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BLOCK SHEAR FAILURE AT DOWELLED STEEL-TO-TIMBER CONNECTIONS

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Presented by A Hanhijärvi

A Jorissen wondered why values were conservative for glulam but just okay for Kerto LVL.

R Foschi wondered why the research was performed when the code was conservative and received clarification that this mode of failure was not originally considered in EC5 which led to a failure in Finland and A Hanhijärvi further responded that the comparison was focused on the Annex which is a later version of EC5.

J König commented that the designers did not use the right version.

R Foschi commented that many years ago in Canada a similar problem was experienced with glulam rivets. Block shear failure occurred with capacity of ½ of code values. This led to changes in code and increased spacing of rivets. Now both block shear and rivet yielding modes are considered in Canadian code.

J König further commented that the accuracy of manufacturing is important.

P Racher discussed the French experience on this type of connections. Designers would be working outside the code with this type of joints.

P Quenneville added that other types of steel (mild) and larger row spacing can influence the issue. A Hanhijärvi agreed that there were many possibilities. The project objectives were very specific. In Finland the steel typically had higher quality than required. There would be a risk of bad design if one assumed mild steel.

Block shear failure at dowelled steel-to-timber connections

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1 Introduction

The design of dowel type joints of timber is well established in the Eurocode 5 by the use of the Johansen theory (Johansen 1949). It has shown to perform well when the fastener diameter is small and consequently the fasteners are slender (see Hilson 1995). With the increase of span length in large timber structures, the use of high capacity dowel type joints is necessary. The high capacity dowelled connections are often implemented by slotted in steel plates and large diameter dowels or bolts. With the increase of the diameter the rigidity of the dowel increases more than the embedment capacity. Therefore with large diameter rigid dowels, also the failure of timber at the joint area becomes more easily critical for the capacity of the connection – not only as embedment failure but through failure of the whole joint area by tension or shear. The failure mechanisms in this manner at the connection area are known as block shear or plug shear.

The lack of design against timber failure as consequence of shear and tension at the connection area (block shear) was found to be the partial reason for a recent failure of a large roof structure in Finland (Anon. 2004, Ranta-Maunus and Kevarinmäki 2003). Although the primary reason for the failure was a manufacturing fault in one connection (missing dowels) of a large glulam truss, the failure would not have proceeded to a catastrophic one, unless the true capacity of the properly manufactured joint had not been much lower than the capacity assumed in the design, which did not include any consideration of timber failure at the joint area. The true capacity of the connection was tested later after the collapse in a full-scale test, in which it was found that the true capacity was only appr. 50% of the design value (Ranta-Maunus and Kevarinmäki 2003). The tests showed also clearly the importance of the block shear failure mechanism as the critical one. At the time of the design of the roof, the ENV-version of the Eurocode 5 did not contain any mention of this type of failure mechanisms.

The aim of the present work is to improve the grounds for design of heavy-duty dowelled connections by experimental investigation of the timber failure at the joint area in joints implemented by steel plates loaded in tension. Alltogether more than 150 tension tests were made with glulam and Kerto-LVL specimens. The experimental program contained tests of both double-shear and multiple shear (4- and 6- shear) plane connections. In double shear, both timber-steel-timber and steel-timber-steel specimens were tested. In multiple shear the outermost parts were allways timber.

2 Symbols

a_1	dowel spacing parallel to grain
a_2	dowel spacing perpendicular to grain
a_3	dowel end distance
a_4	dowel edge distance
B	specimen height
b	block shear failure mechanism
b-r	block shear failure mechanism with calculational shear failure capacity > tension failure capacity
b-t	block shear failure mechanism with calculational tension failure capacity > shear failure capacity
CoV	coefficient of variation
d	dowel diameter
DF	design failure mode (critical failure mechanism according to design)
$F_{\max}$	failure load in tests
F_{Bk}	calculated characteristic load-carrying capacity of connection according to EC5 Annex A (block/plug shear)
F_{Bm}	calculated load-carrying capacity of connection according to EC5 Annex A (block/plug shear) and using mean properties
F_{Rk}	calculated characteristic load-carrying capacity of connection according to EC5 assuming $n_{\mathrm{ef}} = n$
F_{Rm}	calculated load-carrying capacity according to EC5 assuming $n_{\mathrm{ef}} = n$ and using mean properties of the test material
F_{Sk}	calculated characteristic load-carrying capacity according to EC5 assuming splitting etc. ($n_{\mathrm{ef}} \neq n$) but not block/plug shear
F_{Sm}	calculated load-carrying capacity according to EC5 assuming splitting etc. ($n_{\mathrm{ef}} \neq n$) but not block/plug shear and using mean properties of the test material
F_{Tm}	calculated capacity according to the EC5 assuming only tension failure and using mean properties of the test material and cross-section reduction due to dowel holes
N	number of specimens
n	number of dowels in a row
n_{ef}	effective number of dowels in a row
m	number of dowel rows
p	plug shear failure
row	row shear failure
s/r	splitting or row shear failure
T	tension failure mechanism (of cross-section)
TF	test failure mode (prevailing failure mechanism in test)
t_1	thickness of outer timber member
t_2	thickness of inner timber member
t_{S}	thickness of steel plate
$v_{\max}$	connection slip at maximum load
ρ_{m}	mean density of the test material

3 Material

All glulam for the tests was manufactured in an industrial process from spruce (*Picea abies*) wood. To get more homogenious properties, the lamellas were specially selected.

The selection was made using a commercial strength grading machine, which measures the natural frequency (Dynagrader). First, a sufficiently large batch of lamellas was graded with settings of grade MT30 (=C30). Second, the pieces which had passed the requirements of this grade were re-graded using the settings of MT40 and only those pieces with failed this higher criterion were taken for the production of the test glulam. Thus the lamellas had properties exceeding the requirements for MT30 but not MT40. The LVL for the tests was produced at the Kerto-LVL factory of Finnforest Oyj in Lohja, Finland.

Dowels were produced by cutting and machining from cold drawn steel bars. The binder bolts were produced from the same material as the dowels and the smooth length was always at least a few mm's longer than the width of the joint, i.e. in no case did the threaded part touch the wood or the steel plates. The dimensional accuracy of the diameter of the dowels and bolts was very good.

