PRESS GLUED CONNECTIONS - RESEARCH RESULTS FOR DISCUSSION AND STANDARDIZATION

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KEYWORDS

Nail press gluing and screw press gluing, composite structures, head pull-through capacity, adhesive bond quality

1 SCREW AND NAIL PRESS GLUING

Press glued connections performed with screws, nails, or staples is used in multidisciplinary applications in wood industry. The fasteners are used to hold two timber elements together while the adhesive cures in between them, or to provide curing pressure on the adhesive. Full composite action between assembled elements can be achieved. It is used in new structures to assemble hollow box elements for instance, but also to reinforce damaged structural components. The ExpoDach in Hannover, Germany, and the Sibelius Hall in Lahti, Finland, contain screw press glued load bearing elements, see Figure 1. Other examples are the Waldau Stadium in Stuttgart, Germany, and the Leonardo da Vinci bridge in Ås, Norway.

The main advantage of the press gluing methods is that they can be used on a construction site or on locations where use of presses is impractical. More common is to apply the method in workshops of small-, or in production halls of large, companies. It allows them to remain flexible and competitive and still meet a wide variety of customer requirements to size and dimensions of a product.

The opinion amongst the wood construction industry about the final quality and strength of the achieved bond varies. This is explained perhaps by the lack of a broadly supported standards and the many combinations of adhesives, materials, methods, and production conditions under which the press glued bond is established. One of the main doubts is whether the chosen fasteners can generate sufficient curing pressure for the used adhesive. Standardised methods to test or qualify the final bond are not available either. Hence, there is a need to evaluate methods and materials used.

The presented work first discusses the state of the art of the nail and screw press gluing methods by presenting earlier work and contents of current standards. Then the achievable average curing loads are measured for staples, nails and screws. After the

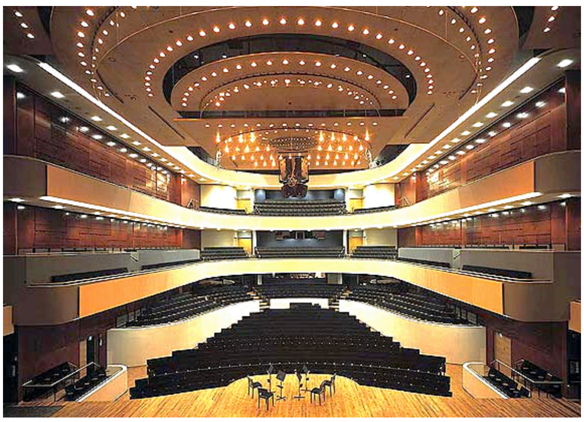


Figure 1: *Outstanding example of structures manufactured using the press gluing technique; the ExpoDach in Germany (Boller 2006) (left),and the Sibelius Hall in Finland (Artec 2015) (right)*

evaluation of bond quality resulting from different production conditions, recommendations to industry and for further work are given. The presented work is a summary of work also reported in Franke et al. (2018).

2 APPLICATION AND STATE OF THE ART

2.1 Applications of screw press glued connections

Screw gluing and nail press gluing techniques are used to produce ribbed panels, hollow box elements, box beams, I-beams, join glued laminated timber beams, etc., see Steck (1988) and Kairi (2000). Some examples of basic structural components are shown in Figure 2 and Figure 3.

Kairi (2000) and Hillmer (2014) list different dimensions and materials used for box elements and ribbed panels using Kerto and solid wood. Steck (1988) and Widmann (2014) provide examples of how plywood or solid wood panels are used as external reinforcement of holes and notches in beams. Damaged curved and tapered beams with tensile cracks perpendicular to the grain are repaired by applying external reinforcements. Stiffness and strength of load bearing timber elements in (historic) structures is increased by press gluing extra lamellas onto them. Bratulic & Augustin (2016) carried out experiments to join Cross Laminated Timber elements using washer head screws with head diameters of 22 mm and 35 mm. Glued laminated timber beams were joined using double threaded fasteners, see Sieber (2003). The listed examples illustrate the wide variety of applications and materials used.

2.2 Standards and recommendations

Screw press gluing is only regulated in the German National Annex of Eurocode 5, which refers to the DIN 1052-10:2012 valid previously. Up to 2004 nails were also allowed through the DIN 1052-1:1988. Now, only screws with a thread diameter larger than 4 mm are to be used. The reference surface per fastener is 15000 mm^2 with a maximum intermediate distance between fasteners of 150 mm. The fasteners should have a smooth shaft throughout the head side material so that it is possible to pull two assembled elements together. The maximum difference in moisture content of the joined materials should be 4 M% and both should be lower than 15 M%. Maximum allowed material thicknesses are 50 mm and 45 mm for wood based panels and solid wood, respectively. The adhesives used should have been tested according to the DIN EN 301:2006-09 type 1 test, where resistance to temperatures above 50°C is tested. Material temperatures should be at least 18°C and guidelines described in technical data sheets should be followed.

