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SERVICEABILITY STIFFNESS OF TIMBER CONNECTIONS WITH DOWELS AND SLOTTED-IN STEEL PLATES

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ABSTRACT: The paper presents experimental stiffness measurements from large scale tests on dowel connections with both single and double slotted-in steel plates. The intended use of the results is quantification of the effect connections have on the stiffness of trusswork in glulam buildings. An engineering model of the connection stiffness is proposed and evaluated in view of the test results. The paper also shows comparisons of measured results to guidelines in European standards for timber engineering.

KEYWORDS: Stiffness, connection, dowel, serviceability, experiment, model

1 INTRODUCTION

The height of timber buildings has increased significantly within the last decennium. Several buildings with 10 to 20 stories using load carrying systems purely in wood have been built at various locations throughout the world. However, very little experience has been reported with respect to their in-service properties - like wind-induced vibrations. Dynamical properties are dependent on mass, stiffness and damping properties of the buildings. Several high-rise buildings, like “Treet” (14 stories, 2014) [1], and “Mjøstårnet” (18 stories, 2019, see Figure 1) [2], have used large trusswork in glulam with connections of slotted-in steel plates and dowels. The most exposed connections in the Mjøstårnet trusswork (see Figure 2) have in the order of 800 shear planes in a single connection. Although the stiffness of a single shear plane for a single dowel is given in [3], it is known from experiments that connections having large numbers of dowels cannot be sufficiently evaluated as only a summation of single dowels, see for example [4]. This is an important issue for high-rise buildings as the stiffness of joints is crucial for their dynamic response.

The objective of the experimental investigation has been to perform series of tests to get experimental results for quantification of elastic stiffness of connections with multiple dowels, suitable for modelling of connection stiffness for serviceability evaluations. The test series consists of experiments ranging from a single dowel and one slotted in steel-plate, up to connections with 2 slotted-in steel plates and 35 dowels. The investigation is limited to dowels having 12 mm diameter, which is most used in the Nordic countries.

Figure 1:*Mjøstårnet in Norway, 18 story glulam building.*

2 MATERIALS AND METHODS

2.1 MATERIALS

The wooden materials used was glulam GL30C according to [5]. This type of glulam usually consists of combined lay-up of two or more different strength classes of lamellas. In this case the outer lamellas are of strength

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class T22, and the inner lamellas T15. However, as the majority of the dowels usually are located in the inner lamellas, the tests have been performed on T15 lamellas and material properties for T15 lamellas are used throughout this paper, see [5]. The mean stiffness moduli are $E_{0,mean} = 11500$ MPa, $G_{mean} = 720$ MPa, while the density is $\rho_{mean} = 430$ kg/m^3.

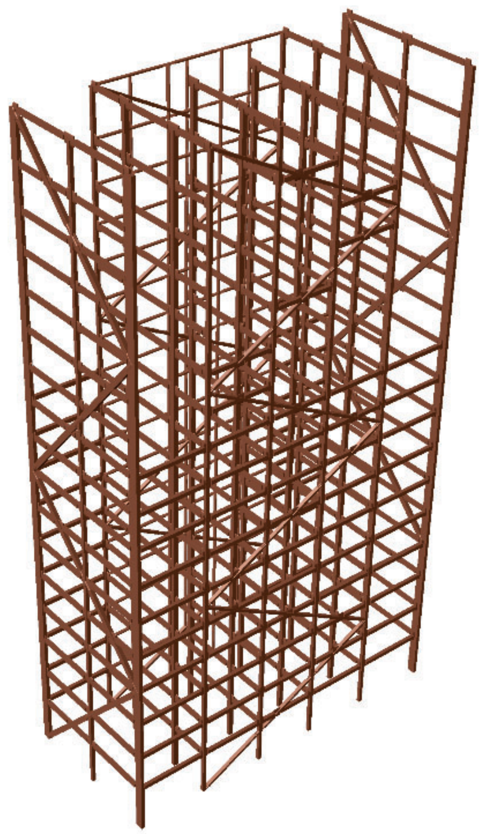

***Figure 2** Numerical model of the glulam trusswork used in Mjøstårnet.*

The steel plates in the slots are of quality S355 and have thickness 10 mm. All dowels have diameter of 12 mm and are of high strength stainless steel (class EN 1.4418) with yield strength 755 MPa. For all specimens the dowel spacing is 60 mm in the grain direction (a_1) and 55 mm in the perpendicular direction (a_2), which is a very common spacing for this type of dowel connections.

2.2 SMALL SCALE AXIAL TESTS

Two series of small-scale tests with one steel plate have been performed: the first is uniaxial tests loaded in the grain direction, confer Figure 3, while the second, shown on Figure 4, is in principle a three-points bending test. Both test series contain results from 1 dowel and up to 3 x 3 dowels, arranged in various layouts and loaded along grain direction, see Figure 3, or perpendicular to grain direction, see Figure 4. The notation used is as follows; a capital indicates a line in the grain direction, while a number indicates a row perpendicular to grain. A dowel in the middle will hence have identification B2, a row of 3 dowels in the middle in grain direction B123, a row perpendicular in the middle A1B1C1, while all dowels in the group becomes A123B123C123.

