Fatigue Strength of Dowel Joints in Timber Structures

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Summary
The increased use of large span glulam timber structures is in part due to the development of more efficient connections with slotted-in steel gusset plates combined with steel dowels. In timber road bridges, also the fatigue behaviour of such connections must be considered. The paper shows that fatigue damage and failure may occur in timber structures with dowel connections when subjected to fatigue loading. The fatigue strength is dependent on the stress ratio, which is the ratio between the minimum and maximum stress. The fatigue strength can be considered to be a linear decaying function of the logarithm of the number of cycles. Use of maximum stress as fatigue strength parameter seems to be more reasonable than use of the stress range. The bridge part of the new Eurocode 5 timber code has proposed fatigue verification rules in an informative annex, and the fatigue design verification is commented in view of the present test results.

1. Introduction

During the last decades the use of glulam timber in large span truss structures has increased significantly. In Norway the athletic facilities built for the 1994 Winter Olympics at Lillehammer may serve as examples of this tendency where the speed skating rink at Hamar (The Viking Ship) may be best known. More recently, the terminal building at the new Oslo Airport was constructed using a glulam timber roof system. In all cases the structural systems were exposed and used as an architectural feature. One of the key factors which made these large timber structures competitive economically is the development of joints with slotted-in steel plates (gusset plates) combined with steel dowels. This type of joints has now been used in many timber road bridges [1]. Evenstad Bridge was the first large timber bridge in the Nordic countries, and was opened for road traffic in 1996. Later, larger bridges have been built including an arch bridge with a span of 70 meters at Tynset, Norway, as well as a bridge for very heavy military traffic at Rena, Norway.

Whereas buildings are subjected to predominantly static loading, the moving traffic loads on the bridges may cause fatigue effects. The number of load cycles and load amplitudes will depend on the traffic pattern at the bridge site. However, at present there is very little information available on the fatigue strength of timber connections, and the design codes give few guidelines. In a comprehensive literature survey [2] only one paper on this subject was identified [3]. Here, three connections with 4 dowels in a row parallel to the grain were tested, and the residual static strength after a prescribed number of load cycles was determined. The tentative conclusion stated that the
fatigue strength was good [3]. Fatigue of bolted connection is addressed in [2] and [4] while the fatigue behaviour of wood material under various loading conditions has been addressed in [5]. Examples on applications involving metal fasteners and a comprehensive treatment on the subject fracture and fatigue of wood may be found in [6]. Clearly, in order to extend the use of timber road bridges to larger spans more data on fatigue of dowel joints in timber structures are needed. The present design rules are very limited and most likely insufficient or non-documented. Furthermore, the theoretical basis for the damage evolution and a predictive analytical theory seems to be lacking. For this reason a Nordic research programme was performed, where tests have been carried out on dowel type connections with 2 or 3 dowels in one row perpendicular to the grain [7], [8]. The present investigation extends this work to larger specimens and more dowels in each connection.

2. Fatigue verification

Fatigue design for wood-based materials are summarised in [9]. The fatigue life of engineering materials is traditionally represented in the form stress-life or strain-life curves following Wöhler’s classical work. The fatigue strength is normally determined on the basis of cyclic tests with constant amplitude. Such a stress or load process is uniquely defined by the stress range $\Delta \sigma$ and the stress ratio $R$ with the following definitions:

$$\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} \quad \text{and} \quad R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}$$