Engineering companies have listed additional recommendations such as the use of counter head fasteners with minimum thread diameters of 5 mm and suggest a list of adhesives. Application quantities are about 250 g/m^2 and the resulting glue line thicknesses should be lower than 0.3 mm. The adhesive in the assembled elements should at least be allowed to cure for three hours before further

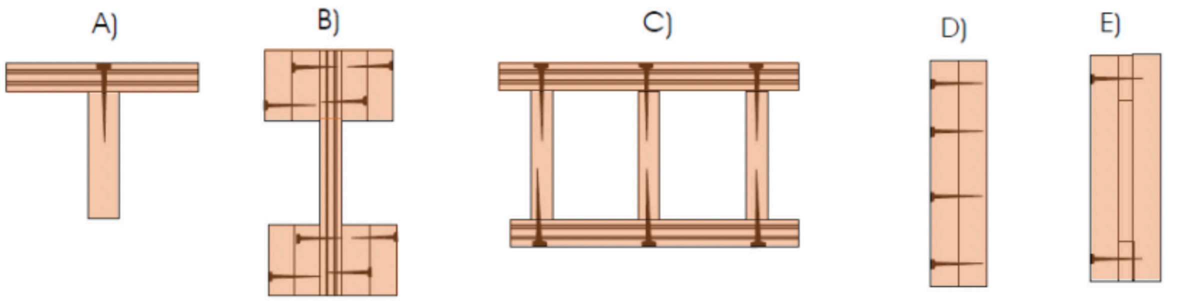


Figure 2: *Structural members produced with press glued connections, T-Beam (A), I-Beam (B), Ribbed panel (C), Double Beam (D), Box-Beam (E) (Kairi, 2000)*

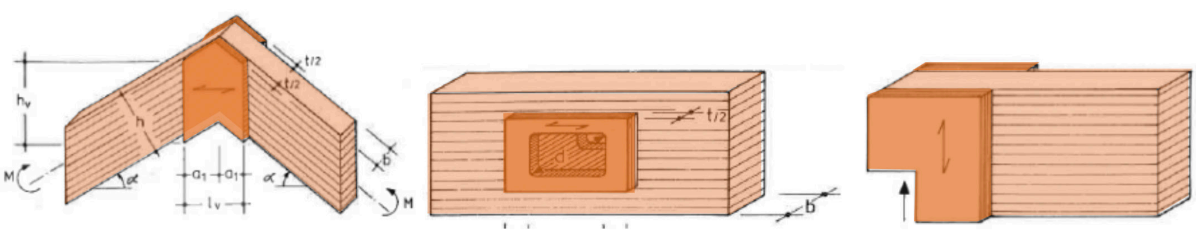


Figure 3: *Connection assembled, reinforced end notch or hole (Steck, 1988)*

machining or transport is done. The final bond quality is to be tested by assembling additional elements for destructive tests. The bond quality could be tested by splitting the bond and evaluate the amount of substrate failure. Finally, a log should be maintained in which the used materials, production conditions, etc. should be documented per produced element (Besmer und Bruning, Pirmin Jung 2010).

Pneumatic or vacuum presses offer an alternative to the screw and nail press gluing. Hydraulic presses are used only when curing pressures above 0.6 N/mm^2 are needed.

2.3 Used fasteners

Figure 4 shows an overview of fasteners that are - or could - be used for press gluing applications. Common are the counter head screws, and new might be the fully threaded screws with a varying thread angle. The slope of the thread changes at a certain point along the length of the fastener, and are ideal to tighten two materials onto each other. Some structures are assembled with scrails but continuous quality control is maintained at the production line. The advantage of the scrail is that they can be inserted with nail guns, but can also be removed once the adhesive has cured. The use of staples is economically very attractive, since these fasteners can be inserted at frequencies up to 5 Hz. The fasteners are also cheap to produce and many can be loaded into a magazine. Wave nails were also observed but the resulting bond was not used as a load bearing connection.

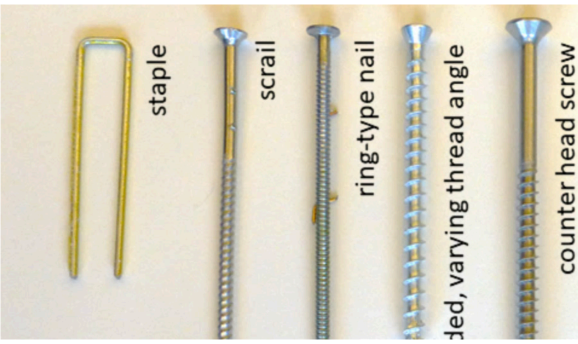


Figure 4: *Overview of different pin type fasteners used already and suggested to be suitable for screw- or nail press gluing applications*

2.4 Used adhesives

Kairi et al. (1999) joined Kerto panels using one-component polyurethane (1C-PUR) adhesive Purbond HB110, applied with a quantity of 250 g/m^2. Bond shear capacity of 6 N/mm$_2$ were achieved with a glue line thickness under 0.3 mm. Kurt (2003) used Gap-filling Phenol Resorcin Formaldehyde (G-PRF) to join Douglas fir Plywood to spruce beams with screws. Glue line thicknesses up to 0.508 mm still produced sufficient mean shear capacities around 6 N/mm^2. Gerber et al. (2006) compared a synthetic rubber adhesive (RBA) to a 1C-PUR adhesive when joining plywood and engineered strand board to radiata pine beams. Average shear capacity of 4.4 N/mm^2 were achieved using the PUR adhesive. Rug et al. (2010) joined solid wood, birch plywood panels, and laminated veneer lumber to glued laminated timber beams using PRF and Epoxy adhesives using scrails. Hillmer (2014) obtained average shear capacity around 5.5 N/mm^2 and 4.5 N/mm^2 with screws and scrails, respectively.

