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Experimental Study on Wood-Adhesive-Steel-Bolts Hybrid Connections with Slotted-in Steel Plates

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ABSTRACT

Structural connections are one of the most important parts influencing the overall performance of a wooden structure. The way of design of these can lead both to increasing and decreasing internal stresses occurring in the load-carrying elements and total deformations of the structure. Typical mechanical joints in wooden structures are defined as plastic hinges or, at best, semi-rigid. The innovative hybrid proposed in the paper with adhesive added between elements can be much stiffer than a typical connection, which can lead to assuming rigid joint and significant reduction in stresses and deformations of a structure. The research comprised 30 specimens in three groups (10 per each group: reference – without adhesive, hybrid with one-component PUR – polyurethane adhesive and hybrid with one-component PVAc – polyvinyl acetate adhesive) tested on the MTS 809 testing machine up to failure. An innovative idea was to connect elements initially by applying an accurately predicted tightening torque value to bolts. This resulted in obtaining enough clamping pressure between elements for adhesive curing, with none other equipment. The load was applied in parallel-to-grain wood direction. The results showed that utilising hybrid connection caused, both for PUR and PVAc adhesive, a huge increase in stiffness. When comparing to the reference no-adhesive, bolted connection, this was 2365% stiffer (nearly 24 times). Load-carrying capacity was higher too, however, the increase was not that significant and was at the level of 14.4% and 27.1%, for PUR and PVAc adhesives, consecutively. Worth noting is that the hybrid connection could continue to work after adhesive failure with 60% higher stiffness than the reference one and its load-carrying capacity was only 10% lower than the reference. Hybrid connections of this type can potentially serve as structural joints because of the innovative concept of combining components. Steel plates can be covered with adhesive and then inserted between wooden parts. Next, the tightened bolts can work as clamps producing enough pressure for adhesive curing, enabling the joint to be assembled directly on the construction site. Despite the mentioned advantages, before providing the connections' design methods, the idea needs to be tested towards various effects influencing wooden structures. Incorporating numerical modelling can be extremely important too.

Keywords: hybrid connections for wooden structures; wood-adhesive-steel-bolts; slotted-in steel plates; experimental tests.

INTRODUCTION

Wooden structure performance depends on its structural connections, which can either amplify or mitigate internal stresses and deformations. Traditional mechanical joints are often considered somewhat flexible, with plastic hinges being the norm. However, a novel hybrid connection, incorporating adhesive between elements, offers a notable enhancement in stiffness. This heightened rigidity can effectively decrease stresses and deformations, significantly benefiting the overall structure. To give a broader context and emphasise its importance, the section was split into three parts. The first two include recent investigations on bolted or adhesively bonded joints, when the methods were used separately, and the next one comprises recent investigations on hybrid connections.

Stamatopoulos et al. [1] performed an experimental study on fifty-six specimens with singular threaded rods embedded both perpendicular- and parallel-to-grain direction in spruce and pine glue laminated timber (GLT). Rahim et al. [2] investigated steel-wood-bolted connection loaded parallel-to-grain for softwood on sixty specimens. Steel plates were mounted by four bolts with different diameters in a layout on both sides of the wooden element. The general conclusion from the research was that the stiffness of bolted timber connections for softwood depended on the bolt diameter, number of rows and bolts, end distance and edge distance. Wang et al. [3] tested the lateral performance of bolted connections. First, the stiffness determination for pressing single bolts with different diameters into the wood was done. Next, the authors performed a shearing test of the wood-dowel connection. The last part of the work comprised tests on beam-column joint moment-carrying behaviour analysis. Lokaj et al. [4, 5] tested round spruce wood samples, in three grain angle orientations, connected with steel plates by bolts. The main conclusion was that the performance of connections for round timber was similar to typical standard squared connections. Jensen and Quenneville [6] investigated failure modes in bolted timber connections loaded parallel to the grain. Connections with a very low slenderness ratio with a single and with multiple bolts in a single row were tested. Sawata and Yasamura [7] similarly to Kharouf et al. [8] conducted research on a single bolt with a slotted-in steel plate with parallel and perpendicular to wood grain orientations. Johanides et al. [9, 10] analysed a connection made from spruce wood with metal mechanical dowel-type fasteners. Not only a common combination of bolts and dowels, but also fully threaded screws were used for the connection. The used fasteners were placed in one symmetrical circle. The conclusion was that a connection using fully threaded screws provided a better load-carrying capacity. Several scientists conducted research on the influence of tightening torque and resulting preload force in bolts on the performance of bolted connections. Matsubara et al. [11] tried to find how the torque influences the separation in bolted joints loaded axially. The ultimate tensile load was stated to decrease when the preload force increased. Awaludin et al. [12] examined the effect of preload in bolts on damping response and ultimate moment-carrying capacity of timber joint with steel side plates. The superiority of pre-stressed joint was shown by a significant increase in initial stiffness and a small increase in ductility and ultimate moment resistance. Next, in [13] the authors stated that introducing preload force into the bolts can increase the stiffness of connection at the first loading phase by causing higher friction between the adjacent elements. The failure forms of joints were similar regardless of applied preload value. Subsequently, in [14] the effectiveness of bolts pretension after one year of stress relaxation measurement was evaluated. The pre-stressing effect was stated as negligible without regular re-stressing. Preloading bolts and determining contact pressure is important not only in wooden structures, but exemplary in steel ones, as reported by Grzejda [15, 16].

Pecnik et al. [17] investigated eighteen double-lap shear timber connections with thick flexible polyurethane adhesives. Spruce wood elements were connected by three different two-component PUR adhesives of varied thickness. The general conclusion from the research was that compared to mechanical dowel-type screwed connection with a typical arrangement of fasteners, all tested adhesive joints showed significantly higher values in terms of elastic stiffness and strength. Angelidi et al. [18] tested experimentally nineteen double-lap timber-to-timber joint specimens in tension and compression. Spruce wood elements were bonded by two different adhesives: brittle epoxy and ductile acrylic. The conclusion was that epoxy-bonded joints exhibited a stiff-linear load-displacement response up to brittle failure and ultimate loads in compression were much higher than in tension. Also, acrylic-bonded joints showed a highly nonlinear and ductile load-displacement response in tension and premature adhesion failure in compression. Vallee et al. [19] compared specimens with slotted-in steel plates bonded with epoxy adhesive to dowel-type joints. In both cases, spruce wood blocks were used. Embedment length for adhesive joints varied, and it was stated that the higher embedment length, the higher joint capacity was. The authors also analysed the influence of different connection types on the structural behaviour of full-scale trusses. The general conclusion from the research was that the capacity of bonded joints was higher than the doweled one and the adhesively bonded trusses achieved a significantly higher failure load compared to the mechanically connected trusses. Another group of adhesive connections are steel-steel or wood-wood joints. Such a bonding type is worth emphasizing, even though this is not of direct interest in the conducted research. Doluk et al. [20] evaluated a surface treatment effect on the strength of single-lap adhesive joints. The main conclusion was that the method of surface treatment affects the strength. Similarly, Rudawska et al. [21] conducted research on the influence of steel degreasing methods on shear strength of single-lap adhesive joints and drew the conclusion that the most effective method was spraying extraction naphtha. The same authors performed an analysis of selected factors on the strength of wood adhesive joints [22]. At least one important conclusion was drawn, especially that technological process as adequate pressure application during adhesive curing is crucial. The author of the paper has experience in testing wood-wood and wood-CFRP adhesively bonded connections in a double-lap shear testing scheme. This was done, among others in works [23–27].

