CANTILEVER GLULAM BEAM FASTENED WITH LONG THREADED STEEL RODS

Pål Ellingsbø¹, Kjell Arne Malo²

ABSTRACT: Glulam cantilever beams connected through a steel-plate using long threaded rods as fastener have been explored. The cantilever beam is a model of a propeller in a water turbine and must be designed for very large moment actions at the connection. Two experimental studies have been carried out, one for the withdrawal capacity of threaded rods and one for the behaviour and strength of the cantilever beam joint. Threaded steel rods with diameter of 16 mm and lengths up to 1000 mm were considered. The withdrawal experiments showed that the effective length needed to achieve steel failure was about 800 mm. A three-dimensional numerical finite element model, was used to analyze the withdrawal problem. The simulations revealed that internal failure in the timber is likely to occur due to the large strains in the threaded rods prior to the steel tension failure. The glulam cantilever beam connections were tested and comparisons to analytical expressions showed good agreement. Different moisture content had little effect on the failure modes and ultimate load. For the rotational stiffness, observations showed a reduction in stiffness when introducing multiple parallel threaded. The study improves the knowledge of threaded bars used as fasteners. Further work is needed on the group effect behaviour no the stiffness as well as strength.

KEYWORDS: Glulam cantilever beam, threaded steel rods, withdrawal capacity, numerical simulations.

1 INTRODUCTION

The tidal movement contains a lot of energy and several companies are working with technology to convert this energy into electric power. A concept power station, Morild shown in Figure 1, is a floating installation consisting of two turbines, each having two contra rotating propellers. This power station is submerged, but floating, in contrast to other tidal energy projects which are based on fixed seabed installations.

Due to economy, easy machining and a submerged density similar to water, glulam is chosen as the structural material in the prototype propeller blades. The connection between the blades and the generator axel transfer both shear forces and large moment actions due to the heavy distributed loading from the water pressure. The propeller blades acts as cantilevered beams where the cantilever has a cut normal to grain direction at the support which will be fastened to a steel spindle header plate by mechanical fasteners [1, 2].

The attachment of the cantilever beams to the steel spindle head on the turbine rotor is shown in Figure 2 and Figure 3 and consists of long threaded steel rods installed through holes in a adapter steel-plate. On the tension side the threaded steel rods transfer the forces, while on the compressive side, direct contact stress transfer the forces from the timber to the steel plate. The intended use of the rods is to carry forces in the direction of the rod axis only. The components in horizontal and vertical direction carry the moment and the shear force of the joint, respectively. Friction properties between steel and wood might also transfer some shear force.

Figure 1: Morild II floating power station
The main challenges in this propeller concept are the transfer of bending moments up to 2500 kNm, and the size of the threaded rods necessary in this application. The rods will have a length of approximately 1800 mm and diameter of 26 mm. The effective length of the threaded rods will vary, therefore the rods are made for the longest lengths and are cut where needed. A preliminary version of the threaded steel rod intended to use in the full size joints is shown in Figure 4.

Applications of threaded steel rods of this size are a priori not known to the authors.

2 GENERAL CONSIDERATIONS

The behaviour of metallic fasteners in connections is quite complex and lack of information, results and rules hampers the innovation in structural timber design. The metallic fastener connections depend on the interaction between the fasteners, the different failure mechanics and the wood properties. Experimental testing is needed to gather the basic parameters needed for calculations as well as the basic information about the behaviour. The large variability of the results due to the spread in the material properties limits the immediate outcome and calls for large and expensive test series. Numerical simulations allow for a wider range of case studies at lower costs, and eliminate the number of experimental tests needed. However, failure mechanisms, interaction between parts as well as the material properties needed for numerical studies, still make experimental testing mandatory. However, the combination of the two makes a good approach for a verifications and product development.

2.1 AXIAL FASTENERS

Studies [3] shows that the capacity obtained in a connection based on self-tapping screws or threaded rods, introduces joints with high capacity which can be both axially loaded and moment resisting. Screws can also be used as reinforcements to increase the load carrying capacity.

