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FATIGUE RESISTANCE OF ADHESIVE BONDED CONNECTIONS WITH AND WITHOUT INTERNAL STEEL PLATES IN LARGE TIMBER STRUCTURES

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ABSTRACT: A modular wooden wind turbine tower has been developed by the Swedish company Modvion AB, where the prefabricated modular elements are connected by glued timber-timber edge joints and by hybrid timber joints with bonded-in perforated steel plates. The application of wood-based products in such a demanding application and high-performance structure is challenging and a variety of questions had to be solved to ensure a reliable performance. The fatigue performance of the adhesive bonded connections has been evaluated in a research project and is presented in this paper. Test specimens of the fatigue resistance of the adhesive and the bond line has been developed. Different stress ratios with alternating loads and high numbers of load cycles have been tested. The results of the tests are presented in this paper.

KEYWORDS: Bonded-in steel plates, adhesive testing, butt-joints, fatigue strength

1 INTRODUCTION

The transition towards renewable energy supply is more urgent than ever. The need and demand for innovations that enable the construction of tall wind turbines (>150 metres hub height) is very high for Sweden and elsewhere to fully exploit the potential of wind power and reach 100% renewable electricity production.

A modular wooden wind turbine tower has been developed by the Swedish company Modvion AB [1] and a first 30 m tall demonstrator used for research of the Swedish Wind Power Technology Center (SWPTC) at the university of Chalmers has been built near Gothenburg, Sweden (Figure 1).

The tower developed by Modvion has a conical shape and is made of prefabricated modular elements made of LVL, that allow for easy transportation also on remote sites.

Building modular wind turbine towers enables further development towards higher wind turbines and contributes to a lower cost per kWh without logistical barriers. Modular towers made of wood with innovative joining solutions enable tall wind turbines at lower cost, lower weight and provide an efficient installation process. The LCA analysis carried out shows that the wood material contributes to 90% lower CO2 emissions than competing tower structures made of steel and stores Carbon for several years ahead. In addition, there is the possibility of reusing the wooden material in the tower as a construction material.

Nevertheless, the modularity requires strong connections that can be joined on-site. Butt-joints with bonded-in perforated high-strength steel plates are developed for the wooden wind turbine towers by Modvion. These joints are similar to other existing solutions [2].

__Figure 1:__ Demonstrator of the wooden wind turbine tower used for research on Björkö island near Gothenburg, Sweden

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2 DESIGN OF TIMBER TOWERS

2.1 GENERAL

Timber is so far mainly used in buildings and infrastructure applications. Consequently, the design parameters specified in design codes and guidelines, and material properties declared by producers are based on these applications.

Wind turbines made of steel and/or concrete elements can be designed in accordance with the International standard for the design of Wind turbines, IEC 61400 [3]. The design of timber structures follows the basic principles for structural design given in EN 1990, load cases in EN 1991 and specifications for timber materials in EN 1995 (Eurocode 5). These standards are based on similar methods with partial coefficients to achieve sufficient safety margins on both materials and loads. Wooden wind turbine towers can to a large extent be designed by combining these standards. However, there is a gap between innovation and existing design standards as this has not been done before on a large scale.

2.2 FATIGUE OF BONDED JOINTS

2.2.1 General

A good level of knowledge of the fatigue performance of the steel plates exists, however, there is a clear lack of basic and more detailed knowledge of the fatigue performance of the adhesive, its bond to the timber, and the timber itself.

In particular, knowledge and data are missing regarding the fatigue strength of the timber at very large numbers of cycles at low load levels. Current fatigue provisions limit the maximum number of load cycles to approx. $5 \cdot 10^7$. A fatigue threshold (or cut off limit) for wood has been mentioned in some research [4], but not in the design standard for timber bridges EN 1995-2. Existing tests on bonded timber joints [5] are typically below this maximum number of load cycles.

2.3 Fatigue design in Eurocode 5

In the 2004 version of Eurocode 5, the specification on fatigue design is given in the part for bridge structures EN 1995 – 2 (EC5-2) [6]. Kreuzinger and Mohr [7][8] derived the material parameters in the respective chapter based on the literature at the time of drafting.