Review on hybrid connections used in wooden structures was done, among others, by Shober and Tannert [28]. Wang et al. [29] tested twelve specimens composed of spruce GL28c class GLT elements connected with the birch plywood plates in a four-point bending static scheme. The plates were adhesively bonded to two sides of the elements by two-component PUR adhesive on a varied joint area with pressure obtained by clamping and then applying screws. It was shown that the global stiffness can be higher when the joint area is larger, compared to the continuous GLT beam with the same span and cross-sectional properties. In [30] the author used three types of adhesives (MUF, PRF and 2C PUR) to join spruce GL28cs class GLT beams with plywood. The idea was planned to be utilised in hybrid connections. Three types of preparing connection were checked: screw-adhesive, clamping by clamps and application of weight loads. The specimens in a total number of sixty were tested under shearing conditions. The conclusions drawn were that 2C PUR adhesive exhibited the highest bonding strength than MUF and PRF adhesives regardless of the pressing methods. Each adhesive showed satisfactory bonding performance; however, screw-adhesive was recommended because of the ease of operation in the potential structural uses. Imakawa et al. [31] investigated the mechanical properties of hybrid joints composed of coniferous wood, steel plates, adhesive and screws. Narrower steel plates were fastened to the wooden block using screws of different diameters. Nine specimens with different adhesives (API, 1C PUR and 1C PUE) applied between steel plate and wooden block were tested. The study found that using adhesives with screws can enhance connection stiffness and load-carrying capacity. Ghoroubi et al. [32] examined timber-to-timber joint connected by adhesive and mechanical anchorages together with adhesive, with varying bonding lengths and layouts of anchorages. Pine wood was used to prepare elements and PUR adhesive to bond the connection. Each specimen underwent the same pressure and pressing time. After adhesive curing, mechanical anchorages were placed in prior drilled holes. Twenty-one specimens were tested in an axial tension testing scheme, where timber-to-timber connection was under shearing. The general conclusion from the research was that load-carrying capacity increased significantly when mechanical anchorage was used in the timber-to-timber connections with the adhesive. Shi et al. [33] tested short and long-term performance of bonded steel-wood joints under controlled environmental conditions. The steel plates contained vulcanised rubber on the surface. These were connected to the GL30c spruce wood blocks using two-component PUR adhesive and six screws aiming to ensure a proper clamping pressure up to the adhesive curing. The general conclusions from the research were that the bonded steel plate showed good short and long-term mechanical behaviour, whereas applying a rubber layer improved the ductility and mechanical stability of the joint. Yang et al. [34] tested fifteen specimens made of GL30c class GLT in two separate double-lap shear connections with one steel plate placed inside wooden elements and two steel plates placed outside and a large hollow steel dowel in the centre. The steel plates were bonded to wood using two-component PUR adhesive, and the outers were covered with a rubber foil and thirty-four screws were used as an addition to mount the plates. The general conclusion from the experiments was that a significant increase in the load-carrying capacity was obtained by introducing a rubber foil layer.

In summary, hybrid connections are an object of current scientific research. However, the amount of research done so far is limited, and in the author's opinion, the knowledge of the subject can be significantly enriched by the research conducted in this article. The proposed solution has not been encountered in the scientific literature, which proves its innovation.

MATERIALS AND METHODS

Experimental tests were performed on the MTS 809 testing machine. A total of 30 samples were prepared for the experiments (10 per each group: reference – without adhesive, hybrid with PUR adhesive and hybrid with PVAc adhesive). Tests were displacement-controlled with testing speed equal to 2 mm/min in the testing scheme given in Figure 1. Specimens were tested in tension parallel to wood grain orientation up to failure understood as damage observed for the reference samples without adhesive. The critical point was a visible, sudden force drop on a force-displacement path preceded by a characteristic cracking sound. The first sample from each group was used to check whether the results were gathered correctly, estimate the testing time need for the sample and to initially predict the form of failure. These samples were then omitted in the interpretation of results; therefore, the number of reliable specimens tested under the same conditions and then used in further analyses was equal to 9 per each testing group. Specimens prepared for the tests comprised:

- seasoned and planed Spruce wood of density 420–480 kg/m^3 and moisture content 10–13% with dimensions of 40×60×200 mm
- S235 class raw steel plates with dimensions of 4×60×190 mm
- One-component adhesives for professional application in wooden structures: Kleiberit 501.0 PUR (polyurethane) and Kleiberit 303.0 PVAc (polyvinyl acetate)
- M6 5.8 class bolts (ultimate tensile strength equal to 500 MPa and yielding strength equal to 400 MPa), M6 self-locking nuts and M6 Ø24 mm A2-304 stainless steel washers

Several steps were taken to prepare the specimens properly. First, wooden elements were cut to the final dimensions from square timber with section dimensions of 40×60 mm, omitting any visible defects as knots or cracks. Next, eight openings per each element were drilled using Ø7 mm drill in a spacing being consistent with this on steel plates prepared by CNC milling. Openings patterns for wooden elements and steel plates were based on the PN-EN-1995-1-1:2010 [35] and PN-EN-1993-1-8:2006 [36] standards, respectively. Both patterns are shown in Figure 2.

Both wooden elements and steel plates were dusted and degreased with extraction naphtha before being connected. Three groups of specimens screwed using M6 5.8 class bolts, M6 self-locking nuts and M6 Ø24 mm A2-304 stainless steel

