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STUDY OF STEEL-TO-TIMBER CONNECTIONS WITH VERY THIN STEEL PLATES

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ABSTRACT

The development of a new hybrid construction consisting of laminated veneer lumber made of softwood or beech and cold-formed steel sections leads to connections with steel sheet thicknesses smaller than 2 mm. To design the hybrid construction, the load displacement behaviour of the connections between the components is required. Therefore, single-shear tests with two fasteners are conducted to investigate the load-displacement behaviour of the connections. The tests are stopped at predefined displacement stages of 4 mm, 8 mm or carried out until failure. After the tests, the specimens are opened to observe the progressive deformations in the connections. The focus of the evaluation is on the deformation process of fasteners, steel sheet and timber material as well as the failure modes of the connections. A comparison of the fastener deformation and the development of plastic hinges at different displacement stages shows, that a clamping effect is present for a steel sheet thickness greater than or equal to 1 mm. As a basis for the single-shear tests, all input parameters of the connections are determined to enable the calculation of the load-bearing capacity. The calculated load capacity of the connections still significantly underestimates the ultimate load in the tests.

Keywords: connections, very thin steel plates, timber, LVL.

INTRODUCTION

In times when material costs are high compared to labour costs, hybrid constructions with economical use of materials represent cost-effective solutions. Such a hybrid construction can be a combination of laminated veneer lumber (LVL) made of softwood or beech and cold-formed steel sections for floor slabs and shear walls with steel plate thicknesses smaller than 2 mm. Fig. 1 shows a possible schematic structure of a hybrid element with a trapezoidal cold-formed steel sheet. For the design of these hybrid structures, knowledge of the load-displacement behaviour of the steel-to-timber connections is important as it has a great influence on the load-bearing behaviour of the whole structure. For the investigation of the connections in the hybrid elements, these must be divided into the two types of connection “steel-to-timber” and “timber-to-steel”, as can be seen in Figure 1. This distinction is necessary due to the manufacture of the hybrid elements. At the first step the trapezoidal cold-formed steel sheet is connected to the lower timber panel so that the steel sheet is penetrated first and a “steel-to-timber” connection is produced. At the second step the upper timber panel is connected to the trapezoidal cold-formed steel sheet so that the timber panel is penetrated first and a “timber-to-steel” connection is produced. The designation of the connection is chosen in such a way that the material named first is also penetrated first. To make the production as easy as possible, the connections were made without pre-drilling. Self-drilling screws from the field of lightweight metal construction and ringed shank nails from the field of timber construction were selected as fasteners. The nails were inserted using pneumatic driving devices. The fact that this is also possible through non-pre-drilled steel sheets was already shown by the investigations in Ehlbeck and Eberhart [1]. In order to verify this, investigations were carried out in Strübel [2] on the production of joints in hybrid elements with different fasteners. The three fasteners used in this study proved to be the most suitable for use in the hybrid elements.

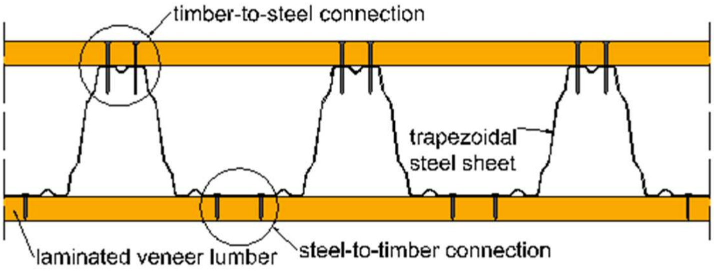


Fig. 1 – Schematic construction of the hybrid element.

In order to investigate the load-displacement behaviour of steel-to-timber connections with very thin steel plates, single-shear connection tests with two fasteners were carried out. The thickness of the steel plates was varied between 0.75 and 1.5 mm. In timber constructions, thickness of steel plates is usually larger than 1.5 mm. For a better understanding of the mechanical behaviour, the conducted tests were stopped at predefined displacement stages of 4 mm, 8 mm and finally carried out until failure. After the tests, the specimens were opened. This allowed a comparison of the embedment and fastener deformation at different displacement stages. This testing method has already been carried out in Kuck and Sandhaas [3] for connections in hardwoods and is called "multi-stage tests".