Screws press gluing generally results in a better bond capacity. Most obtained bond shear capacities were said to be better than the material properties. Sufficient shear capacity can however be obtained with an insufficient substrate failure ratio. Gerber et al. (2006) makes an important note, claiming that the presence of the fasteners is an advantage, as they contribute to a ductile failure of the connection once the adhesive has failed.

1C-PUR adhesives are popular nowadays, but Beaud et al. (2006) warns that these might not properly cure at wood moisture contents below 8 M%. It is logically recommended to join materials at sufficient moisture contents as PUR adhesives require water during the curing process. The study also showed that even if the moisture contents of the material were sufficient during the adhesive's curing, shear load capacities could drop once moisture contents were below 8 M%. Dry conditions can be accounted for by moisturizing the wood prior to gluing, see also Kägi (2005) and Kläusler (2014). Humid conditions will accelerate the PUR-curing, requiring faster assembly of materials.

3 MEASUREMENT OF COMPRESSION LOADS

3.1 Typical load histories and evaluation of curing loads

The surface integral of the pressure distributed around the fastener, between the bonded surfaces, is equal to the tensile load present in the fastener itself, see Figure 5 (left). Miniature load cells were used to measure this tension/total compression load. The load cells were arranged in a triangular setup so that fasteners could be inserted in between these. A gap of 2 mm was maintained between the plate and

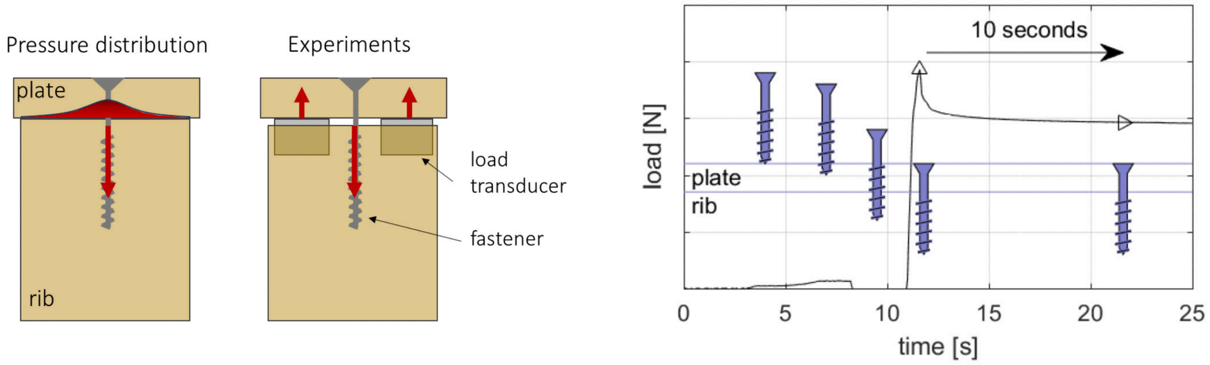


Figure 5: *Visualisation of the pressure between two joined elements, and the measurement of curing load (left). The screw position during the drilling and the measured load, the maximum load, and the determination of the curing load 10 second after the peak load are visualised (right)*

rib: enough to prevent contact, but also allowed tests with short fasteners.

A typical load history of the generated compression load by the fastener is shown in Figure 5 (right). Common is the peak load that develops when the fastener is inserted, a rapid drop afterwards that changes into a converged curing load. Depending on the fastener type, sampling frequencies of 20 Hz to 100 Hz are needed to measure this peak, although it is not a representative curing load. The compression load obtained from the experiments was obtained 10 seconds after the peak occurred. To calculate the 5% quantiles of the compression loads, the lognormal distribution described in FprEN 14358:2015, Section 3 was used.

3.2 Previous research on achievable compression loads

Bratulic & Augustin (2016) suggest that the generated compression load is closely related to the head diameter of the fastener. If the used head diameter is too large, Kairi et al. (1999) warn that tip pull-out capacity can be exceeded. Hillmer (2014) and Rug et al. (2012) tested scrails and obtained loads around 200 N. Tests with 4 mm fasteners resulted in compression loads around 600 N. Kairi et al. (1999) and Bratulic & Augustin (2016) obtained loads between 2000 N and almost 9000 N with different washer head screws. These values are used later in Section 3.5. Kairi et al. (1999) also measured the compression loads of double threaded screws in Kerto and obtained a range from 0 N to 1970 N. The low values were said to be caused by a small difference in the two thread angles, through which the head and point side member could not be pulled together.