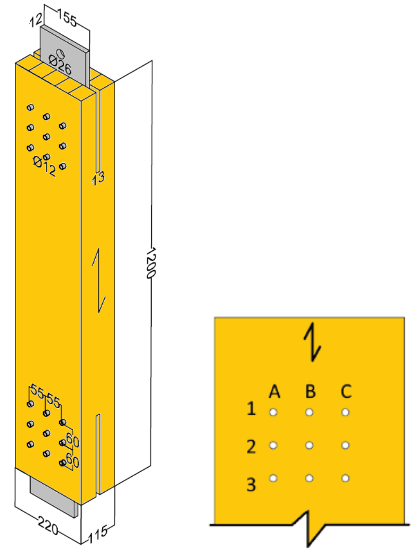

***Figure 3:**Specimene for loading parallel to grain and to the right, naming of dowel configurations.*

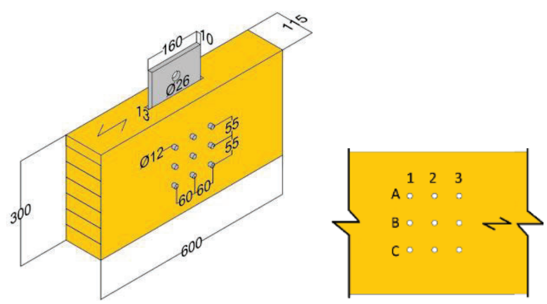

***Figure 4:**Specimene for loading perpendicular to grain and to the right, naming of dowel configurations.*

2.3 LARGE SCALE COMPONENT TESTS

The second test series contains three types of connections with two slotted-in steel plates, see Figure 5, and up to 5x7 dowels arranged in various patterns, confer Figure 6. The experimental setup for these tests is depicted in Figure 8. Note that the "Bottom" connection shown in Figure 5 is not evaluated herein.

2.4 INSTRUMENTATION AND MEASUREMENTS

All test setups are statically determined and hence the force distribution is well known. The stiffness is characterized by the applied load and the relative displacement between the steel plate (or plates), and the surrounding wood close to the steel plates. Each steel plate has two LVDTs, one at each edge, in order to cancel

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out any rigid body motion by averaging the measurements from the two sides, confer Figure 7 and Figure 8.

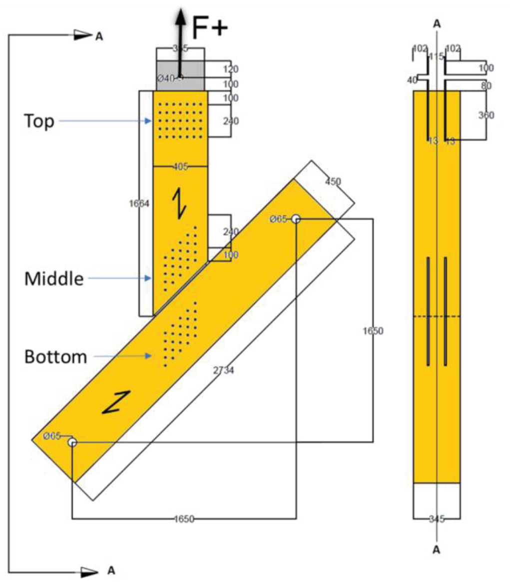

Figure 5:Setup for large scale glulam diagonal components. Three different connections in one setup; TOP connection, MIDDLE connection and BOTTOM connection.

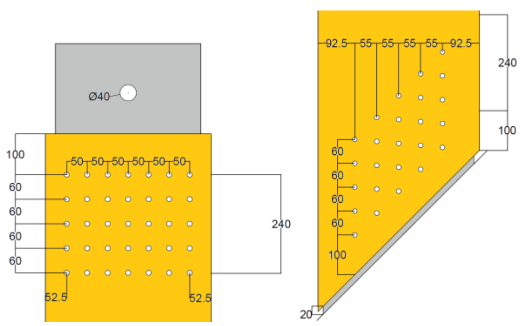

Figure 6:Lay-out for the diagonal connections loaded along grain. Left: TOP connection and right: MIDDLE connection.

A connection is here defined as the transfer of forces between a steel plate(s) and a glulam component by use of shear loaded dowels. The steel plates have two connections, either to another glulam component or to the loading or reaction devices.

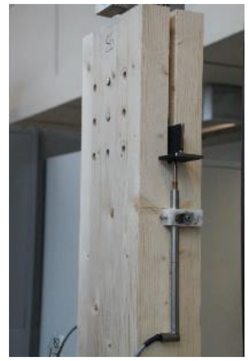

Figure 7: *Small scale test setup and instrumentation.*

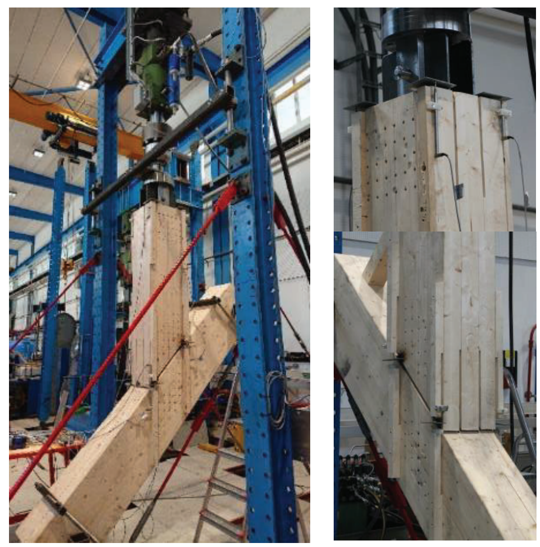

Figure 8: *Diagonal test setup with three dowel connections*

2.5 TEST PROGRAM

For the small-scale tests with loading in grain direction, three glulam specimens with a connection in each end were used (total six different connections). Eight different dowel configurations were used, confer Figure 9.