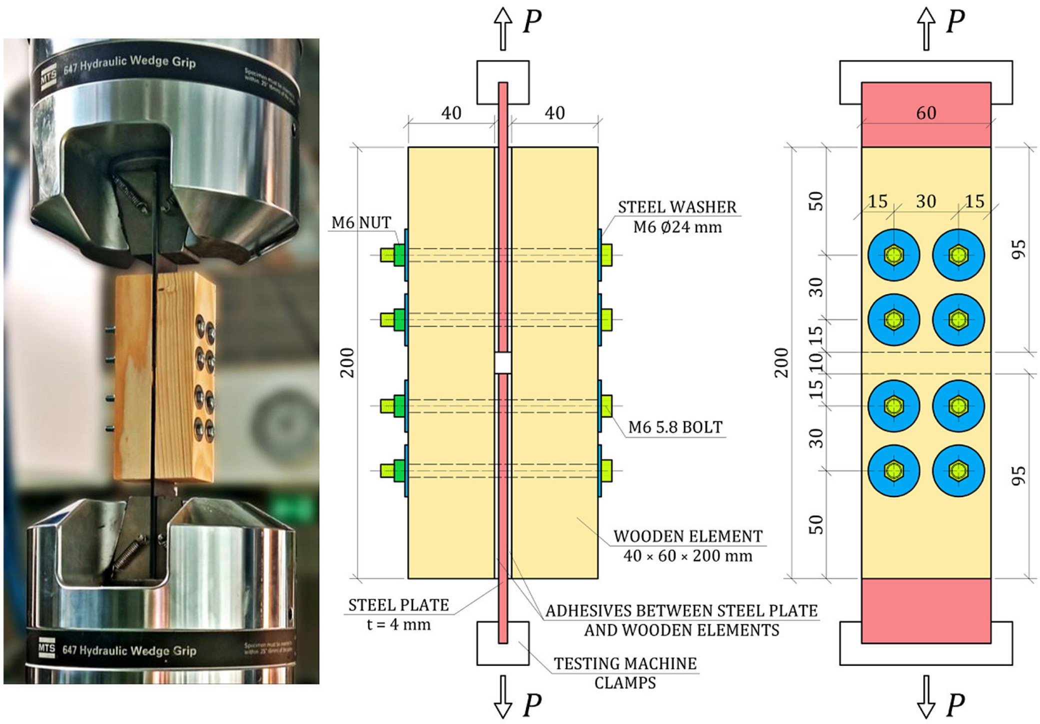

Figure 1. Experimental setup: laboratory testing stand and described testing scheme – front and side view (dimensions in mm)

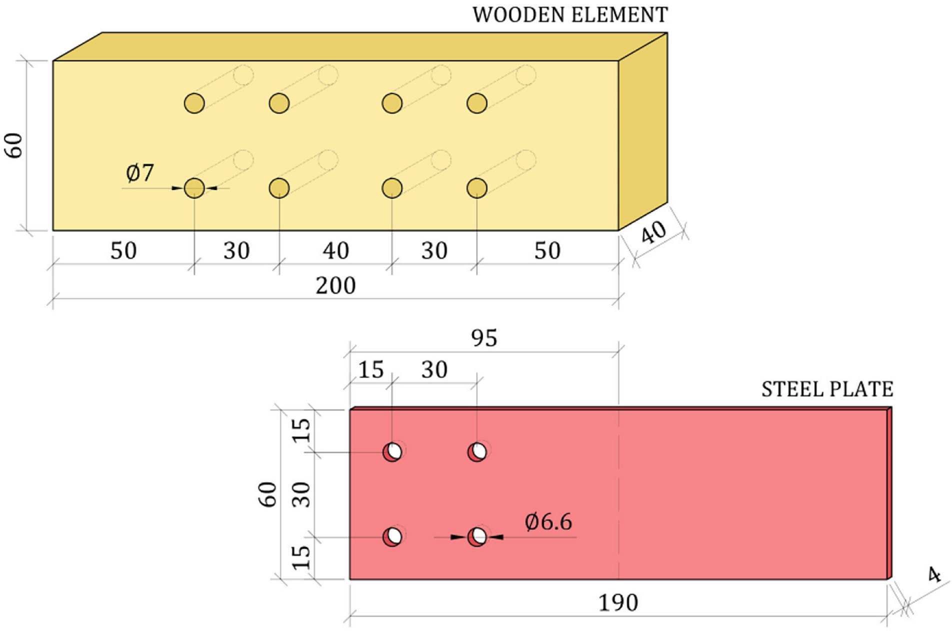

Figure 2. Openings pattern in wooden element (yellow) and in steel plate (red) – dimensions in mm

washers were planned: without adhesive between wooden and steel parts, or "hybrid" adhesively bonded with Kleiberit 501.0 PUR adhesive and adhesively bonded with Kleiberit 303.0 PVAc adhesive. The adhesive was dispersed on the less porous surface of the steel plates using a roller and then applied to wooden elements. Subsequently, steel washers, bolts and nuts were placed in openings and both steel plates were hand-stretched to remove possible clearances resulting from slightly different openings diameters. Nuts were tightened using certified Wera dynamometric screwdrivers. Tightening torque of each single bolt used to connect both no-adhesive and adhesively bonded samples was equal to 4 Nm (0.5 Nm to eradicate self-locking nut resistance + 3.5 Nm to obtain desired preload force in bolt), being the value consistent with the earlier authors' studies [37]. According to the aforementioned investigations, 4 Nm tightening torque value should cause at least 2 kN preload force value in each bolt, leading to proper bolt embedment and simultaneously producing enough pressure for adhesive joint (0.6 MPa according to the adhesives technical cards [38, 39]). When a proper pressure was applied, the adhesive layer thickness should be negligibly small and should not exceed 0.1 mm. Next, specimens were left for adhesive curing for 48 hours.

The bolts in hybrid connection were used as clamps, by producing a proper pressure value because of tightening torque. No other clamps were used to introduce higher pressure. The recent paper introduces a novel approach not found in existing literature. For equal conditions, the bolts were re-tightened to 4 Nm before machine testing, as preloading force may be lost during sample preparation [14].

RESULTS AND DISCUSSION

Results from the tests were gathered in graphs separately for each group. Next, several analyses were performed in subsequent tables. Figure 3 presents results for no-adhesive samples (B), Figure 4 for adhesively bonded with PUR adhesive (PUR) and Figure 5 for adhesively bonded with PVAc adhesive. The same scale was used for each graph for enabling initial direct comparison of some easy visible differences between the experimental curves.

A different behaviour was observed between no-adhesive and hybrid connections. Reference samples started with high stiffness up to 5 kN of axial force, which was probably caused by increased friction between components because of the preload force applied to bolts by tightening torque. After the first stage, the connection continued to work as a typical dowel-type one preceded by component elements adjustment and then through pressure transferred from bolts to wood.

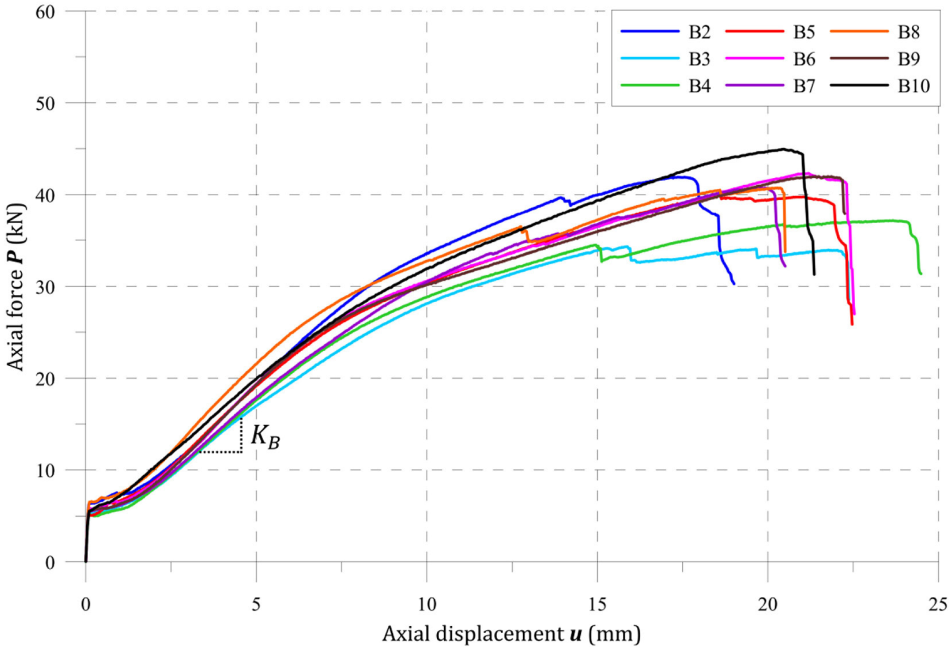

Figure 3. Force-displacement paths for no-adhesive specimens

The behaviour of hybrid connections both with PUR and PVAc adhesives was comparable. The samples showed high stiffness in the first stage of the connection work. Next, because of adhesive delamination, a sudden force drop was observed; after that, the specimens behaved similarly to reference specimens, however much smaller critical displacements were observed. More sophisticated comparisons can be performed after statistical analyses presented in Tables 1–3. As several measurements were done, an uncertainty estimation was performed for experimental data as in earlier author's work [40], being given by formula 1:

