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LOAD CARRYING CAPACITY OF JOINTS WITH DOWEL TYPE FASTENERS IN SOLID WOOD PANELS

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1 Introduction

Solid wood panels with cross layers (Fig. 1) have been used more and more frequently in timber engineering in recent years. Their use in constructions requires their connection with each other and with other components of the construction. To that purpose dowel-type fasteners can be used. It is possible to position the fasteners perpendicular to the plane of the panels or in their narrow sides. In this paper only the first possibility will be discussed.

The load carrying capacity for dowel-type fasteners is usually calculated according to Johansen's yield theory [3], [4]. Embedding strength as well as the yield moment of the fasteners are important parameters in this calculation. Withdrawal strength is needed to calculate the load carrying capacity of axially loaded screws or nails. The aim of a current research project at the University of Karlsruhe is to develop a proposal for calculating the load carrying capacity of joints with dowel type fasteners in solid wood panels.

Fig. 1: Solid wood panels with cross layers - two examples of products
(pictures: Informationsdienst Holz)

2 Characteristics of the test material

Solid wood panels consist of boards crosswise laminated with a minimum of three layers. Some panels are produced with gaps between the narrow sides of the boards. The maximum width of gaps is limited to 6 mm. In addition, grooves with a width of about 2,5 mm are sawn into the boards of some products. Fig. 2 shows cross-sections of different solid wood panel products. Table 1 gives some statistic information about the gaps.

Fig. 2: Cross-sections of panels without and with gaps between boards and grooves

Table 1: Width of gaps between boards of one layer for some different products

Manufacturer/ product	Build-up	Width [mm] of gaps in								
		Outer layers			Interlayers			Centre layer		
		mean	max.	95% fractile	mean	max.	95% fractile	mean	max.	95% fractile
1	17-17-17-17-17	0,6	2,1	1,6	1,6	7,3	3,4	1,0	3,0	2,3
2	19-22-19	0,4	2,0	1,3	-	-	-	0,5	2,2	1,8
2	34-13-34-13-34	0,2	1,0	1,0	1,4	6,8	3,3	2,0	6,7	4,5
4	9,5-6,8-9,5-6,8-9,5	0	0	0	0,6	5,4	3,5	0	0	0

The characteristic density (at normal climate, 20°C/65% RH) of solid wood panels was determined by analysing altogether 2299 test specimens out of a range of products from different manufacturers (Table 2). This revealed a minimum 5th percentile density of 400 kg/m³ for product 2. Taking this result into account a characteristic density of 400 kg/m³ is proposed for solid wood panels made of European spruce (*Picea abies*).

Table 2: Density of solid wood panels

Manufacturer/ product	n	ρ_{mean} kg/m³	ρ_{min} kg/m³	ρ_{max} kg/m³	Coefficient of variation %	$\rho_{0,05}$ kg/m³
1	515	470	415	630	5,11	430
2	906	437	372	578	6,02	400
3	208	458	406	507	5,18	423
4	670	459	397	558	5,75	419

3 Embedding strength

3.1 Test set-up

To determine the embedding strength of solid wood panels with cross layers 620 embedment tests according to EN 383 [5] were carried out, involving tests with a load under 0°, 45° and 90° to the grain of the outer layers. Furthermore the position of fasteners was varied, as shown in Fig. 3. They were placed in areas without gaps (pos. 1), placed in gaps (pos. 2 to 4) or over gaps (pos. 5).

For tests with fasteners loaded parallel and perpendicular to the grain direction of the outer layers it was possible to apply the geometry of test specimens as specified in EN 383. To carry out embedment tests with fasteners loaded under 45° to the grain the size of test specimens had to be increased due to plug shear failure in outer layers.