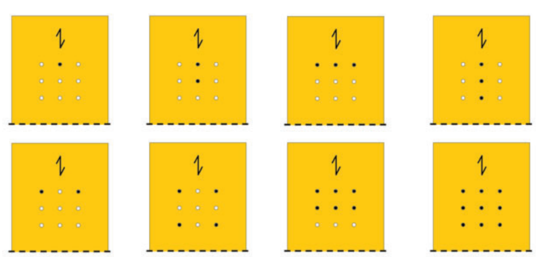

Figure 9: *Dowel configurations for small scale tests, loading in grain direction.*

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For loading perpendicular to grain, six configurations shown in Figure 10 were tested, using in total three specimens.

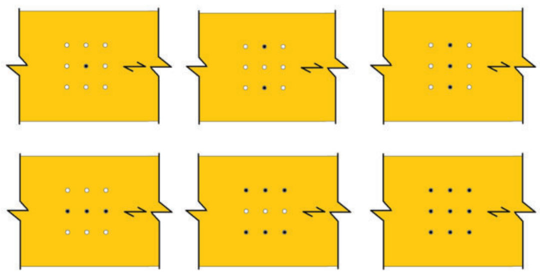

Figure 10: Dowel configurations for small scale tests, loading perpendicular to grain.

Only one specimen for the large-scale diagonal test setup was available, and here 5 different configurations were tested. The tests were performed by sequentially installing an additional row of dowels along the grain, starting from the ends of the connections. For the TOP connection the number of dowels perpendicular to grain $n_{90} = 7$ was kept constant, while the MIDDLE connection had $n_{90} = 5$ constantly.

2.6 LOADING PROTOCOL AND EVALUATION

The initial stiffness is not necessarily representative of a building in a wind exposed situation. Wind loading has usually a quasi-static part in addition to the turbulence causing vibrations. Therefore, the zero mean force situation is not likely to occur, as the quasi-static part of the wind loading is commonly large. Consequently, the effect of initial slips is of minor importance in this context.

The methods for evaluation of stiffness in ISO 6891 [6] do not fully cover the needs for quantification of stiffness for dynamic response evaluation. Therefore, a more suitable loading and evaluation protocol has been worked out for the test series and presented in Figure 11. The loading protocol is based on cycling the load between 10 and 40 % of the estimated maximum load, both on the tensile and compressive side. Finally, the load is cycled between +40 % and -40 %, passing through the domain of zero force. As it may be observed from Figure 12, or better from Figure 13, it takes a few cycles before the cycles stabilize and they appear on top of each other on the plots.

The plots in Figure 12 show tensile cycling corresponding to the first sequence in Figure 11, while the second block with cycling on the compressive side is shown on Figure 13. The plots show quite considerable hysteretic loops and picking specific points for stiffness calculation might lead to unnecessary large scatter in results, dependent on the choice of points (shown as pink dots on the plots). In the authors opinion it is much better to utilize all the information in the cycles and use the method of least squares to fit a straight line to the stable cycles (the cycles after stabilization).

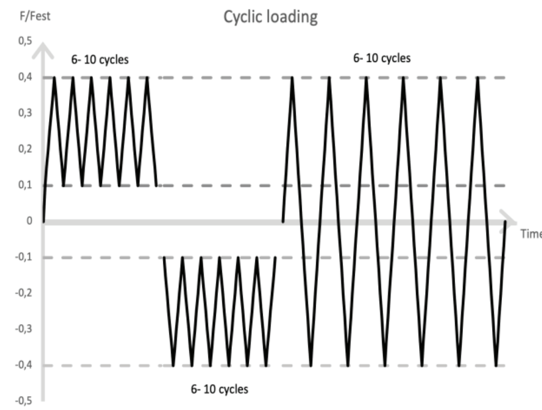

Figure 11: Loading protocol for stiffness evaluation

This is shown as dashed lines in the plots, and this stiffness measure is also more consistent with the numerical modelling of structures. Consequently, the latter method is used herein, and typically four values for the stiffness are determined. In the results section, stiffness evaluated from cycling in tension in denoted *tension* (tens), cycling in the compressive domain is denoted *compression* (comp). The large cycles passing through zero force, are called *Fully Reversed* and these cycles are evaluated separately both on the tensile side (FRt) and on the compressive side (FRc), as visualized on Figure 14.
The horizontal distance between the two dashed stiffness lines for fully reversed cycles shown on Figure 14 is a measure of the initial slip in the connection. The initial slip is not further reported herein, but a treatment of this issue can be found in [7].