$$x = \bar{x} = \frac{\Sigma x_i}{n} \rightarrow s_{\bar{x}} = \sqrt{\frac{\Sigma (x_i - \bar{x})^2}{n(n-1)}} \quad (1)$$

where: x – measurement, $\bar{x}$ – measurement mean, n – number of measurements, $s_{\bar{x}}$ – measurement uncertainty.

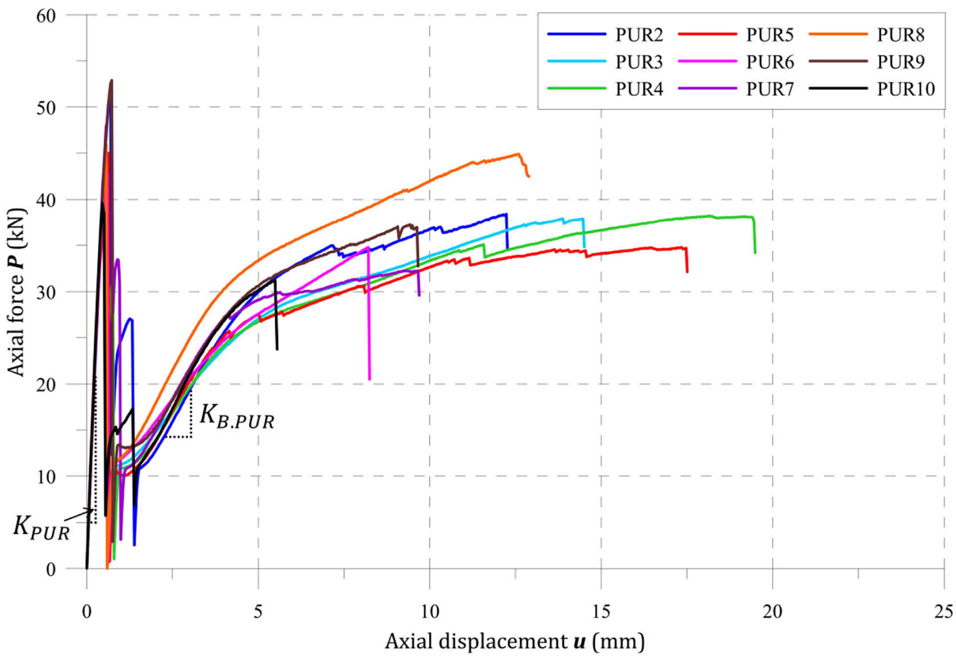

Figure 4. Force-displacement paths for hybrid specimens adhesively bonded with PUR adhesive

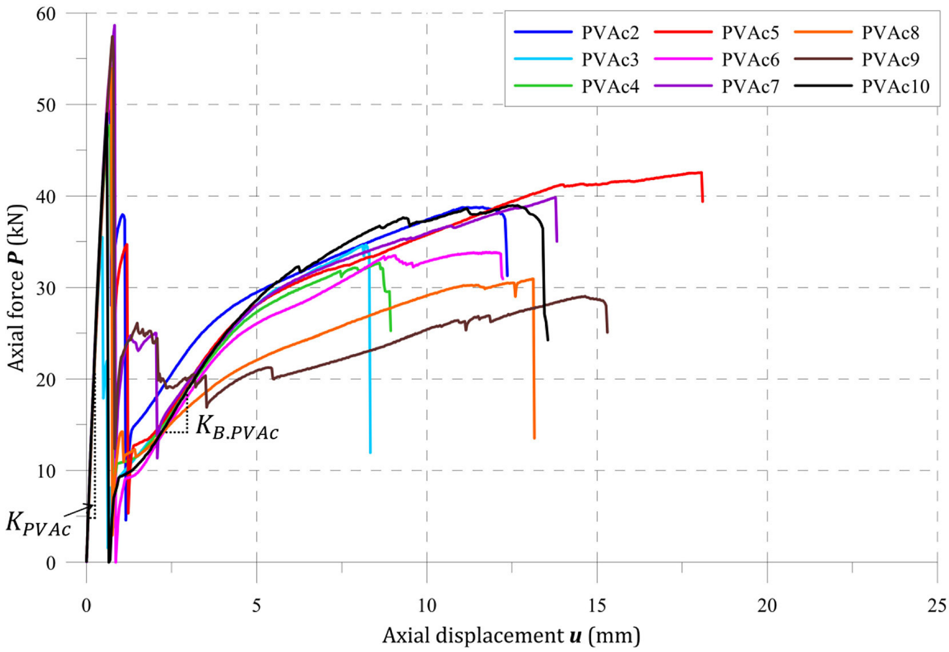

Figure 5. Force-displacement paths for hybrid specimens adhesively bonded with PVAc adhesive

Stiffness properties (K_B, K_{PUR}, $K_{B.PUR}$ K_{PVAc}, $K_{B.PVAc}$) were defined as a slope of the corresponding linear parts of the force-displacement curves and failure forces ($P_{max.B}$, $P_{max.PUR}$, $P_{max.B.PUR}$, $P_{max.PVAc}$, $P_{max.B.PVAc}$) were determined both as adhesive layer failure and dowel-type connection failure.