The steel plates were manufactured by laser cutting from steel quality S355 using an NC-machine tool. The dowel holes were cut to diameter Ø13 mm and Ø8.7 mm for the dowel diameters 12 and 8 mm, respectively.

All test specimens were manufactured so that a similar dowelled connection was manufactured at both ends of the specimen. Thus, actually, twice as many joints were tested than the number of specimens shows. However, the actual strength of only the weaker one of the pair of joints in one specimen was obtained – and it can be only said that the other one was at least as strong.

3.1 Double shear connection specimens

The double-shear test series are listed in Tables 1 and 2 for glulam and Kerto-LVL, respectively. Double shear test series of the timber-steel-timber type were made with unattached timber parts: For glulam the two halves were obtained by splitting a glulam beam into two and manufacturing the specimen using the two halves but leaving them unattached in the middle part. For LVL specimens the two halves were obtained from two pieces of LVL coming from the same manufacture batch. Both standard type Kerto-S and cross-veneered Kerto-Q were tested.

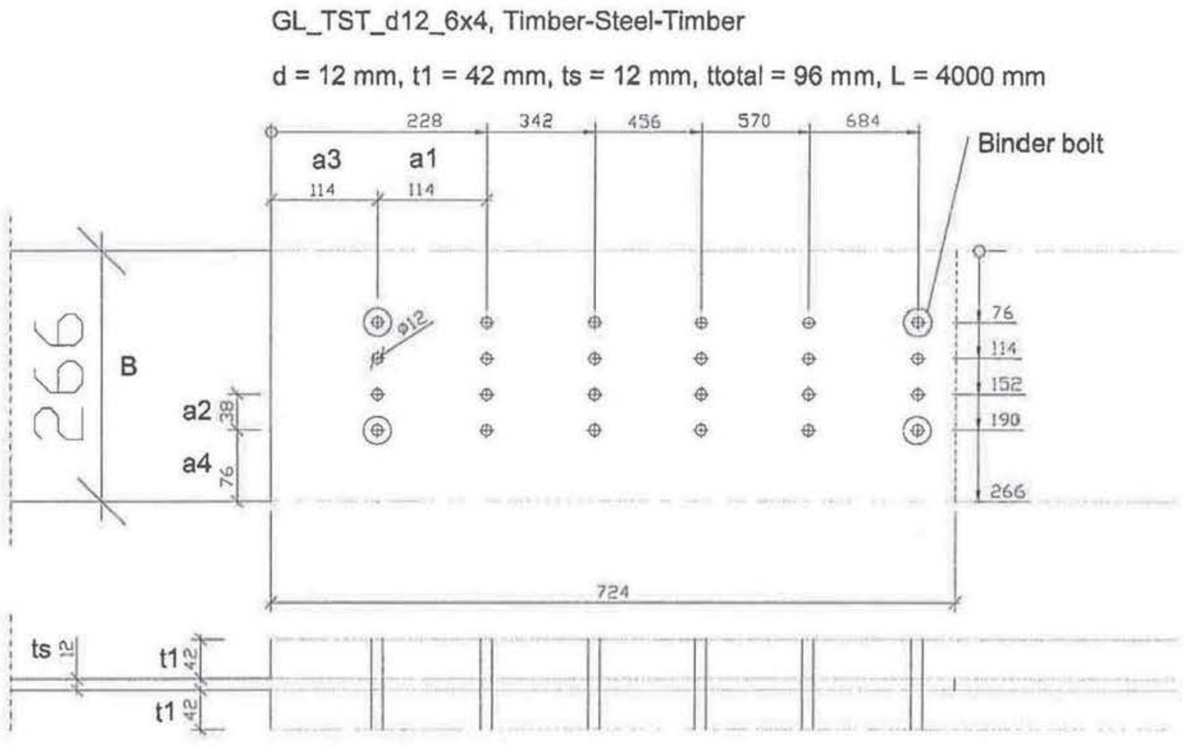

Figure 1. Example of a double shear dowelled timber-steel-timber connection used in the tests (GL_TST_d12_6x4).

Table 1. Glulam series with double-shear dowelled connections.

Series name	Dowel pattern n x m	dowel diam. d mm	thick-ness t_1 or t_2 mm	width B mm	steel plate t_s mm	spacing parall. a_1 mm	spacing, perp. a_2 mm	end dist. a_3 mm	edge dist. a_4 mm	N
Timber-Steel-Timber, Dowel diameter 12mm										
GL28h, $t_1 = 42$ mm, $d = 12$ mm, dowel strength.cl. 8.8, $a_2 = 38$ mm, $a_3 = a_1$										
GL_TST_d12_12x2	12 x 2	12	42	220	12	93	38	93	91	3
GL_TST_d12_8x3	8 x 3	12	42	244	12	105	38	105	84	3
GL_TST_d12_6x4	6 x 4	12	42	266	12	114	38	114	76	5
GL_TST_d12_4x6	4 x 6	12	42	296	12	114	38	114	53	3
Steel-Timber-Steel, Dowel diameter 12mm										
GL28h, $t_2 = 90$ mm, $d = 12$ mm, dowel strength cl. 8.8, $a_3 = \max(a_1; 84\text{ mm})$, $t_s = 6$ mm										
GL_STS_d12_12x2	12 x 2	12	90	250	6	84	48	84	101	3
GL_STS_d12_8x3	8 x 3	12	90	262	6	120	48	120	83	3
GL_STS_d12_6x4	6 x 4	12	90	276	6	60	58	84	51	5
GL_STS_d12_4x6	4 x 6	12	90	304	6	60	40	84	52	3
GL_STS_d12_3x8	3 x 8	12	90	372	6	84	36	84	60	3
Timber-Steel-Timber, Dowel diameter 8mm										
GL28h, $t_1 = 28$ mm, $d = 8$ mm, dowel strength cl. 10.9, $a_2 = 26$ mm, $a_3 = 80$ mm										
GL_TST_d8_12x2	12 x 2	8	28	158	8	64	26	80	66	3
GL_TST_d8_6x4	6 x 4	8	28	192	8	80	26	80	57	3
Steel-Timber-Steel, Dowel diameter 8mm										
GL28h, $t_2 = 60$ mm, $d = 8$ mm, dowel strength cl. 10.9, $a_3 = 80$ mm, $t_s = 4$ mm										
GL_STS_d8_12x2	12 x 2	8	60	174	4	56	32	80	71	3
GL_STS_d8_6x4	6 x 4	8	60	190	4	40	40	80	35	3

Table 2. Kerto-LVL series with double-shear dowelled connections. Kerto-S is standard LVL and Kerto-Q is cross veneered.