3 RESULTS

The experimental results are given in tables and plots, where n_0 denotes the number of dowels in grain direction, while n_{90} is the number of dowels perpendicular to grain. As explained in Section 2.6 the stiffness has been evaluated in four different domains, one-sided cycling in tension (tens), in compression (comp), and fully reversed cycling evaluated separately both on the tension side (FRt) and on the compressive side (FRc). The columns denoted "Aver" or "Average" are the average of the four evaluated stiffnesses. All stiffnesses are given as stiffness per fastener and shear plane in kN/mm. For comparison, the Eurocode 5 [3] expression for this is

$$k_{ser} = 2 \cdot \frac{\rho_{mean}^{1.5} \cdot d}{23} = 2 \cdot \frac{430^{1.5} \cdot 12}{23} = 9.304 \text{ kN/mm} \quad (1)$$

where ρ_{mean} is the mean density of wood (kg/m^3) and d is the dowel diameter (mm). The total stiffness of the connection Eurocode 5 [3] is calculated by multiplying the stiffness k_{ser} with number of shear plane per fastener, herein either 2 (small-scale) or 4 (large-scale), and multiplied with the total number of fasteners $n_0 \cdot n_{90}$.

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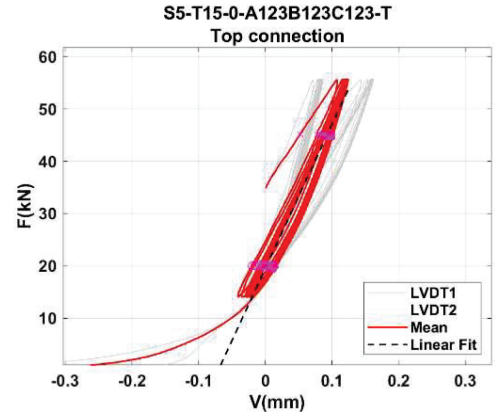

Figure 12: *Example on cycling on the tensile side for small scale specimen.*

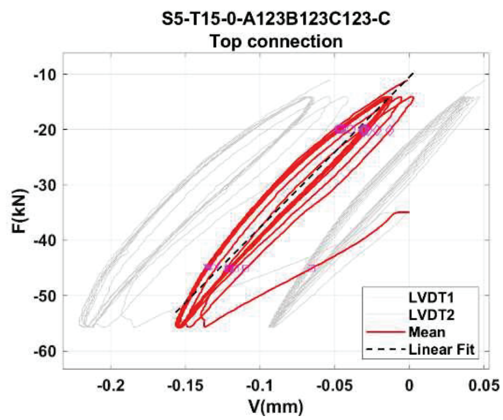

Figure 13: *Example on cycling on the compressive side for small scale specimen.*

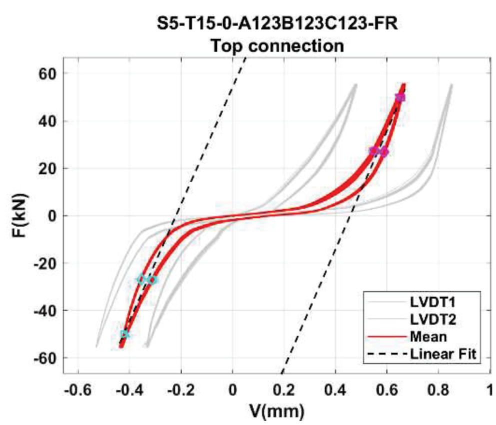

Figure 14: *Example on fully reversed cycles passing through zero force.*

3.1 RESULTS FROM SMALL-SCALE TESTS

Table 1 gives the measured stiffnesses per fastener and shear plane with loading in grain direction. The number of dowels in the grain direction is varied, keeping the number of fasteners perpendicular fixed, either one or three. The average results are plotted in Figure 15, and it may be observed that the stiffness decrease with the number of fasteners in the grain direction n_0. Comparing the blue line having $n_{90} = 1$, to the red line having $n_{90} = 3$, also an interaction between n_0 and n_{90} is probable.

Table 1: *Small scale specimen, loading in grain direction, stiffness per fastener and shear plane.*

Configuration	n	n0	n90	tens	comp	FRt	FRc	Aver
B1	1	1	1	24.64	25.98	19.26	21.69	22.89
B12	2	2	1	14.71	16.50	13.28	14.33	14.71
B123	3	3	1	12.77	15.92	12.05	14.31	13.76
A1B1C1	3	1	3	19.04	19.96	16.33	17.29	18.16
A12B12C12	6	2	3	14.19	15.18	12.88	14.11	14.09
A123B123C123	9	3	3	12.12	14.09	10.98	12.75	12.49

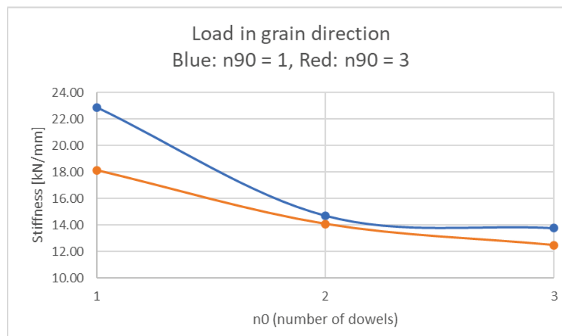

Figure 15: *Average stiffness from small scale specimens, loading in grain direction.*

Configurations with loading perpendicular to grain are given in Table 2 and the average stiffness is plotted in Figure 16, keeping the number of fasteners in grain direction n_0 constant. An increase of fasteners n_{90} in the load direction (here perpendicular) decreases the stiffness. From the plot it is suggested that an increase of n_0 will further decrease the stiffness.