Mean stiffness of the bolted no-adhesive connection was 3.560 kN/mm and the mean failure force was 40.453 kN. Relative measurement errors for both properties were at the level of 2.52% and 2.56%, consecutively. This meant that the mean value can be a representative value for both properties. The results for hybrid connections were divided into first and second, both stiffness and failure force. The first one meant mainly the properties of adhesive layers, while the second meant the properties of the dowel-type work phase. Mean first stiffness and failure force for specimens bonded with PUR adhesive were 87.752 kN/mm and 46.291 kN with relative error

Table 1. Statistical analysis of stiffness and failure force results for bolted no-adhesive specimens (B)

Sample	Stiffness		Failure force	
	K_B (kN/mm)	$(x_i-\bar{x})^2$ (kN/mm)^2	$P_{max.B}$ (kN)	$(x_i-\bar{x})^2$ (kN)^2
B2	3.591	0.00101	41.924	2.16512
B3	3.331	0.05247	34.314	37.68198
B4	3.230	0.10868	37.152	10.89475
B5	3.694	0.01801	39.916	0.28784
B6	3.503	0.00324	42.338	3.55456
B7	3.420	0.01955	40.731	0.07763
B8	4.088	0.27873	40.747	0.08659
B9	3.811	0.06302	41.996	2.38233
B10	3.370	0.03589	44.955	20.27377
Statistical analysis	$\bar{x}$ (kN/mm)	$\Sigma(x_i-\bar{x})^2$ (kN/mm)^2	$\bar{x}$ (kN)	$\Sigma(x_i-\bar{x})^2$ (kN)^2
	3.560	0.581	**40.453**	77.405
	$s_{\bar{x}}$ (kN/mm)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)
	0.090	**2.52**	1.037	**2.56**

Table 2. Statistical analysis of stiffness and failure force results for hybrid specimens with PUR adhesive (PUR)

Sample	First stiffness		First failure force		Second stiffness		Second failure force	
	K_{PUR} (kN/mm)	$(x_i-\bar{x})^2$ (kN/mm)^2	$P_{max.PUR}$ (kN)	$(x_i-\bar{x})^2$ (kN)^2	$K_{B.PUR}$ (kN/mm)	$(x_i-\bar{x})^2$ (kN/mm)^2	$P_{max.B.PUR}$ (kN)	$(x_i-\bar{x})^2$ (kN)^2
PUR2	90.849	9.59125	52.565	39.36044	6.767	0.11821	38.409	3.13638
PUR3	83.130	21.36415	41.133	26.59940	5.203	1.48978	37.911	1.62175
PUR4	85.440	5.34578	44.474	3.30109	5.823	0.36034	38.211	2.47630
PUR5	84.903	8.12090	45.029	1.59283	6.985	0.31602	34.781	3.44692
PUR6	84.730	9.13594	42.804	12.15830	4.843	2.49781	34.781	3.44642
PUR7	90.441	7.22923	52.163	34.48029	7.013	0.34752	32.278	19.00669
PUR8	90.254	6.25655	45.925	0.13409	7.061	0.40692	44.893	68.14912
PUR9	87.857	0.01101	52.909	43.79417	6.393	0.00094	37.238	0.36018
PUR10	92.167	19.48862	39.617	44.54255	7.722	1.68625	31.237	29.16839
Statistical analysis	$\bar{x}$ (kN/mm)	$\Sigma(x_i-\bar{x})^2$ (kN/mm)^2	$\bar{x}$ (kN)	$\Sigma(x_i-\bar{x})^2$ (kN)^2	$\bar{x}$ (kN/mm)	$\Sigma(x_i-\bar{x})^2$ (kN/mm)^2	$\bar{x}$ (kN)	$\Sigma(x_i-\bar{x})^2$ (kN)^2
	87.752	86.543	**46.291**	205.963	**6.423**	7.224	**36.638**	130.812
	$s_{\bar{x}}$ (kN/mm)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN/mm)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)
	1.096	**1.25**	1.691	**3.65**	0.317	**4.93**	1.348	**3.68**

at the level of 1.25% and 3.65%, respectively. The small relative measurement errors meant the mean value was representative. The second mean stiffness and failure force were equal to 6.423 kN/mm and 36.638 kN with relative measurement errors at the level of 4.93% and 3.68%, respectively. Still, the errors were smaller than 5%.

Mean first stiffness and failure force for specimens bonded with PVAc adhesive were 87.782 kN/mm and 51.405 kN with relative error at the level of 0.84% and 4.50%. The error remained under 5%, as earlier. Next, the second stiffness and failure force were 5.158 kN/mm and 35.702 kN with relative errors at the level of 7.05% and 4.24%. Despite a slightly larger than 5% error, the correlation of the results remained reliable.

The most desired properties of the structural connections are the stiffness and load-carrying capacity before damage occurrence. Therefore, increases in the first stiffness and failure load of

Table 3. Statistical analysis of stiffness and failure force results for hybrid specimens with PVAc adhesive (PVAc)

Sample	First stiffness		First failure force		Second stiffness		Second failure force	
	K_{PVAc} (kN/mm)	$(x_i-\bar{x})^2$ (kN/mm)^2	$P_{max.PVAc}$ (kN)	$(x_i-\bar{x})^2$ (kN)^2	$K_{B.PVAc}$ (kN/mm)	$(x_i-\bar{x})^2$ (kN/mm)^2	$P_{max.B.PVAc}$ (kN)	$(x_i-\bar{x})^2$ (kN)^2
PVAc2	87.273	0.25941	52.564	1.34423	5.650	0.24237	38.787	9.51769
PVAc3	83.673	16.88194	35.468	253.98498	5.705	0.29972	34.661	1.08349
PVAc4	86.441	1.79757	47.715	13.61621	5.375	0.04704	32.679	9.13644
PVAc5	86.981	0.64114	52.671	1.60290	5.796	0.40682	42.571	47.18961
PVAc6	88.788	1.01123	55.254	14.81531	5.549	0.15305	33.821	3.53536
PVAc7	90.384	6.77184	58.642	52.37341	5.235	0.00597	39.849	17.20409
PVAc8	87.520	0.06885	53.920	6.32543	3.893	1.60144	30.940	22.66904
PVAc9	87.798	0.00027	57.416	36.13098	2.854	5.30933	29.041	44.36405
PVAc10	91.180	11.54474	48.994	5.81054	6.365	1.45615	38.965	10.64932
Statistical analysis	$\bar{x}$ (kN/mm)	$\Sigma(x_i-\bar{x})^2$ (kN/mm)^2	$\bar{x}$ (kN)	$\Sigma(x_i-\bar{x})^2$ (kN)^2	$\bar{x}$ (kN/mm)	$\Sigma(x_i-\bar{x})^2$ (kN/mm)^2	$\bar{x}$ (kN)	$\Sigma(x_i-\bar{x})^2$ (kN)^2
	87.782	38.977	**51.405**	386.004	**5.158**	9.522	**35.702**	165.349
	$s_{\bar{x}}$ (kN/mm)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN/mm)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)	$s_{\bar{x}}$ (kN)	$\frac{s_{\bar{x}}}{\bar{x}}$ (%)
	0.736	**0.84**	2.315	**4.50**	0.364	**7.05**	1.515	**4.24**

hybrid connections were compared to properties represented by a no-adhesive, bolted connection. For easier results interpretation, these were gathered in Table 4.

As shown in Table 4, using hybrid connection caused a huge increase in stiffness, both for PUR and PVAc adhesive. The mean stiffness increase comparing to the reference no-adhesive, bolted connection was 2365% (nearly 24 times stiffer). Load-carrying capacity was higher too, however, the increase was not that significant and was at the level of 14.4% and 27.1%, respectively. It is worth noting that the hybrid connection could still continue to work after adhesive failure with 60% higher stiffness than the reference one and its load-carrying capacity was only 10% lower than the reference. Of course, when the stiffness is radically reduced, the entire static scheme of the structure changes, causing much different stresses distribution in structural elements. Nevertheless, this study is not focused on the mentioned topic. Since the paper mainly focuses on hybrid connections, no-adhesive specimens were only used as a reference. Therefore, failure forms were not analysed individually for each specimen. As failure for each specimen was very similar, a representative example providing every probable failure form was presented in Figure 6. Behaviour was very comparable to this observed in other papers on bolted connections mentioned in the introduction section [1–14].