MATERIALS

Wood products

Laminated veneer lumber made of softwood (**LVL-X**, STEICOLVL X Z-9.1-842 2019) and beech (**BB**, BauBuche ETA-14/0354 2021) with cross layers were used. Both products were stored at a standard climate of 20°C temperature and 65 % relative air humidity. The used panels of LVL-X had a thickness of 39 mm with three cross layers in accordance with Z-9.1-842 (2019) and their mean density was 621 kg/m³ at a mean moisture content of 9.1 %. The BB panels had only two cross layers in cross-section with a thickness of 40 mm and their mean density was 819 kg/m³ at a mean moisture content of 6.6 %. Based on the applied pressure and heat during the manufacturing process of BB panels, local density varied over the height of the BB panel [4].

Steel plates

The used steel plates were made of galvanised steel DX 51 D+Z 275 according to EN 10143 and had a thickness between 0.75 and 1.5 mm. The steel properties were determined with tensile tests according to EN ISO 6982-1 and the mean yield strength was $f_y = 391$ N/mm² at a mean tensile strength of $f_u = 446$ N/mm². These properties are similar to S320 GD steel which is usually used for cold-formed steel sections.

Fasteners

For the connections between the thin steel plates and the wood products three different types of fasteners were investigated and are shown in Table 1. The fasteners can be divided into the two types of connection. For the “steel-to-timber” connection a self-drilling screw and a ringed shank nail were used. In these connections the head of the fasteners ensured that the steel plate was pressed firmly against the wood member so that no gap remained. The self-drilling screw had a drill point with a length of 8 mm. With this tip it is possible to drill through steel sheets up to 2 mm thickness. For the drilling process, the tip is made of carbon steel and hardened. The remaining parts of the screw are made of stainless steel due to the screw's field of application in lightweight metal construction. Normally the screw has a washer to improve the load bearing capacity of the fastener and to make the fastener self-sealing. In this study, the screws are tested without a washer, as a sealing function is not required for the application under investigation. The ringed shank nails were driven through the sheets with a pneumatic driving device. This required pressures ranged from 0.6 MPa for specimens with steel sheet thickness of tN = 0.75 mm and LVL-X up to 1.4 MPa for steel sheet thickness of tN = 1.5 mm and BB.

For the “timber-to-steel” connection a self-drilling screw without drill point is investigated. This screw is also fabricated of stainless steel with a hardened carbon steel tip. In these connections, a rapid penetration of the steel sheet is necessary to prevent a gap between timber and steel sheet. The self-drilling screw without drill point allowed a production without gap.

Table 1 – Investigated fasteners for connections between very thin steel plates and wood products.

Type of fastener:	Diameter of:		
	shank d_s	Core d_1	Head d_{head}
 **nail**: ringed shank nail: 4.5 x 40 for steel-to-timber connection	4.5 mm	3.5 mm	7.7 mm
 **screw 1**: self-drilling screw: 6.0 x 38 for steel-to-timber connection	4.4 mm	4.2 mm	10.7 mm
 **screw 2**: self-drilling screw without drill point: 6.0 x 90 for timber-to-steel connection	5.2 mm	4.9 mm	11.8 mm

EXPERIMENTAL PROGRAMME

The experimental test programme embraced “standard test” to determine several input parameters such as yield moment or embedment strength of investigated fasteners. These parameters are fundamental to calculate the load-bearing capacity of “steel-to-timber” and “timber-to-steel” connections according to the EYM. The load-bearing capacity and progressive plasticisation of the fasteners was investigated with so-called “multi-stage tests”, as they had already been carried out in Kuck and Sandhaas [3] for connections in hardwoods. In this study single-shear connection tests with two fasteners were carried out and the conducted test specimens were stopped and opened at predefined displacement stages u. This allowed a comparison of embedment and screw deformation at different displacement stages.

Input parameters

For the accurate calculation of the load-bearing capacity, detailed knowledge of all input parameters is essential, as described in Kuck and Sandhaas [3]. Therefore, the following important input parameters were determined: embedment strength f_h, withdrawal parameter f_{ax}, head pull-through parameter f_{head} and steel properties of the screws, yield moment M_y and tensile capacity F_{tens}. The investigations carried out to determine the input values are listed in Table 2.

Table 2 – Test program of standard tests for input parameters.

