WCTE 2014 Quebec City Canada August 10-14
World Conference on Timber Engineering

LOAD CARRYING CAPACITY OF LARGE MORTISE AND TENON JOINTS IN WOODEN MITRE GATES

Jan-Willem van de Kuilen[1,2], Jorick van Otterloo[1], Geert Ravenshorst[1], Peter de Vries[1]

ABSTRACT: Wooden mitre gates are used for centuries in waterways and canals. For newly built as well as the renewal of such gates, a number of wood species is used, ranging from oak to dense tropical hardwoods. As mitre gates have high loads to withstand, their strength verification has become more and more important. As strength verification rules for the complex mortise and tenon joints are lacking in most design codes, a research project has been performed to understand better the stress flow in these connections. A literature survey, an analytical analysis and a FEM analysis have been performed within this research project. The results allow for a much better understanding of the stress flow and of the resistance of these joint types.

KEYWORDS: Mortise and tenon joints, Mitre gates, FEM Modelling, Notches, Eurocode 5.

1 INTRODUCTION

Lock gates are an essential part in many waterways in Europe and North-America. Originally the mitre gates were made of wood species like oak or elm, treated for durability with tar. During the last century such doors have been increasingly made from azobé (*Lophira alata*), a heavy tropical hardwood, with high natural durability and well known mechanical properties [1]. The species is assigned to strength class D70 of European standard EN 338 Strength classes [2]. The mitre gates are still built with real craftsmanship and according to traditional designs that have been perfected during hundreds of years.

A picture of a mitre gate in a dry lock is shown in figure 1. In this case, wood species azobé has been used, but other species such as cumaru may also be chosen. Timber sizes in such an application are around 350 x 350 mm.

Construction companies are recently obliged by building authorities to prove that the structure satisfies safety standards on e.g. strength more extensively than in former times. However, construction companies are not able to prove whether the mortise and tenon joint between the crossbeams and posts in such a wooden mitre gate satisfies strength requirements [3],[4]. Experience from practice however indicates that damage in relation with these connections is practically unknown.

[1] Jan-Willem van de Kuilen, Delft University of Technology, Delft, The Netherlands, j.w.g.vandekuilen@tudelft.nl
[2] TU Munich. Email: vandekuilen@hfm.tum.de

The main goal of this research is to obtain a valid and sensible method for the strength analysis and verification of the mortise and tenon joint in a mitre gate made of hardwoods. Therefor it is important to figure out how the internal forces and stresses are distributed and how this connection can satisfy the requirements from standards and codes. In addition, the question is raised whether any modifications to design rules are necessary when hardwoods are used in these kinds of ´notched´ connections. The research has been partly performed as a master thesis project at Delft University of Technology [12].

Figure 1: *Wooden mitre gate during maintenance*

2 STRUCTURAL ANALYSIS

2.1 MITRE GATES

A mitre gate has main beams with tenon and mortise joints on both sides. The tenons are fixed in the mortise using wooden dowels, often made of wood species demerara greenheart. A top view of a mitre gate mechanical system and the left and right details are shown in Figure 2, with the water pressure as a distributed load on the cross beam. The system is symmetrical so the loads are transferred by compression and bending in the cross beam to the foundation on the left side. On the right side there is the symmetry axis or the centre line of the lock.

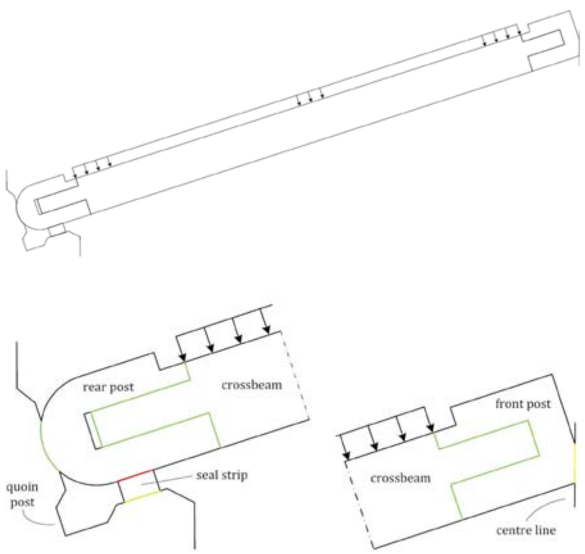

Figure 2: *Mechanical system (top view) and details of a mitre gate*

The principle of the connection is shown in Figure 3. Calculations common in practice assume a simple force distribution. However, the specific geometry of the joint including the specific supports and the combined loading in compression parallel, compression perpendicular, shear and bending makes the stress situation in the joint very complex. In fact, the joint is a highly complex detail that requires great skills to produce.
A literature survey has been performed for the analysis of the tenon, as here typical tensile stresses perpendicular to the grain are expected when the crossbeam is loaded in bending. A fracture energy approach has been used by [5][6],[7].