Series name	Dowel pattern $n \times m$	dowel diam. d mm	thick-ness t_1 or t_2 mm	width B mm	steel plate t_s mm	spacing parall. a_1 mm	spacing, perp. a_2 mm	end dist. a_3 mm	edge dist. a_4 mm	N
Timber-Steel-Timber, Dowel diameter 12mm										
Kerto-S, $t_1 = 39$ mm, $d = 12$ mm, dowel strength cl 8.8, $a_2 = 38$ mm, $a_3 = \max(a_1; 105\text{mm})$										
KS_TST_d12_12x2	12x2	12	39	162	12	84	38	105	62	3
KS_TST_d12_8x3	8x3	12	39	180	12	93	38	105	52	3
KS_TST_d12_6x4	6x4	12	39	204	12	105	38	105	45	5
KS_TST_d12_4x6	4x6	12	39	266	12	105	38	105	38	3
Kerto-Q, $t_1 = 39$ mm, $d = 12$ mm, dowel strength cl. 8.8, $a_2 = 38$ mm, $a_3 = 105$mm										
KQ_TST_d12_6x4	6x4	12	39	258	12	105	38	105	72	3
Steel-Timber-Steel, Dowel diameter 12mm										
Kerto-S, $t_2 = 75$ mm, $d = 12$ mm, dowel strength cl. 8.8, $a_3 = 105$ mm, $t_s = 6$ mm, $F_{Rk} = 624$ kN										
KS_STS_d12_12x2	12x2	12	75	228	6	84	48	105	90	3
KS_STS_d12_8x3	8x3	12	75	224	6	105	48	105	64	3
KS_STS_d12_6x4	6x4	12	75	252	6	84	60	105	36	5
KS_STS_d12_4x6	4x6	12	75	272	6	84	40	105	36	3
KS_STS_d12_3x8	3x8	12	75	324	6	84	36	105	36	3
Timber-Steel-Timber, Dowel diameter 8mm										
Kerto-S, $t_1 = 27$ mm, $d = 8$ mm, dowel strength cl. 10.9, $a_2 = 26$ mm, $a_3 = 105$ mm										
KS_TST_d8_12x2	12x2	8	27	116	8	56	26	105	45	3
KS_TST_d8_6x4	6x4	8	27	138	8	64	26	105	30	3
Steel-Timber-Steel, Dowel diameter 8mm										
Kerto-S, $t = 51$ mm, $d = 8$ mm, dowel strength cl. 10.9, $a_3 = 105$ mm, $t_s = 4$ mm										
KS_STS_d8_12x2	12x2	8	51	160	4	56	32	105	64	3
KS_STS_d8_6x4	6x4	8	51	174	4	56	42	105	24	3
Kerto-Q, $t = 51$ mm, $d = 8$ mm, dowel strength cl. 10.9, $a_3 = 60$ mm, $t_s = 4$ mm										
KQ_STS_d8_12x2	12x2	8	51	210	4	56	32	60	89	3
KQ_STS_d8_6x4	6x4	8	51	224	4	56	42	60	49	3

3.2 Multiple shear connection specimens

The multiple shear tests series are shown in Tables 3 and 4 for glulam and LVL, respectively.

Multiple shear test series were made with connected members except one series (GL-4Sh_d8_AZ). The glulam specimens were manufactured from split glulam, but the split parts were glued together using two battens of either 14 mm thickness or 10 mm thickness depending on the steel plate thickness 12 mm or 8 mm, respectively. Similarly, LVL-specimens were manufactured by gluing the parts together. The gluing was made as screw-gluing with polyurethane glue. Series GL-4Sh_d8_6x4_AZ was made with unattached members and was used as a parallel series to GL-4Sh_d8_6x4_A to see, if the capacity depends on whether the timber members are glued together or not.

Table 3. Glulam series with multiple shear dowelled connections.

Series name	Dowel pattern n x m	dowel diam. d mm	thick-ness t_1 / t_2 mm	width B mm	steel plate t_s mm	spacing parall. a_1 mm	spacing perp. a_2 mm	end dist. a_3 mm	edge dist. a_4 mm	N
4-Shear, Timber-Steel-Timber-Steel-Timber, Dowel diameter 12mm										
GL28h, $d = 12$ mm, dowel strength cl. 8.8, $a_2 = 38$ mm, $a_3 = a_1$, $t_s = 12$ mm										
GL 4Sh d12 12x2A	12x2	12	42 / 90	250	12	93	38	93	106	3
GL_4Sh_d12_12x2B	12x2	12	35 / 104	250	12	93	38	93	106	3
GL_4Sh_d12_6x4A	6x4	12	42 / 90	276	12	114	38	114	81	3
GL 4Sh d12 6x4B	6x4	12	35 /104	276	12	114	38	114	81	3
4-Shear, Timber-Steel-Timber-Steel-Timber, Dowel diameter 8mm										
GL28h, $d = 8$ mm, dowel strength class10.9, $a_2 = 26$ mm, $a_3 = 80$ mm, $t_s = 8$ mm										
GL 4Sh d8 12x2A	12x2	8	28 / 60	174	8	64	26	80	74	3
GL_4Sh_d8_12x2B	12x2	8	22 / 72	174	8	64	26	80	74	3
GL_4Sh_d8_6x4AZ(*	6x4	8	28 / 60	192	8	80	26	80	57	3
GL_4Sh_d8_6x4B	6x4	8	22 / 72	192	8	80	26	80	57	3
GL 4Sh d8 6x4A(*	6x4	8	28 / 60	192	8	80	26	80	57	3
6-Shear, Timber-Steel-Timber-Steel-Timber-Steel-Timber, Dowel diameter 8mm										
GL28h, $d = 8$ mm, dowel strength class10.9, $a_2 = 26$ mm, $a_3 = 80$ mm, $t_s = 8$ mm										
GL 6Sh d8 12x2	12x2	8	28 / 60	174	8	64	26	80	74	3

Table 4. Kerto-LVL series with multiple shear dowelled connections.