The specification for the fatigue design of timber structures in the next generation of Eurocode 5 will be incorporated in the main part and can be found in prEN 1995-1-1 [9]. The specifications are based on the same theory and data as in the 2004 version but are slightly more extensive.

The design strength (or analogously the resistance) for the verification of fatigue $f_{fat,d}$ should be calculated from the characteristic strength f_k at static loading according to the following formula:

$$f_{fat,d} = k_{fat} \frac{f_k}{\gamma_{M,fat}} \tag{1}$$

where k_{fat} is the reduction factor for fatigue and $\gamma_{M,fat}$ is the partial factor for the fatigue resistance, which may be considered as equal to the partial factor under static load unless other information is given in the National Annex.

The reduction factor k_{fat} can be calculated as follows:

$$k_{fat} = 1 - \frac{1 - R_T}{a_{fat}\left(b_{fat} - R_T\right)} \log\left(\beta n_{obs} T_{Life}\right) \tag{2}$$

where R_T is the stress ratio, n_{obs} is the number of constant amplitude stress cycles per year, T_{Life} is the design service life of the structure expressed in years, and β is the factor based on the damage consequence which can have a value of 1 or 3.

The two coefficients a_{fat} and b_{fat} represent the type of fatigue action and are given in Table 1.

Table 1: *Values of coefficients* $\boldsymbol{a_{fat}}$ *and* $\boldsymbol{b_{fat}}$ *for timber members subjected to arbitrary state of stress*

	a_{fat}	b_{fat}
Timber members with $\sigma_{d,max}$ mainly being		
• compression, perp. or parallel to grain	2,0	9,0
• tension parallel to grain	9,5	1,1
• tension perpendicular to grain	4,7	2,1
Timber members mainly being subjected to		
• shear	6,7	1,3
Connections with		
• dowel-type fasteners with $d \leq 12\ mm$	6,0	2,0
• nails	6,9	1,2

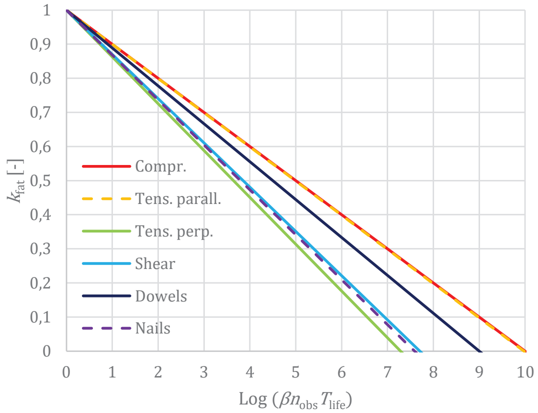

Figure 2: *Example of the reduction factor* $\boldsymbol{k_{fat}}$ *for different stress states and details with* $\boldsymbol{R_T = -1}$.

No specification or values of coefficients are given for the bond line or the glue line failure for different adhesives. The existing test methods for the fatigue testing of bonded joints, such as for glued-in rods when following EN 17334 [10], are not suited to evaluate and potentially classify the fatigue performance of the adhesive itself and the bond line strength. Instead, the steel member is often the element governing the fatigue resistance of the joint [11].

2.4 Impact of testing frequency on fatigue strength

The loading frequency can have an effect on the results of the fatigue tests. Typical frequencies reported in the literature on connections with mechanical fasteners are in the range of approx. 1-3 Hz.

More detailed studies on the impact of testing frequency on the fatigue strength is reported in the literature for tests on wood-based materials. Bond and Ansell [12] state that at high frequencies adiabatic heating of the specimens may occur due to the hysteresis in the mechanical behaviour of the timber. The good insulation property of the timber limits the heat dissipation and may create heat build-up within the specimen. This can be a particular issue for connections with heat sensitive adhesives. In mechanical connections, also the frictional heating between shear surfaces should be considered. In addition, high frequencies might lead to longer fatigue life (in terms of number of cycles).

A very large range with frequencies from 1-100 Hz has been studied by Thompson et al. [13] on tests on chipboard. For this wide range, a clear impact of the frequency on the fatigue strength was observed: the fatigue strength was higher for the high frequencies of 10 and 100 Hz compared to 1 Hz.