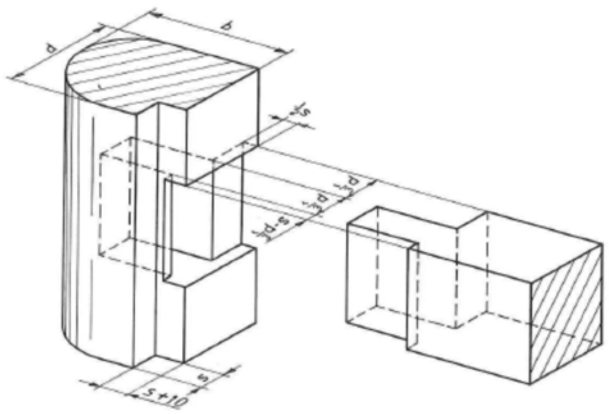

Figure 3: *3D exploded view of a mortise and tenon joint*

2.2 CONNECTION CONFIGURATION

In a connection of a lock gate, building authorities expect a strength verification using the following unity check as given by Eurocode 5:

$$\tau_d = \frac{1.5V_d}{bh_{ef}} \leq k_v f_{v,d} \tag{1}$$

where

$$k_v = \frac{k_n\left(1+\frac{1.1i^{1.5}}{\sqrt{h}}\right)}{\sqrt{h}\left(\sqrt{\alpha(1-\alpha)}+0.8\frac{x}{h}\sqrt{\frac{1}{\alpha}-\alpha^2}\right)} \tag{2}$$

The value of k_n depends on the wood product, for sawn wood is has the value of 5 and $\alpha=h_{ef}/h$.
For the other parameters reference is made to figure 4, taken from Eurocode 5, 2005.

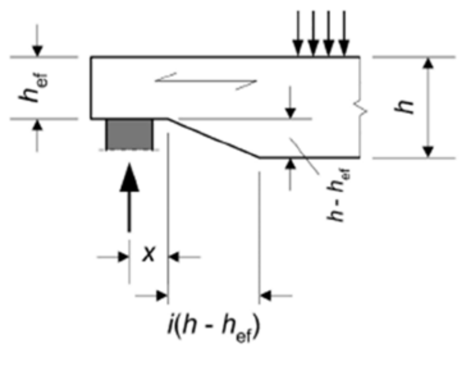

Figure 4: *Notched beam approach of Eurocode 5.*

The verification of a tenon or notch is therefore done by performing a shear stress check, although the real failure mechanism is splitting. This is done for simplifying the necessary calculation for the engineer in practice. Therefore the factor k_n was calibrated, as reported in [7} with tests on softwood.

The problem with this equation is that when it is applied on the joint of figure 3, the unity check is never satisfied for the high water pressure working on the outer side of the mitre gate. An exploded view of the joint is given in figure 5.

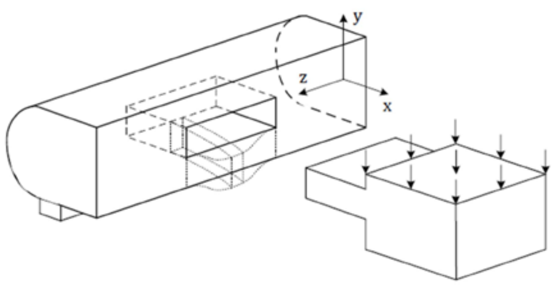

Figure 5: *Exploded view of the mortise and tenon joint with support action in the z-axis.*

It should be noted that the wood fibre direction is in the z-direction for the element on the left and in the x-direction for the element on the right.

Apart from the fact that the tenon is not adequately represented by equation (1) and (2), the shear strength values for hardwoods are not well established. European test standard EN 408 requires gluing of steel strips on wooden specimens before the shear test can be performed. This is however not possible for dense hardwoods. The shear strength depends heavily on the load case and the stress situation. In the European strength class standard EN 338 [2, 2010], a shear strength value of 5 MPa is specified, down from 6 MPa in the 2003 version. For the shear strength of azobé in beams, a characteristic strength value of 14.2 MPa was reported in [1]. Such a difference has a clear consequence for the outcome of equation (1).