Table 2: *Small scale specimen, loading perpendicular to grain*

Configuration	n	n0	n90	tens	comp	FRt	FRc	Aver
B2	1	1	1	10.51	11.59	10.17	11.27	10.89
A2C2	2	1	2	9.84	11.18	9.52	11.14	10.42
A2B2C2	3	1	3	9.28	10.38	9.16	10.11	9.73
A123C123	6	3	2	7.72	9.08	7.81	9.03	8.41
A123B123C123	9	3	3	6.02	6.87	5.94	6.93	6.44

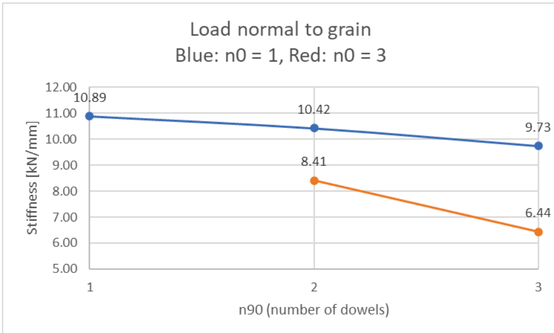

Figure 16: *Small scale, loading perpendicular to grain*

The configurations highlighted with yellow colour in Table 1 and Table 2 are comparable. Letting the stiffnesses obtained for perpendicular loading be scaled with the comparable stiffness obtained for loading in grain direction, we obtain the ratio of stiffness between loading perpendicular and along the grain and these ratios are presented in Table 3. The stiffness ratios based on the average data are between 0.48 and 0.54, i.e. the stiffness for loading perpendicular to grain is roughly only half of the stiffness for loading along the grain.

Table 3*: Stiffness ratios for loading perpendicular to grain vs loading in grain direction. Small scale specimen with comparable configuration*

n0	n90	tens	compr	FRt	FRc	Average
1	1	0.4265	0.4461	0.5280	0.5196	0.4755
1	3	0.4874	0.5200	0.5609	0.5847	0.5360
3	3	0.4967	0.4876	0.5410	0.5435	0.5158

3.2 RESULTS FROM LARGE-SCALE TESTS

The different configurations for the large-scale tests differ only by the number of installed dowels in the grain direction, n_0, while keeping the number of dowels perpendicularly constant at the maximum, which is 7 and 5 for the TOP and MIDDLE connections, respectively. Note that the loading for the TOP and MIDDLE connections is along the grain, while the BOTTOM connection has loading at 45 degrees relative grain and is therefore not included herein. The experimental results are given in Table 4.

The stiffnesses obtained from the four evaluation schemes (cyclic tension, cyclic compression, fully reversed compression and fully reversed tension) are plotted as separate curves in Figure 17 for the TOP connection. Note that the top connection has $n_{90} = 7$ and a rectangular lay-out of dowels. The lay-out for the MIDDLE connection is close to a parallelogram with 45 degrees between crossing lines. The loading for the MIDDLE connection is also along grain and the results for increasing number of dowels along grain n_0 are plotted on Figure 18. All these evaluations and measurements are in good agreement, and there is a clear trend of decreasing stiffness with increasing number of dowels in the grain direction.

Table 4: *Large scale specimen, vertical loading, stiffnesses in kN/mm per fastener and shear plane.*

Connection	n0	n90	tension	compr	FRt	FRc	Average
Top	1	7	7.93	12.49	9.07	11.08	10.14
Middle	1	5	15.15	21.23	10.23	12.30	14.73
Top	2	7	4.23	8.02	4.61	6.45	5.83
Middle	2	5	10.51	12.90	9.07	8.00	10.12
Top	3	7	2.60	5.83	3.72	5.43	4.39
Middle	3	5	7.47	8.53	5.64	6.49	7.03
Top	4	7	2.64	3.66	3.45	3.12	3.22
Middle	4	5	6.06	7.93	5.55	6.58	6.53
Top	5	7	1.99	3.78	2.53	2.95	2.82
Middle	5	5	4.92	6.91	3.82	5.76	5.35

The comparable stiffness from Eurocode 5 is 9.3 kN/mm, Equation (1), and it is obvious that this stiffness can only be achieved for connection having few dowels, roughly 10 dowels at most, independent of configuration. For more dowels the stiffness per fastener and shear plane will be considerably smaller. All configurations for the large-scale tests (and small-scale tests as well) show the same decreasing stiffness with increasing number of dowels in the grain direction.

From the small-scale tests presented on Figure 15 and Figure 16, for loading in grain direction and perpendicular respectively, it seems necessary to take into account the number of dowels in both directions (n_0 and n_{90}) as there is a clear interaction between them.

The obtained stiffness measurements were averaged and are presented on Figure 19, one curve for each large-scale connection. The average stiffness per fastener and shear plane is larger for the MIDDLE connection than for the TOP connection, but they are almost parallel and clearly show the same tendency of decreasing stiffness with increasing n_0. Furthermore, there is a clear trend to approaching an asymptotic value for $n_0 \geq 5$.