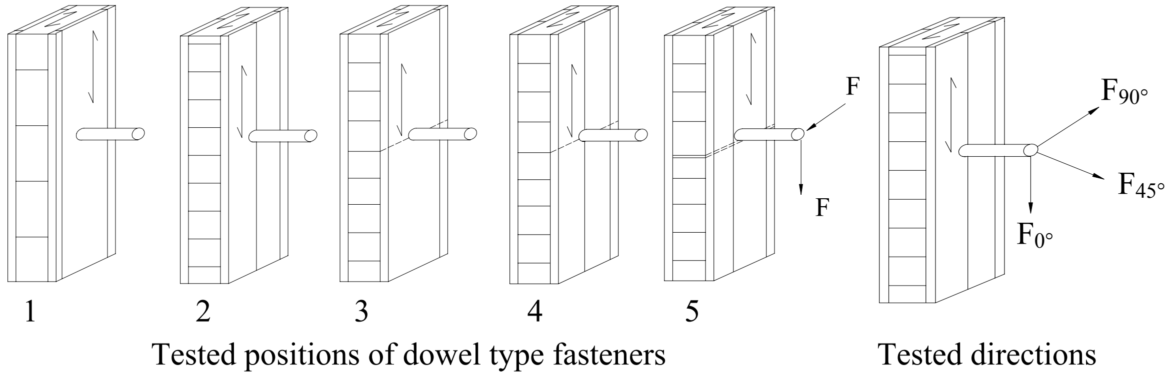

Fig. 3: Positions of fasteners and load direction in embedment tests, schematic sketch

3.2 Results for dowels

For dowels it was possible to develop the following two models for embedment strength on the basis of a multiple regression analysis of 438 test results. In the first model the embedment strength as given in equation (1) is independent of the build-up of the panels. The correlation coefficient r is equal to 0,75. The embedment strength depends on the diameter d of the dowel, the density ρ of the solid wood panel and the angle α between load and grain direction of the outer layer.

$$f_{h,pred} = \frac{0,035 \cdot (1 - 0,015 \cdot d) \cdot \rho^{1,16}}{1,1 \cdot \sin^2\alpha + \cos^2\alpha} \quad \text{in N/mm}^2 \qquad (1)$$

$r = 0,75$

Additionally the second model (eq. (2)) takes into account the build-up of the panels as defined in Fig. 4.

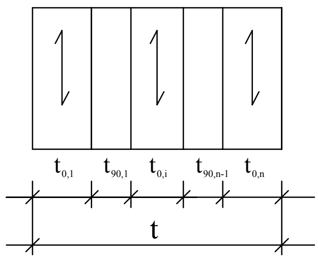

Fig. 4: Definition of thickness of layers for eq. (2) and (3), in case of a panel with 5 layers

$$f_{h,pred} = 0{,}037 \cdot (1 - 0{,}016 \cdot d) \cdot \rho^{1,16} \cdot \left[\frac{\sum_{i=1}^{n} t_{0,i}}{t \cdot \left(1{,}2 \cdot \sin^2\alpha + \cos^2\alpha\right)} + \frac{\sum_{j=1}^{n-1} t_{90,j}}{t \cdot \left(1{,}2 \cdot \cos^2\alpha + \sin^2\alpha\right)} \right] \quad \text{in N/mm}^2 \qquad (2)$$

$r = 0{,}74$

The validity of equation (1) and (2) is limited to panels which fulfill the following conditions:

- Maximum thickness of one layer: 40 mm
- Ratio of layers with different grain directions as defined in Fig. 4:

$$0{,}95 < \frac{\sum t_{0,i}}{\sum t_{90,j}} < 2{,}1 \qquad (3)$$

Fig. 5 shows the results of embedment tests over the predicted values for model 1.

The characteristic embedment strength on basis of equation (1) for a characteristic density of 400 kg/m³ can be calculated according to the following expression:

$$f_{h,k} = \frac{0{,}031 \cdot (1 - 0{,}015 \cdot d) \cdot \rho_k^{1,16}}{1{,}1 \cdot \sin^2\alpha + \cos^2\alpha} = 32 \cdot \frac{1 - 0{,}015 \cdot d}{1{,}1 \cdot \sin^2\alpha + \cos^2\alpha} \quad \text{in N/mm}^2 \qquad (4)$$