2.3 EXPERIMENTAL RESEARCH

As current design equations in Eurocode 5 for notched beams are based on tests on spruce, it is uncertain whether these rules are also valid for other species, especially dense hardwoods. Therefore, an experimental program was setup, in order to obtain more information on the fracture energy for hardwoods. A number of azobé beams were tested as shown in Figure 6. The beams have been conditioned at 20°C and 85% RH. Normally, conditioning should take place at 65%, but for dense tropical hardwoods this is very difficult to realise. First of all, it takes a long time to condition, but there is also a risk of introducing drying cracks. In addition, the application of azobé is in outdoor situations, in lock gates most of the time (partly) under water.

Different configurations have been tested, with the tenon located in the centre of the specimen, but also with the tenon placed slightly more to the compression side of the beam. Also tapered notches have been analysed for comparative analysis, but these results are not included here.

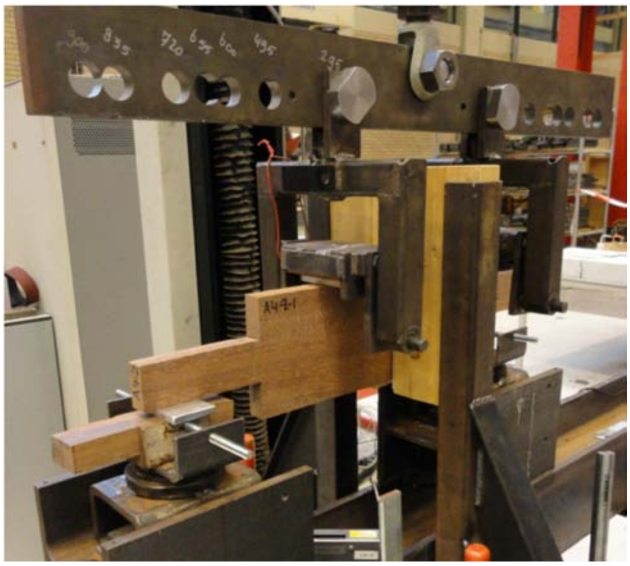

Figure 6: *Test on a tenon*

2.4 FEM MODEL

Using finite element modelling the force and stress distribution is analysed in detail using a 2D FE-model. The model is based on a ´true´mitre gate, spanning 3 meters, having a closing angle of 30° and a distributed load of 32.5 kN/m´. The size of the rear post is taken having a 300 mm thickness (direction perpendicular to plane of gate) and 450 mm width. The length of the rear tenon is 300 mm or equivalent to 2/3 of the width.

The transfer of the force from the tenon into the post is not directly located above the support (the seal strip) of the post. As a result a 3D effect will occur, whereby the load will be redistributed in the post as drawn in figure 5. The 3D effect identified in Figure 5 is taken into account by adding an elastic support to the lower part of the post. A similar effect will take place at the upper side of the tenon, but this has not been modelled. The FEM model is used to determine the force flow and the stresses near the supports and around the mortise and tenon.

Commercial software Abaqus is used for all modelling processes. Three stages have been identified:

- Pre-processing/modelling: Abaqus CAE is used to create the model which includes among other things the geometry, material properties and the mesh.
- Processing/finite element analysis: Abacus Standard is used to solve the numerical problem. Its output is stored in an output file and contains displacements, stresses, etc.
- Post-processing: Abaqus Viewer is used to display the results in various ways to evaluate the results.

The finite element (FE) model build for this research is characterized by:

- Linear elastic material within 2 dimensions;
- Characteristics of the mitre gate's parts: solid, homogeneous and deformable, where the plane strain assumption is applied;
- The boundary parts are characterised as analytical rigid wires;
- The lower part of the rear post is supported by an elastic support to take account for 3D load transfer;
- Orthotropic material behaviour is assumed where the different fibre directions of the mitre gate's parts are taken into account;
- Calculation steps are of the general static type:
- Equations are solved directly;
- The Full Newton solution technique is used;
- Interaction properties at contact surfaces are characterised by
  - interaction by surface-to-surface contact;
  - normal behaviour by "hard" contact, where separation is allowed;
  - friction is defined by isotropic Coulomb friction;
- Definition of the mesh:
  - Different elements of the mitre gate are meshed separately;
  - The element type used is a 4 node bilinear plane strain quadrilateral. Reduced integration and enhanced hourglass control are applied.

