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ON-SITE GLUING AND WEATHER EFFECTS ON TALL WOODEN WIND TURBINE TOWERS

Viktor Norbäck[1], **Pierre Landel**[2], **Erik Dölerud**[3], **Anders Wickström**[4]

ABSTRACT: Modvion develops modular wind turbine towers made of wood. The application requires strong and stiff connections and to achieve the desired performance, a hybrid connection with perforated steel plates slotted into LVL modules is used. The parts will be glued together on site, using a polyurethane adhesive (PUR), providing high strength and stiffness to the connection. This paper presents a preliminary screening on how temperature and relative humidity of the surrounding air during assembly and curing will influence the strength of the bond glued on-site. Static tests were performed on the hybrid connections which were glued and cured in different climates. Tests were also performed at different hardening times to evaluate strength growth in the studied climates. The test results show that at cold temperatures of 9 °C to 12 °C there is a breakpoint where the rate of strength growth starts to decline. The experiments show also that the relative humidity may influence the final strength of the bond. However, the low number of tested specimens brings uncertainties to this observation. High temperatures up to 27 ºC and dry climates down to 20% RH did not impact the strength of the tested hybrid connections.

KEYWORDS: Hybrid connection, Polyurethane adhesive, On-site gluing, LVL, Glued-in plates connection type

1 INTRODUCTION

The Swedish company Modvion AB is developing modular wind turbine towers made of wood [1]. To be competitive, the production method must be both fast and reliable, following specific standards [2]. To achieve this a recently developed joining technique is used, where the LVL wall-modules are assembled on-site, combining adhesive and perforated steel plates. Thin plates made of high-strength steel are inserted into slots in the wall-modules and bonded using a two-component polyurethane (PUR) adhesive. The method results in strong and stiff connections with glue-dowels through the holes of the plate. This hybrid type of glued-in plate joints has been used in different timber building applications to elegantly assemble CLT, LVL, and GLT elements. Research and development works have been performed in central Europe [3] and in Germany, where the commercial and certified HSK-system from the company TiComTec is available [4]. This technology is similar to glued-in rods in glued structural timber products, which adhesively bond steel rods and timber members. Standardized testing methods and requirements for glued-in rods are defined in the European standard EN 17334:2021 [5]. Some experimental studies on the gluing procedures of glued-in rod joints have shown important outcomes concerning the mechanical effects of elevated moisture contents [6] and temperatures [7].

Connections with glued-in plates provide a strong and stiff joint compared to more traditional mechanical connections for timber structures, e.g., screws and dowels. It can be applied with high precision and keeps the steel elements encapsulated in the timber structure, which protects the steel and allows for additional architectural possibilities. However, the mechanical properties of glues are affected by the temperature and relative humidity of the surrounding air when gluing. As a result, the application process of adhesives for structural timber products is recommended for controlled conditions that are mostly offered in factories. Gluing processes applied on building sites, with uncontrolled and variable weather conditions, are not common.

To be competitive the assembly of tall modular wind turbine towers must be fast without compromising the safety of the workers. To maximize the efficiency of assembly, it is important to have better knowledge on the strength growth of the glued hybrid joints and how it is affected by the temperature and the moisture content of the surrounding air.

This study focuses on how the strength and the rate of strength growth of the hybrid joints used in Modvion's towers vary depending on weather conditions during gluing and curing. Temperature, humidity and curing time are investigated experimentally to determine the impact on the capacity of the joints at different curing times. This screening is aimed to identify suitable weather conditions

[1] Viktor Norbäck, RISE Research Institutes of Sweden, Sweden, viktor.norback@ri.se
[2] Pierre Landel, RISE Research Institutes of Sweden, pierre.landel@ri.se
[3] Erik Dölerud, Modvion AB, Sweden, erik@modvion.com
[4] Anders Wickström, RISE Research Institutes of Sweden, Sweden, anders.wickstrom@ri.se

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when assembling the tower and which environmental parameters require further investigation to ensure that the joints perform as desired.

Uni-axial, destructive compression tests were performed on small-scale hybrid joint test specimens. Tests were performed in a reference climate of 20 ºC and 65% RH, which is to resemble good weather conditions. The same test procedure was performed on test specimens, glued and cured in different extreme climates. The studied climates are high and low temperatures and high and low relative humidity.

2 TEST PROCEDURE

Small-scale tests of the hybrid joint were performed at RISE's lab in Borås by Viktor Norbäck and Pierre Landel. The procedure involves destructive compression tests on specimens glued and cured in climates with different temperatures and relative humidity.