Eurocode 5 [4] allows axially loaded screws for angles between screw axis and grain direction larger than 30 degrees. Joints with screw diameter larger than 12 mm, needs experimental verification.

The objective of the present work is to explore the utilization of axially loaded threaded rods with application to the fastening of wooden turbine blades. In order to explore the behaviour of the concept joint shown in Figure 2, axially loaded long threaded rods, parallel and near parallel to the grain direction is studied.

Two experimental test series on withdrawal capacity and failure modes of axially loaded threaded rods were analysed and numerical analysis of the withdrawal tests have been carried out.

The behaviour and design of the concept cantilever beam joint have also been considered.

3 WITHDRAWAL EXPERIMENTS

The withdrawal capacity tests [5] consisted of axially loaded threaded steel rods, parallel to the grain direction. The wood material in all the tests was glulam L40 (with strengths roughly in the range between C28c and C32c) with 12% MC. SPAX threaded steel rods with diameter of 16 mm were used in the testing. The effective length of the threaded steel rod varied from 300 to 800 mm. The average measured density in the tests was 479 kg/m³, while the characteristic density was calculated to 410 kg/m³.

Results from the withdrawal experiments are given in Figure 5. The observed failure load shows a small increase for increase in the effective length of the threaded steel rods. The figure also shows that the failure mode changes from timber to steel failure when the effective length exceeds 600 mm. A length exceeding 800 mm gave no increase in the observed failure load, and all specimens observed had steel failure.

The observed steel failure occurred about 15 – 25 mm into the threaded region. Figure 6 shows the axial steel failure in the net section. The average value for the steel failures was 87800 N, giving an ultimate steel strength of...
of the material properties of wood. Figure 7 shows the structural and meshed model represented with the timber material coordinates.

The geometrical representation of the rod was accurate described by the original dak file used for manufacturing (available online at the SPAX homepage).

4.2 MATERIAL PARAMETERS

Wood is an anisotropic material, but with characteristic orthogonal properties. With the material orientations in timber denoted L, T and R, the conversion to numerical orientations consists of L=1, T=2 and R=3. In addition, transversal isotropic behavior, with equal properties in the T and R direction was assumed. The property $E_L/E_T \approx E_L/E_R \approx 35$ used in most timber codes and results from studies [7] support the choice.

The material parameters used for the glulam emanate from a literate study [8-10], which is summarized in Table 1 The elastic parameters used for input to numerical analyses is given in the rightmost column of Table 1 and accommodates to some extent the higher quality of the glulam used in the tests.
All parameters in Table 1 are mean values and apply to 12% MC, air temperature of 20 degrees and density $\rho = 420$ kg/m$^3$. No non-linear or plastic effects were implemented for the wood properties. Steel properties was modelled isotropic, with $E = 210$ GPa and $\nu = 0.33$. Based on available information, a yield stress of 500 MPa and ultimate stress of 776 MPa were used. Linear hardening up to ultimate stress and thereafter constant stress was assumed. No failure criteria were implemented in the model.

**Table 1: Values of timber parameter for numerical analysis**

<table>
<thead>
<tr>
<th>Material</th>
<th>GL28c</th>
<th>GL38c</th>
<th>GL32c</th>
<th>Average values</th>
<th>Input for analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>12000</td>
<td>15160</td>
<td>16300</td>
<td>14487</td>
<td>14580</td>
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<tr>
<td>$E_2$</td>
<td>400</td>
<td>565</td>
<td>470</td>
<td>492</td>
<td>500</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>75</td>
<td>95</td>
<td>110</td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>750</td>
<td>950</td>
<td>1160</td>
<td>953</td>
<td>1100</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.0333</td>
<td>0.0333</td>
<td>0.0335</td>
<td>0.0339</td>
<td>0.0339</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.0063</td>
<td>0.0063</td>
<td>0.0067</td>
<td>0.0064</td>
<td>0.0064</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>0.0025</td>
<td>0.0027</td>
<td>0.017</td>
<td>0.0655</td>
<td>0.0655</td>
</tr>
<tr>
<td>$\nu_{13}$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\nu_{13}$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**4.3 STRESS DISTRIBUTION**

The stress intensity will decrease along the threaded rod, from the head towards the tip where it has to be zero. For the threaded steel rod, the von Mises equivalent stress was evaluated and plotted for a path coinciding with the centre axis of the threaded rod. The von Mises equivalent stress plotted in Figure 8, shows that the maximum stress was obtained in the threaded part of the rod close to the head.

