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Boris Azinović, Andreja Pondelak, Jaka Gašper Pečnik and Vaclav Sebera

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FLEXIBLE POLYMER CONNECTIONS FOR CLT STRUCTURES

Boris Azinović[1], Andreja Pondelak[2], Jaka Gašper Pečnik[3] and Vaclav Sebera[4]

[1,2] Slovenian National Building and Civil Engineering Institute, Department of structures
Dimičeva ul. 12, 1000 Ljubljana
e-mail: boris.azinovic@zag.si, andreja.pondelak@zag.si

[3,4] InnoRenew CoE, Department of Materials
Livade 6, 6310 Izola
e-mail: jaka.pecnik@innorenew.eu, vaclav.sebera@innorenew.eu

SUMMARY: This paper explores the possibility of using flexible polymer adhesives to dissipate energy in CLT buildings during earthquakes. In the first series of tests, pull-off tests of various polyurethane (PUR) adhesives were performed. The connection was tested in pull-pull configuration using monotonic, tension-only loading. The tests have shown that the adhesive can resist large deformations already in tension loading and with small thicknesses of the bond-line. Based on the pull-off test results, one adhesive has been selected for further testing. Monotonic lap-shear tests were performed with the selected adhesive and thick bond-line (3 mm and 6 mm). The results show, that the standard method for lap-shear testing (EN 205) needs to be adapted for thick glue-line. It was found that the strength of 3 mm glue-line is higher than 6 mm one, which is in agreement with adhesion theory. The flexible PUR adhesives could potentially be used in CLT structures for anchoring the CLT wall with “flexible” glued-in rods or as a “flexible” vertical shear connection between the CLT walls. Such systems have a potential to dissipate energy in seismic areas.

KEY WORDS: CLT connections, flexible adhesive, polyurethane, energy dissipation, pull-off, lap-shear.

1 INTRODUCTION

Cross-laminated timber (CLT) is becoming an increasingly popular building material in Europe and across the world. The versatility of CLT has encouraged engineers to build multi-storey structures in earthquake prone areas, although there is limited experience and research about the behaviour of such structures during earthquakes.

The behaviour of CLT buildings during earthquakes depends mainly on the behaviour of the connections between adjacent panels. If the connections between the panels are strong enough these structures are able to achieve damage-free performance even during the strong earthquakes. However, if the connections are too rigid, large accelerations can occur in the upper stories. This may result in injuries to occupants and damage to property which is not acceptable in terms of serviceability. Therefore, the structural system should be modified to incorporate the dissipative behaviour. This can be achieved with dissipative connections which may be installed in different parts of the structure. Several solutions of dissipative connections have already been suggested so far to improve the ductile response of CLT buildings [1-5] but the research has been mainly focused on the mechanical connectors with concentrated plasticity. In such systems, the dissipation is concentrated in a small area which must be very carefully designed in order to prevent damage to other parts of the structure. In addition, the mechanical connectors are robust and difficult to hide inside the construction.

Therefore, the aim of this research is to investigate alternative options for energy dissipation by employing adhesive joints made of deformable polymer materials between the panels. For this purpose, elastic adhesives based on polyurethane could be used. Adhesives with good deformable properties have already been developed at the Cracow University of Technology for elastic joining of structural elements and to provide protective coating. They have already been successfully applied for the repair and seismic strengthening of cracked masonry structures [6-8]. The initial pull-off adhesion tests show that the new adhesive could also be used for gluing timber elements.

The flexible adhesive with energy dissipating properties allows for various applications in CLT structures to increase their seismic performance. The adhesives could be applied to the vertical joints between adjacent panels or they could be used in combination with glued-in rods (both options are schematically shown in Figure 1). For this purpose, the panels should be broken up into smaller wall segments which allow panel rocking movement during the seismic event. When the rocking occurs, the energy is dissipated by the adhesive layer in vertical joins and/or glued-in rods. In this paper, experiments of pull-off and lap-shear behaviour of various polyurethane (PUR) adhesives are presented.