	Material	t_N in mm	Load-grain-angel	No. of tests			Parameter	Test setup according to standard
				nail	screw 1	screw 2		
Embedment	steel	0,75		10	10	10	$f_h = \frac{F_{max}}{d \times t}$ [N/mm²]	EN 383 (2007)
		1,00			10	10		
		1,25			10	10		
		1,50			10	10		
	BB		0°	10	10	10		
	LVL		0°	10	10	10		
Withdrawal	steel	0,75				10	$f_{ax} = \frac{F_{max}}{d \times l_d}$ [N/mm²]	EN 1382 (2016)
		1,00				10		
		1,25				10		
		1,50				10		
	BB		90°	10	10			
	LVL		90°	10	10			
Head pull-through	steel	0,75		10	10		$f_{head} = \frac{F_{15mm}}{d_{head}^2}$ [N/mm²]	EN 1383 (2016)
		1,00		5	5			
		1,25		5	5			
		1,50		10	10			
	BB		90°			10		
	LVL		90°			10		
Yield moment				10	10	10	M_y in Nm	EN 409 (2009)
Tensile capacity				10	10	10	F_{tens} in kN	EN 14592 (2012)

Multi-stage tests

In order to investigate the load-displacement behaviour of “steel-to-timber” and “timber-to-steel” connections with very thin steel plates, single-shear connection tests with two fasteners per connection were carried out. To observe the plastic deformation processes in the connections, the tests were stopped at predefined displacement stages. After the tests, the specimens were opened to compare embedment and screw deformation at different displacement stages. The tests were conducted with the three previously described fasteners. An overview of all connection tests is given in Table 3. The test specimen layout and loading is shown in Figure 2. Spacing and end distances of the fasteners amounted to 90 mm (15 d for screws and 20 d for nail) to ensure a ductile behaviour of the connections. The specimen width was 100 mm, whereby the thickness was 39 mm for LVL-X and 40 mm for BB. The steel sheets were U-shaped with a flange length of 15 mm to obtain more stability and the thickness of the steel sheets were 0.75, 1.0, 1.25 and 1.5 mm. The displacements between steel sheet and timber were recorded and evaluated by using LVDTs (Linear Variable Differential Transformers). All displacements shown in this paper are therefore relative displacements in shear planes of connections and no machine displacements.

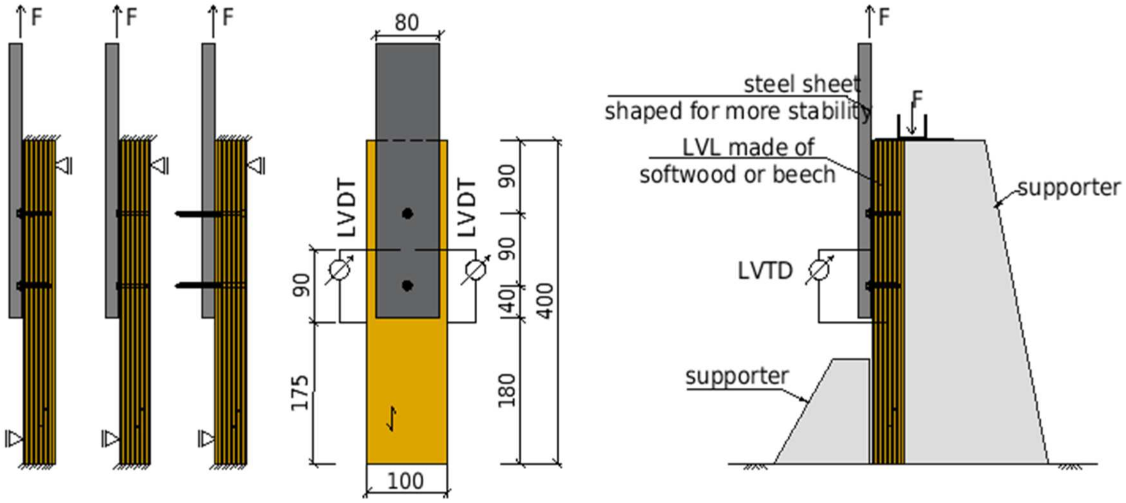


Fig. 2 – Test specimens and test setup for the multi-stage tests. All in [mm].

Table 3 – Test program of multi stage tests.

Fastener	Steel sheet thickness		BB			LVL-X	
	t_N in [mm]	u = 4 mm	u = 8 mm	Failure	u = 4 mm	u = 8 mm	Failure
nail	0.75	3	3	3	3	3	3
	1.50	3	3	3	3	3	3
screw 1	0.75	3	3	3	3	-	3
	1.00	3	3	3	-	-	-
	1.25	3	3	3	-	-	-
	1.50	3	3	3	3	3	3
screw 2	0.75	3	3	3	3	-	3
	1.50	3	3	3	3	3	3

Exemplary load-displacement curves with the predefined displacement stages u are shown in Figure 3. The first opening stage u = 4 mm was located after the transition from elastic to plastic connection behaviour to see the first plastic deformations in the connections. The next stage at 8 mm was used to monitor the plastic deformation progress of the fasteners and steel with load increase due to the rope effect. In order to evaluate the load-bearing capacity of the connections the last stage was chosen until connection failure.