where $\sigma_{\text{max}}$ and $\sigma_{\text{min}}$ are the characteristic maximum and minimum stresses respectively from the fatigue action. The use of $\Delta \sigma$ as the governing stress parameter for fatigue design is similar to the current practice for welded steel structures. For steel structures there exists residual welding stresses as high as the yield stress $f_y$ in tension at the location of a potential fatigue crack, and the material will hence experience stresses that vary between $f_y$ and $(f_y - \Delta \sigma)$ at this position. For this reason $\Delta \sigma$ is used as the fatigue stress parameter. For timber structures there seems to be few physical reasons and little experimental evidence that justifies the use of $\Delta \sigma$ as the only stress measure. Based on results reported in [7] and [8], and on the general fatigue data for wood [9] and [10], it seems apparent that the stress ratio $R$ should be included when determining the fatigue strength. Furthermore, taking into account the effect of the duration of load on the strength of wood, it might be reasonable to consider the use of $\sigma_{\text{max}}$ as an alternative load parameter. Both the stress range $\Delta \sigma$ and $\sigma_{\text{max}}$ may be normalized by a reference stress $\sigma_r$ which typically will be a tensile, compressive or a shear strength. A normalized maximum stress may then be expressed by:

$$f_{\text{max}} = \frac{\sigma_{\text{max}}}{\sigma_r} = \frac{\Delta \sigma}{(1 - R)} \frac{1}{\sigma_r}$$

To evaluate the fatigue strength of dowel joints in wooden members the normalised stress range $\Delta f = \Delta \sigma/\sigma_r$ or normalized maximum stress $f_{\text{max}}$ in possibly combinations with the stress ratio $R$ have been used herein. The fatigue design verification then may read:

$$\Delta \sigma = \Delta f \sigma_r \leq f_{\text{fat,d}} \quad \text{or} \quad \sigma_{\text{max}} = f_{\text{max}} \sigma_r \leq f_{\text{fat,d}}$$

where $f_{\text{fat,d}}$ is the design fatigue strength relating the fatigue strength to the number of cycles $N$, for given joints lay-outs and mechanical fasteners.
3. Fatigue Testing of Dowel Joints

Evenstad bridge [1], which is used as a model for the joints considered, has five equal spans, each with a span width of 36 meters. Each span consists of timber truss with a curved upper cord. Depending on the ratio of dead weight relative to the traffic magnitude and location of the loading, the axial force in the member will vary between tension and compression. In order to limit the scale effects and to reproduce test conditions similar to that of a prototype, it was decided to use large-scale specimen of a splice type connection with geometry resembling that of Evenstad Bridge. The tests were done with uniaxial loading.

The material used was Nordic pine (Pinus silvestris), and all specimen were produced from a single batch of machine graded timber C30 (MT30) with a characteristic bending strength of 30 MPa. The member length was 1680 mm, and the cross-section width and thickness were 200 mm and 140 mm respectively. The connections had two gusset plates and 12 dowels, see picture on Figure 1 and the drawing on Figure 2. This specimen design allowed two connections to be fatigue tested simultaneously. Dowels and holes with diameters 12 mm and 12.5 mm respectively were used. The spacing of the dowels parallel to the grain was 100 mm, and the distance to the free end was 120 mm. In the direction normal to the grain the spacing was 100 mm and the edge distance was 50 mm. The thickness of the outer wood layers were 31 mm while the middle layer was 60 mm. Note that the length of the dowels was 120 mm, which is less than the 140 mm thickness of the specimen. The dowel connection was designed such that the static strength was limited by the embedding strength of the timber, without yielding in the dowels. The material properties of the dowels were not determined, but based on previous tests yield stress was estimated to exceed 600 MPa, with a ultimate stress $f_u$ of about 750 MPa. The test specimens were preconditioned at 65 % RH and 20°C (12% moisture), and in the test laboratory the temperature was kept constant at 20°C and the humidity was controlled. To study the importance of the stress ratio $R$ on the fatigue strength, the tests were performed with two stress ratios, $R = -1$ and 0.1.

The most likely stress ratio for the connections of the truss members in bridges of the Evenstad type would be $R > 0$, as load reversals would be rather unlikely. However, it was considered that a stress ratio of $R = -1$ would be the most extreme situation, and hence it was included. The tests were conducted at the Norwegian University of Science and Technology, NTNU. The tests were performed with a load frequency ranging from 0.5-4.0 Hz. The loading frequency may be of importance in timber structures [5], as it may govern the temperature history and moisture content during the tests.