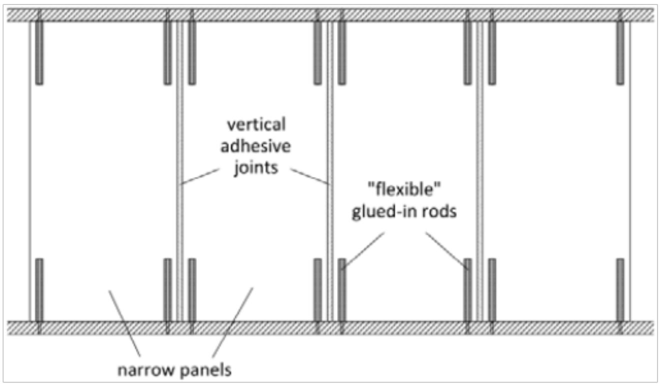


Figure 1: Possible use of flexible polymer adhesives in CLT structures

2 EXPERIMENTS

The experiments were performed at the Slovenian National Building and Civil Engineering Institute (pull-off tests) and at InnoRenew CoE (lap-shear tests). The tested pull-off specimens were composed of 2 timber pieces (dimensions 24 x 38 x 200 mm) made of spruce (*Picea abies L.*), which were glued according to the producer instruction at the cross section perpendicular to the fibre direction (Figure 2a). After sanding the surface, ZP primer was applied on the timber pieces [7]. Primer was left for an hour to dry completely. On the surface prepared with primer, 5 various adhesives were applied to connect the two timber pieces; (i) PMM, (ii) PSM, (iii) PS, (iv) PST and (v) PTS [7]. For each of the 5 adhesives, at least 7 specimens were tested. The tests were performed as displacement controlled using Universal testing machine Zwick Roell Z050 at constant rate 2 mm/min until failure of specimens was achieved.

a. b.

Figure 2: Configuration of: a. Pull-off tests, b. lap-shear tests.

For lap-shear tests beech (*Fagus Sylvatica L.*) boards were used as suggested in the standard EN 205. The grain direction was following longitudinal direction of the boards, which were planned and sanded to a thickness of 5 mm (+/- 0.2 mm) and cut into boards with final dimensions of 170 × 150 mm in length and width, respectively. Moisture content (MC) was measured with a dielectric measuring device for each board. ZP primer was applied, similarly as with the pull-off tests to cover the bonding surface. After primer dried out, two samples were prepared with thin 3 mm and thick 6 mm glue line. Spacers of desired thickness were glued on the edges of panel to create barriers for the enclosure where adhesive was poured in. Two component adhesive PS was then precisely weighted in separated containers and mixed together using an electrical drill and metal fork. After 1 min of mixing both components together, adhesive was poured into the prepared wooden panels with spacers. Second panel was put on the top of the adhesive layer, to create three-layer composite of wood-adhesive-wood. No specific pressure was required, load was only applied to close the gaps between the spacers and panels. Three sandwich panel for 3 mm and two sandwich samples for 6 mm glue-line samples were prepared. Samples were dried 72 h to cure completely. After curing, samples were cut into final dimensions of 170 × 20 mm (longitudinal vs. crosswise) and put into climate chamber with standard climate conditions at 20 °C temperature and 65% relative humidity for 10 days. After conditioning, 8 specimens for 3 mm and 6 specimens for 6 mm glue-line were cut according to EN 205 standard for tensile test to determine static strength of adhesive bond. Static tensile tests were carried out using Universal testing machine Zwick Roell Z050 with testing speed of 5 mm/min.

3 RESULTS

The first sub-chapter presents the selection of adhesives for further testing, where pull-off tests were performed as a decision tool. The failed bond-line surface was additionally characterized by SEM imaging to discover the characteristic failure. In the second sub-chapter, basic behaviour of 3 mm and 6 mm thick glue line under tension shear loading is presented.

3.1 Pull-off tests

Results of pull-off strength differ according to the de-cohesion or de-adhesion effect. When the sample's failure occurs between the adhesive and the timber part coated with primer the predominant failure mechanism was de-adhesion, while when it occurs within the adhesive then it is de-cohesion (Figure 3). Between the 5 tested adhesives the pull-off strength varies as it promotes different types of failure or their combination. Dependence of the pull-off strength on the adhesive selections is shown in Table 1. Obtained results compared to tensile strength of adhesive itself do not show direct correlation, therefore, meaning that for some adhesives de-adhesion was predominant failure mechanism.