3.3 Head pull-through and tip pull-out capacities

The achieved compression loads are compared to the characteristic head pull-through capacities in Section 3.5 using the DIN EN 1995-1-1:2010. The head pull through capacity for screws was calculated using:

$$F_{head,Rk} = f_{head,k}\, d_h^2 (\rho_k/350)^{0.8} \quad \textbf{(1)}$$

Parameters affecting the head pull through capacity are the strength $f_{head,k}$, head diameter d_h, and material characteristic density ρ_k. $f_{head,k}$ is provided by manufacturers. One way to achieve greater head pull-through capacities is to use larger head diameters. Then, the head pull through capacity of the double threaded screws was calculated using the formulations for the pull-out capacity of threaded part. This is calculated using the length of the full or effective threaded length l_s, the characteristic withdrawal capacity $f_{ax,k}$ and thread diameter d.

$$F_{ax,Rk} = f_{ax,k}\, d\, l_s\, (\rho_k/350)^{0.8} \quad \textbf{(2)}$$

The fasteners are to be oriented 90° perpendicular to the fibre direction. Material densities of 350 kg/m³ were used through which the equations can be simplified somewhat. The calculated values were similar to those given in the individual product data sheets. An illustration of a screw with the indicated geometrical parameters is observed in Figure 6.

The head pull through capacity for smooth nails is calculated using the characteristic strength $f_{head,k}$ and the head diameter d_h, see also in Figure 7.

$$F_{head,Rk} = f_{head,k}\, d_h^2 \quad \textbf{(3)}$$

Material density is included in the formulation of $f_{head,k}$. Once a part of the shaft in the head side material is shanked or has rings, the capacity of this part may be added using the equation for the withdrawal capacity. This uses the characteristic strength $f_{ax,k}$, the shanked length (in the head side member) l_{ef} and the shaft diameter d.

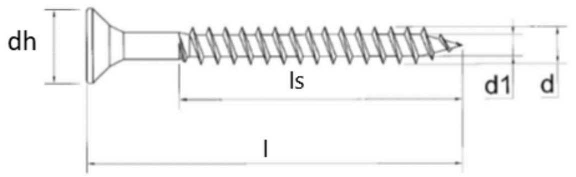


Figure 6: *Partially threaded fastener with counter sunk head*

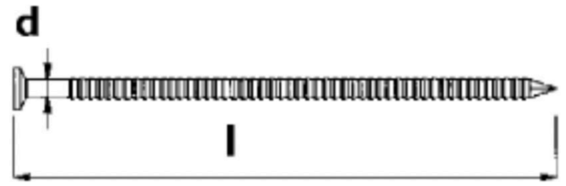


Figure 7: *Ring nail with almost fully shanked shaft*

$$F_{ax,Rk} = f_{ax,k}\, l_{ef}\, d \qquad (4)$$

Material densities are included in the formulation of $f_{ax,k}$.

3.4 Obtained compression loads for all fasteners

Table 1 lists the tested nails, staples and screws, some are also observed in Figure 4. The geometries of these fasteners are not uniform. The choice for these fasteners was based on whatever was provided by manufacturers, observed in practice, or recommended in literature and product folders. Tests with smaller fasteners were performed in three-layer solid wood panels of 27 mm thickness. The larger screws (d > 6 mm) were tested in solid wood boards of 40 mm thickness.

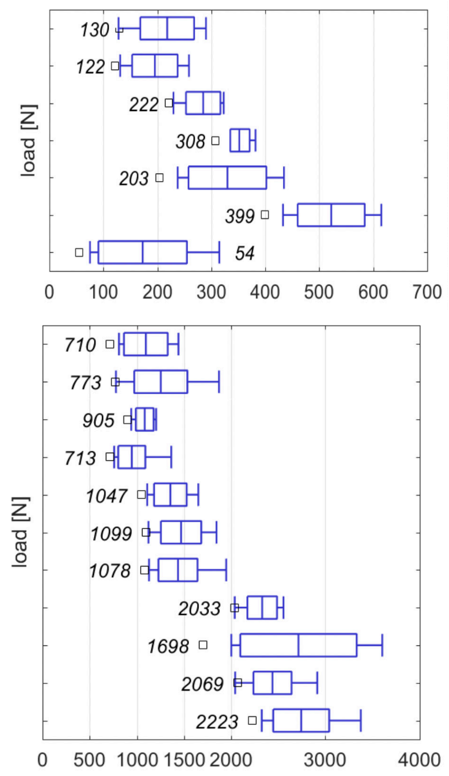
The achieved loads by the nail type fasteners were between 100 N to 600 N. The staples showed the largest spread with a Coefficient of Variation (CV) of 48 %. The reluctant attitude towards staples in press gluing applications is understood when the 5% quantile is calculated, i.e. very low values are obtained.