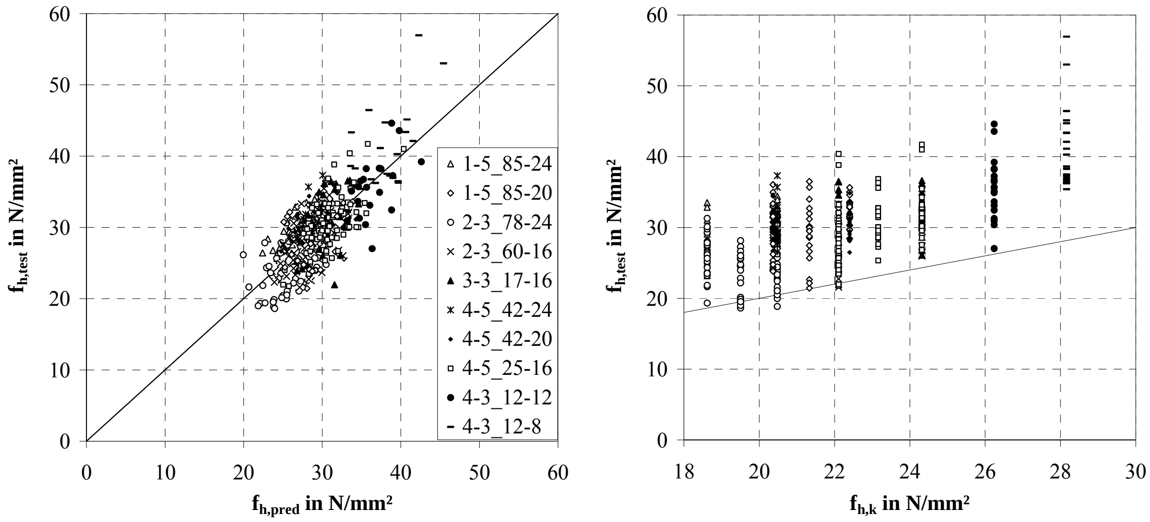

Fig. 5: Comparison of test results and predicted resp. characteristic values for dowels

3.3 Results for screws and nails

On the basis of a regression analysis of 179 tests with screws and nails the embedment strength can be derived as:

$$f_{h,pred} = 0{,}13 \cdot d^{-0,53} \cdot \rho^{1,05} \quad \text{in N/mm}^2 \qquad (5)$$

$r = 0{,}83$

A comparison of predicted values and test results is shown in Fig. 6. The correlation coefficient was determined as r = 0,83. At present the validity of equation (5) has to be limited to panels with layers thinner than 7 mm. In equation (5) the embedding strength is independent of the angle α. This result corresponds to the research results of Blaß and Bejtka [1], [2] for self-tapping screws.

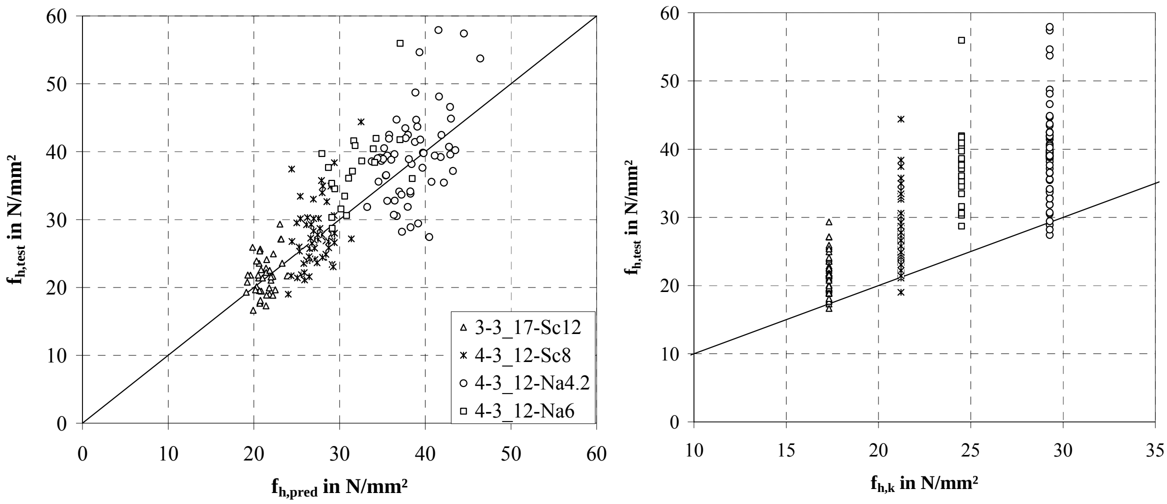

Fig. 6: Comparison of test results and predicted resp. characteristic values (screws/nails)

By inserting a characteristic density of 400 kg/m³ in equation (5) the characteristic embedment strength can be proposed as:

$$f_{h,k} = 0{,}112 \cdot d^{-0{,}5} \cdot \rho_k^{1{,}05} = 60 \cdot d^{-0{,}5} \qquad \text{in N/mm}^2 \qquad (6)$$

4 Load carrying capacity

4.1 Calculation Model

The load carrying capacity of joints in solid wood panels under lateral load can be determined according to Johansen’s yield theory. For connections with screws and nails in solid wood panels with thin layers ($t_i \leq 7$ mm) it is possible to use the embedment strength from equation (5) resp. (6) for the calculation.