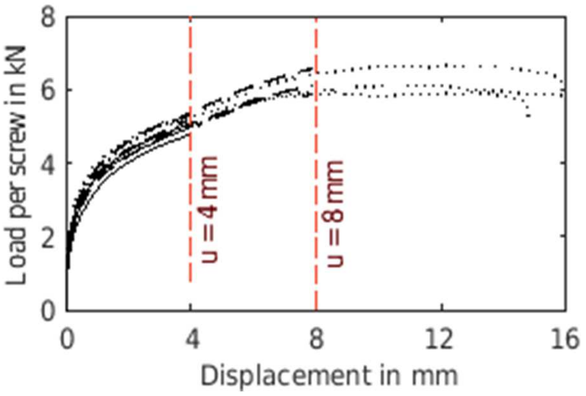


Fig. 3 –Load-displacement curves of steel-to-timber connection with self-drilling screw in LVL-X.

RESULTS AND DISCUSSION

Input parameters

An overview of all results of the "standard tests" is shown in Table 4. The embedment strengths for timber and steel specimens are determined uniformly by dividing the maximum embedment load achieved at 5 mm through specimen thickness and nominal diameter of the fasteners. Interpreting the results, different core diameters and tips of the fasteners are to be considered. The results clearly show that the average embedding strengths achieved in BB are twice as high as those in LVL. The drill point of the self-drilling screw 1 has a similar effect to predrilling, so that only the threaded part is cut into timber material or sheet steel. The self-drilling screw 2 without drill point displaces the wood fibres or steel sheet. This leads to pre-damage and compaction of the surrounding wood. For this reason, a higher embedment strength could be expected for the screw 2. The results of the embedment tests show higher embedment strengths for the self-drilling screw 2 without drill point in both timber materials BB and LVL. In the steel sheet lower strength values are achieved in the test with the self-drilling screw 2 without drill point.

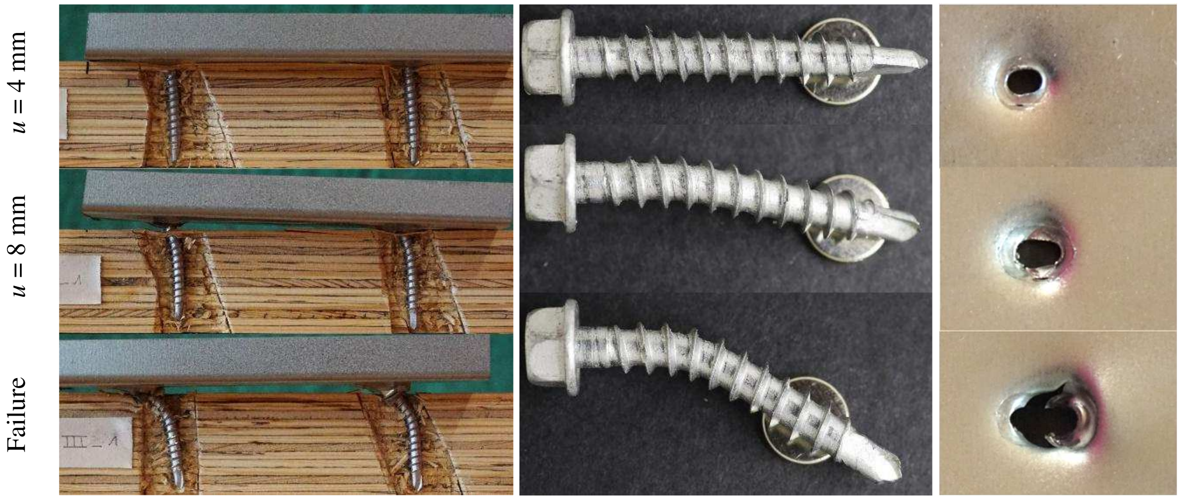
The withdrawal capacities are determined uniformly by dividing the maximum load through insertion depth and nominal fastener diameter. The different core diameters and tip lengths of the fasteners must be taken into account when interpreting the results. The results show that the withdrawal capacities achieved in BB are more than twice as high as those in LVL. The head pull-through parameters were determined with maximum load up to 15 mm machine displacement. The results show a linear increase of the head pull-through parameter with increasing the steel sheet thickness. In all steel specimens the maximum load was reached before a displacement of 15 mm. During the tests in BB with screw 2, the tensile capacity of the screw is reached and the screw breaks in 6 out of 10 tests. Nevertheless, the head pull-through parameter in BB is twice as high as in LVL.