Specimen with installed gusset plates and dowels is shown in Figure 2. A view of the test specimen after installation in the test frame is given in Figure 1. Traditional test frames and hydraulic actuators were used.
3.1. Load parameters.

The static reference values were determined from three specimens randomly drawn from the batch. The static tests gave a mean connection resistance $F_r = 410$ kN. The fatigue test results are given in terms of the associated numbers of cycles to failure $N$ (log scale) versus normalised stress ranges $\Delta f$ or maximum stress $f_{max}$ with respect to $F_r$. The load parameters were determined by

$$\Delta f = (F_{max} - F_{min}) / F_r$$

where $F_{max}$ and $F_{min}$ are the maximum and minimum loads, and the stress ratio $R$ given by

$$R = \frac{F_{min}}{F_{max}}$$

and the relation to the normalised maximum stress is

$$f_{max} = \frac{F_{max}}{F_r} = \frac{\Delta f}{1 - R}$$

The fatigue loading conditions and results are described in more detail in [11], [12] and [13].

3.2. Cycles to failure

The results from 48 tests on dowel connections are plotted for $R = 0.1$ in Figure 3, and for $R = -1$ in Figure 4, where the normalised stress ranges $\Delta f$ is used as parameter. The same results are also plotted in Figure 5 and Figure 6, but here the normalised maximum stress $f_{max}$ has been used as load parameter in addition to stress ratio $R$. The static reference tests have been regarded as a quarter cycle load with a very low load frequency.

![Figure 3 Stress range vs. cycles to failure.](image1)
![Figure 4 Stress range vs. cycles to failure.](image2)

In some of the specimens damage and failure developed very similar in both ends and it was not possible to determine the order of the connection failures. In other cases the specimen was too damaged to be strengthened such that the remaining end connection could be tested further. The number of cycles to failure in those cases was set equal for the two connections. In a number of cases the fractured connection was removed and replaced by a new strengthened connection,
making it possible to cycle the other connection to failure. A small number of the connections failed due to fatigue in the steel gusset plates, followed by damage to the timber. Note that the tests corresponding to the smallest $\Delta f$ or $f_{\text{max}}$ were terminated without failure due to limited equipment availability (Fatigue testing at low frequencies is time consuming!). Hence, using all the data in an estimation of fatigue strength will give results on the safe side, since not all specimens actually have failed due to timber fatigue at the number of cycles given. See reference [13] for further details. However, in view of the very few test results available at present, it seems reasonable to use all the acquired information.

![Figure 5](image1.png)  
**Figure 5** Maximum stress vs. cycles to failure.  

![Figure 6](image2.png)  
**Figure 6** Maximum stress vs. cycles to failure.

4. Discussion

Based on the literature [9] and various proposals for design rules for dowel connections, the choice of fatigue strength parameters most appropriate for design is not obvious. The issues addressed here are the shape of the fatigue strength curves, the significance of the stress ratio $R$ and the choice of strength parameter $\Delta f$ or $f_{\text{max}}$.

The stress range $\Delta f$ and the maximum applied stress $f_{\text{max}}$ are plotted as functions of the log cycles to failure (log N) in Figure 3 to Figure 6. The experimentally obtained number of cycles to failure, $N$, for high values of $\Delta f$ or $f_{\text{max}}$ do not support any assumptions of keeping the fatigue strength unaffected of $N$ up to a given number, for example $10^4$ cycles. In fact, the fatigue strength of the timber connections starts to degrade after very few cycles. Furthermore it has been supposed that there is a fatigue limit at a given level of stresses, leading to the assumption that no fatigue will take place for stresses below that limit. Based on the present results for dowel joints no conclusion can be made. However, if such a fatigue limit exists, it will probably be below normalized stress level of 0.25 and only of interest for larger number of cycles than $10^7$. This implies that for many bridges a fatigue limit will be irrelevant. The experimental results, irrespective of using $\Delta f$ or $f_{\text{max}}$ as strength parameter, give few arguments for a more complicated strength function than a linear dependency of $\log N$. Note that this format is different from the Log-Log format used for fatigue of metal structures. For further discussions, a best fit of a straight line determined by the method of least squares have been added to the plots of the experimental results. The acquired data points have been fitted to the linear equation