Series name	Dowel pattern n x m	dowel diam. d mm	thick-ness t_1 / t_2 mm	width B mm	steel plate t_s mm	spacing parall. a_1 mm	spacing perp. a_2 mm	end dist. a_3 mm	edge dist. a_4 mm	N
4-Shear, Timber-Steel-Timber-Steel-Timber, Dowel diameter 12mm										
Kerto-S, $d = 12$ mm, Dowel strength class 8.8, $a_2 = 48$ mm, $a_3 = 105$ mm, $t_s = 8$ mm										
KS 4Sh d12 12x2	12 x 2	12	38 / 72	228	8	84	48	105	90	3
KS 4Sh d12 6x4	6 x 4	12	38 / 72	252	8	105	48	105	54	3
Kerto-Q, $d = 12$ mm, Dowel strength class 8.8, $a_2 = 48$ mm, $a_3 = 105$ mm, $t_s = 8$ mm										
KQ 4Sh d12 5x4	5 x 4	12	38 / 72	322	8	105	48	105	89	3
4-Shear, Timber-Steel-Timber-Steel-Timber, Dowel diameter 8mm										
Kerto-S, $d = 8$ mm, Dowel strength class 10.9, $a_2 = 32$ mm, $a_3 = 105$ mm, $t_s = 8$ mm										
KS 4Sh d8 12x2A	12 x 2	8	26 / 49	160	8	56	32	105	64	3
KS_4Sh_d8_12x2B	12 x 2	8	20 / 61	160	8	56	32	105	64	3
KS_4Sh_d8_6x4A	6 x 4	8	26 / 49	176	8	56	32	105	40	3
KS 4Sh d8 6x4B	6 x 4	8	20 / 61	176	8	56	32	105	40	3
Kerto-Q, $d = 8$ mm, Dowel strength class 10.9, $a_2 = 32$ mm, $a_3 = 60$ mm, $t_s = 8$ mm										
KQ 4Sh d12 6x4	6 x 4	8	26 / 49	226	8	56	32	60	65	3
6-Shear, Timber-Steel-Timber-Steel-Timber-Steel-Timber, Dowel diameter 8mm										
Kerto-S, $d = 8$ mm, Dowel strength class 10.9, $a_2 = 32$ mm, $a_3 = 105$ mm, $t_s = 8$ mm										
KS 6Sh d8 12x2	6 x 4	8	26 / 49	176	8	56	32	105	40	3

4 Methods

The dowel holes for glulam were drilled using a numerical control (NC) machine tool. The glulam specimens were first allowed to reach equilibrium moisture content in a climate chamber with relative humidity of 65% and temperature 20°C (corresponding to equilibrium moisture content 12%) and drilled within 12h from taking outside the chamber. Then the specimens were taken back to the climate chamber. After that, the steel plates were put in place, dowels inserted as well as the binderbolts and nuts assembled. The LVL specimens were also drilled using a numerical control machine tool, at the Kerto-LVL factory.

All series were kept in a climate chamber (20°C, 65%RH) long enough that they reached the equilibrium moisture content before manufacturing of joints and testing.

The loading was made according to EN26891:1991

5 Results and analysis

The results of the double shear tests are presented in Tables 5 and 6 and the multiple shear tests in Tables 7 and 8 for glulam and LVL, respectively. The presented test results contain the measured mean density, mean maximum slip (v_{max}) and mean maximum load (F_{max}) and its coefficient of variation. The observed failure mechanism is also reported. The prevailing failure mechanism was block shear (Fig. 2), but also tensile failures occurred as well as a few rowshear failures. However, no plug shear failures were detected.

For better comparison of the test results to the design formulas of Eurocode 5 (EC5, EN 1995-1-1:2004) some calculated values based on EC5 equations are also added to Table 5-8. The calculated values represent either characteristic values (subscript k) or mean values (subscript m) and are explained in the list of symbols (Chapter 2). The characteristic values have been calculated based on characteristic material properties as obtained from standards. The mean values are based on the measured values of density of timber and tensile strength of dowels. The mean values of non-measured properties have been assumed the following values:

- Glulam: $f_{tm} = 1.3 * f_{tk} = 29$ N/mm^2, $f_{vm} = 1.3 * f_{vk} = 4.9$ N/mm^2
- Kerto-S: $f_{tm} = 43$ N/mm^2, $f_{vm,edge} = 4.9$ N/mm^2, $f_{vm,flat} = 3.0$ N/mm^2
- Kerto-Q: $f_{tm} = 33$ N/mm^2, $f_{vm,edge} = 5.4$ N/mm^2, $f_{vm,flat} = 1.7$ N/mm^2

The above values for Kerto-LVL are estimated based on initial tests made at VTT according to the product standard EN14374. The values for glulam are an estimation based on experience.

The load-carrying capacity in case of splitting or rowshear is calculated by a reduction of the number of dowels n and capacity given by Johansen theory (EC5, Eqs. 8.1, 8.34):

$$F_{Sk} = \frac{n_{ef}}{n} F_{Rk}, \quad where\ n_{ef} = \min\left(n, n^{0.9} \left(\frac{a_1}{13d} \right)^{0.25} \right) \tag{1}$$

where F_{Rk} is the capacity by the Johansen theory.