2.1 TESTED MATERIAL

The test specimens were assembled from an LVL block with a cut slot in which the steel plate was later slotted. A two-component PUR adhesive was used to glue the two parts together. The glue used was Loctite PURBOND CR821, manufactured by Henkel. Both the timber blocks and the steel plates are shown in Figure 1 with a pen for size reference.

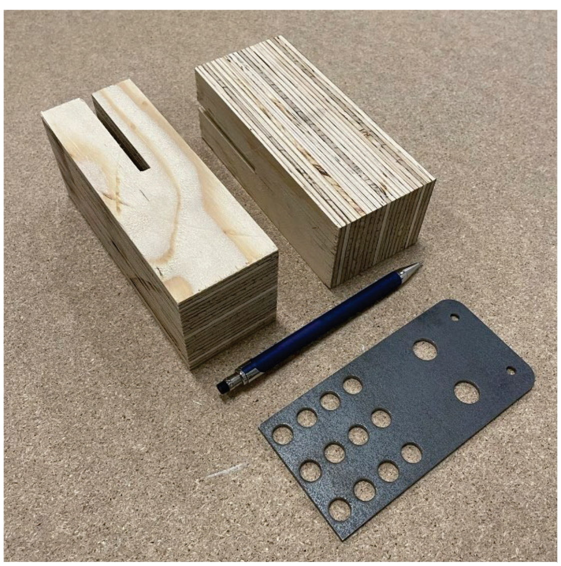

__Figure 1:__ Test specimen parts. LVL blocks with a cut slit from two different sides and the perforated steel plate. The pen acts as size reference.

The perforated steel plates were 3 mm thick and had 16 holes. On the side that was slotted into the LVL block, there were 12 holes of diameter 10 mm. It was in these holes where the glue was cast, forming glue dowels connecting the steel plate to the timber part. On the other side of the plate, there were two pairs of holes of diameter 5 and 13 mm. These holes were not used in the compression tests and are meant for another series of tests where the fatigue strength of the hybrid joints is investigated [8]. The perforated steel plate and its holes were cut with a laser cutter with a tolerance of 0.03 mm. Figure 2 shows a blueprint of the perforated steel plates.

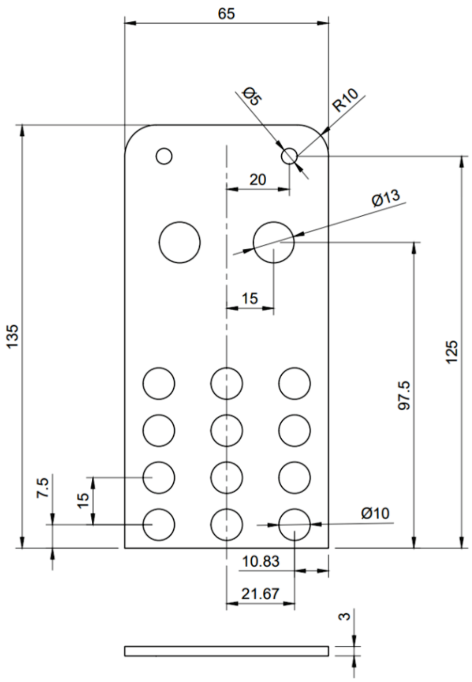

__Figure 2:__ Blueprint of the perforated steel plate which is slotted into the LVL blocks.

The LVL blocks were cut from a larger LVL plate manufactured my Metsä wood. The plate consisted of a cross-layup with 21 veneers and a total thickness of 65 mm. The lay-up sequence was [2L/T/7L/T/7L/T/2L] where L denotes longitudinal veneers and T denotes transversal veneers. The direction of the longitudinal and transversal veneers in relation to the LVL block as well as the dimensions of the blocks are shown in Figure 3. Prior to testing, the components and the glue were conditioned until equilibrium in a constant climate of 20ºC and 60% RH.

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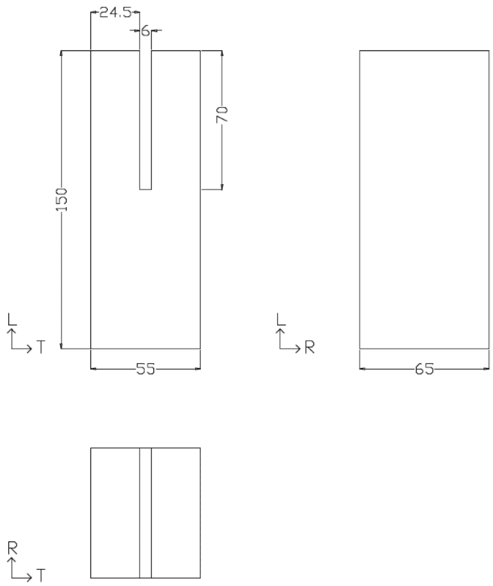