Bonfield and Ansell [14] evaluated the fatigue properties of wood in tension, compression and shear in tests with frequencies of 5 Hz.

Hacker and Ansell [15] performed fatigue tests on wood-epoxy laminates with frequencies between 4 and 7 Hz. It is stated that these frequencies are low enough to avoid sample heating, moisture loss and change in mechanical properties.

Bond and Ansell [12] mention that the rate of stress application (RSA) is the relevant parameter to consider. Different stress levels at constant frequency result in different RSA, which in turn affect the fatigue life of the specimens. They used a constant RSA = 400 MPa/s in their tests resulting in variable frequencies for the different stress levels. Generally, all static and fatigue testing for a particular material should be carried out at the same rate.

Bond and Ansell [12] state that for frequencies exceeding 8 Hz, adiabatic heat generation may cause changes in the properties of the wood.

The frequency of the actual loading in the wooden wind tower is very complex as it is a stochastic phenomenon. For the present case, however, it can be derived that a variable load with $5 \cdot 10^7$ cycles during 20 years' service life has a period of approx. 10 sec (0.1 Hz). It is of course impossible to perform laboratory tests with such low frequency and large number of cycles. Hence, it was decided to perform a first explorative series with different frequencies at high stress ratios and low fatigue life, in order to determine an adequate high frequency.

3 EXPERIMENTS

3.1 OVERVIEW

Different static tension and cyclic fatigue tests of the adhesive bonded joints by Modvion have been carried out at the laboratories of the Swedish institute RISE in Borås, Sweden, between Mars 2022 and January 2023.

The purpose of the experiments was to investigate the fatigue life capacity (curve).

Within the tests, the different stress ratios ($-1 < R < 0{,}1$) and loading-ratios have been varied to study the number of cycles to fatigue in the range of approx. $10^4 - 10^7$.

In order to reach the desired high number of cycles in reasonable time, a relatively high loading frequency of up to 10 Hz is desired. In a preliminary test campaign, the static performance of the specimen and the impact of loading frequency were analysed.

It was confirmed that no impact of frequency on the fatigue resistance was observed in the desired range of frequencies between 1-10 Hz.

3.2 MATERIALS

The objective of the test campaign is to study the fatigue performance of the adhesively bonded joints with polyurethane adhesive in the timber tower by Modvion. In particular the bond line fatigue strength between timber and adhesive in the timber-timber edge joints and the glue dowel fatigue strength in the hybrid timber joints shall be evaluated.

The walls of Modvion's timber towers are made of several layers of special Laminated Veneer Lumber (LVL). First, the thick, curved LVL modules are glued together from thinner, special LVL panels. The precise cutting of the LVL modules is done by a CNC-robot. Four of these modules are assembled on-site to build a tubular section of the tower. The sections are then stacked on top of each other to build the tall conical timber tower.

Two different types of joints are present in the tower:

1. the longitudinal (lap) shear joints between LVL modules in the vertical direction of the tower.
2. the transversal, hybrid butt-joints with perforated steel plates between the tower sections in the horizontal direction of the tower.

The test specimens were developed and chosen accordingly, and are denoted as:

1. *Strong Enough Longitudinal* joint or SEL joint
2. *Strong Enough Transversal* joint or SET joint

The dimensions of the joints are carefully calibrated in order to achieve the desired failure in the bond line or in the adhesive dowels going through the perforated steel plates for the SET joint.

In the tests, the mean density of the LVL was 510 kg/m^3. The LVL veneer layup in the specimens was representative of the layup in the final application in the tower.

3.2.1 The edge joint (SEL)

The edge joint technology with a 3 mm thick 2-component polyurethane adhesive is utilized in Modvion's tower to connect two modules along the length.

All specimens were carefully produced in the factory of Modvion AB as solid specimens with an internal thick glue line (Figure 3 top). At the moment of testing at RISE, Borås, two cuts in transversal direction at a distance of 30 mm were cut using a band saw in order to create the bond surface for the shear tests (Figure 3 bottom). The test

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was inspired by the lap joint test specimen in EN 302-1 [16].