Table 4 – Results of the standard tests in BB, LVL and steel.

	Material	t_N in mm	Load-grain-angle	Steel-to-timber		Steel-to-timber
				Nail	Screw 1	Screw 2
Embedment strength mean f_h in N/mm² (COV in %)	steel	0.75		812 (4.8)	716 (6.1)	710 (4.5)
		1.00			874 (4.8)	779 (6.8)
		1.25			959 (3.5)	846 (4.6)
		1.50			1011 (3.1)	1007 (3.1)
	BB		0°	65.7 (9.4)	57.8 (11.6)	80.4 (8.1)
	LVL		0°	38.4 (14.1)	33.6 (9.6)	35.0 (8.4)
Withdrawal parameter mean fax in N/mm² (COV in %)	steel	0.75				443 (3.8)
		1.00				427 (6.5)
		1.25				461 (8.2)
		1.50				474 (7.2)
	BB		90°	40.0 (9.8)	39.3 (7.2)	
	LVL		90°	14.3 (17.0)	14.1 (11.6)	
Head pull-through mean f_{head} in N/mm² (COV in %)	steel	0.75		48.2 (3.4)	43.1 (3.9)	
		1.00		64.8 (4.6)	59.4 (4.5)	
		1.25		90.2 (2.1)	80.6 (2.5)	
		1.50		97.4 (2.5)	97.9 (3.6)	
	BB		90°			95.1 (8.2)
	LVL		90°			44.9 (7.8)
Yield moment $M_{y,45°}$ in Nm				6.69	11.8	15.9
Tensile capacity F_{tens} in kN				7.56	10.6	14.8

Multi-stage tests

In the following, the results of the multi-stage tests are presented. The focus is on the deformation process of fasteners, steel sheet and timber material as well as the failure modes of the connections. To determine the deformations, the test specimens were opened after the tests and the deformations at predefined displacement stages were documented. An example of the deformation process of the three connection parts (timber, screw, and steel) is shown in Figure 4 for a connection in LVL-X with screw 1 and a steel sheet thickness of 0.75 mm. In the 4 mm stage, no obvious deformations of the screws can be detected. In contrast, first visible embedment deformations are already observed in the steel sheets. However, it should be noted that elastic deformation of the specimens occurs due to unloading and opening. Significant deformations can be seen starting at a displacement stage of 8 mm. At this opening stage, a non-linear behaviour already appears in the load-displacement curves. The embedment deformations in the steel sheets increase and the screws already show plastic hinges. In addition, embedment deformations in LVL-X can be observed. A visible pull-through of the screw head through the steel sheet takes place from relative displacements > 8 mm. In this configuration, the resistance to withdrawal in timber is higher than the head pull-through resistance in the steel sheet. With increasing steel sheet thickness, the deformations in the steel sheet decrease. Instead, the bending angles in the fasteners increase. The bending angles of the plastic hinges were determined with photo documentation and graphical evaluation after opening the test specimens. The results are shown in the chapter "Incremental development of plastic hinges" for screw 1. The thicker steel sheets also lead to a higher head pull-through resistance and thus to a changed failure mode, as described in the next chapter.



deformation in LVL deformation of screw deformation of steel

Fig. 4 – Deformation processes in connections with LVL, screw 1 and steel sheet thickness of 0.75 mm.

Failure modes

The failure mode of the test specimens is characterised by a combination of different failure mechanisms, as can be seen in the deformation process of the connection in Figure 4. In all tests, the fasteners formed at least one plastic hinge. In addition to the plastic hinges of the fasteners, in "steel-to-timber" connections with steel sheet thickness of 0.75 and 1.0 mm final failure of the connection is due to head pull-through in the steel sheet. In connections with steel sheet thickness of 1.25 and 1.5 mm, the final failure of the connection is due to withdrawal failure in the timber part. Sporadic screw failure is also observed in both BB and LVL-X. Thereby, the failure zones in the LVL-X are in the transition area between the carbon steel of the drill point and the stainless steel of the screw, as shown in Figure 5. In BB, the screw heads shear off at two test specimens. This failure was already observed in Meyer [5] in steel-to-timber connections with ringed shank nails and occurs due to a combined action of moment, shear, and normal force. In this study, shearing of the nail head was not seen.

In “timber-to-steel” connections with screw 2, failure occurred due to the formation of one plastic hinge in the timber part and a withdrawal failure in the steel sheet with the exception of the connection in BB and a steel sheet thickness of 0.75 mm. This connection failed mainly due to embedment failure in the steel sheet at displacements of 5 to 6 mm.