The material parameters used are:
E_0 = 20.000 MPa [2]
E_{90} = 1330 MPa [2]
G_{mean} = 1250 MPa[2]
G_{roll} = 91 MPa [9]
υ_{LR} = 0.35 [10]
υ_{RT} = 0.60 [10]

The Poisson ratio violates the assumption for orthotropic materials, but this is accepted for the stress situation under study here. For friction a value of 0.2 is assumed.

3 RESULTS

3.1 EXPERIMENTAL RESULTS

The results of the tests on the tenons show that there is a clear influence of the wood species when comparing spruce and azobé. Even though the tests have been performed on relatively small specimens compared to real mitre gates (but not on small clears) an equivalent shear stress ratio of tenon specimens is found to be 2.67 that azobé is stronger than spruce [11]. Comparing notched specimens (as intended in EC5 and eq- (1) and (2)) a ratio of 4 is found. This means that the unity check of equation (1) can be modified accordingly.
When tenons are compared to notches an increase in strength is found of approximately 2.1 for spruce and 1.9 for azobé, so about 2. In Figure 7a and b two failed specimens are shown, one with a ´parallel´ to the grain crack and one where the crack follows the wood fibres having a large angle to the beam axis.

Figure 7a and b *Tenon beams and crack patterns parallel to the grain and beam axis* ***(a)*** *and a different crack direction showing the influence of fibre angle* ***(b)***.

The results of these test show that modifications are necessary and possible, in order to use an EC5 approach
A proposal for modification of the Eurocode 5 equations could be the introduction of a modification factor for tenon joints relative to notched joints and a second modification factor to take into account the wood species, for instance using a density ratio factor. The factor of 2.67 indicates the existence such a relationship as the density of azobé is around 1100 kg/m^3.

3.2 NUMERICAL RESULTS

The main advantage of the FEM model is that local stress components can be analysed in detail and that the stress flow in the connection can be better understood. It must be emphasized that around discontinuities stresses calculated with FEM-models cannot be compared one on one with strength values. As the connection transfers high compression stresses the model indicates how much is transferred by contact pressure and how much is transferred by friction. In Figure 8 a contour plot is shown of the S11 stresses and the corresponding principal axes in the model. These are the normal stresses parallel to the 1-axis. For the crossbeam this stress component corresponds to the normal stress along the grain. The maximum stress values range from around +7 MPa (orange) to -9 MPa (Blue). For the rear post and seal strip these stress components correspond to the normal stress perpendicular to the grain.

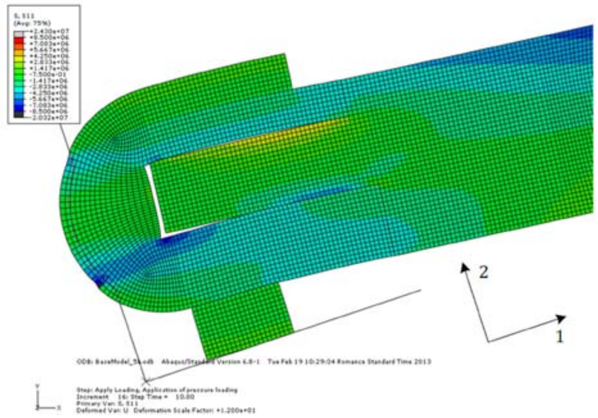

Figure 8 *Contour plot of the stresses S11 for the mortise and tenon joint at the rear post.*

Both compression stresses parallel and perpendicular to the grain in the different parts seem to remain below critical values. The following observations can be made:

- The compression force from the crossbeam is transferred through the upper and lower parts of the rear post to the back of the rear post according about the ratio of sectional surfaces. The two forces are transferred in almost a straight line to the quoin post behind the upper and lower part of the rear post.
- That the compression stresses in the upper and lower part of the rear post are equal to each other can be understood by considering the strains are equal, caused by the relatively stiff crossbeam which deforms the rear post equally.
- A negative bending moment is present in the tenon. The tenon is in fact clamped into the mortise. Apparently, the tenon is relatively long and the traditional expectation that shear deformation is governing is not supported by the numerical result.