Steel plates were glued into the specimens in order to clamp the specimens with the same equipment as the SET-specimens. In this case, the glued joint between the steel plate and the LVL was sufficiently overdesigned to prevent failure.

Figure 3: *SEL-specimen without the cutting (top) and with the two cuts for testing (bottom)*

3.2.2 The hybrid timber joint (SET)

The hybrid timber joint is an adhesive connection using a thin perforated steel plate to join two timber members. It is similar to other bonded connections between steel and timber such as glued-in rods for glued structural timber products or the connection system described in [2].

In Modvion's application, a thick steel plate with a large amount of holes are inserted in slots in the LVL members. Then a 2-component polyurethane adhesive is injected between the LVL and the steel plate. When the adhesive cures, bond to the wooden members is established and "glue-dowels" penetrating the steel plate are formed, which lock the steel plates in place and provide strength and stiffness to the connection. These hybrid joints are utilized in Modvion's timber tower to connect two sections on top of each other's to reach the desired height of the tower. The steel plates have a specific hole pattern in order to avoid stress concentrations.

The dimensions of these specimens were carefully designed to achieve the desired failure mode in the adhesive or the bond line. Hence, the steel plates used in the SET samples have small number of holes for the glue dowels to create the connection. An illustration of the specimens is shown in Figure 4. The desired failure mode with bond line failure was confirmed in static tests.

Figure 4: *Illustration of the SET-specimen*

A variety of different configurations of SET-specimens have been tested as shown in Table 2. The configurations include: two different methods for manufacturing the holes of the steel plates, different adhesion inhibitors applied on the steel plates (SET 200 and 400) , a variation of the glue line thickness, and the number of holes in the steel plate have been varied.

Table 2: *The different sets of SET samples*

SET series	# of samples	Hole manufacturing	Slot thickness [mm]
000	13	Laser-cut	6
200	6	Punched	6
400	12	Laser-cut	6
500	8	Laser-cut	9
Double # holes	8	Laser-cut	6
no hole	4	-	6

3.3 METHODS - TESTING EQUIPMENT

3.3.1 Static tensile tests

The static tensile tests aim to evaluate the tensile strength of the samples. The tensile tests have been performed on a universal testing machine (Instron 1253) with a hydraulic cylinder of 50 kN capacity in both compression and tension. The load was recorded using a load cell with a capacity of 50 kN. Before testing, the samples were stored for several weeks in a conditioned climate of 20 °C and 65% relative humidity.

Special grips were designed and manufactured to secure a stiff and strong connection between the steel plates of the specimens and the test machine and to avoid bending stresses in the specimens.

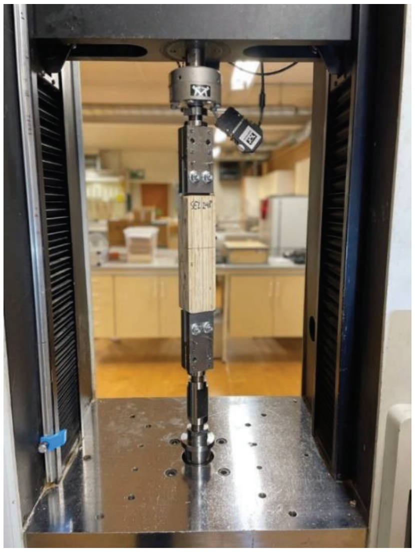

Figure 5: *Test machine Instron 1253 and set-up with SEL sample*

3.3.2 Fatigue tests

In the cyclic fatigue tests the connection's fatigue strength was determined, i.e. the number of loading cycles the connection can withstand for certain loading conditions

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before failure. Sinusoidal cyclic loading was applied at frequencies of 5, 6, 8, and 10 Hz.

The loading amplitudes and the mean load values varied, and three different stress ratios $R = \sigma_{d,min}/\sigma_{d,max}$ were tested:

- $R = -1$, the loading is pulsating, e.g. the load varies sinusoidally between -5 kN (compression) and 5 kN (tension), for an example of a load record see Figure 6.
- $R = 0.1$ in tension, e.g. the load varies sinusoidally between 1 kN and 10 kN, an example of a load record see Figure 7.
- $R = 0.5$, e.g. the load varies sinusoidally between 5 kN and 10 kN.