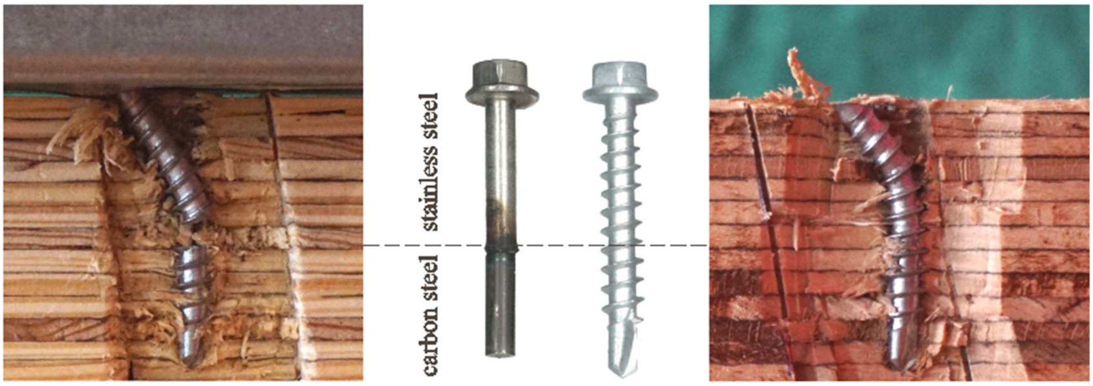
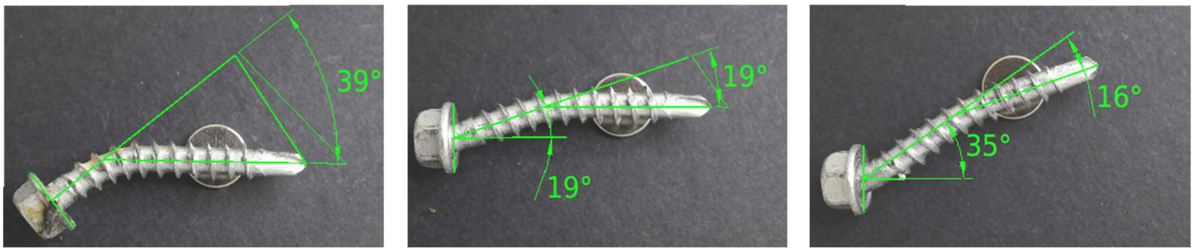


Fig. 5 – Screw failure of screw 1. Left: Failure in LVL-X. Centre: Position of the transition area between carbon steel and stainless steel in screw 1. Right: Failure in BB.

Incremental development of plastic hinges

Carrying out the multi-stage tests allows to observe the increase of the plastic hinges in the fasteners. An overview of plasticising of the screw 1 in test specimens with different steel sheet thicknesses after failure is shown in Figure 6. Significant differences can be seen concerning the location along the screw axis at which plastic hinges are formed. While only one plastic hinge is formed in screws of test specimens with 0.75 mm thick steel sheets, the screws in steel sheets with a thickness of 1.0 mm or more have formed two plastic hinges.



(a) (b) (c)

Fig. 6 – Plasticising of screws with different thickness of steel sheets in connections with LVL-X: 0.75 mm (a), 1.0 mm (b) and 1.5 mm (c).

With increasing steel plate thicknesses, the bending angle of the plastic hinge in the shear plane at the same displacement stages is increasing, as shown in Figure 7. In contrast, the bending angle in the timber part remains almost constant with increasing steel plate thicknesses. In addition, the bending angle in the timber part is no longer raised between the predefined displacement stages u = 8 mm and u = failure. However, bending angles in the shear plane still grow significantly. The resulting asymmetrical deformation of the screw leads to a skewing of the screw tip in the timber part and ends in a withdrawal failure, as described for the connections in LVL-X with 1.25 and 1.5 mm thick steel sheets.