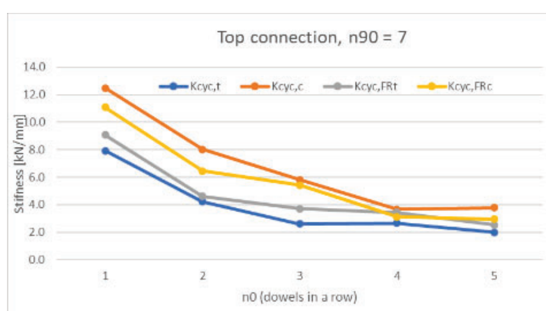

Figure 17: *Large scale diagonal test, TOP connection, loading in grain direction.*

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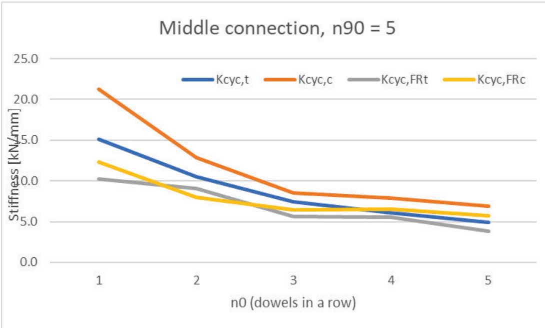

Figure 18: *Large scale MIDDLE connection, loading in grain direction.*

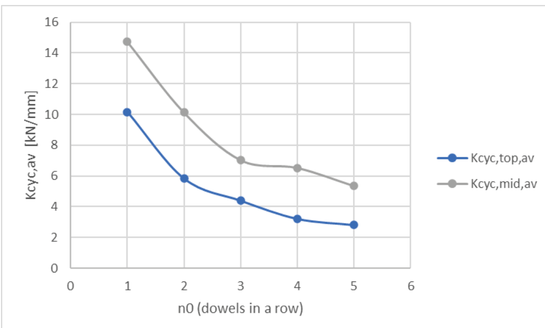

Figure 19: *Stiffness per fastener and shear plane for the two different dowel connections in the diagonal test setup.*

By scaling all stiffnesses with the stiffness value for one dowel in the grain direction, we can express the results by a relative ratio of effective numbers of dowels, depending on the number in grain direction, see plot on Figure 20. Note that the information used here involves the effect from both along and perpendicular to the grain and thus shows the sum of the effects from the number of dowels in both directions simultaneously. The MIDDLE connection has in all cases number of dowels perpendicular grain $n_{90} = 5$, and shows a decreasing trend with n_0. The TOP connection, which has $n_{90} = 7$, shows in comparison smaller effective numbers.

By combining the results from small-scale and large-scale tests, we have configurations which clearly show that there is similar trend from the number of dowels perpendicular to grain, see graphs on Figure 21, where the number of dowels along the grain is kept constant for each curve.

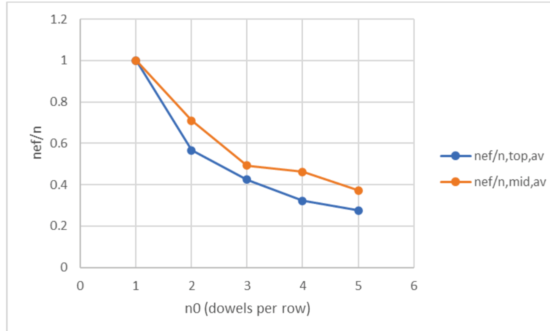

Figure 20: *Effective number of dowels in the grain direction in the diagonal test setup with three different dowel connections.*

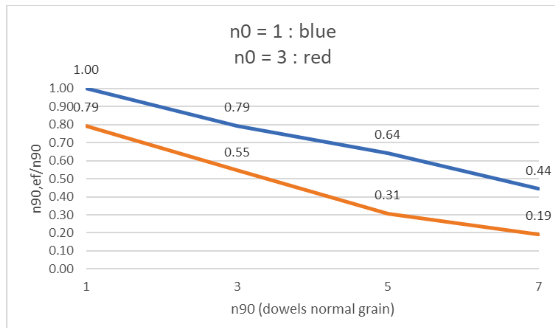

Figure 21: *Effective number of dowels perpendicular to grain, combination of small and large scale tests.*

4 MODEL FOR CONNECTION STIFFNESS OF DOWEL JOINTS

4.1 Model considerations

The stiffness of the dowel connections is dependent on the layout and cannot, with sufficient accuracy, be calculated just by a linear addition of the shear planes. Eurocode 5 [3] underestimates the stiffness for a single dowel, while the stiffness is severely overestimated for connections with large number of dowels. Herein, the number of wooden specimens is low. Therefore, effects of varying embedding stiffnesses of wood, thicknesses of layers and varying spacing cannot be determined from the present test series. The focus has only been on the effect of the number of dowels, keeping all other parameters constant.

4.2 Model

The idea behind the model is to use the information already available in codes like Eurocode 5 [3] together with simple modifications. Hence, the stiffness for a single steel-to-wood dowel connection k_{ser} is modelled by Equation (1).
Assuming that all shear planes contribute with the same stiffness, the method for stiffness evaluation from Eurocode 5 [3] is

$$K_{ser,EC5} = k_{ser} \cdot n_{spd} \cdot n_0 \cdot n_{90} \quad (2)$$

where n_{spd} is the number of shear planes per dowel. A regular dowel pattern is assumed herein such that the total number of dowels equals the product $n_0 \cdot n_{90}$.