In other cases the embedment strength depends on the angle between load and grain direction so that additional investigations are necessary. Here obviously the embedment strength of a layer loaded in grain direction is larger than of one loaded perpendicular to the grain (see Fig. 7). In the following the load carrying capacity of dowels in a steel-to-solid-wood-panel connection with an inner steel plate is derived exemplarily. According to Johansen’s yield theory three failure modes are possible. The load carrying capacity is the minimum value of these three modes. Failure mode 1 is characterized by an embedment failure of all layers as shown in Fig. 7.

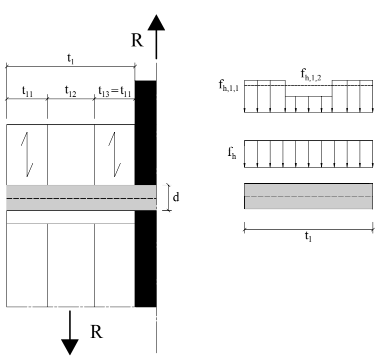

Fig. 7: Failure mode 1

In this failure mode the load carrying capacity can be directly calculated by using the embedment strength from equation (6).

$$R = f_h \cdot d \cdot t_1 \tag{7}$$

In the second failure mode with one plastic hinge the load carrying capacity depends on the distance x (Fig. 8). For a solid wood panel with three layers two cases (2.1 and 2.2) have to be taken into consideration as shown in Fig. 8.

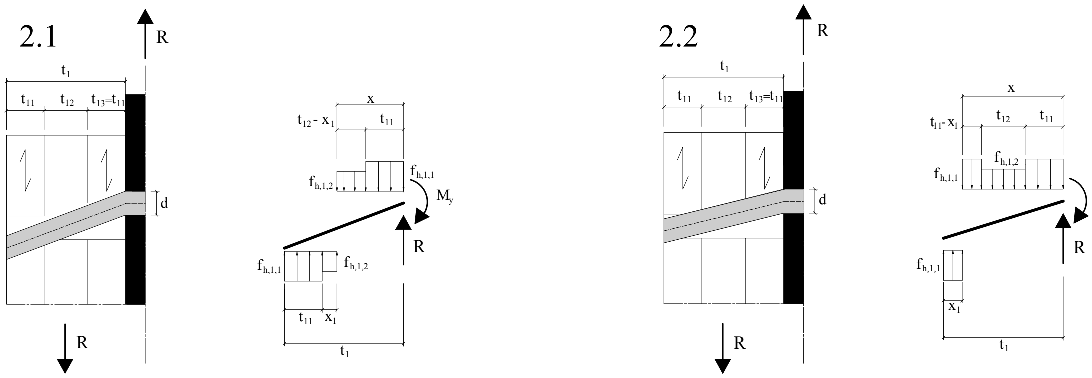

Fig. 8: Failure mode 2.1 and 2.2

By using the substitutions

$$\beta_{1,2}=f_{h,1,2}/f_{h,1,1} \tag{8}$$

and

$$\psi=t_{11}/t_1 \tag{9}$$

the load carrying capacity for failure mode 2.1 and 2.2 can be calculated as follows.

Failure mode 2.1:

$$R = f_{h,1,1} \cdot d \cdot t_1 \cdot \left[\sqrt{2} \cdot \sqrt{\beta_{1,2} \cdot \left(\beta_{1,2} \cdot \left(2 \cdot \psi^2 - 2\psi + 1\right) + 2 \cdot \psi \left(1 - \psi\right) + \frac{2 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2} \right)} - \beta_{1,2} \right] \tag{10}$$

for

$$\psi \le \frac{1}{2} \left(\beta_{1,2} + 1 - \sqrt{\beta_{1,2}^2 + 1 + \frac{4 \cdot M_y}{d \cdot f_{h,1,1} \cdot t_1^2}} \right) \tag{11}$$