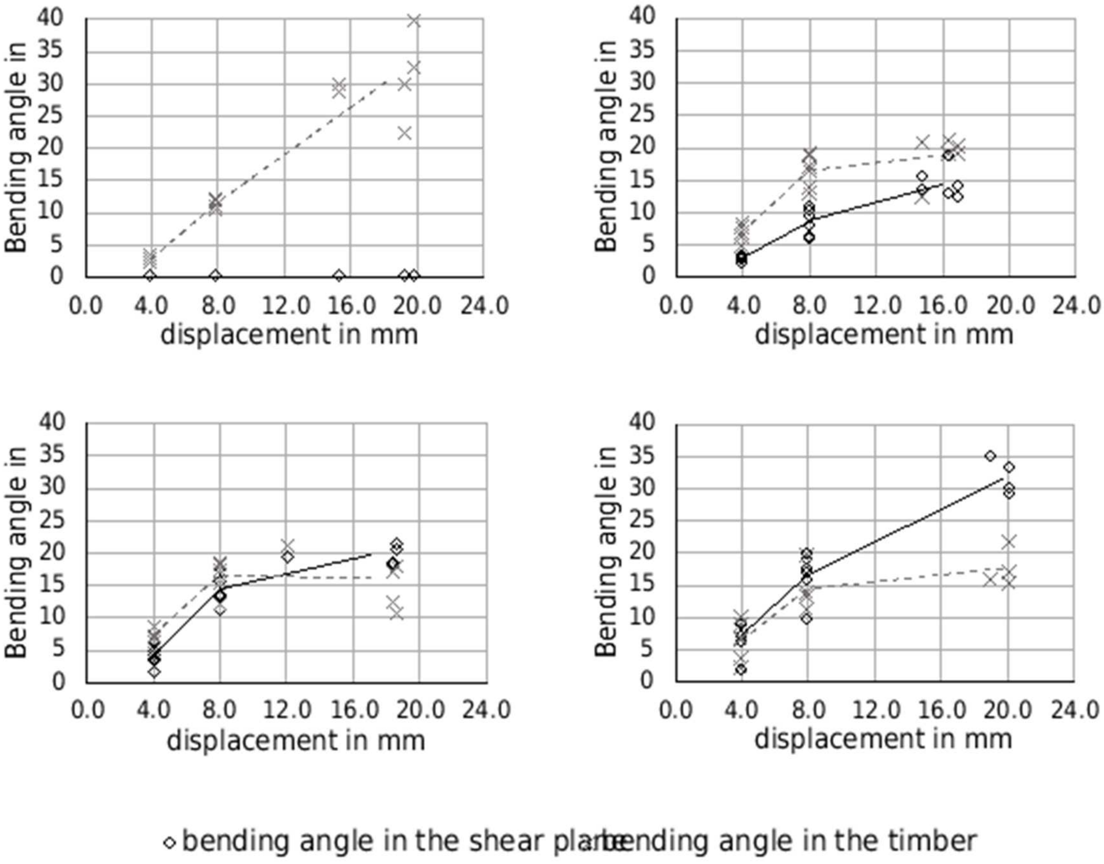


Fig. 7 – Bending angle of screws in connections with different thickness of steel sheets: 0.75 mm (left top), 1.0 mm (right top) 1,25 (left bottom) and 1.5 mm (right bottom).

COMPARISON WITH EYM

According to Eurocode 5 [6], all examined connections are connections with thin steel plates, as the steel plate thickness t is less than or equal to half the fastener diameter ($t \leq 0.5 \cdot d$). The calculation equations for connections with thin steel plates assume a pinned restraint of the fastener in the steel plate. The tests, however, showed that for steel plates of thickness greater than or equal to 1.0 mm and the used self-drilling screws 1, the steel plate acted as a clamped restraint for the screw. Such a clamped restraint can also be activated in nailed steel-to-timber joints with ringed shank nails as shown in Ehlbeck and Görlacher [7]. In both cases, the mean value of the load-bearing capacity $F_{v,R}$ in accordance with the equations for thin steel plates underestimates the load achieved in the tests. Therefore, the load-bearing capacities were calculated using the equations for timber-to-timber connections including the rope effect according to the EYM. For this purpose, all determined input parameters such as embedment strength f_h, withdrawal capacity f_{ax} and head pull-through capacity f_{head} were required. The steel plate is treated like a timber cross-section. The ratio of embedment strengths β is calculated as $f_{h,t}/f_{h,s}$. All input parameters can be taken from Table 4. The rope effect $\Delta F_{v,R}$ is considered as 25 % $F_{ax,R}$. The load-bearing capacities calculated with the equations according to the EYM are listed in Table 5. The calculation identifies failure mode d (one plastic hinge per shear plane). This load-bearing capacity corresponds more or less to the load-bearing capacity based on equations for connections with thin steel plates. In order to take the clamping effect into account in the calculation, the load-bearing capacity for these connections was additionally determined with the failure mode f (two plastic hinge per shear plane). In both cases, the mean value of the load-bearing capacity significantly underestimates the load achieved in the tests. One reason for this underestimation could be a higher friction between timber and steel sheet compared to the assumed rope effect $\Delta F_{v,R}$ in the EYM. Another factor could be the higher local density at the edge of BB panels. This leads to a higher embedment strength exactly in the area where embedment failure occurs in the tests. To substantiate these assumptions, further experiments must be carried out to determine these influences.

