined, as shown in Figure 13. The new design approach, based on fracture mechanics methods, encloses the important parameters which influence the load capacity of the connection and would improve the current international design approaches. The comprehensive design approach presented for LVL as well as for solid wood previously published (Franke & Quenneville 2011a) could further be modified to a more simplified design equation for the practical design engineers and a code proposal but it can also already be used in its current state.

6 Acknowledgement

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