Failure mode 2.2:

$$R = f_{h,1,1} \cdot d \cdot t_1 \left(\sqrt{2} \cdot \sqrt{\psi \cdot \left(2 \cdot \beta_{1,2} - 2\right) + 2 - \beta_{1,2} + \frac{2 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} + 2 \cdot \psi + \beta_{1,2} \cdot \left(1 - 2 \cdot \psi\right) - 2 \right) \tag{12}$$

for

$$\psi \ge \frac{1}{2} \left(\beta_{1,2} + 1 - \sqrt{\beta_{1,2}^2 + 1 + \frac{4 \cdot M_y}{d \cdot f_{h,1,1} \cdot t_1^2}} \right) \tag{13}$$

In failure mode three the load carrying capacity depends on the position of the second plastic hinge. For a panel with three layers there are three cases to be considered as follows.

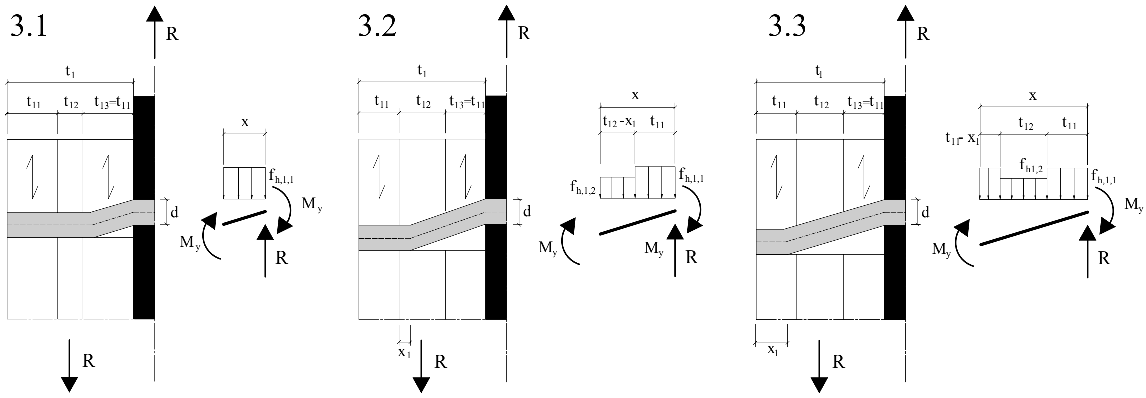

Fig. 9: Failure mode 3.1 to 3.3

Failure mode 3.1:

$$R = \sqrt{2}\sqrt{2 \cdot f_{h,1,1} \cdot M_y \cdot d} \qquad \text{for} \quad \psi \geq 2 \cdot \sqrt{\frac{M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} \tag{14}$$

Failure mode 3.2:

$$R = f_{h,1,1} \cdot d \cdot t_1 \cdot \psi \left(1 - \beta_{1,2} + \sqrt{\beta_{1,2} \cdot \left(\beta_{1,2} - 1 + \frac{4 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2 \cdot \psi^2} \right)} \right) \tag{15}$$

for

$$\psi \leq 2 \cdot \sqrt{\frac{M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} \qquad \text{and} \qquad \frac{\psi}{\beta_{1,2}} \cdot \sqrt{\beta_{1,2} \cdot \left(\beta_{1,2} - 1 + \frac{4 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2 \cdot \psi^2} \right)} + \psi \leq 1 \tag{16}$$

Failure mode 3.3:

$$R = f_{h,1,1} \cdot d \cdot t_1 \left(\beta_{1,2} \left(1 - 2 \cdot \psi\right) + 2 \cdot \psi - 1 + \sqrt{2 \cdot \psi \left(\beta_{1,2} - 1\right) - \beta_{1,2} + 1 + \frac{4 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} \right) \tag{17}$$

for

$$\psi \leq 2 \cdot \sqrt{\frac{M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} \qquad \text{and} \qquad \sqrt{2 \cdot \psi \cdot \left(\beta_{1,2} - 1\right) - \beta_{1,2} + 1 + \frac{4 \cdot M_y}{f_{h,1,1} \cdot d \cdot t_1^2}} + \psi \geq 1 \tag{18}$$

The shown way of calculation is already complex for a panel with three layers. Besides the variability of the density of different layers and gaps are not taken into account.