Failure of the connection can be represented by several phenomena. Wood can undergo ductile failure in two directions: perpendicular and parallel to the grain. Damage occurring in a perpendicular direction could be understood as the indentation of steel washers into wood, which was followed by the ductile failure of steel washers. Simultaneously, the crushing of the wood in parallel-to-grain direction was caused by the bolts working as a dowel-type fastener. Ductile failure of bolts was the next probable phenomenon, being followed by wood and bolts fracture. Determining whether the wood or bolt broke first was difficult, because of lack of inside monitoring

Table 4. Comparison of the obtained results for B, PUR and PVAc specimens

Specimen type	Mean stiffness (kN/mm)	Increase relative to the reference sample (%)	Mean load-carrying capacity (kN)	Increase relative to the reference sample (%)
B (reference)	3.560	-	40.453	-
PUR	87.752	**2364.9**	46.291	**14.4**
PVAc	87.782	**2365.8**	51.405	**27.1**

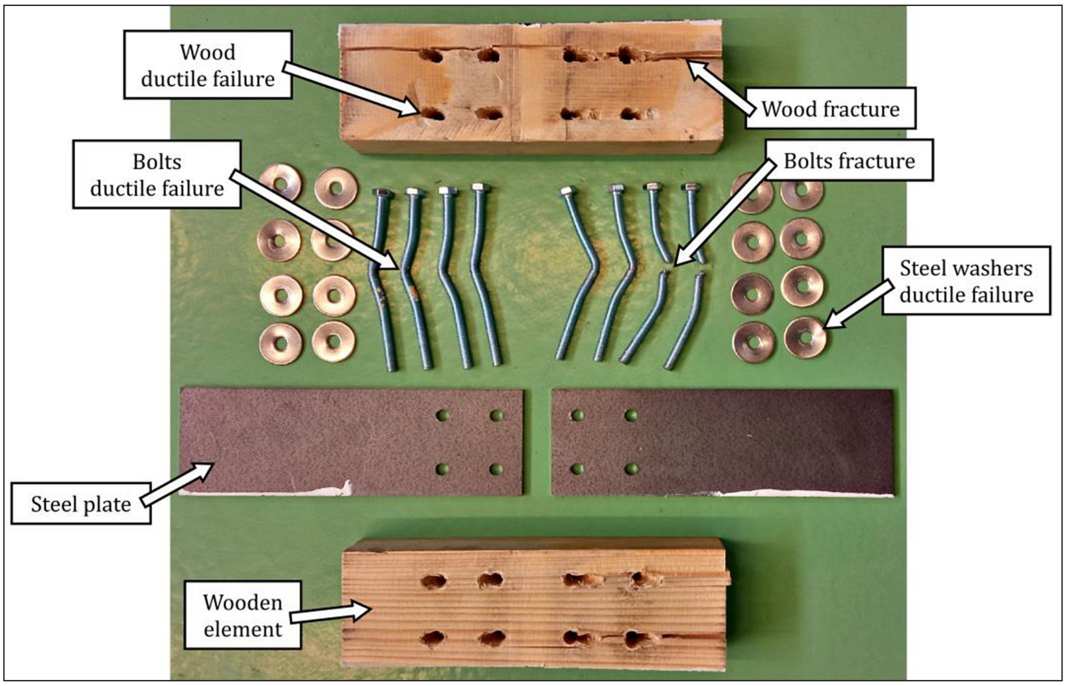

Figure 6. Forms of failure of B reference specimens

of the specimens. When analysing hybrid specimens and assuming adhesive ultimate strength as a leading damage criterion, two general forms of failure can be distinguished. The first, most desired, is cohesive failure when the ultimate adhesive cohesion is exceeded. The second one failed due to insufficient adhesion. Cohesive failure can be divided into two groups: failure of the adhesive layer between steel plate and wood, and a wood shear cracking.

Separating PUR and PVAc samples, as the B samples, proved impossible because of random fracture in two different adhesives. Taking the samples apart by hand made little sense, because of the strength of the adhesive bonding, thereby, introducing artificial damage to the parts was inevitable. Thus, the failure forms were interpreted by comparing visible parts of steel plate, being connected with wood at the tests beginning, after damage. Exemplary failure forms were presented and described in Figure 7, while all the results were gathered in Table 5.

After adhesive layer failure, the second failure was comparable to this for the B specimens. However, this was omitted in results presentation, because of a secondary importance and problems with disassembling adhesively bonded samples. Noticeably, specimens were damaged mainly because of the cohesive failure of the adhesive layer. When dividing the samples into three groups,

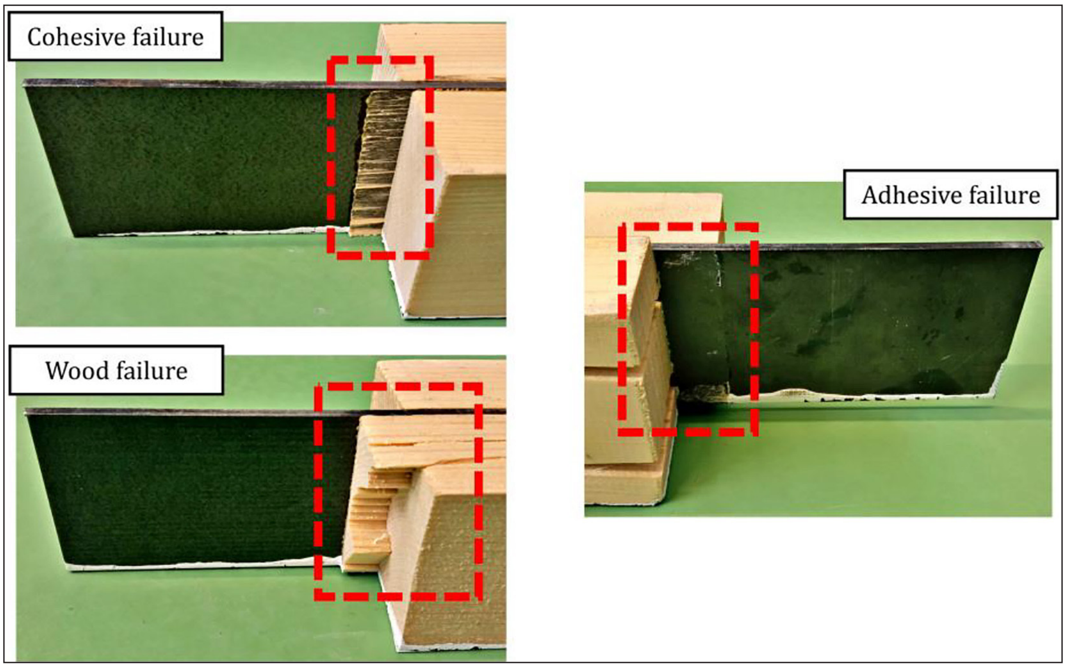

Figure 7. Forms of failure of PUR and PVAc specimens

Table 5. Forms of failure of PUR and PVAc specimens and corresponding failure force. COH – cohesive or wood failure, ADH – adhesive failure