Considering all plots on Figure 15 to Figure 21, a decaying behaviour of the average shear plane stiffness is observed. It will be unphysical that the decaying behaviour with increasing number of dowels ends up with zero average stiffness, so an asymptotic behaviour is expected, confer Figure 19.
The introduction on an effective number of fasteners also for stiffness evaluation has been proposed by several authors, see for example [8]. This can simply be introduced in Equation (2) by a non-dimensional modification factor M on the number of fasteners. A simple asymptotic expression for dowels on a single row along the grain can be:

$$M_0 = m_0 \cdot \left(q_{0,1} + q_{0,2} e^{\frac{1-n_0}{r_0}}\right) \quad (3)$$

where m_0 is the calibrated value for one dowel in grain direction. The parameter r_0 together with the parameters $q_{0,1}$ and $q_{0,2}$ govern the non-dimensional asymptotic decrease. A similar approach in the transvers direction reads:

$$M_{90} = m_{90} \cdot \left(q_{90,1} + q_{90,2} e^{\frac{1-n_{90}}{r_0}}\right) \quad (4)$$

By replacing n_0 with the product $n_0 M_0$ and n_{90} with $n_{90} M_{90}$ in Equation (2), the model stiffness becomes:

$$K_{ser,mod} = k_{ser} \cdot n_{spd} \cdot n_0 m_0 \cdot \left(q_{0,1} + q_{0,2} e^{\frac{1-n_0}{r_0}}\right) \cdot n_{90} m_{90} \cdot \left(q_{90,1} + q_{90,2} e^{\frac{1-n_{90}}{r_{90}}}\right) \quad (5)$$

For a single dowel, the exponential term equals unity, and therefore for easy calibration, we let always

$$q_{\alpha,1} + q_{\alpha,2} = 1 \quad (6)$$

Here α denotes 0 or 90 directions and $q_{\alpha,1}$ is the asymptotic value. Furthermore, for only one dowel Equation (5) reduces to

$$K_{ser,mod} = k_{ser} \cdot n_{spd} \cdot m_0 \cdot m_{90} = k_{ser} \cdot n_{spd} \cdot m \quad (7)$$

Equation (7) can be used for calibration in the two orthogonal directions, but as it herein is only dealt with either loading in the grain or perpendicular to grain direction, only one parameter is needed, and hence the simplification $m_0 \cdot m_{90} = m$ has been made.
From Table 1 and configuration B1 (one single dowel), the stiffness per shear plane is about 23 kN/mm and taking $k_{ser} = 9.3$ kN/mm from Equation (1), the parameter m becomes $m = 2.5$. Similarly, utilizing the results in Table 3 and Figure 16, the parameter m for a single dowel loaded perpendicular to grain is $m = 1.3$.
The model for serviceability stiffness of a dowel connection with multiple slotted in steel plates and multiple dowels, loaded either along grain or perpendicular to grain, then becomes:

$$K_{ser,mod} = k_{ser} \cdot m \cdot n_{spd} \cdot n_0 \left(q_{0,1} + q_{0,2} e^{\frac{1-n_0}{r_0}}\right) \cdot n_{90} \cdot \left(q_{90,1} + q_{90,2} e^{\frac{1-n_{90}}{r_{90}}}\right) \quad (8)$$

where k_{ser} is calculated according to Eurocode 5, see Equation (1), and n_{spd} is the number of shear planes per dowel. The effect from an increasing number of dowels in the grain direction has been evaluated from the measured results plotted in Figure 19, while for the effect from the number of dowels perpendicular to grain, the information presented in Figure 21 was used. The resulting model parameters for 12 mm dowels embedded in Norway spruce GL30c are specified in Table 5.

***Table 5** Model parameters for 12 mm dowels*

	Along grain			**Perpendicular grain**		
Number of dowels	n_0			n_{90}		
Model symbols	$q_{0,1}$	$q_{0,2}$	r_0	$q_{90,1}$	$q_{90,2}$	r_{90}
Model values	0.3	0.7	2	0.3	0.7	4
Loading direction	$m = 2.5$			$m = 1.3$		

The resulting model stiffness per shear plane and dowel for loading along grain and for varying number of dowels in grain direction is shown with dashed lines in Figure 22 for the two different diagonal connections, note the difference in n_{90}. For comparison, the continuous lines show the measured stiffness.

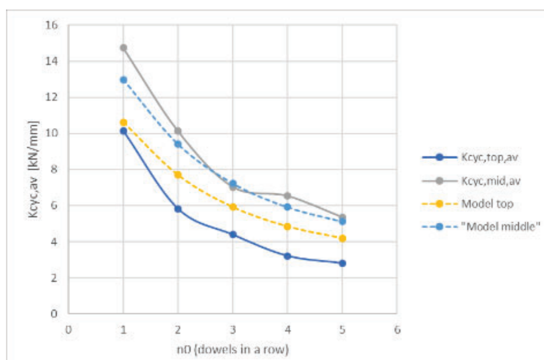

***Figure 22** Modelled and measured stiffness per shear plane and dowels ($\mathbf{n_{90,top}} = \mathbf{7}$ and $\mathbf{n_{90,middle}} = \mathbf{5}$.)*

Keeping the number of dowels constant in grain direction and varying the number of dowels in perpendicular direction, the relative reduction in modelled stiffness is shown on Figure 23 using dashed lines, while the measured results are shown with continuous lines.