In many cases, which are dependent on the type of connection, the build-up of the solid wood panels and the diameter and yield moment of the fastener, a simplified calculation of the load carrying capacity using the embedment strength given in paragraph 3 is possible. For some configurations the yield moment develops in the outermost layers. This allows to directly use their embedment strength for the calculation. In conclusion, the limits for the application of simplified calculations have to be defined for different build-ups of solid wood panels.

4.2 Tests

In order to confirm the calculated load carrying capacities 88 tests with connections with dowel type fasteners positioned perpendicular to the plane of solid wood panels were planned. The tests also provide a basis for the required spacing, edge and end distances for the fasteners. Table 3 shows the specimen parameters and table 4 shows the results of the first 28 tests. The test set-up is documented in Fig. 10. A comparison between test results and calculated load carrying capacities is given in Fig. 11. A significant difference between the calculated load carrying capacity and the test results is determined only for specimen 1-24-2S_1.1 (R_{test}/R_{cal}=0,85). It is assumed that a plug shear failure which occurred in the outer layers is the reason for this discrepancy.

In most of the tests a displacement of more than 15 mm was reached. Even if a plug shear failure or splitting occurred in the outer layers, the load kept a constant level or dropped only marginally. Typical load-displacement-curves are displayed in Fig. 12. Fig. 10 (right) shows an opened connection after the test.

Table 3: Specimen parameters

Specimen	n	Type	Fasteners									Build-up of solid wood panel	
			Type	d mm	M_y Nm	t_1 mm	t_2 mm	$a_{1,t}$	a_1	$a_{2,c}$	Number of fasteners per row	Side members	Middle member
1-24-2S_1.1	4	T-S-T	dowels	24	1191	60	-	7·d	5·d	3·d	3 (one row)	19-22-19	steel plate
1-20-22_1.1	6	T-T-T	dowels	20	779	60	128	5·d	5·d	3·d	3 (one row)	19-22-19	34-13-34-13-34
1-20-22_1.2	6	T-T-T	dowels	20	779	60	128	5·d	4·d	3·d	3 (one row)	19-22-19	34-13-34-13-34
1-20-22_1.3	3	T-T-T	dowels	20	779	60	128	4·d	4·d	3·d	3 (one row)	19-22-19	34-13-34-13-34
1-12-42_1.1	3	T-T-T	screws	12	58,5	27	146	10·d	4·d	2,5·d	2 (one row)	8,5-10-8,5	34-22-34-22-34
1-12-42_1.2	3	T-T-T	screws	12	58,5	27	146	12·d	5·d	3·d	2 (one row)	8,5-10-8,5	34-22-34-22-34
1-12-42_1.3	3	T-T-T	screws	12	58,5	27	146	6·d	3·d	3·d	2 (one row)	8,5-10-8,5	34-22-34-22-34

Table 4: Results of the tests

Specimen	Number of Specimens n	Mean density ρ_m in kg/m³		Load carrying capacity per fastener and shear plane $F_{u,mean}$ in kN
		Side members	Middle members	
1-24-2S_1.1	4/3)[1]	435	-	31,7
1-20-22_1.1	6	430	417	24,7
1-20-22_1.2	6/5)[1]	425	433	22,1
1-20-22_1.3	3	463	433	23,5
1-12-42_1.1	3/2)[1]	440	411	7,28
1-12-42_1.2	3	438	430	7,49
1-12-42_1.3	3	424	438	6,88
)[1] 1 specimen with tensile failure				

Fig. 10: Test-set-up for connections 1-24-2S_1.1 and 1-12-42_1.2,
opened connection 1-20-22_1.2.2 (right)