Figure 3: Damaged surface after failure under pull-off tests

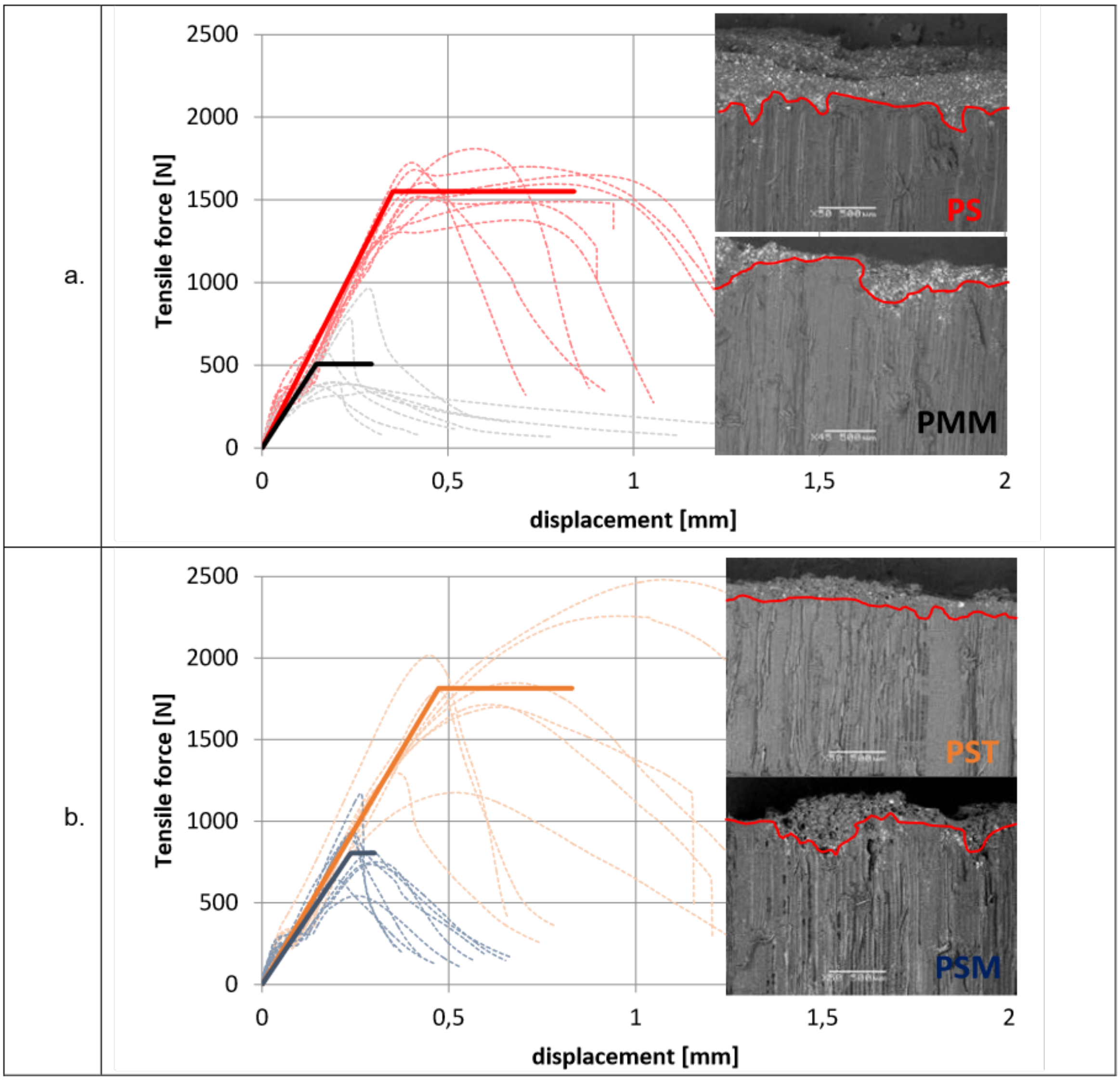
For each of the failed specimens, the force displacement diagram was idealised with a bi-linear curve according to the procedure described in [9]. From the idealised curve a sort of ductility factor was estimated as a quotient between the displacement at failure and displacement at initiation of damage (Table 1). The average ductility value for the examined adhesives was approximately 2 in all cases, proving the assumption that the bond-line doesn't fail in brittle manner.

Table 1: Average results of pull-off experiments

Adhesive	Tensile strength of adhesive [N/mm^2]	Pull-of strength of bond-line [N/mm^2]	Average ductility of idealized curves
PTS	3.1	1.29	2.08
PST	4.0	1.99	1.76
PS	2.5	1.70	2.39
PSM	2.2	0.88	1.27
PMM	1.0	0.56	2.02

In Figure 4, all of the results are shown in the form of force displacement diagrams, where dotted curves represent each test series and thick lines the idealized bi-linear curves. In addition, a typical failed surface for each adhesive is shown. The images of failed surfaces were produced by scanning electron microscope (SEM), where magnification was approximately 50 in all cases. A cut was made from the side to observe the penetration of the adhesive into the timber part. The red line represents the boundary between adhesive and timber coated with ZP primer. The characterization of the bond-line revealed a good correlation with results of pull-off strengths. It was found, that PMM and PSM are the most prone to de-adhesion effect. This consequently proved to have a large effect on the pull-off strength, which was lower than 1 N/mm^2 for both adhesives. For this reason, PMM and PSM were excluded for further investigation as they seem to be inappropriate in terms of bonding on wood surface coated with ZP primer.