Sample	Form of failure	$P_{max.PUR}$ (kN)	Sample	Form of failure	$P_{max.PVAc}$ (kN)
PUR2	COH	52.565	PVAc2	COH	52.564
PUR3	ADH	41.133	PVAc3	ADH + COH	35.468
PUR4	ADH + COH	44.474	PVAc4	COH	47.715
PUR5	ADH	45.029	PVAc5	COH	52.671
PUR6	ADH + COH	42.804	PVAc6	COH	55.254
PUR7	COH	52.163	PVAc7	ADH + COH	58.642
PUR8	ADH	45.925	PVAc8	COH	53.920
PUR9	COH	52.909	PVAc9	COH	57.416
PUR10	ADH	39.617	PVAc10	COH	48.994

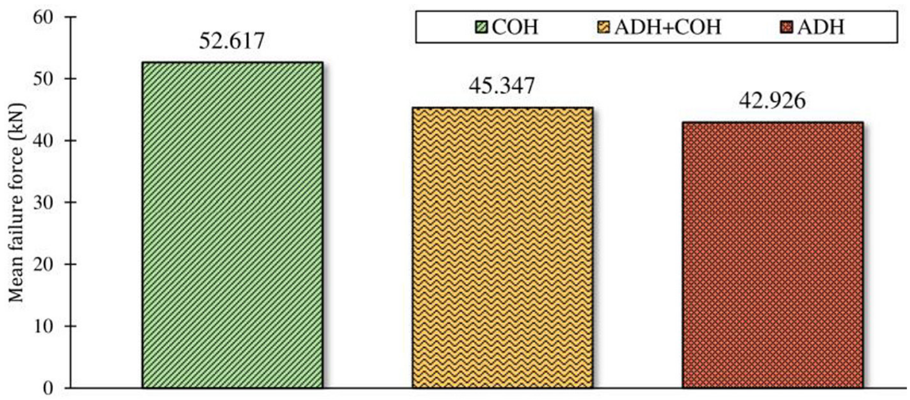

Figure 8. Mean failure force depending on the form of failure

then calculating mean maximal force for each group and comparing the results (Figure 8), visible is that the highest load-carrying capacity of the connection was obtained while the most desirable cohesive form of failure was observed. However, several samples failed because of lack of enough adhesion between steel plate and wooden parts. Therefore, checking an influence of different surface treatment before bonding elements with adhesive is advisable to be done as further research.

CONCLUSIONS

To summarise, a total of 30 specimens (10 per each group: reference – without adhesive, hybrid with PUR adhesive and hybrid with PVAc adhesive) were tested on the MTS 809 testing machine up to failure. The load was applied in parallel-to-grain wood direction. Statistical analysis of 9 specimens for each group showed that the obtained results were statistically valid, and the mean values of the properties can be a reliable representative.

The findings showed that employing a hybrid connection led to a large increase in stiffness for both PUR and PVAc adhesives. Compared to the no-adhesive, bolted reference connection, this increase amounted to 2365% greater stiffness (almost 24 times higher). Load-carrying capacity was higher too, however, the increase was not that significant and was at the level of 14.4% and 27.1%, for PUR and PVAc adhesives, respectively. It is noteworthy that even after adhesive failure, the hybrid connection maintained 60% higher stiffness than the reference, with only a 10% decrease in load-carrying capacity. However, it is important to acknowledge that significant reduction in stiffness alters the static scheme of the entire structure, leading to different stress distributions in structural elements. This aspect, however, was not covered in the paper and requires further analysis in future studies.

Hybrid connections of this type can potentially serve as structural joints because of the innovative concept of combining components. Steel plates can be covered with adhesive and then inserted between wooden parts. Next, the bolts, tightened with a proper tightening torque value, can work as clamps producing enough clamping pressure for adhesive curing, using no other equipment, enabling the joint to be assembled directly on the construction site. The author knows that applying the assumptions proposed in the article requires many other studies. Necessary is, among other things, to test the strength of the connection between impregnated wooden elements and anti-corrosion protected steel elements, because adhesion may vary. Other important directions of research include behaviour under cyclic and long-term loads and durability under changing environmental conditions.

When the aforementioned analyses are provided, the design methods can be evaluated properly. Incorporating numerical modelling based on complex Finite Element models, validated by laboratory tests, can be extremely important in this case. Preparing such models and performing analyses are planned in the near future.