The counter head screws generated compression loads between 700 N and 2000 N. Some of the screws also showed a large spread with a CV up to 32 %. Varying thread screws generated higher average compression loads and had a smaller CV of 20 %. The fasteners with thread diameters of 6 mm and more proved that high adhesive curing loads can be generated. The washer head screw could be less preferred over the double threaded fasteners due to the large spread, CV of 36 %, in generated loads. Optically, washer head screws might not be preferred either in a finished product. The double threaded fasteners can generate similar loads as the washer head screws, but have a smaller spread and smaller head diameters.

Literature mentions that compression loads reduce 25 % to 30 % during the three hours after initial fastening.

Table 1: Tested fasteners, nails, staples and screws, with head diameters, thread diameters, (threaded) lengths (left) and box plots with minima, maxima, means and 5% quantile values (right).

	ID	d	d_h	l	l_s/l_{ef}
Nails/staples		*mm*	*mm*	*mm*	*mm*
Scrails	NS1.1	3.2	5.9	75	40
Scrails	NZ1.2	3.2	6.9	75	40
Ring nails	NR2.1	2.8	6.8	75	
Ring nails	NR2.2	3.1	7.1	90	
Ring nails	NR2.3	3.4	7.4	100	
Ring nails	NR2.4	3.8	7.9	110	
Staples	NC3		15	75	
Screws					
CH/Würth	SC1	5.0	9.6	80	50
CH/SPAX (HR)	SC2	5.0	9.7	80	50
CH/Fischer (HR/SR)	SC3	5.0	9.7	80	50
CH/Rothoblaas (HR/SR)	SC4	5.0	10	80	40
VT/Heco	SV5.1	4.0	6.1	70	Full
VT/Heco	SV5.2	4.5	6.8	70	Full
VT/Heco	SV5.3	4.5	6.8	80	Full
VT/Heco	SV5.4	5.0	9.6	80	Full
WH/SPAX	SW6	6.0	13.6	100	60
DT/SFS WT-T	SD7	6.5	8	90	40/35
DT/Würth	SD8	6.0	8.2	120	50/15



CH (counter head), VT (varying thread), WH (Washer head), DT (double thread), HR (milling ribs under the fastener head), SR (milling ribs on the fastener shaft)

This is calculated with respect to the measured peak loads, see Figure 5. Now, the long-term load is compared to the load measured 10 seconds after the nailing/screwing. The tested scrails showed a remarkable average increase of 6 %, accounted to cooling of the fastener. The highest decrease was 2 %. Loads measured with the counter head screws reduced between 6 % and 12 % after three hours, the double threaded fasteners reduced between 14 % and 19 %. Since there is a correlation between the generated compression load and the reduction over three hours, it is expected that this could also be related to the moment after the peak load, from which the initial compression load is obtained. This point needs to be chosen smart in future measurements. More results concerning group loads, production methods, and use of other materials are found in Franke et al. (2018).

3.5 Comparison of achieved values with those available in literature

Section 3.2 already listed previously measured compression loads. Materials used throughout these studies were not uniform. Results obtained from literature and from above mentioned experiments are normalized to a material density of 350 kg/m³ using the 5% quantile of the material density and Equation (1):

$$F_{head,5\%,350} = F_{head,5\%}\,(350/\rho_{5\%})^{0.8} \qquad (5)$$

The 5% quantiles are plotted in Figure 8, where the compression load is compared to fastener head diameter. The filled markers are own experiments, and the empty markers are obtained from literature. The latter were multiplied by 0.7 to account for a 30 % reduction of the maximum measured values.

The 5% quantile of the load generated by the scrails are a little over than 100 N. The ring type nails perform better at values around 200 N to 300 N. The varying thread, the washer head, and double threaded screws perform better than the counter head screws.

Figure 9 illustrates the relation between the measured compression loads against their characteristic head pull through capacities. Literature values were not added. The scrails, nails, counter head, and washer head fastener generate lower compression loads than can be calculated from their head pull through capacities. Those of the varying thread fastener are higher.

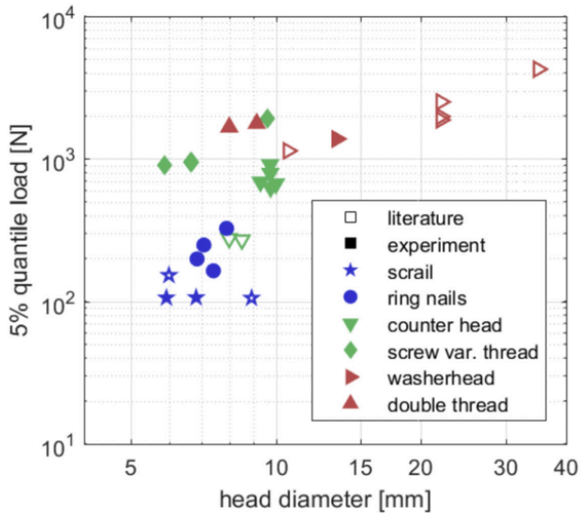


Figure 8: *Comparison of obtained experimental results corrected to 350 kg/m³ density as a function of fastener head diameter*