The load-carrying capacity in case of block or plug shear failure has been calculated by the formula (A.1) in the Annex A of EC5:

$$F_{bs,Rk} = F_{Bk} = \max \begin{cases} 1.5 A_{net,t} f_{t,0,k} \\ 0.7 A_{net,v} f_{v,k} \end{cases} \tag{2}$$

where $f_{t,0,k}$ and $f_{v,k}$ are the tensile and shear strengths of the material, respectively, and $A_{net,t}$ and $A_{net,v}$ are the areas along the assumed failure surface that are under tension and shear stress, respectively. The areas are calculated as (Annex A Eq. A.2, A.3):

$$A_{net,t} = L_{net,t} t_1 \tag{3}$$

$$A_{\mathrm{net,v}} = \begin{cases} L_{\mathrm{net,v}}\, t_1 & \text{embedment fail. or steel} - \text{timber} - \text{steel connection} \\ \dfrac{L_{\mathrm{net,v}}}{2}\left(L_{\mathrm{net,t}} + 2t_{ef}\right) & \text{other cases} \end{cases} \qquad (3)$$

where t_{ef} is the calculational distance from the surface to the dowel plastic hinge according to the Johansen theory. The magnitudes of $L_{\mathrm{net,t}} = (m-1)*(a_2-d)$ and $L_{\mathrm{net,v}} = (n-1)*(a_1-d)+(a3-d)$ (see Fig. 2).

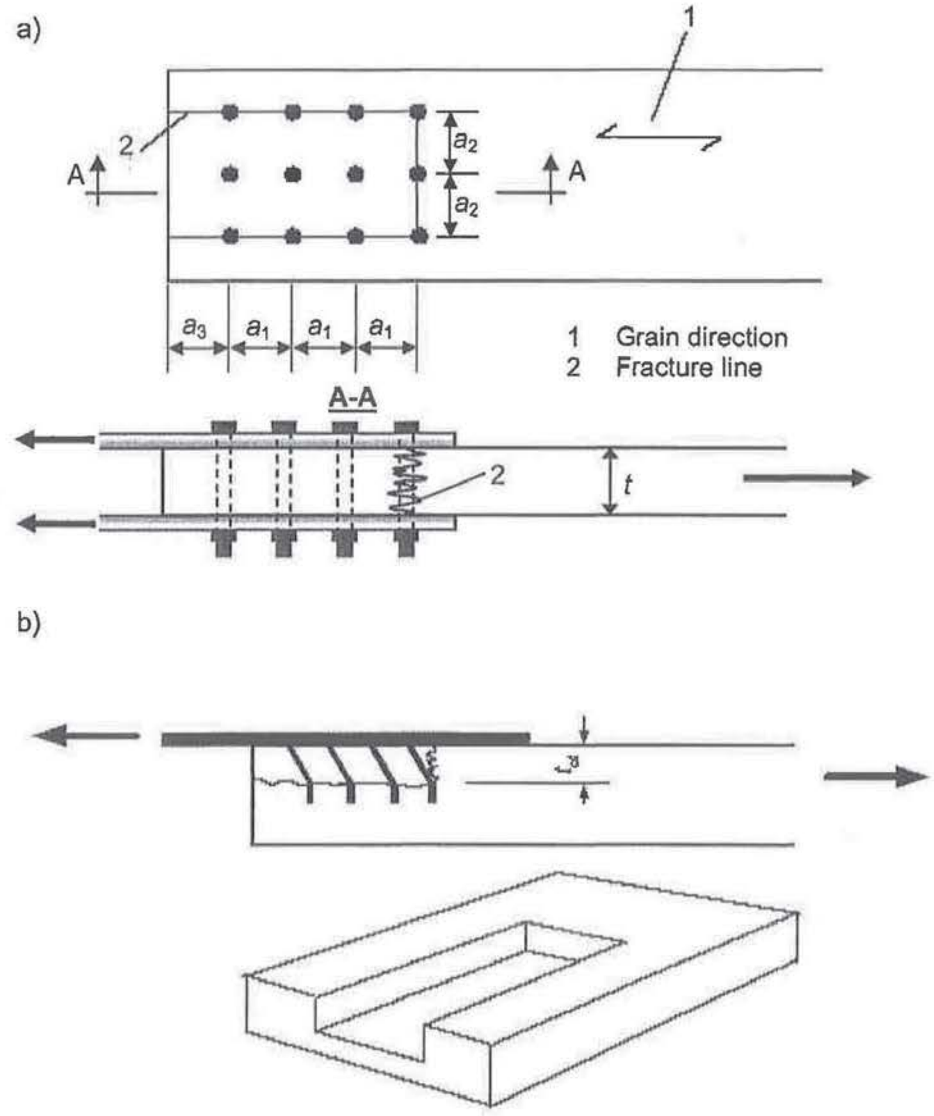

Figure 2. a) Block shear failure and b) plug shear failure of a dowelled connection.

Table 5. The calculated capacities and test results of the glulam series with double-shear dowelled connections. Symbols: see Chapter 2.

Series name	F_{Sk} kN	F_{Bk} kN	DF	F_{Rm} kN	F_{Sm} kN	F_{Bm} kN	F_{Tm} kN	ρ_m kg/m^3	v_{max} mean mm	F_{max} mean kN	F_{max} CoV %	TF	F_{max} / F_{Sm}	F_{max} / F_{Bm}
Timber-Steel-Timber, Dowel diameter 12mm														
GL28h, t_1 = 42 mm, d = 12 mm, Dowel strength cl. 8.8, F_{Rk} = 520 kN														
GL TST d12 12x2	356	297	p	579	397	385	459	466	1.9	424	8.3	b	1.07	1.10
GL_TST_d12_8x3	382	315	p	574	422	409	487	460	2.0	504	11.6	b	1.19	1.23
GL_TST_d12_6x4	402	332	p	585	452	430	511	474	2.3	529	4.4	b	1.17	1.23
GL TST d12 4x6	418	319	p	577	464	415	525	464	2.8	571	6.2	b	1.23	1.38
Steel-Timber-Steel, Dowel diameter 12mm														
GL28h, t_2 = 90 mm, d = 12 mm, dowel strength cl. 8.8, F_{Rk} = 576 kN														
GL STS d12 12x2	385	353	b-r	635	424	459	567	462	2.4	537	2.8	b	1.27	1.17
GL_STS_d12_8x3	438	353	b-r	644	490	459	567	475	3.7	646	7.4	b	1.32	1.41
GL_STS_d12_6x4	379	363	b-t	625	411	472	572	447	3.0	606	10.1	b	1.47	1.28
GL_STS_d12_4x6	395	369	b-t	638	438	479	582	467	2.6	552	6.0	b	1.26	1.15
GL STS d12 3x8	442	442	b-t	638	490	575	693	466	4.0	671	1.5	row	1.37	1.17
Timber-Steel-Timber, Dowel diameter 8mm														
GL28h, t_1 = 28 mm, d = 8 mm, dowel strength cl. 10.9, F_{Rk} = 279 kN														
GL TST d8 12x2	193	148	p	314	217	191	222	472	1.9	266	5.6	b	1.23	1.39
GL TST d8 6x4	218	164	p	296	232	214	250	425	1.6	238	17.7	b	1.03	1.11
Steel-Timber-Steel, Dowel diameter 8mm														
GL28h, t_2 = 60 mm, d = 8 mm, dowel strength cl. 10.9, F_{Rk} = 318 kN														
GL STS d8 12x2	212	163	b-r	355	237	212	264	468	2.6	295	21.6	b	1.24	1.39
GL STS d8 6x4	209	168	b-t	353	232	219	264	462	2.0	299	4.8	(*	1.29	1.37