$$\bar{f} = A \log N + B$$ [7]
with the restriction that the static value \( \log N = -0.6 \) should equal unity. The obtained constants are listed in Table 1. Here, \( f \) is the experimentally determined strength parameter, either \( f_{\text{max}} \) or \( \Delta f \), while \( \bar{f} \) is the corresponding quantity calculated by Eq. [7]. The normalised residual \( r \), in addition to the maximum deviations \( d \) between experimental and calculated strength, may serve as a measure of the goodness of the fit. The computations read:

\[
r = \sqrt{\frac{\sum (f - \bar{f})^2}{n}} \quad \text{and} \quad d = \sqrt{\max(f - \bar{f})^2}
\]

Table 1 Resulting parameters to Eqs. [7] - [8].

<table>
<thead>
<tr>
<th>( f )</th>
<th>( R )</th>
<th>( A )</th>
<th>( B )</th>
<th>( r )</th>
<th>( D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{max}} )</td>
<td>0.1 &amp; -1</td>
<td>-0.072</td>
<td>0.956</td>
<td>0.093</td>
<td>0.223</td>
</tr>
<tr>
<td>( \Delta f )</td>
<td>0.1 &amp; -1</td>
<td>-0.070</td>
<td>0.958</td>
<td>0.083</td>
<td>0.208</td>
</tr>
<tr>
<td>( f_{\text{max}} )</td>
<td>0.1</td>
<td>-0.066</td>
<td>0.960</td>
<td>0.059</td>
<td>0.126</td>
</tr>
<tr>
<td>( \Delta f )</td>
<td>0.1</td>
<td>-0.074</td>
<td>0.955</td>
<td>0.046</td>
<td>0.131</td>
</tr>
<tr>
<td>( f_{\text{max}} )</td>
<td>-1</td>
<td>-0.098</td>
<td>0.941</td>
<td>0.038</td>
<td>0.071</td>
</tr>
<tr>
<td>( \Delta f )</td>
<td>-1</td>
<td>-0.048</td>
<td>0.971</td>
<td>0.078</td>
<td>0.147</td>
</tr>
</tbody>
</table>

The fatigue data have been plotted separately for the two \( R \)-values in order to assess the effect of the stress ratio \( R \) on the number of cycles to failure. Besides the static data, we have only seven data points for \( R = -1 \), which cannot be considered to be sufficient for any clear conclusions. In Table 1 the two first lines contain results from computations according to Eqs. [7] - [8] without making any distinction between the stress ratios \( R \). Comparing these two first lines with the other lines where the two different stress ratios \( R \) are accounted for, we can see that the goodness of fit (parameters \( r \) and \( d \)) is much better when stress ratio is taken into account. This is independent of the choice of stress parameter, \( f_{\text{max}} \) or \( \Delta f \). Comparing to the results obtained for \( R = 0.1 \), Figure 3 and Figure 5, with the plots for \( R = -1 \), Figure 4 and Figure 6, it is seen that the slopes (\( A \) in Table 1) of the fitted lines differ considerably. It is therefore apparent that the stress ratio \( R \) should be included in fatigue design of dowel joints in timber structures.