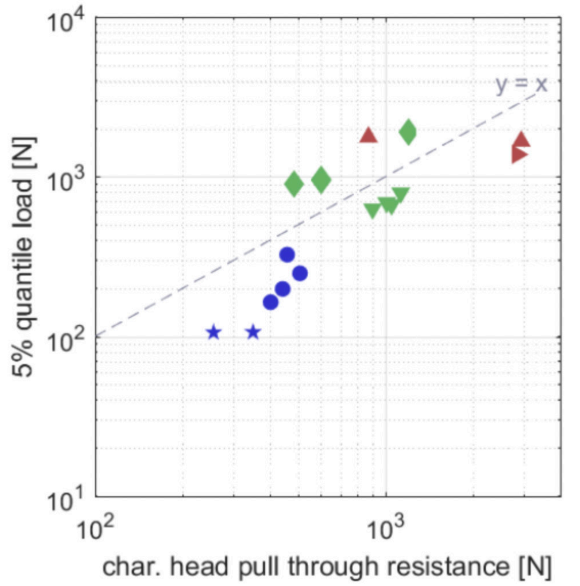


Figure 9: *Experimental results corrected to 350 kg/m³ density compared to characteristic head pull through capacities*

4 METHODS TO EVALUATE THE RESULTING BOND

4.1 Material and test matrix

The tests were performed using two 1C-PUR adhesives, a more liquid and viscous one, adhesive A and adhesive B respectively. Both adhesives recommended a curing pressure of at least 0.1 N/mm². A quantity of 250 g/m² was used which was achieved within 6 % of the targeted value. Adhesive A and adhesive B recommended a maximum glue line thickness of 0.1 mm and 0.3 mm, respectively.

Three separate conditions were investigated: ideal conditions (IC), the production conditions (PC) and other conditions (OC), see also Table 2. The pressure

Table 2: Overview of different glue tests with ideal conditions, under production conditions, and other conditions that were carried out.

Condition	Low pressure	Medium pressure	High pressure
Constant pressure	0.02 N/mm², IC1	0.13 N/mm², IC2	0.20 N/mm², IC3
Fasteners every 150 mm	Scrail, 0.02 N/mm², PC1	5 mm screw 0.11 N/mm², PC2	6 mm screw 0.17 N/mm², PC3
Worst case		Uneven application, OC1 Constant spacing 0.3 mm, OC2 Wedge spacing 0.6 mm, OC3	0.3 mm 
Constant glue line thickness		Adhesive A, OC4 Adhesive B, OC5	0.6 mm 

levels on the adhesive in the ideal conditions was maintained at a constant level during the curing process. Boards 30 mm thick and 100 mm wide were used here. In the production conditions, three fastener dimensions were used to supply curing pressure between a three-layer solid wood panel and a 100 mm wide rib: A scrail, a 5 mm counter head screw, and a 6 mm counter head screw. The lowest achievable curing pressure was generated with a scrail at an intermediate fastener distance of 150 mm. The heads of the 5 mm and 6 mm screws were drilled 2 mm deeper than usual into the wood to generate higher adhesive curing pressures. In the remaining tests (OC), an uneven application of adhesive was performed and intentionally created constant and wedge shaped spacing were created between the glued elements. In the two remaining conditions, the glue line thickness was maintained constant throughout the adhesive curing with the universal testing machine. The used timber was conditioned two weeks in a climate of 20°C and 65 % relative humidity. The shear tests were performed two weeks after the gluing.

4.2 Resulting bond quality

The EN 14080:2013, Appendix D, provides a method to evaluate bond quality by suggesting minimum relations between shear capacity and substrate failure ratio. This relation is given for each individual sample, but also for the mean of all samples. Both relations should be passed. A lignin activator was used to facilitate the evaluation of substrate failure ratio since the used PUR was colourless. The results are shown through the box plots in Figure 10 and the pass/failed evaluation of the EN 14080:2013 in Table 3.

Figure 10 shows that shear capacity only does not provide a complete evaluation of the bond. Although shear capacities over 6 N/mm² are obtained, substrate failure ratio can still show a large spread and be insufficient: IC1, PC1, OC2-OC4. Curing of the adhesive while the bond thickness is maintained constant resulted in higher shear capacities, but also in a greater spread of the substrate failure rate. Tests with the intentionally created large gaps showed that glue lines in PUR adhesives are to be maintained to a minimum if a good bond is needed.

Table 3: Overview of pass and fails for the different test setups.

Test	Single values	Average	Total
IC1	Fail	Pass	Fail
IC2	Pass	Pass	Pass
IC3	Pass	Pass	Pass
PC1	Fail	Fail	Fail
PC2	Pass	Pass	Pass
PC3	Pass	Pass	Pass
OC1	Pass	Pass	Pass
OC2	Fail	Pass	Fail
OC3	Fail	Fail	Fail
OC4	Fail	Fail	Fail
OC5	Pass	Pass	Pass

5 DISCUSSION

5.1 Optimization of achievable curing pressure through choice of fastener

The experiments with fasteners proved that fastener head design affects the achievable compression loads. Drilling ribs under the fastener's head reduce the spread of the measured loads. The double threaded fasteners achieve similar mean loads as the washer head screws, but with a small spread. It is noted though that this depends on the difference in thread angle that the double threaded fasteners have. Varying thread fasteners outperform counter head screws too, although care should be taken as to where the transition in thread angle occurs.