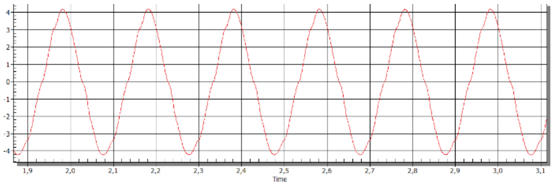

Figure 6: *Example of a load record in machine Instron 1253 during a fatigue test at 5 Hz and R = -1, with pulsating load varying sinusoidally between +4.2 kN and – 4.2 kN. The time in [s] is on the horizontal axis, and the load in [kN] is on the vertical axis.*

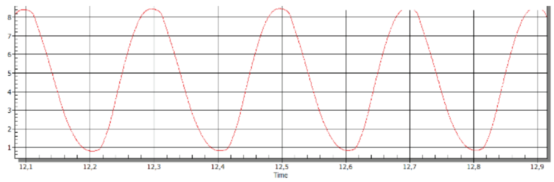

Figure 7: *Example of a load record in machine Instron 1253 during a fatigue test at 5 Hz, and R = 0.1, with load varying sinusoidally between +8.5 kN and +0.85 kN. The time in [s] is on the horizontal axis, and the load in [kN] is on the vertical axis.*

Two machines were used for the fatigue tests at RISE in Borås. The Instron 1253 and a special machine for long-term testing with a hydraulic cylinder (capacity 100 kN) called the Blå-Rigg, (Figure 7). Before testing, the samples were stored for several weeks in a conditioned climate of 20°C and 65% relative humidity. However, the ambient climate during the fatigue testing was not controlled and varied between 19-23ºC and 40-70 % RH.

Figure 8: *Fatigue test machine* ***Blå-Rigg*** *and set up with a SET sample*

4 TEST RESULTS

4.1 The edge joint specimens (SEL)

4.1.1 SEL static tests

Ten SEL samples were tested in the Instron 1253 machine. The load was applied at a constant displacement rate of 0.5 mm/min until failure. The mean value of the bonline shear strength is approx. 6 MPa and the CoV is 5.2%.

4.1.2 SEL fatigue tests

For the fatigue tests, 34 samples were tested to failure at different load levels and frequencies. One loading ratio $R = -1$, i.e. pulsating loading from tension to compression, has been studied in this test series.

In Figure 9, the results are presented in a log-linear diagram with the number of cycles to failure with respect to the applied (sinusoidal) stress level in the glue line (SEL Fatigue in blue), and the relative results from the static tests (SEL Static in red).

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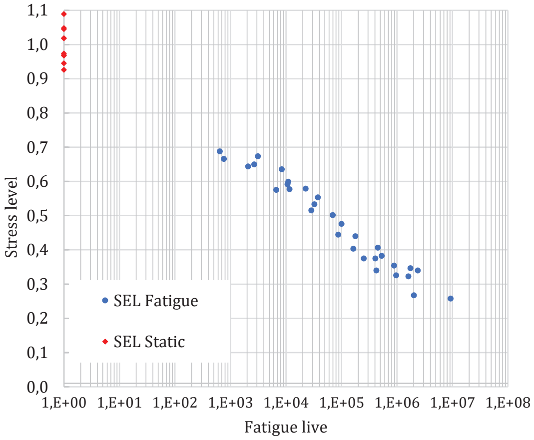

Figure 9: *Results of the SEL fatigue tests*

4.1.3 The SEL failure mode

For both static and fatigue tests the failure mode was similar and happened in both the adhesive, in the wood and/or at the bond line interface between both materials. From visual inspection, the mean value of the surface share with wood failure is approximately 60 %, i.e. about 40 % failure at the adhesive or at the bonding interface. However, a large variation of the surface share ratio can be observed. Some examples of the failure surfaces SEL specimens are shown in Figure 10.