Figure 3: *Blueprint of the LVL blocks with a cut slot.*

2.2 Test procedure

From the conditioned climate of 20°C and 60% RH, the specimens were moved and conditioned in a new climate for 48 hours. When two days had passed, the steel and the timber were glued together using the two-component PUR adhesive, which reaches full strength after 7 days and 75% after 2 days according to the manufacturer Henkel [9]. When gluing, 3D-printed plastic holders were clamped onto the timber blocks as shown in Figure 4. In the holders, there was a slot where the steel plate was inserted to be kept in the correct position when gluing. Before inserting the steel plate, a soft foam material was inserted at the bottom of the slot in the timber block to avoid glue from hardening beneath the steel plate. The foam material's stiffness was much lower compared to steel and timber. Thereafter, the slot in the LVL block was partly filled with adhesive, leaving room for the steel plate.

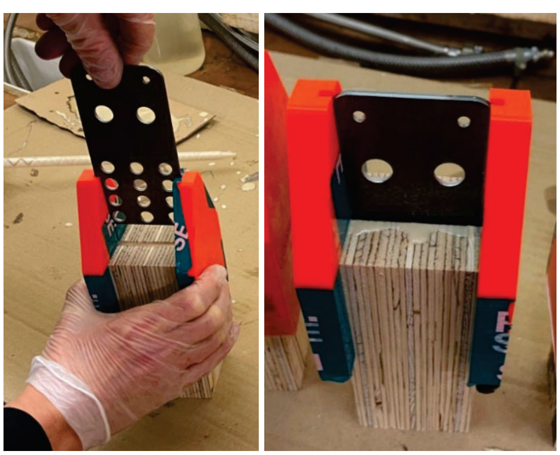

Figure 4: *The perforated steel plates slotted into the slit in the LVL using plastic holders.*

Immediately after applying the glue and inserting the steel plates the test specimens were put back in the same climate as before assembly to harden for a certain time. The number of tests in different climates and at different curing times are shown in Table 1. Note that the curing climate is a target climate. There is a variability of up to 0.1°C and 1.2% RH from the target climate.

Table 1. *The number of tests in different climates and for different curing times. Before curing the parts were conditioned for 2 days in the corresponding climate.*

Curing climate	Number of tests	Curing time
20°C 65% RH	1	3.17 h
	1	4.25 h
	1	5.17 h
	1	18.55 h
	1	1 day
	1	3 days
	1	4 days
	1	5 days
12°C 60% RH	3	1 day
	3	5 days
9.1°C 60% RH	3	1 day
	3	5 days
20°C 25% RH	3	1 day
	3	5 days
20°C 95% RH	3	1 day
	3	5 days
27°C 60% RH	3	1 day
	3	5 days

After a certain time, which varies for different test series, the specimens were loaded until failure in a hydraulic press. Two different hydraulic presses were used, both manufactured by Instron, one model 1253 and the other model Satec. 11 tests were performed with model 1253 and 27 tests with model Satec. Two machines were used due to logistic reasons. The setup for both machines was the same; a steel adapter was pushed onto the perforated steel plate from above, compressing the specimen against

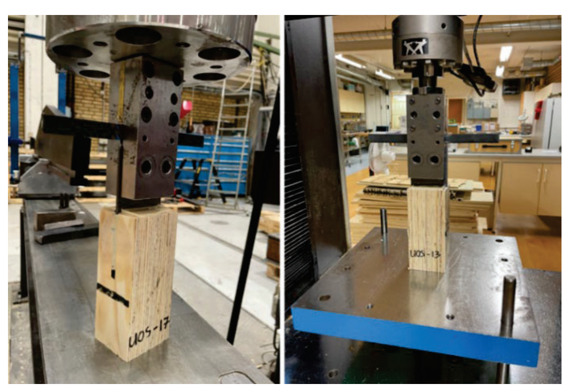

Figure 5: *Compression test setup in both machines. To the left: Instron model Satec. To the right: Instron model 1253.*

a fixed surface beneath it. The tests were deformation controlled with a constant deformation increment over time. Figure 5 and Figure 6 show examples of the test setup for both hydraulic presses. The foam material was considered to not take any significant loads because of its low stiffness in comparison to steel and LVL.