Table 5 – Comparison of load-bearing capacities per screw and shear plane based on the EYM.

fastener		t	t_{req}	β	$\Delta F_{v,R}$	$F_{v,R}$	failure mode EYM	$F_{v,R}$ $/F_{exp}$	failure mode exp	$F_{mode\ f}$	$F_{mode\ f}$ $/F_{exp}$
		[mm]	[mm]	-	[kN]	[kN]		-		[kN]	-
nail	LVL-X	0.75	39.3	0.047	0.63	2.13	d	0.56	a/d		
		1.50	38.5	0.034	0.62	2.30	d	0.46	f	2.74	0.55
	BB	0.75	39.3	0.081	0.73	2.65	d	0.49	a/d		
		1.50	38.5	0.058	1.45	3.59	d	0.48	f	4.19	0.56
screw 1	LVL-X	0.75	37.3	0.047	0.79	2.93	d	0.51	d		
		1.00	37.0	0.038	0.78	2.96	d	0.47	f	3.81	0.61
		1.25	36.8	0.037	0.78	3.00	d	0.50	f	3.81	0.63
		1.50	36.5	0.033	0.77	3.09	d	0.51	f	3.81	0.63
	BB	0.75	37.3	0.080	1.23	3.24	a	0.54	a		
		1.50	36.5	0.057	2.18	5.15	d	0.45	f	6.12	0.54
screw 2	LVL-X	0.75	39.0	0.049	0.50	3.02	d	0.67	d		
		1.50	39.0	0.035	1.07	3.74	d	0.48	d		
	BB	0.75	40.0	0.113	0.50	3.19	a	0.75	a		
		1.50	40.0	0.080	1.07	4.96	d	0.54	d		

CONCLUSIONS

An experimental investigation of steel-to-timber and timber-to-steel connections with very thin steel sheets is presented. The multi-stage tests allow an observation of the increasing deformations of the connection parts. The different failure mechanisms of the test specimens show a complex interaction between the connecting parts. Although all input parameters for the calculation of the load-bearing capacity were determined, the loads achieved in the tests are significantly underestimated. Several influencing factors may explain the underestimation. The cross layers in the wood-based materials can lead to a higher embedment strength and thus also to a higher load-bearing capacity of the connections. In the case of BB, the outer layers also have a higher density and therefore also a higher embedment strength. To investigate these influences, further tests should be carried out to determine the embedment strength in LVL with cross layers.

In connections with a steel sheet thickness greater than or equal to 1.0 mm a clamping effect could be observed. With a fastener diameter of 6.0 mm, the ratio between steel plate thickness and fastener diameter is 0.167. This is significantly lower than the limit value of 0.5, above which a partial clamped restraint can be applied according to the Eurocode 5. To make the clamping effect dependent only on the ratio between the steel sheet thickness and diameter of the fastener is not sufficient for the examined connections. The clamping effect depends on other parameters, such as the head diameter of the fastener. To derive a relationship between the head diameter and the steel plate thickness, further investigations would have to be carried out.

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REFERENCES

[1] Ehlbeck J, Eberhart O, Untersuchungen von Stahlblech-Holz-Nagelver-bindungen mit nicht vorgebohrten Stahlblechen von mindestens 2 mm Dicke unter Verwendung von Stahlnägeln. Forschungsbericht, Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe 1988.

[2] Strübel S, Experimentelle Untersuchungen an Stahlblech-Holz Verbindungen mit dünnen Stahlblechen zur Entwicklung eines neuartigen Hybridelements. Doktorandenkolloquium Holzbau Forschung + Praxis, 10–11 March 2022, Stuttgart. University Stuttgart, pp.45-52, 2022.

[3] Kuck E, Sandhaas C, Load-bearing behaviour of partially threaded screws in hardwood. Wood Material Science and Engineering, DOI: 10.1080/17480272.2022.2084453, 2022

[4] Frese M, Density variations in beech LVL: Influence on insertion moment and withdrawal capacity of screws. In Proceedings of INTER, Tacoma, USA, 2019.

[5] Meyer N, Tragfähigkeit mechanischer und geklebter Verbindungsmittel in Buchenfurnierschichtholz. Karlsruher Institut für Technologie, Diss., 2020.

[6] EN 1995-1-1:2004 + AC:2006 + A1:2008 + A2:2014 Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings. European Committee for Standardization (CEN), 2014.

[7] Ehlbeck J, Görlacher R. Mindestnagelabstände bei Stahlblech-Holznagelung. Forschungsbericht, Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe, 1982.