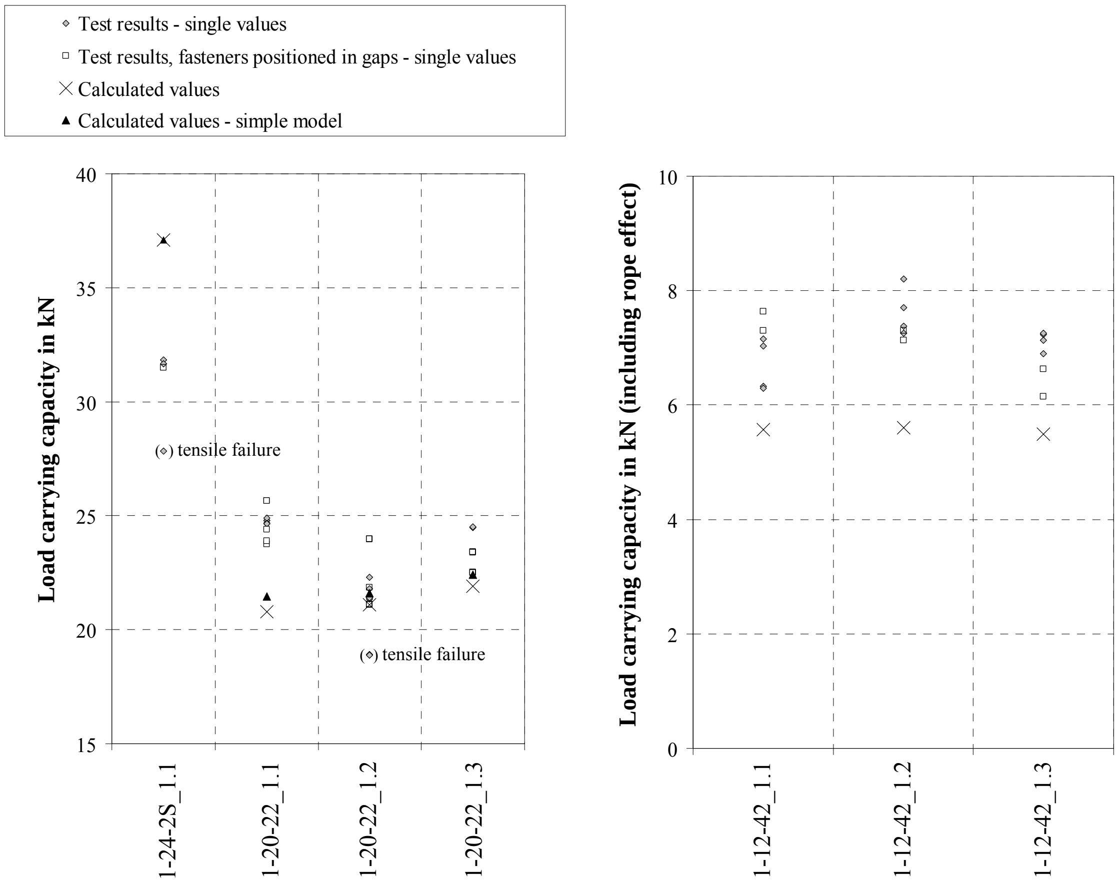

Fig. 11: Comparison between test results and calculated load carrying capacities

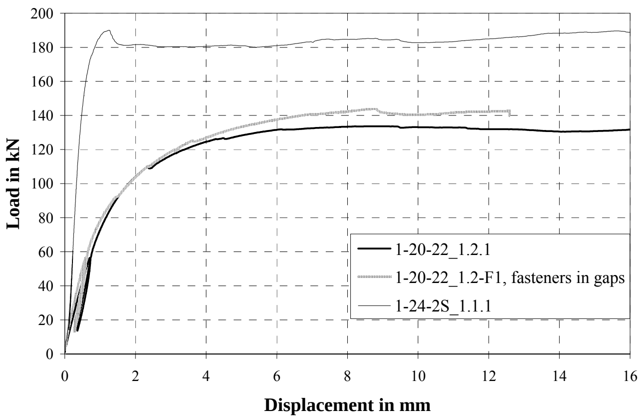

Fig. 12: Typical load-displacement-curves

5 Conclusions

The parameters of solid wood panels with cross layers for calculating the load carrying capacity of dowel type fasteners were examined. For the characteristic density of solid wood panels made of spruce a value of 400 kg/m³ is proposed. On the basis of a statistical analysis of 617 embedment tests it was possible to determine the embedment strength of solid wood panels for dowel type fasteners. The presented functions depend on type and diameter of fasteners, density and particularly on the angle between load and grain direction of the outer layers. Proposals for characteristic values are also given. For the example of a steel-to-solid-wood-panel connection the load carrying capacity is derived. First results of tests with connections in solid wood panels are presented. These tests are important to verify a simplified calculation model. Furthermore they are required to determine the minimum edge and end distances and spacings of fasteners. When the load in the tests reaches the load-carrying capacity, the connections show almost ideal plastic load-displacement behaviour. Even plug shear or splitting of the outer layers do not initiate a brittle failure. These facts show the reinforcement effect in crosswise laminated structures. Further investigations are necessary to determine the influence of plug shearing on the load carrying capacity.

6 References

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