On the other hand, adhesives PTS, PST and PS reached mostly a cohesive failure. The difference in their response is therefore mainly due to different structure of adhesives. As it can be concluded from Table 1, PTS has the lower pull-off strength among these three adhesives. The latter can also be explained by the SEM images, since it appears that PTS has the most porous structure (Figure 4c) and is therefore easier to break under tensile load. Adhesives PS and PST proved to be the most stable and reached similar ductility and strength values (Table 1). The coefficient of variation for PST adhesive was larger than for PS adhesive. Meaning that there were also cases where PST failed in brittle manner. The objective of the research was to discover the most ductile behaviour, which was similar for both PS and PST. Since PST reached the highest pull-off strength, it was selected for further investigation.



c.

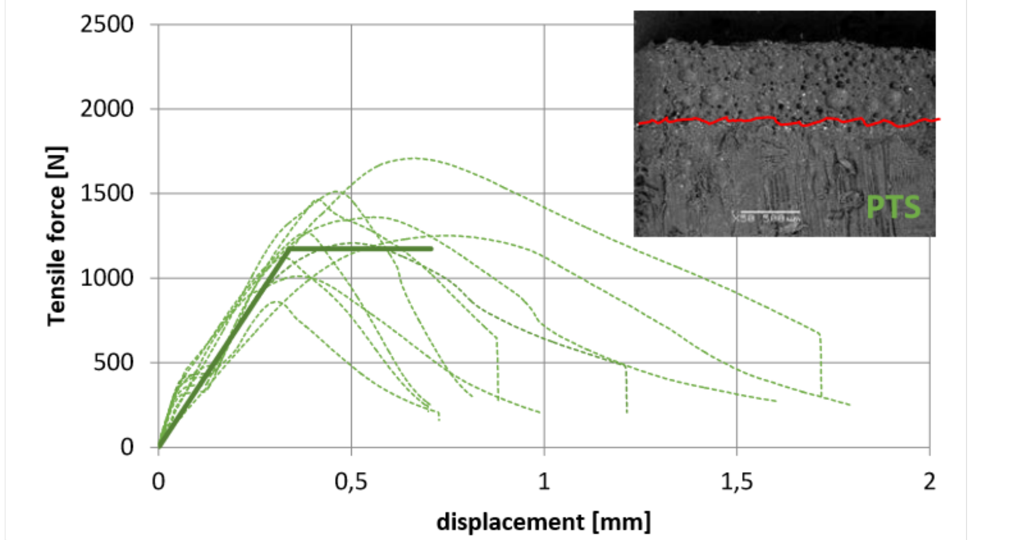


Figure 4: Results of pull-off tests with SEM characterization of adhesives: a.) PS and PMM, b.) PST and PSM and c.) PTS.

3.2 Lap-shear tests

The task of the second part of the study was to perform simple lap-shear tests on the adhesive PST, which was selected as one of the most promising candidates from the pull-off tests. A standard procedure for lap-shear tests, which is described in EN 205 was adapted to test thick glue-line. As it is marked in Figure 5, all the specimens under tensile shear load started breaking at the edge of the bond-line.