**Figure 8: von Mises stress equivalent distribution along the centre axis of the threaded steel rod**

The distance from head to the point of maximum stress was 15 mm. Along the rod axis an exponential decrease occurred, tending towards zero stress as the effective length exceeded 250 mm. The stress components S11, S22 and S12 in the wood are plotted in Figure 9. The evaluated path was parallel to the grain direction, with a 10 mm distance to the threaded rod axis, hence 2 mm from the outer edge of the threaded rod.

**Figure 9: Stresses in the timber member 10 mm from the threaded rod centre axis.**

The longitudinal stress component S11 in the wood close to the threaded rod shows tension behaviour similar to the stress in the threaded steel rod. Maximum of the S11 stress component occurs at a distance of 15 – 50 mm from the head of the threaded steel rod. Local maxima are occurring regularly the first 30 mm with an exponential decay thereafter. The local maximum values are probably due to the threads on the threaded rod. In Figure 10 the upper 30 mm of the stress component curves are shown more closely, and the distance between maximum values for the S11 component coincide with the 6 mm thread distance on the steel rod.

**Figure 10: Stress components from the simulation in the upper 30 mm of the timber member**

The transversal stress component S22 shows tension in the upper 15 mm of the rod, and near zero thereafter. The S22 stress component is exceeding 5 MPa and may cause cracking which is not included in the numerical model. The behaviour in the upper part was similar to the S11 stress component, with the local maxima occurring at regular intervals. The shear stress component S12 has the same distribution as the other components, with maximum occurring 15-20 mm from the head of the threaded steel rod, and exponential decreasing thereafter with some locale maxima.
Figure 11 depicts the normal strain components observed in L (E11) and T (E22) directions, as well as the shear strain E12. It should be noted that especially the shear strain might exceed the failure strain limit [7]. Recalling that also the stress component S22 is close to the strength limit, it is likely that a wood failure takes place close to the start of the threaded region.

Figure 12: Strains from the simulation in the upper 30 mm of the timber member

A closer look at the strain in the upper 30 mm of the timber member in Figure 12 reveals the same development for the strains as for the stresses. The local maxima are occurring with regular intervals corresponding to the length between the threads on the rods.

In the analysis, all strains and stresses come close to zero when the distance from the head exceeds 250 mm on the threaded rod. This tendency does not agree with the previous experimental observations indicating effective lengths of 800 – 1000 mm to achieve steel failure. The numerical analysis does not include any plastic or failure effects for the wooden material. If wood failure takes place, these effects will tend to increase the effective length for steel failure. Failure in the interface zone between steel and wood close to the head will push the most stressed zone further apart from the head, and thus increase the effective length. This effect will be similar to opening a zipper.

5 CANTILEVER GLULAM BEAM EXPERIMENTS

The test setup consists of a scaled slice of the concept cantilevered beam joint, shown in Figure 13, in the plane where the moment action takes place. The cantilever material was Norway spruce glulam beams with dimension 140*585 mm, length 4000 mm, and L40 quality [2]. The beam had a dead weight of q=0,4 kN/m. All cantilever beam tests used the same beam shape shown in Figure 13 and Figure 14.

Figure 13: LEFT – Insertion of threaded rod into beam, RIGHT – Setup for loading

The tensile threaded rods are installed with 30 degree inclination relative to the grain direction, where the grain direction and beam axis coincide.

Out of the concept tests [2] a subset consisting of four tests is chosen, where two tests had a single threaded rod and two tests had two parallel threaded rods. The results for the reported tests are given in Table 2. The threaded rods had a length of 1000 mm and a diameter of 16 mm. The documented characteristic strength was $f_{u,k} = 500$ MPa and the rods were supplied from the manufacturer SPAX.