Figure 10: *Examples of failure surfaces of three tested SEL specimens*

4.2 The hybrid timber joint (SET)

4.2.1 SET static test

Results from the static tests on the SET specimens are presented in Table 3 for the different sets of SET configurations summarized in Table 2. The static tests on the specimens with special steel plates show considerable different resistance: the specimens with steel plates of double amount holes (SET double) show an almost double resistance whereas the specimens with steel plates without any holes (SET no hole), i.e. with smooth steel plates show slightly smaller resistance.

Table 3: *Comparison of the relative mean resistance from the test results for the different sets of SET samples*

SET series	Mean max. load [kN]	CoV max. load [%]
SET 000	100%	13.5%
SET 200	101%	6.7%
SET 400	101%	3.1%
SET 500	102%	3.9%
SET double # holes	193%	16.0%
SET no hole	87%	14.6%

4.2.2 The SET fatigue tests

For the fatigue test of series SET 000 at $R = -1$, a preload of 10 kN was applied in tension to all the samples. This simulates the load of a storm with 50-year return period right after erection the tower. No preload was applied to the other series in the fatigue tests.

The results are presented in Figure 11, in a log-linear diagram with the number of cycles to failure with respect to the applied (sinusoidal) stress level for all specimens.

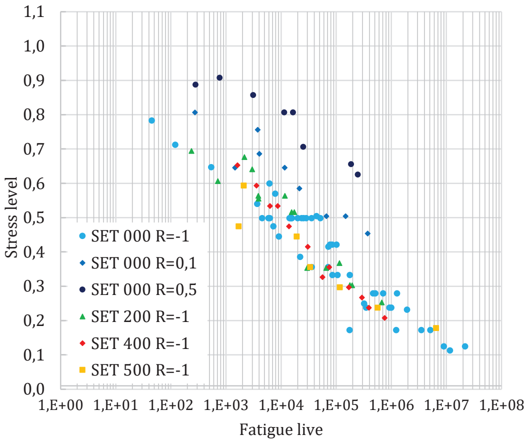

Figure 11*: Results of the SET fatigue tests*

4.2.3 The SET failure mode

For both static and fatigue tests the failure mode is similar and common to most of them: failure always occurred in the glue dowels (100%). But also failures of the bonding at the interface between the steel plate and the adhesive (60-80%), and failures of the bonding at the interface between the wood surface and the adhesive or in the wood material (20-30%) were observed. However, the visual estimation of the ratings is subjective and rough. Figure 12 shows some examples of pictures of tested SET samples and the failure mode.

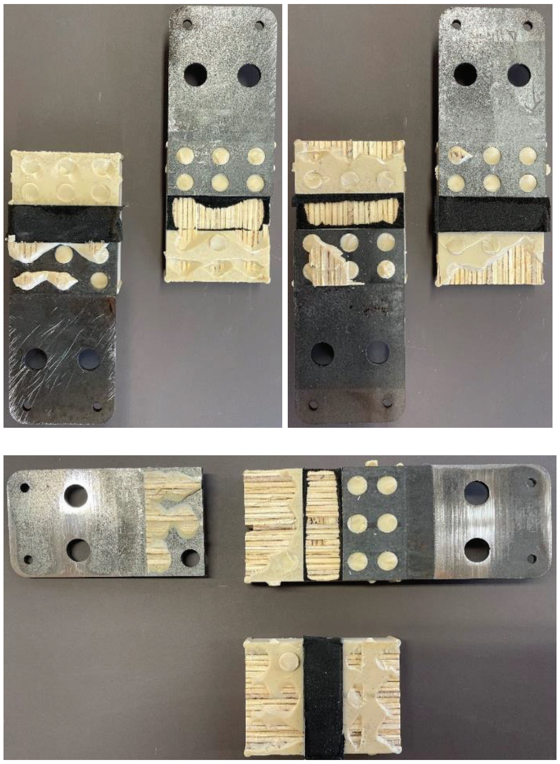

***Figure 12**: Examples of failure surfaces of three tested SET specimens.*

5 CONCLUSIONS

The results of the project described in this paper provide the basis for the design and verification of advanced timber structures for wooden wind turbine towers and allow a better understanding and further development of fatigue-loaded bonded joints in timber construction.

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