*) the dominating failure mode is unclear

Table 6. The calculated capacities and results of the LVL series with double-shear dowelled connections. Symbols: see Chapter 2.

Series name	F_{Sk} kN	F_{Bk} kN	DF	F_{Rm} kN	F_{Sm} kN	F_{Bm} kN	F_{Tm} kN	ρ_m kg/m^3	v_{max} mean mm	F_{max} mean kN	F_{max} CoV %	TF	F_{max} / F_{Sm}	F_{max} / F_{Bm}
Timber-Steel-Timber, Dowel diameter 12mm														
Kerto-S, t_1 = 39 mm, d = 12 mm, Dowel strength cl. 8.8, F_{Rk} = 563 kN														
KS TST d12 12x2	376	331	p	594	397	395	506	499	2.6	400	7.9	b	1.01	1.01
KS_TST_d12_8x3	402	347	p	588	420	414	528	492	2.3	460	6.8	b	1.10	1.11
KS_TST_d12_6x4	426	378	p	603	456	449	572	512	2.6	507	6.1	b	1.11	1.13
KS TST d12 4x6	444	532	s/r	586	462	649	711	488	3.1	598	0.8	b	1.29	0.92
Kerto-Q, t_1 = 39 mm, d = 12 mm, Dowel strength cl. 8.8, F_{Rk} = 542 kN														
KQ TST d12 6x4	411	237	p	561	425	297	586	482	2.6	447	2.1	T	1.05	1.51
Steel-Timber-Steel, Dowel diameter 12mm														
Kerto-S, t_2 = 75 mm, d = 12 mm, Dowel strength cl. 8.8, F_{Rk} = 665 kN														
KS STS d12 12x2	444	386	b-r	722	483	459	719	523	2.7	500	5.2	b	1.04	1.09
KS_STS_d12_8x3	489	325	b-r	726	534	387	662	527	3.2	568	0.8	b	1.06	1.47
KS_STS_d12_6x4	476	567	s/r	736	527	692	719	537	3.7	591	7.1	b	1.12	0.85
KS_STS_d12_4x6	496	551	s/r	753	562	673	705	556	2.8	570	4.9	b	1.01	0.85
KS STS d12 3x8	510	662	s/r	717	551	807	803	518	2.8	561	7.3	b	1.02	0.70
Timber-Steel-Timber, Dowel diameter 8mm														
Kerto-S, t_1 = 27 mm, d = 8 mm, Dowel strength cl. 10.9, F_{Rk} = 303 kN														
KS TST d8 12x2	203	167	p	324	216	199	254	502	1.8	200	7.6	b	0.93	1.01
KS TST d8 6x4	224	180	p	328	243	214	269	514	1.7	241	13.0	b	0.99	1.13
Steel-Timber-Steel, Dowel diameter 8mm														
Kerto-S, t_2 = 51 mm, d = 8 mm, Dowel strength cl. 10.9, F_{Rk} = 344 kN														
KS STS d8 12x2	230	185	b-r	374	250	220	345	524	2.8	296	2.0	b	1.18	1.35
KS STS d8 6x4	246	273	s/r	380	272	333	340	518	3.8	336	2.3	b	1.25	1.01
Kerto-Q, t_2 = 51 mm, d = 8 mm, Dowel strength cl. 10.9, F_{Rk} = 333 kN														
KQ STS d8 12x2	223	188	b-r	341	228	226	354	492	3.7	308	7.0	T	1.35	1.36
KQ STS d8 6x4	239	203	b-t	348	249	254	350	501	3.9	335	7.3	b,T	1.35	1.32

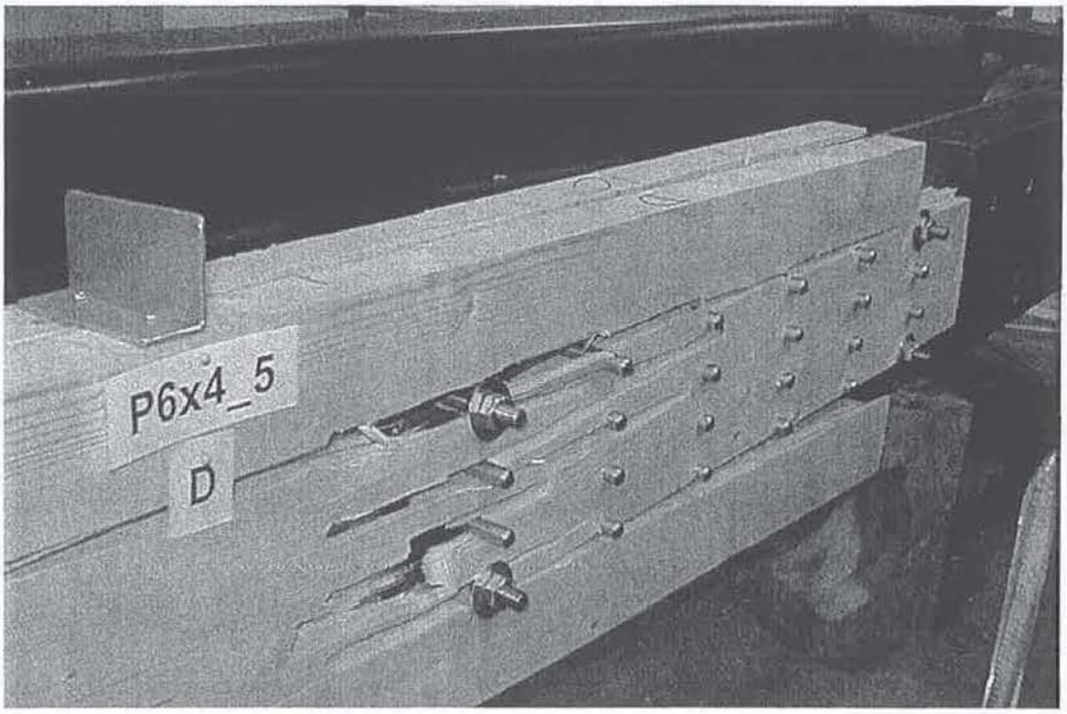

Figure 3. Typical failure by the block shear failure mechanism.