Figure 14: Test beam

Optical measurement equipment recorded the planar deformations on the specimen surface, and both stiff motions and strains was monitored [11]. In addition, displacement transducers were placed at the top and bottom of the cross section at the supported end. At the loading point both load and deformation was monitored

5.1 OBSERVATIONS FROM CONCEPT JOINT TESTING

Cracking near by the compression zone was observed in the two initial tests. Figure 15 shows the localization of the cracks, caused by the tensile stress normal to the grain. The stress occurred due to the combination of tensile forces in the inclined rods and friction between
the steel plate and the cantilevered beam. In both initial tests, the crack was between 45 and 60 mm from the bottom, the length of the crack extended to 1000 mm at the failure load. The failure mode in the threaded rod was not pure tension failure, but the combination of shear forces from the rigid body rotation about the crack tip, and tension from the moment action.

The joint was reinforced an additional threaded rod perpendicular to the tensile rods, at 60 degrees inclination to the grain. This reinforcement prevented the cracking and no major cracks were observed in the specimens, but minor cracks did develop in the compression zone without any observed influence on the capacity.

![Figure 15: Cracking due to tension perpendicular to the grain](image)

### 5.2 TEST RESULTS

The test results are given in Table 2, for comparable test with one or two tensile rods, and one reinforcement rod. The moisture content varied from 12 % to 24 %. The tests were performed according to the NS-ISO 681 standard, with a preloading procedure that consists of two constant load periods and a load reversal.

**Table 2: Test Results**

<table>
<thead>
<tr>
<th>Test number</th>
<th>Rods</th>
<th>Failure load (kN)</th>
<th>Rotational stiffness (kNm/deg)</th>
<th>Moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1-4</td>
<td>1</td>
<td>11,20</td>
<td>4300</td>
<td>12</td>
</tr>
<tr>
<td>B-2-1</td>
<td>1</td>
<td>11,47</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>B-3-1</td>
<td>2</td>
<td>20,01</td>
<td>6450</td>
<td>20</td>
</tr>
<tr>
<td>B-3-2</td>
<td>2</td>
<td>21,03</td>
<td>-</td>
<td>21</td>
</tr>
</tbody>
</table>

### 5.3 EFFECTS OF MOISTURE CONTENT

The effect of moisture content on the connection capacity is of great interest since the intended application is submerged in water. Tests carried out to explore the moisture influence are presented in Figure 16. Load versus displacement at the tip for two beams with the same configuration, but with different moisture content are shown. No difference in the failure load due to different moisture content is observed. However, the elastic stiffness of the wet specimen was slightly smaller, and the displacement at failure increased by 20%. Failure mode for both specimens was steel tension failure in the threaded rods.

![Figure 16: Wetted and dry cantilever test sample](image)

### 5.4 ROTATIONAL STIFFNESS

The observed rotational stiffness of the concept connection was for one threaded rod 75 KNm/rad, and for two threaded rods 110 KNm/rad. The moment – rotation relationships at the support is shown in Figure 17. Some ductility in the connections is observed, and it seems to be independent whether one or two parallel threaded rods are used.

![Figure 17: Rotational stiffness with one and two rods](image)

The total increase in stiffness was only 50 % when introducing the second threaded rod, indicating a group effect. Further tests with more threaded rods should be conducted to investigate the reduction in stiffness due to groups of rods. The rate of reduction might be faster for a higher number of rods as the compression strength of the timber will have increased impact on the rotational stiffness when the number of threaded steel rods increases.

### 6 ANÁLYTICAL CALCULATION

A sketch of simple analytical model for the moment capacity of the tested cantilever connection is shown in Figure 18. The analytical calculations were done with assumed linear material and behavior compliant with Navier’s hypothesis. Yield strength for the threaded steel
rods was stated from the manufacturer as \( f_{ck} = 500 \text{ MPa} \), but from the withdrawal experiments the steel strength was found to be \( f_{t} = 776 \text{ MPa} \). The kernel diameter of the rods used were 12 mm, giving a net area \( a_{net} = 113.1 \text{ mm}^2 \).