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REFERENCES

1. Stamatopoulos H, Massaro FM, Qazi J. Mechanical properties of laterally loaded threaded rods embedded in softwood. European Journal of Wood and Wood Products 2022; 80: 169–82. https://doi.org/10.1007/s00107-021-01747-6
2. Rahim NL, Raftery G, Quenneville P, Ing DS, Nabialek M, Jaya RP, Ibrahim NM, Al Bakri AMM, Sliwa A. The stiffness of steel-wood-steel connection loaded parallel to the grain. Archives of Civil Engineering 2022; 68: 37–50. https://doi.org/10.24425/ace.2022.140628
3. Wang XT, Zhu EC, Niu S, Wang HJ. Analysis and test of stiffness of bolted connections in timber structures. Constr Build Mater 2021; 303. https://doi.org/10.1016/j.conbuildmat.2021.124495
4. Lokaj A, Klajmonová K, Mikolášek D, Vavrušová K. Behavior of round timber bolted joints under tension load. Wood Research 2016; 61: 819–30.
5. Lokaj A, Dobes P, Sucharda O. Effects of loaded end distance and moisture content on the behavior of bolted connections in squared and round timber subjected to tension parallel to the grain. Materials 2020; 13: 1–21. https://doi.org/10.3390/ma13235525
6. Jensen JL, Quenneville P. Experimental investigations on row shear and splitting in bolted connections. Constr Build Mater 2011; 25: 2420–5. https://doi.org/10.1016/j.conbuildmat.2010.11.050
7. Sawata K, Yasumura M. Estimation of yield and ultimate strengths of bolted timber joints by nonlinear analysis and yield theory. Journal of Wood Science 2003; 49: 383–91. https://doi.org/10.1007/s10086-002-0497-3
8. Kharouf N, McClure G, Smith I. Elasto-plastic modeling of wood bolted connections. Comput Struct 2003; 81: 747–54. https://doi.org/10.1016/S0045-7949(02)00482-0
9. Johanides M, Lokaj A, Dobes P, Mikolasek D. Numerical and Experimental Analysis of the Load-Carrying Capacity of a Timber Semi-Rigid Dowel-Type Connection. Materials 2022; 15. https://doi.org/10.3390/ma15207222
10. Johanides M, Mikolasek D, Lokaj A, Mynarcik P, Marcalikova Z, Sucharda O. Rotational stiffness and carrying capacity of timber frame corners with dowel type connections. Materials 2021; 14. https://doi.org/10.3390/ma14237429
11. Matsubara D, Wakashima Y, Shimizu H, Kitamori A. The load factor in bolted timber joints under external tensile loads. Journal of Wood Science 2020; 66. https://doi.org/10.1186/s10086-020-01857-4
12. Awaludin A, Hirai T, Hayashikawa T, Sasaki Y, Oikawa A. Effects of pretension in bolts on hysteretic responses of moment-carrying timber joints. Journal of Wood Science 2008; 54: 114–20. https://doi.org/10.1007/s10086-007-0914-8
13. Awaludin A, Hirai T, Hayashikawa T, Sasaki Y. Load-carrying capacity of steel-to-timber joints with a pretensioned bolt. Journal of Wood Science 2008; 54: 362–8. https://doi.org/10.1007/s10086-008-0962-8
14. Awaludin A, Hirai T, Hayashikawa T, Sasaki Y, Oikawa A. One-year stress relaxation of timber joints assembled with pretensioned bolts. Journal of Wood Science 2008; 54: 456–63. https://doi.org/10.1007/s10086-008-0985-1
15. Grzejda R. Determination of Bolt Forces and normal contact pressure between elements in the system with many bolts for its assembly conditions. Advances in Science and Technology Research Journal 2019; 13: 116–21. https://doi.org/10.12913/22998624/104657
16. Grzejda R. FE-modelling of a contact layer between elements joined in preloaded bolted connections for the operational condition. Advances in Science and Technology Research Journal 2014; 8: 19–23. https://doi.org/10.12913/22998624/561
17. Pečnik JG, Gavrić I, Sebera V, Kržan M, Kwiecień A, Zając B, Azinović B. Mechanical performance of timber connections made of thick flexible polyurethane adhesives. Eng Struct 2021; 247. https://doi.org/10.1016/j.engstruct.2021.113125
18. Angelidi M, Vassilopoulos AP, Keller T. Ductile adhesively-bonded timber joints – Part 1: Experimental investigation. Constr Build Mater 2018; 179: 692–703. https://doi.org/10.1016/j.conbuildmat.2018.05.214
19. Vallée T, Tannert T, Hehl S. Experimental and numerical investigations on full-scale adhesively bonded timber trusses. Materials and Structures/Materiaux et Constructions 2011; 44: 1745–58. https://doi.org/10.1617/s11527-011-9735-8
20. Doluk E, Rudawska A, Brunella V. The influence of technological factors on the strength of adhesive joints of steel sheets. Advances in Science and Technology Research Journal 2020; 14: 107–15. https://doi.org/10.12913/22998624/116549
21. Rudawska A, Nalepa J, Müller M. The Effect of Degreasing on Adhesive Joint Strength. Advances in Science and Technology Research Journal 2017; 11: 75–81. https://doi.org/10.12913/22998624/66500
22. Rudawska A, Maziarz M, Šajgalík M, Valášek P, Zlamal T, Iasnii V. The influence of selected factors on the strength of wood adhesive joints. Advances in Science and Technology Research Journal 2018; 12: 47–54. https://doi.org/10.12913/22998624/92099
23. Kawecki B, Podgórski J. Numerical and Experimental Research on Delamination of Glulam Elements. Archives of Civil Engineering 2018; 64: 15–29.

24. Kawecki B, Podgórski J. The effect of glue cohesive stiffness on the elastic performance of bent Wood–CFRP beams. materials 2020; 13: 1–23. https://doi.org/10.3390/ma13225075
25. Kawecki B. Guidelines for FEM modelling of wood-CFRP beams using ABAQUS. Archives of Civil Engineering 2021; 67: 175–91. https://doi.org/10.24425/ace.2021.138493
26. Kawecki B. Selection of the parameters for numerical models of full girders made of wood-polymer composites reinforced with fibres (in Polish). Lublin, Poland. Http://Bc.Pollub.Pl/Dlibra/Publication/13966: Wydawnictwo Politechniki Lubelskiej; 2021.
27. Kawecki B. Numerical Modelling and Experimental Testing on Polyurethane Adhesively Bonded Joints Behaviour in Wood-Wood and Wood-Carbon Fibre Reinforced Polymer Layouts. Advances in Science and Technology Research Journal 2023; 17: 36–52. https://doi.org/10.12913/22998624/159723
28. Schober KU, Tannert T. Hybrid connections for timber structures. European Journal of Wood and Wood Products 2016; 74: 369–77. https://doi.org/10.1007/s00107-016-1024-3
29. Wang T, Wang Y, Ringaby J, Crocetti R, Wålinder M, Blomqvist L. Glulam beams adhesively bonded by birch plywood plates in moment-resisting beam-to-beam connections. Eng Struct 2024; 302. https://doi.org/10.1016/j.engstruct.2024.117471
30. Wang T, Wang Y, Crocetti R, Wålinder M, Bredesen R, Blomqvist L. Adhesively bonded joints between spruce glulam and birch plywood for structural applications: experimental studies by using different adhesives and pressing methods. Wood Mater Sci Eng 2023; 18: 1141–50. https://doi.org/10.1080/17480272.2023.2201577
31. Imakawa K, Ochiai Y, Aoki K, Hori N, Takemura A, Yamaguchi T. Mechanical properties of hybrid joints in timber structures. Journal of Wood Science 2022;68. https://doi.org/10.1186/s10086-022-02043-4
32. Ghoroubi R, Mercimek Ö, Sakin S, Anil Ö. Experimental investigation of bonding behavior of anchoraged timber-to-timber joint. Archives of Civil and Mechanical Engineering 2022; 22. https://doi.org/10.1007/s43452-021-00328-x
33. Shi B, Yang H, Liu J, Crocetti R, Liu W. Short- and long-term performance of bonding steel-plate joints for timber structures. Constr Build Mater 2020; 240. https://doi.org/10.1016/j.conbuildmat.2019.117945
34. Yang H, Crocetti R, Larsson G, Gustafsson J. Experimental study on innovative connections for large span timber truss structures. Proceedings of the IASS WORKING GROUPS 12 + 18 International Colloquium 2015 Bio-based and Bio-inspired Environmentally Compatible Structures, 2015.
35. PN-EN-1995-1-1:2010 - Eurocode 5: Design of timber structures - Part 1–1: General - General rules and rules for buildings. Warsaw: 2010.
36. PN-EN-1993-1-8:2006 - Eurocode 3: Design of steel structures - Part 1–8: Design of joints. Warsaw: 2006.
37. Kawecki B. Tightening torque to preload relationship for M6 bolts mounted in softwood using steel washers 2024. https://doi.org/10.5281/zenodo.10843756
38. Kleiberit 501 - Technical Card. n.d. https://doi.org/https://interior-construction.kleiberit.com/fileadmin/Content/Documents/PL/Info_Sheets/501_PUR_Leim_PL.pdf
39. Kleiberit 303 - Technical Card. n.d. https://doi.org/https://interior-construction.kleiberit.com/fileadmin/Content/Documents/PL/Info_Sheets/303_D3_Leim_PL.pdf
40. Podgórski J, Kawecki B. Solution for Determining Modulus of Elasticity of Natural Materials Using Vibrations of Non-Uniform Circular Cross-Section Cantilevers. Materials 2023; 16. https://doi.org/10.3390/ma16103868