The wood industries' reluctant attitude towards use of staples in press gluing applications is understood: a low mean and large spread. The mean compression

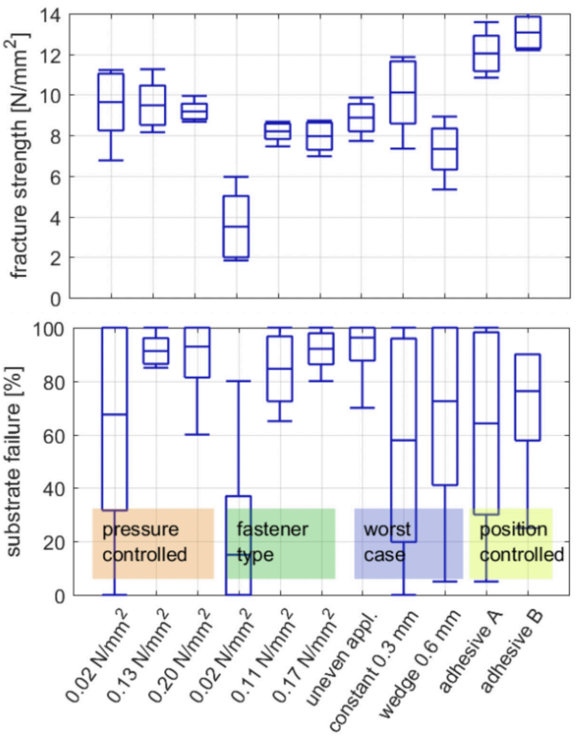


Figure 10: *Shear fracture and substrate failure rate as function of different adhesive application and curing method*

loads are similar to what was measured with scrails. A large potential for application of staples is imagined once compression loads can be better controlled, either by spread of the staple's legs or application of a choice of coating to improve the friction between wood material and staple.

5.2 Fastener distances to generate an average curing pressure of 0.1 N/mm²

Not all adhesives used in press gluing methods require a curing pressure. When they would, the obtained compression loads can be used to estimate the needed number of fasteners per distance covered or area. For instance, some 1C-PUR adhesives require minimum curing pressures of 0.1 N/mm² in their technical data sheets. This threshold is used together with the average curing load to calculate a theoretical fastener distance on different rib widths in Table 4. The maximum intermediate distances of 150 mm suggested earlier in Section 2.2 are maintained. Once fastener distances are too close, a double row of fasteners could be imagined too. The fastener distance *s* was calculated by dividing the achieved mean load *F* by the product of minimum curing pressure *P* and rib width *w*.

$$S = F/(P\ w) \qquad \textbf{(6)}$$

For example, one scrail every 33 mm on a 60 mm wide rib is close, but is also realistic. The additional advantage of using thinner ribs is also that gaps due to slight torsion of ribs, such as simulated in OC3, remain small. It should be noted that scrails and ring nails have limited tightening capacities. It is recommended to ensure sufficient spread of the adhesive before shooting the fasteners.

5.3 Choice of adhesive and final bond quality

The EN 14080:2013, Appendix D, provides a helpful way to quantify the quality of the bond. The test is relatively easy to perform. It is perhaps too conservative due to neglected additional ductility of the connection such as suggested by Gerber et al. (2006). The test allows for low material rolling shear down to 4 N/mm² under the condition that a 100 % material failure is achieved.

Epoxy and PRF adhesives are frequently used in screw and nail press gluing applications. The first adhesive requires almost no curing pressure at all but is more brittle, which could lead to stress concentrations in the bond. PRF is used when it is likely that glue line thicknesses are expected to be large.

6 CONCLUSIONS AND RECOMMENDATIONS

It is important to realize that fastener distance, fastener type, used adhesive is not the complete part of the puzzle. Parameters like achieved glue line thickness, surface quality, production conditions, etc., are elements that are all important to guarantee the final bond quality.

A measurement setup was successfully developed

Table 4: Minimum fastener distances along a rib for a curing pressure of 0.1 N/mm²

		Fastener distance as single row for width of		
	Mean load [N]	60 mm	80 mm	100 mm
Scrail 3.2 mm	200	33	25	20
Ring nail 2.8 mm	250	42	31	25
Counter sunk head 5 mm	1000	150	125	100
Varying thread 4.5 mm	1400	150	150	140
Washer head 6 mm	2700	150	150	150

which allowed the measurement of compression loads generated by fasteners. The measured peak load should however not be used as reference to estimate the average curing pressure. Instead, a load measured after this peak should be used. For nails and staples, the 10 seconds seems to be a reasonable point. It could be stretched a little for screws in the future.

Press gluing with nails or staples is not popular amongst wood construction industry. The large spread in generated compression loads is a possible explanation. They do offer economical solutions, but additional quality control is recommended.