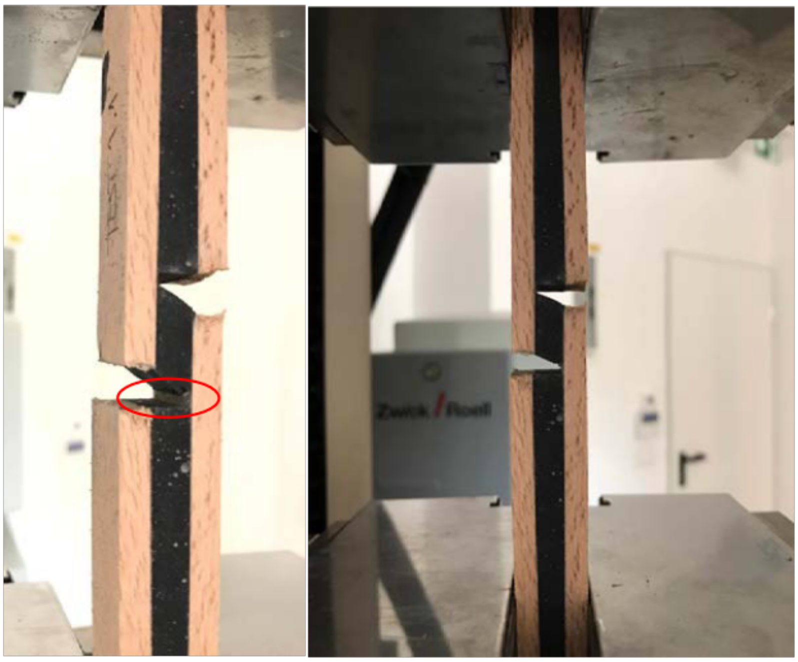


Figure 5: Point of fracture in the lap-shear test specimens.

Diagrams with force-displacement relationships for 3 mm and 6 mm bond-line are plotted in Figure 6, where orange lines represent 3 mm and black 6 mm thick bond-line. Integer numbers from Test 1 - Test 8, represents 3 mm bond line, one's with decimal numbers from Test 1.1 – Test 6.1 represents 6 mm bond line. As it seen from the diagram, 6 mm bond-line shows lower stiffness and smaller variability compared to 3 mm bond line. However, lower maximum forces were reached. The stiffness variability of 3 mm glue bonds samples may be explained by a higher variability of the bonding area (see Table 2). These preliminary tests showed that thinner glue-lines results in higher strengths, however, the displacement at initiation of failure is lower for thinner glue-line.

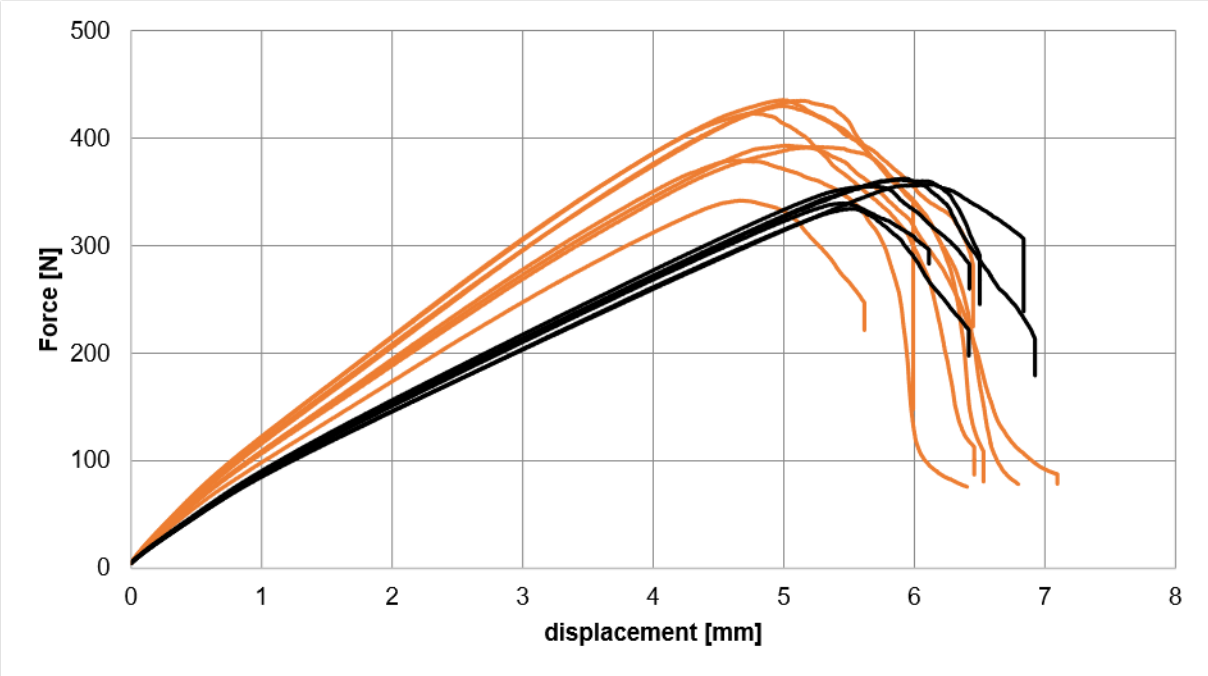


Figure 6: Force-displacement relationship for 3 mm (orange) and 6 mm (black) glue line under monotonic tensile shear test.