Figure 18: Concept sketch of connection and force distribution

With the assumption of elastic material and a dead weight \( q = 0.4 \text{ kN/m} \) for the beam the following maximum moment and external load was obtained:

\[
M_{\text{max}} = f_t \cos(30) a_{w} h = 50.2 \text{ kNm} \tag{2}
\]

\[
P_{\text{max}} = \frac{1}{4} (M_{\text{max}} - q l^2/2) = 11.8 \text{ kN} \tag{3}
\]

Table 3 shows the efficiency, computed as the ratio between test failure load and the maximum theoretical load \( P_{\text{max}} \) of the threaded rods in the connection. The efficiency for one rod was 0.95 and 0.97, while the introduction of two parallel fasteners reduces the efficiency to 0.85 and 0.89. This reduction could also indicate possible group effect on strength.

Table 3: Efficiency of threaded rods in connection

<table>
<thead>
<tr>
<th>Test number</th>
<th>Rods</th>
<th>Failure load (kN)</th>
<th>Calculated failure (kN)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1-4</td>
<td>1</td>
<td>11.20</td>
<td>11.8</td>
<td>0.95</td>
</tr>
<tr>
<td>B-2-1</td>
<td>1</td>
<td>11.47</td>
<td>11.8</td>
<td>0.97</td>
</tr>
<tr>
<td>B-3-1</td>
<td>2</td>
<td>20.01</td>
<td>23.6</td>
<td>0.85</td>
</tr>
<tr>
<td>B-3-2</td>
<td>2</td>
<td>21.03</td>
<td>23.6</td>
<td>0.89</td>
</tr>
</tbody>
</table>

7 CONCLUDING REMARKS

The steel quality of the threaded rods limits the axial capacity, and the effective length of the threaded rods used in the concept joint should be long enough to ensure a steel failure in the rods. The advantage of the smaller variations in steel properties should be utilized in the design and is achieved with long effective lengths. For an effective length of 800 mm or more, there was no observation of timber failure in the tests, supporting the use of long threaded steel rods parallel or near parallel to the grain orientation. In the concept joint however, an angle of 30 degrees between the rods axis and grain direction reduce the risk of failure due to cracks along the grains.

The experiments also show that wood density has a negligible impact on the withdrawal capacity of the threaded bars.

The cantilever experiments showed that different moisture content had no effect on the capacity of the joint. The rotational stiffness was slightly decreased for increased moisture content in the tests, due to the reduction of young’s modulus with increasing moisture. Threaded rods installed with inclination to grain direction might introduce large tensile forces which in turn might lead to tensile failure normal to grains and crack development. The extra reinforcement using a threaded steel rod perpendicular to the loaded threaded rods prevented the crack development.

A small group effect was observed for the ultimate strength of the connection when introducing an additional fastener since the efficiency dropped with 10 %. For the rotational stiffness the increase was 50 % in strength when adding the second parallel threaded steel rod, indicating a larger group effect. More work on multiple fasteners has to be performed before conclusions on the group effects can be drawn.

Numerical analysis revealed the stress distribution along the threaded rod and in the threaded steel rod maximum stress was found close to the head. The effective length leading to negligible stress and strains was found only to be 250 mm, in contrast to the experimental observations of about 800 mm. This was explained by the lack of plastic and failure properties of the wood material in the numerical model. Further simulations with these effects included should be performed.

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REFERENCES

[1] Malo, K.A., Konsept for innfestning av rotorblad i limtre,R-09-08, Department of Structural Engineering, Norwegian University of Science and Technology NTNU, Trondheim, Norway, (In Norwegian)

[2] Malo, K.A. and Ellingsbø, P., Fastening of glulam rotor blades using threaded rods. Experimental test results and evaluation,Department of Structural Engineering, Norwegian University of Science and Technology NTNU, Trondheim,


Fish, J. and Belytschko, T., A first course in finite elements. 2007, Chichester: Wiley. XIV, 319 s., pl.