The variety of screws tested showed that some fasteners can provide high adhesive curing pressures. The head typology affects this curing load and fasteners could be optimised to achieve higher curing loads without much redesign of the fastener.

The EN 14080:2013 provides a first evaluation of the remaining bond quality. It is believed to be too conservative since the ductility of the fastener is not considered in the failure behaviour. A test setup could be redesigned to include this in future assessments of the bond quality.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Beaud P, Niemz P, Pizzi A (2006): Structure-Property Relationships in One-Component Polyurethane Adhesives for Wood: Sensitivity to Low Moisture Content, Journal of Applied Polymer Science, Vol. 101, pp. 4181-4192.

Besmer und Bruning GMBH: Schraubenpressverklebung im Holzbau, www.holzmitschwung.ch

Bratulic K and Augustin M (2016): Screw Gluing – Theoretical and experimental approach on screw pressure distribution and glue line strength, WCTE 2016 conference proceedings, Vienna, Austria.

DIN 1052-1:1988-04; Holzbauwerke, Teil1: Berechnung und Ausführung, Deutsches Institut für Normung e. V., Beuth Verlag GmbH, Berlin, Germany.

DIN EN 1995-1-1:2010-12: Eurocode 5: Bemessung und Konstruktion von Holzbauten Teil 1-1: Allgemeines – Allgemeine Regeln und Regeln für den Hochbau, Deutsches Institut für Normung e. V., Beuth Verlag GmbH, Berlin, Germany, 2010.

DIN EN 1995-1-1/NA:2010-12: Nationaler Anhang – National festgelegte Parameter – Eurocode 5, Deutsches Institut für Normung e. V., Beuth Verlag GmbH, Berlin, Germany, 2010.

DIN 1052-10:2012-05: Herstellung und Ausführung von Holzbauwerken – Teil 10: Ergänzende Bestimmungen, Deutsches Institut für Normung, Beuth Verlag GmbH, Berlin, Germany, 2012.

FprEN 14358:2015: Holzbauwerke - Berechnung und Kontrolle charakteristischer Werte, Europäisches Komitee für Normung (in revision).

Franke S, Schiere M, Franke B (2018): Investigation and analysis of press glued connections for timber structures, report number K.007404.77FE-V1, Bern University of Applied Sciences, Switzerland.

Gerber C, Crews K, Sigrist C (2006); Screw- and nail-gluing techniques for wood composite structures, Proceedings of the 19th Australasian Conference on the Mechanics of Structures and Materials, pp.1023-1029.

Hillmer V (2014); Nagelpressverklebung – Einflüsse von Maschineller Fertigung und örtlicher Versetzung, Bachelorarbeit HAWK, Studiengang Holzingeniuerwesen.

Kägi A (2005): Untersuchung zum Einfluss der Holzfeuchte und ausgewählter technologischen Parameter auf die Verklebungsgüte von Fichtenholz mit einem 1K PUR für tragende Holzbauteile, Bern University of Applied Sciences, Thesis Nr. F/4/D/389/05/5.

Kairi M, Kaloinen E, Koponen S, Nokelainen T, Fonselius M, Kevarinmäki A (1999): Screw gluing Kerto-LVL structures with Polyurethane, Otawood publication, HUT Laboratory of Wood Tecnology, HUT Laboratory of Structural Engineering, VTT, Espoo.

Kairi M (2000): Schraubenverleimungen erlauben neue Möglichkeiten im Ingenieurholzbau, Holzbauforum Conference Proceedings, Garmisch-Partenkirchen, Germany.

Kläusler O (2014): Improvement of One-Component Polyurethane Bonded Wooden Joints under Wet Conditions, Doctoral Thesis 22157 ETH Zürich, Switzerland.

Kurt, R (2003): The strength of press-glued and screw-glued wood-plywood joints, Holz als Roh- und Werkstoff (61), pp. 269-272.

Pirmin Jung Holzbauingenieure (2010): Schraubenpressklebung im Holzbau, Merkblatt Intern und Extern.

Rug W, Linke F, Eichbaum G (2013); Vergleichende Untersuchung zum Pressdruck von Nagelschrauben in Langzeitversuchen, Hochschule Eberswalde, Bericht Nummer 2012-PB-00-010.

Rug W, Gümmer K, Gehring S (2010): Schraubenpressklebung mit Nagelschrauben, Bautechnik 87 (Heft 1).

SN EN 14080:2013 (2014): Holzbauwerke - Brettschichtholz und Balkensschichtholz – Anforderungen, Schweizer Ingenieur und Architektenverein, Zürich, Switzerland

Sieber, D (2003): Brückenschlag über Fünf Jahrhunderte, SFS-intec PraxisReport 15: p. 6–7.

Steck, G (1988): Bau-Furniersperrholz aus Buche, Informationsdienst Holz, Entwicklungsgemeinschaft Holzbau (EGH), Düsseldorf, Germany.

Widmann R (2014): Sanierung und Verstärkung von Brettschichtholz, S-WIN Fortbildungs Kurs Tagungsband.