3 RESULTS, ANALYSIS, AND DISCUSSION

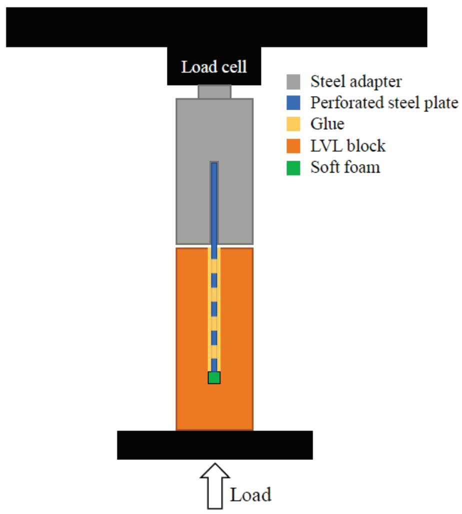

Figure 6: *Principal image of the test setup and the different materials.*

Figure 7 shows a scatter plot including all tested specimens with maximum load in kilonewtons on the vertical axis and curing time in hours on the horizontal

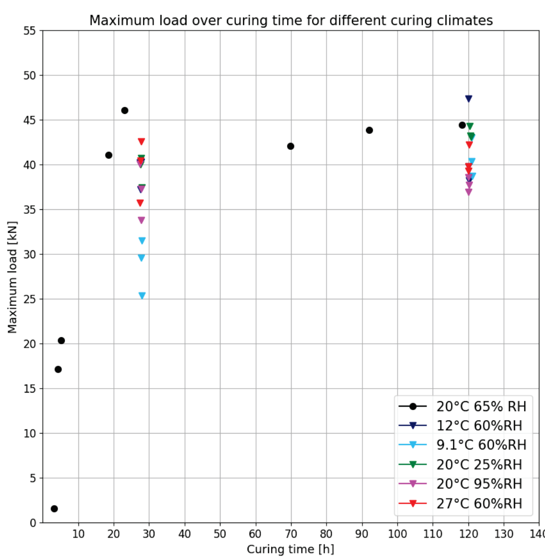

Figure 7: *Maximum load over curing time for different curing climates. On the horizontal axis: Curing time in hours. On the vertical axis: Maximum load in kilonewtons.*

axis. The circular data points correspond to the test series studying hardening time in the reference climate of 20°C and 65% RH. The triangular data points correspond to the different assembly and hardening climates at times 27 and 120 hours.

From interpretation of the scatter plot, the strength of the joint starts to build up somewhere between three and four hours at the reference climate. The specimen tested after 3.17 hours demonstrated close to no strength and the specimens tested after 4.25 and 5.17 hours show a strength closer to 20 kN. In addition, for the specimen tested after 3.17 hours the glue was still more or less liquid. To investigate the strength growth of that particular test specimen, the steel plate was slotted back into the LVL block to be tested again after another hour of curing. This time the capacity was much higher similar to the other specimens tested after four to six hours and that had a strength of around 20 kN. The results from the two loadings of the same test specimen are presented in Table 2.

Table 2: *Test results for the same specimen first loaded after 3.17 hours and then loaded once more after a total curing time of 4.50 hours.*

Curing climate	Curing time	Maximum load
20°C 65% RH	3.17 h	1.55 kN
	4.50 h	18.71 kN

During the first day, the strength increased at a high rate up to a level that corresponds to the strength of specimens cured for three, four and five days. This indicates that full strength is reached after the first day of curing in the reference climate. For test specimens cured in other climates, the same trend was observed. Thus, no significant strength growth was noticed after the first day of hardening. However, the specimens cured at 9.1°C and 60% RH were an exception, with lower strength after one day of curing compared to the other specimens cured in other climates. This shows that low temperatures of 9.1°C will influence the curing time of the hybrid joints. The specimens cured at 12°C showed no trend of slower curing time, which suggests a breakpoint for the strength growth between 9.1°C and 12°C at 60% RH.

After 5 days, the specimens cured at 9.1°C and 60% RH had strength in the same range as the other curing climates. This is an indication that the final strength is unaffected by temperatures down to 9.1°C.

Humid climates of 95% RH did not affect the strength growth but may influence the final strength of the specimen. All three specimens tested at 20°C and 95% RH had lower strength compared to the other specimens. However, the number of data points in each climate is low which brings uncertainties as to whether this assumption would be valid if more tests were made in the same climate.

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The static loading tests in compression showed two different types of failures. The displacement-to-loading diagrams from the tests exhibit either a brittle failure (Figure 8) or a ductile failure (Figure 9).