Table 7. The calculated capacities and test results of the Glulam series with multiple-shear dowelled connections. Symbols: see Chapter 2.

Series name	F_{Sk} kN	F_{Bk} kN	DF	F_{Rm} kN	F_{Sm} kN	F_{Bm} kN	F_{Tm} kN	ρ_m kg/m^3	v_{max} mm	F_{max} mean kN	F_{max} CoV %	TF	F_{max} / F_{Sm}	F_{max} / F_{Bm}
4-Shear, Dowel diameter 12mm														
GL28h, d = 12 mm, dowel str. cl. 10.9, t_s = 12 mm, F_{Rk} = 1040 kN (A), 1122 kN (12x2B), 1447 (6x4B)														
GL_4Sh_d12_12x2A	781	702	p,b-r	1216	833	910	1096	447	2.0	968	6.9	b,b	1.16	1.06
GL_4Sh_d12_12x2B	769	744	p,b-r	1196	820	965	1096	449	2.1	1084	5.7	b,b	1.32	1.12
GL_4Sh_d12_6x4A	881	589	p,b-r	1240	958	762	1106	463	1.4	856	5.9	b,b	0.89	1.12
GL_4Sh_d12_6x4B	1118	616	p,b-r	1592	1230	798	1106	462	1.8	1069	6.3	b,b	0.87	1.34
4-Shear, Dowel diameter 8mm														
GL28h, d = 8 mm, dowel strength class10.9, t_s = 8 mm, F_{Rk} = 558 kN (A), 689 kN (B)														
GL_4Sh_d8_12x2A	385	335	p,b-r	598	413	435	511	447	2.0	501	20.3	b,b	1.21	1.15
GL_4Sh_d8_12x2B	476	363	b-r,b-r	791	546	468	511	471	1.9	530	4.3	b,b	0.97	1.13
GL_4Sh_d8_6x4AZ	437	282	p,b-r	606	474	366	518	458	2.0	586	6.1	b,b	1.24	1.60
GL_4Sh_d8_6x4B	539	299	b-r,b-r	765	599	388	517	455	1.8	478	15.9	b,b	0.80	1.23
GL_4Sh_d8_6x4A	437	282	p,b-r	596	467	366	518	444	1.8	546	4.5	b,b	1.17	1.49
6-Shear, Dowel diameter 8mm														
GL28h, d = 8 mm, dowel strength class10.9, t_s = 8 mm, F_{Rk} = 837 kN														
GL_6Sh_d8_12x2	655	400	p,b-r	879	688	521	786	431	1.7	765	11.7	b,b	1.11	1.47

Table 8. The calculated capacities and test results of the LVL series with multiple-shear dowelled connections. Symbols: see Chapter 2.

Series name	F_{Sk} kN	F_{Bk} kN	DF	F_{Rm} kN	F_{Sm} kN	F_{Bm} kN	F_{Tm} kN	ρ_m kg/m³	v_{max} mm	F_{max} mean kN	F_{max} CoV %	TF	F_{max} / F_{Sm}	F_{max} / F_{Bm}
4-Shear, Dowel diameter 12mm														
Kerto-S, d = 12 mm, Dowel strength class 10.9, F_{Rk} = 1226kN														
KS 4Sh d12 12x2	819	758	p,b-r	1314	878	898	1418	525	2.3	898	7.6	b,b	1.02	1.00
KS 4Sh d12 6x4	928	886	b-t,b-t	1312	993	1065	1418	523	2.2	1157	1.2	b,b	1.17	1.09
Kerto-Q, d = 12 mm, Dowel strength class 10.9, F_{Rk} = 1188kN														
KQ 4Sh d12 5x4	900	623	b-t,b-r	1272	963	779	1449	527	4.3	1196	3.1	b,b	1.24	1.53
4-Shear, Dowel diameter 8mm														
Kerto-S, d = 8 mm, Dowel strength class 10.9, F_{Rk} =604kN (A), F_{Rk} = 702 kN (B)														
KS 4Sh d8 12x2A	404	364	p,b-r	658	440	431	683	538	1.8	460	8.8	b,b	1.05	1.07
KS_4Sh_d8_12x2B	469	396	b-r,b-r	790	528	468	684	540	2.0	511	2.5	b,b	0.97	1.09
KS_4Sh_d8_6x4A	433	382	b-t,b-t	660	473	466	683	541	1.5	492	1.1	b,b	1.04	1.06
KS 4Sh d8 6x4B	503	419	b-t,b-t	772	553	504	684	528	1.7	528	2.8	b,b	0.95	1.05
Kerto-Q, d = 8 mm, Dowel strength class 10.9, F_{Rk} = 584 kN														
KQ 4Sh d12 6x4	418	324	b-t,b-t	618	443	396	701	518	2.3	584	4.9	b,b	1.31	1.47
6-Shear, Dowel diameter 8mm														
Kerto-S, d = 8 mm, Dowel strength class 10.9, F_{Rk} = 906 kN														
KS 6Sh d8 12x2	649	567	b-t,b-t	876	627	462	670	550	1.7	729	8.8	b,b	1.16	1.58