In this investigation both \( \Delta f \) and \( f_{\text{max}} \) have been used as alternative strength parameters. By comparison of Figure 3 and Figure 5, no significant differences may be observed with respect to the representation and goodness of the fits. Note that there is only 10% difference between the two stress measures \( f_{\text{max}} \) or \( \Delta f \) for \( R = 0.1 \). However, considering \( R = -1 \) only, see Figure 4 and Figure 6, \( f_{\text{max}} \) should be the preferred strength parameter. For this case the calculated results for \( r \) and \( d \) in Table 1 give for \( f_{\text{max}} \) only half of the values obtained for \( \Delta f \). Therefore, the choice between the strength parameters \( \Delta f \) and \( f_{\text{max}} \) seems to be irrelevant for \( R = 0.1 \), but might be important for alternating loading e.g. \( R = -1 \). In that case, the use of \( f_{\text{max}} \) gives a better representation of the fatigue strength. It seems to be no physical reasons to prefer \( \Delta f \) instead of \( f_{\text{max}} \) as the strength parameter. However, this conclusion is made on the basis of very few available experimental results and more experiments should hence be conducted.

4.1. Eurocode 5 Fatigue Verification

Based on the experimental results, included those reported herein, a linear dependency of \( \log N \) similar to Eq. [7] has been proposed as basis for fatigue design in Eurocode 5 [14], where bridges in particular are covered in Part 2 [15].
Using the notations in Eurocode 5, the expressions for the fatigue design verification are:

\[ \sigma_{d,max} \leq f_{\text{fat},d} \quad \text{and} \quad f_{\text{fat},d} = \frac{k_{\text{fat}} f_k}{\gamma_{M,\text{fat}}} \quad [9] \]

\( f_{\text{fat},d} \) relates the fatigue strength to the corresponding characteristic static strength \( f_k \cdot \gamma_{M,\text{fat}} \) is the partial safety factor for material properties in fatigue and equals 1.0. The fatigue strength can then be given by a fatigue strength ratio \( k_{\text{fat}} \), which depends on the stress ratio \( R \) and the number of cycles \( N \). \( k_{\text{fat}} \) can be directly compared to the term \( f_{\text{max}} \) used herein, and it is calculated by

\[ k_{\text{fat}} = 1 - \frac{\log N}{a(b - R)} \quad [10] \]

For dowels connections the parameters are \( a = 6 \) and \( b = 2 \). These parameters correspond, in Eq. [7], to the slopes \( A = -0.0789 \) and \( A = -0.1111 \) for \( R = 0.1 \) and \( R = -1 \) respectively, see Table 1 for comparison with the experimental results. In Figure 7 and Figure 8, Eq. [10] has been plotted together with the present fatigue results. Note that \( k_{\text{fat}} \) and \( f_{\text{max}} \) are a dimensionless parameters which relates the fatigue strength to the static strength. The design considerations in Eurocode 5 are a combination of the parameters \( a \) and \( b \) and the use of characteristic static strength \( f_k \). The effect of moisture variation is not present in the test results. It is well known that higher moisture contents and variations in moisture can lower the strength considerably. Eurocode 5 does not seem to account for this effect, which probably should be done in the future.

![Figure 7](image1.png) Maximum stress vs. cycles to failure, \( R = 0.1 \), EC5 compared to test results.

![Figure 8](image2.png) Maximum stress vs. cycles to failure, \( R = -1 \), EC5 compared to test results.

5. Concluding Remarks and Acknowledgements

The static and fatigue strength of a dowel connection for a glulam timber member have been tested. The results from six static component tests and 42 fatigue-tested connections have been presented. The following concluding remarks are made:

- Fatigue damage and failure may occur in timber structures with dowel connections when subjected to fatigue loading.
- The fatigue strength depends on the stress ratio, which is the ratio between the minimum and maximum stress.
- The fatigue strength can be considered to be a linear decaying function of the logarithm of the number of cycles.
• Use of maximum stress as fatigue strength parameter seems to be more reasonable than use of the stress range.
• A comparison with the fatigue design verification in Eurocode 5 has been made.

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6. References