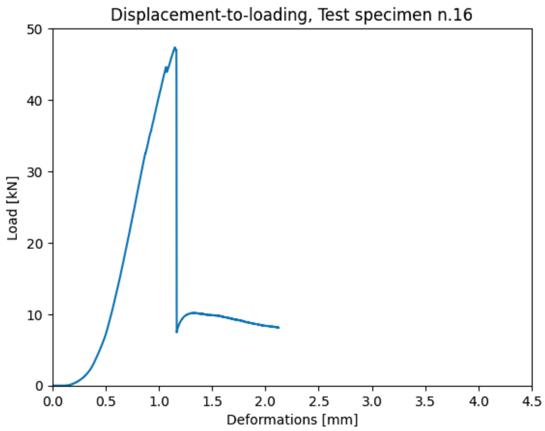

Figure 8: *Displacement-to-loading diagram for a specimen exhibiting a brittle failure.*

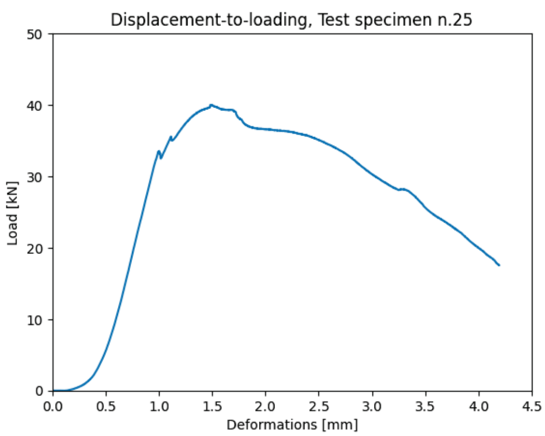

Figure 9: *Displacement-to-loading diagram for a specimen exhibiting a ductile failure.*

After testing, the samples were cut and split to inspect the quality of the gluing inside the joints and possibly reject the samples with lack of glue. Further analysis of the correlation between the failure modes and types would require a larger number of test replicates. Figure 9 and Figure 10 shows pictures of different tested samples and the types of failure modes.

The manufacturing process of gluing the test specimens resulted in specimens of varying quality, according to the testing operators own reflections. This may influence the results, e.g., some specimens had excess glue on top of the timber block and some had a string of glue between the steel plate and the soft foam. The extra glue can influence the joints' ability to transfer loads between the steel plate and the timber part and thus, increase the strength of the test specimen.
In contrast, some specimens had a lack of glue when hardened due to leakage inside or outside the timber

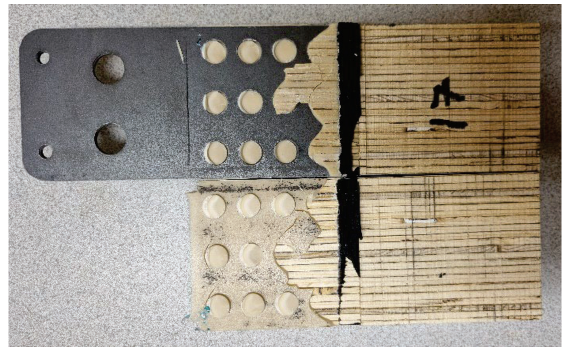

Figure 10: *Combined failure in the glue dowels, the steel-to-glue interface and in the wood-to-glue interface.*

Figure 11: *Failure solely in the glue dowels and in the steel-to-wood interface.*

block. This resulted in a gap at the top of the timber slot of a few millimetres which can lead to lower strength.

Two test machines were used, Instron model Satec and Instron 1253. From the calibration of the machines there is an error of 190 N for model Satec and 330 N for model 1253 for loads in the magnitude of the tests. The measurement uncertainties from the load cells are considered negligible in relation to the spread of quality from assembling the connections in combination with the spread of the material properties of timber.

4 CONCLUSIONS

In this preliminary study, the influences of curing time, ambient temperature and relative humidity when gluing an innovative hybrid connection type are investigated. The experimental results contribute to identifying the critical ambient parameters of such connections glued on-site. Moreover, they bring new knowledge on how to increase the construction speed of larger timber structures without jeopardizing the construction workers' safety or the structural properties of modular towers.

From the results presented in this paper the following conclusions are made:

- High temperatures up to 27 °C and a low relative humidity down to 25% do not influence the strength growth nor the final strength of the tested specimens.
- Strength growth is initially slow when the glue is more liquid. After 3-4.5 hours the curing starts

and strength grows more rapidly, reaching close to full strength after 24 hours of curing.

- Low temperatures down to 9.1°C of the materials and the surrounding air will slow down the rate of strength growth. It does not impact the final strength of the joints.
- There is a possibility that high moisture content in the materials and the surrounding air will influence the final strength of the joint. More test data are recommended to support this outcome.

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