In Table 2, measurements of the bond line area and maximum force are presented. Glue-line of 3 mm thickness exhibits higher strength than 6 mm glue-line. F_{max} values obtained at the static tests, can be used to define amplitude cycles for cyclic evaluation, which will be a topic for further studies.

Table 2: Measurements of a bond line area for specimens dedicated to the static test with maximum force at break (F_{max}) and calculated strengths.

Sample	Specimen	Bond length [mm]	Bond width [mm]	Thickness [mm]	Bonding area [mm^2]	F_{max} [N]	Strength [N/mm^2]
3 mm	T1	12.0	20.2	13.5	242.2	391.8	1.62
3 mm	T2	11.8	20.2	13.5	238.4	379.2	1.59
3 mm	T3	11.6	20.2	13.7	233.9	393.1	1.68
3 mm	T4	12.8	20.1	13.7	257.4	434.7	1.69
3 mm	T5	12.7	20.2	13.8	256.0	435.4	1.70
3 mm	T6	12.1	20.3	13.5	245.1	423.1	1.73
3 mm	T7	12.3	19.9	13.6	245.4	430.0	1.75
3 mm	T8	10.8	20.2	13.5	218.2	342.0	1.57
median		12.1	20.2	13.6	243.7	**408.1**	**1.69**
SD		0.6	0.1	0.1	11.8	31.0	0.06
6 mm	T1.1	12.7	20.1	16.6	254.0	362.4	1.43
6 mm	T2.1	12.7	20.2	16.2	255.5	355.2	1.39
6 mm	T3.3	12.3	20.3	16.8	249.7	357.0	1.43
6 mm	T4.1	12.3	20.2	16.2	248.8	339.4	1.36
6 mm	T5.1	12.4	20.2	16.4	249.5	361.4	1.45
6 mm	T6.1	12.4	20.1	16.2	248.4	334.4	1.35
median		12.4	20.2	16.4	249.6	**356.1**	**1.41**
SD		0.2	0.1	0.2	2.8	10.8	0.04

As seen from the Figure 6, all the diagrams exhibit similar behaviour. The elastic part is nonlinear, but can be decomposed to two linear elastic parts. Such behaviour is typical for hyperelastic materials such as rubber and it seems, that bond-line is thick enough to show such behaviour. The nonlinear elastic part ends with the yield point and very small part of the plastic region. The elastic part of the deformation composes about 70-90 % of whole deformation range. From the maximal forces, the strength of the bond-line was computed for all lap shear tests. Average results are depicted in Table 3. The lower strength of thicker bond-line is in an agreement with adhesion theory.

Table 3: Descriptive statistics of lap-shear test.

specimen	Mean (MPa)	SD (MPa)	CoV (%)	Median (MPa)	*n*
Beech 3 mm	1.67	0.06	3.7	1.69	8
Beech 6 mm	1.40	0.04	2.6	1.41	6

4 CONCLUSIONS AND FURTHER WORK

The pull-off tests of flexible polyurethane adhesives applied on timber coated with ZP primer were made. The tests have demonstrated promising behaviour of the adhesives PS and PST in terms of their ductility already with thin glue-line and tensile loading. Mostly cohesive failure occurred, which indicates that the potential of high elastic deformation capability of these two adhesives could be exploited also when bonded to timber.

Results of monotonic lap-shear tests for the selected adhesive PST showed that relatively large elastic displacement can be expected in tensile shear loading. The average displacement at initiation of failure for 3 mm thick bond-line was approximately 5 mm, which proves the initial assumption of deformation capability. The tests have also shown that load-carrying resistance of the connection is proportional to the thickness of the adhesive. It was found that the strength of 3 mm glue-line is higher than 6 mm one, which is in agreement with adhesion theory.

To test the seismic behaviour of the connections with "flexible" PUR adhesives, a series of cyclic tests on larger specimens with realistic boundary conditions is necessary. For this reason, the presented research was performed as a preliminary decision tool for selecting adhesives for further evaluation. A more detailed work plan for testing glued-in rods and vertical connections with flexible adhesive PS or PST under cyclic loading is planned. Further research will provide more reliable information, whether the resistance of flexible connections with PUR adhesives is sufficient to be used for seismic resistant CLT structures. Cyclic tests are also necessary to evaluate the energy dissipation capacity, which is crucial information on whether the flexible connections can be used for seismic energy dissipation.

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