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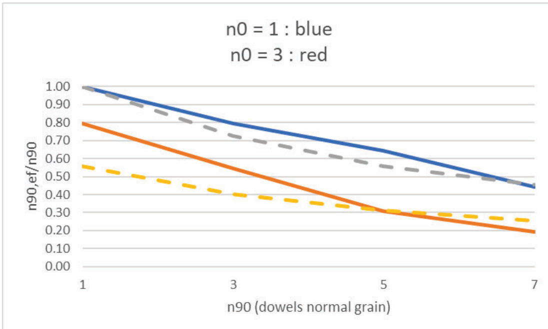

Figure 23 *Relative reduction of stiffness per shear plane and dowel for varying number of dowels perpendicular to grain.*

In the present test series, it has been emphasized to only vary the number of dowels and keep all other parameters constant. However, the test series contain two different lay outs of tests; the small-scale tests having a single slotted in steel plate, and large scale having two plates. The wooden materials are from the same production, but, of course, considerable variation is to be expected due to many local effects like knots etc. Most of the results have been obtained by just installing more dowels in the same specimen. However, for the small-scale specimen several specimens had to be used in order to get the desired configurations without removing any dowels. Therefore, higher variability must be expected in the regime with few dowels. For the determination of the model parameters, most emphasis has been put on the domain where the total number of dowels exceeds 10.

4.3 Verification

Stiffnesses from the connection measurements are compared to the model results in Table 6. Here, Equation (8) has been used with the parameters specified in Table 5 and, and with k_{ser} from Equation (1), (Eurocode 5, [3]). The measured and the modelled stiffness for loading along and perpendicular to grain show the same ratio of stiffness, the grain direction is about 1.9 times stiffer than perpendicular.

Eurocode 5 shows about the same stiffness for loading along grain as the model when the total number of dowels is around 10. For higher number of dowels Eurocode 5 largely overestimates the stiffness, while the developed model is in good agreement with the measurements.

Table 6 *Comparison of connection stiffness from measurements, analytical model and Eurocode 5.*

	Connection			Stiffness kN/mm		
Load directio	n_{spd}	n_0	n_{90}	Measured	Model	EC5
0	2	3	3	225	169	168
90	2	3	3	116	88	168
0	4	5	7	540	586	1303
n	4	5	5	522	512	930

To get a better understanding of the dependency of the number of dowels in the two directions in the model, a plot of the reduction in stiffness is shown on Figure 24 for up to 100 dowels using the parameters from Table 5. The asymptotic value of the reduction of stiffness in the model given by Equation (8) is in this case

$$\frac{K_{ser,mod,asymptote}}{k_{ser} \cdot m \cdot n_{spd} \cdot n_0 \cdot n_{90}} = q_{o,1} \cdot q_{9o,1} = 0.09 \qquad (9)$$

Compared to the Eurocode 5 stiffness computation by Equation (2), the asymptotic value in the model becomes 0.225, as the parameter $m = 2.5$ is required for the fitting of the present model to a single dowel.

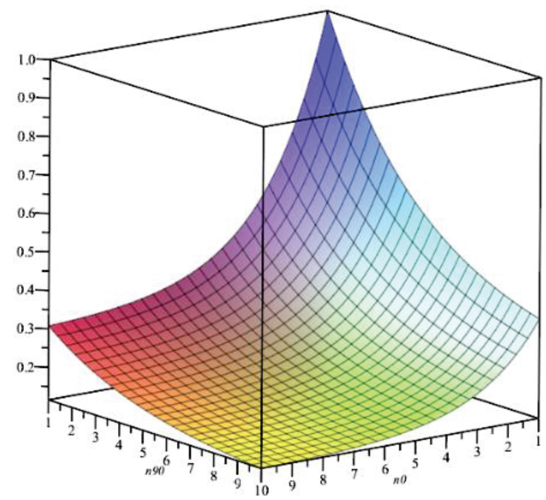

Figure 24 *Average relative stiffness dependent on dowels in the two directions.*

4.4 Limitations and extensions

Available number of tests having many dowels in both directions and multiple slotted in steel plates are few. Furthermore, stiffness measurements are not very well defined and are sensitive to the load level as well as to experimental conditions. Furthermore, the variability in wood material properties is large, and makes comparisons between various tests hard.

The proposed model herein is made in a multiplicative way, such that the various effects might be treated separately. The parameters in Table 5 are given for $a_1 = 60 = 5d$ and $a_2 = 55 = 4.6\, d$. Probably, the q and r parameters in Equation (8) will be dependent on the spacing between the dowels, and this effect can be considered by modifying the parameters and make them dependent on the spacing. This is not a part of the present paper and consequently the bottom connection shown in Figure 5 is not included herein.

Moreover, it is well known that inner and outer parts of a dowel connection with multiple steel plates seldom have the same stiffness per shear plane. This effect can be considered by using an effective number of shear planes n_{spd}. Dowel diameter dependency and dowel surface properties (friction) can put into the k_{ser} parameter.

5 CONCLUSIONS

The paper presents and discusses an approach for stiffness estimation of large dowel connections. Input parameters are the number of dowels on rows parallel and perpendicular to grain, and the number of shear planes per dowel. Both loading along and perpendicular to grain can be evaluated. The shear plane stiffness, and thereby the dependency on dowel diameter and density, is calculated by use of Eurocode 5 [3]. The model is compared to experimental results as well as the simple approach in design standards like Eurocode 5 [3].
The model is developed for dowel connections with 12 mm dowels and commonly used spacing in the Nordic countries.

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