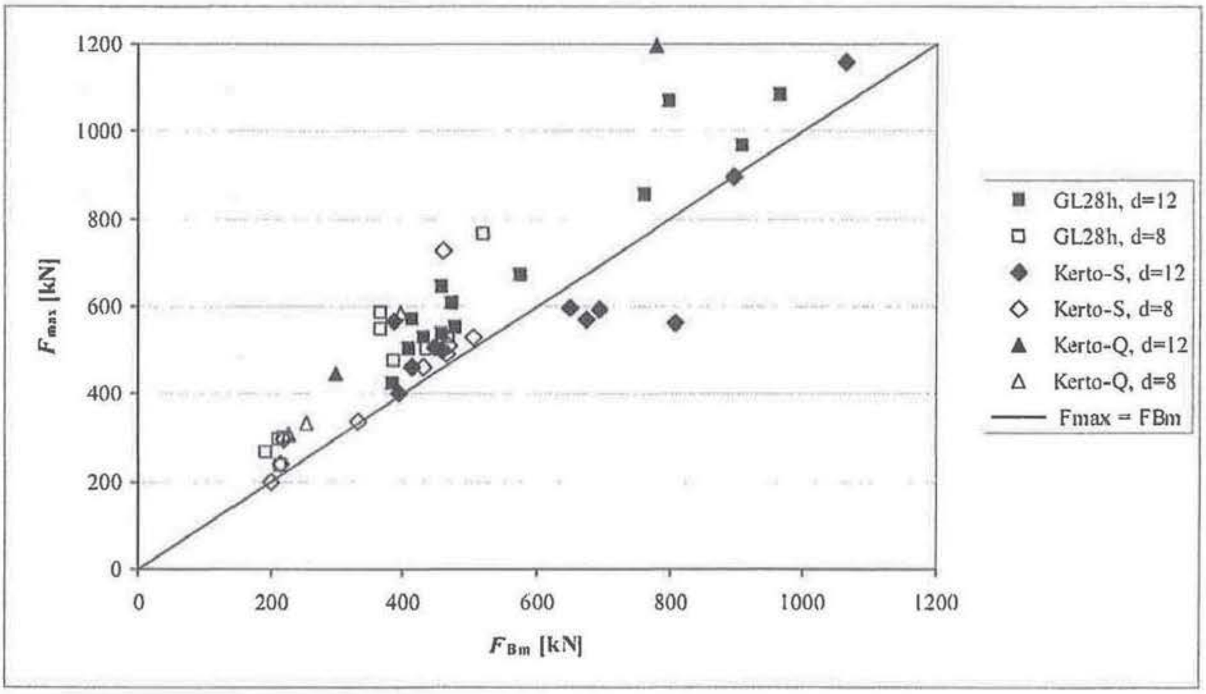

Figure 4. F_{max} plotted agains F_{Bm}. Each point is the mean result of one series. Note that in all four series which are under the F_{max} = F_{Bm} line, the critical design is not due to block shear but splitting or rowshear, represented by F_S, and in all four cases $F_{max} > F_{Sm}$.

6 Discussion

One surprising feature in the results is that the observed failure mode is in a large proportion different than what the calculation of the capacity value is based on (EN1995-1-1:2004). Especially this concerns the double-shear timber-steel-timber series and the outer timber members of the multiple-shear series. In a large part of the series of these kinds, the calculation of the capacity is based on the plug-shear failure mechanisms, whereas the observed failure was block shear. In fact, in no cases was plug shear observed. For the Kerto-Q LVL the plug shear failure design value is in some cases very low, due to the low shear strength of the cross-veneers (rolling shear). However, in no cases was the plug shear observed for the Kerto-Q specimens, either. The plug shear failure does not occur, because the dowels remain straight or bend very little before failure and failure occurs as block shear.

Another general observation is that, even if according to the design equations the failure load due to block or plug shear and splitting (F_{Bm} and F_{Sm}) are very close to each other, and F_{Sm} is even lower than F_{Bm}, there were almost no cases of splitting or rowshear failure detected, which should be represented by F_{Sm} (only few series showed rowshear). This indicates that the equation by which F_{Sm} is calculated is too conservative for these types of connections, although the dowels were rather rigid.

Kerto-Q behaves differently from what could be anticipated from design equations. The low value of flatwise shear strength leads calculationally to very low capacity, if the critical failure mechanism is plug shear. However, in practice the plug shear does not occur due to rigid dowels and the capacity is much higher than expected by design calculations.

7 Conclusions

Based on the large experimental data that has been gathered by the loading of more than 150 specimens and 300 connections, the following recommendations can be given for the development of the design of dowelled timber-to-steel connections:

- The plug shear failure mechanism does not occur in the connection area contrarily to what the design equations in EC5 (EN 1995-1-1:2004; Annex A) suggest. This is due to the fact that the relatively rigid dowels remain straight or bend very little before failure, which is then mostly due to the block shear mechanism. Failure by plug shear would probably require the development of fully developed plastic hinges, which does not occur at the failure level of block shear. The design equations assume the fully developed plastic hinges in order to determine the failure mechanism based on the Johansen theory.
- If the mean material property values are substituted in the design equations of EC5, the value of F_{Sm} and F_{Bm}, representing splitting or rowshear failure and block shear or plug shear failure, respectively, are often very close to each other. In many cases the value of F_{Sm} is lower that F_{Bm}. However, in these experimental tests no pure splitting failure was observed and rowshear in only few series. This indicates that the equation for the reduction effect of the number of dowels in a row is too conservative for these connections, because it does not take into account the slenderness of the dowels.
- Connections with cross-veneered Kerto-Q-LVL showed much higher experimental capacities than could be anticipated from the design calculations using the characteristic values in EC5. This is due to the fact that the plug shear failure does not occur because of rigid dowels and because the low flatwise shear strength reduces the calculational capacity dramatically in case of plug shear.
- When the calculational failure mode of EC5 is block shear (b-r, b-t) it can be concluded that the formulas result usually in clearly conservative design for glulam,

but they are approximately on the right level for Kerto-S-LVL. Higher coefficients (instead of 1.5 and 0.7) could therefore be used for glulam in Eq. (2). However, the following additional condition should be given for the failure mode b-r (block-shear with shear capacity higher than tension): it works only if the edge distance a_3 is sufficiently large so that the tensile capacity of the outermost timber strips is enough to carry the whole failure load. It is apparent that, in most block shear failure cases, a simultaneous combination of tensile and shear stress is acting.

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