In Figure 9 the S22 stresses are shown in a contour plot. The stresses are the normal stresses parallel to the 2-axis. For the crossbeam this stress component corresponds to the normal stress perpendicular to the grain. For the rear post and seal strip (the small rectangle at the bottom) these stress components correspond to the normal stresses perpendicular to the grain as here the grain is in the 3-axis..

- Behind the mortise high tension stresses have developed as the clamped tenon presses upwards on the rear post.
- Due to the large compression force being transferred on a concave surface, at the back of the rear post large compression stresses perpendicular to the grain develop. The compressive stresses are slightly higher than design strength, but taking the confined stress state into account, strength is estimated to be large enough.
- The upper end of the tenon is pressed against the mortise on a small surface. Therefore also relative high stresses develop here.
- A large part of the load is transferred via the elastic support and a smaller part via the seal strip as the spread of normal stress for the first mentioned part is much larger. It is remarkable that the values of the stress at both parts seem to be comparable.
- At the pit of the tenon relatively tension stresses perpendicular to the grain occur.

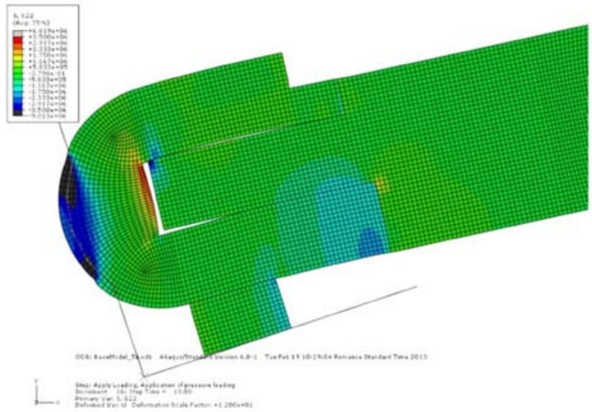

Figure 9 *Contour plot of the stresses S22 for the mortise and tenon joint at the rear post.*

The tension stresses perpendicular to the grain behind the mortise is caused by the upward acting force the tenon exerts. It is however to be expected this tension force reduces when force transfer within 3D geometry is considered as the upward acting force can be transferred to a greater area. As the maximum stress is around 3.5 MPa, it is expected that the load carrying capacity is sufficient when considering the 3D effect. Assuming a similar effect as modelled on the lower side of the mortise (see Figure 4) tension stresses perpendicular to the grain are expected to reach a maximum value of around 1.5 N/mm^2, which does not pose a serious problem for heavy hardwoods..

A third check is made on the shear stresses in the connection and the contour plot is shown in Figure 10.

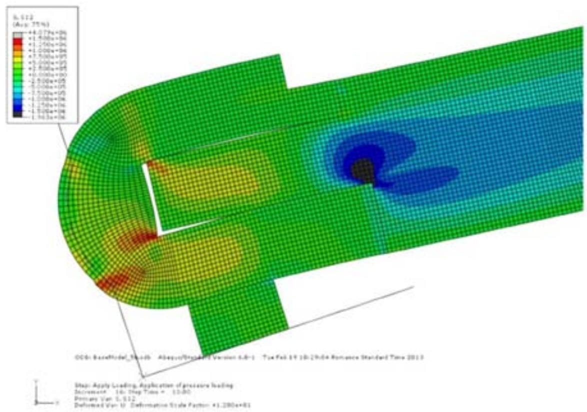

Figure 10: *Contour plot of the shear stresses (S12)*

At the pit of the tenon the highest shear stresses develop as is to be expected from the geometry. For the mitre gate analysed here, the stresses remain relatively low with a peak of around 2 MPa. Shear stresses actually have to occur, as the lower part of the beam is forced to bend along with the upper part of the beam.

The following observations with regard to shear can be made:

- In the tenon it is clearly visible that the shear force changes sign. The line of action of the reaction force on the tenon lies at the point where the shear force is equal to zero. The sign of the shear force also indicates that a negative moment acts in the tenon.
- Due to the transfer of compression forces on a concave shape (see also figure 9), at the lower back side of the rear post, high shear stresses develop.
- As the tenon presses onto the top part of the rear post, shear stresses also develop in the upper part of the rear post.

A sensitivity analysis on the friction coefficient did not show a large influence on the load transfer.
At the same time, the FEM model shows that the traditional approach of a notched beam as presented in Eurocode 5 needs modifications in order to be applicable to mortise and tenon joints such as discussed here.

4 CONCLUSIONS

For a wooden mitre gate manufactured according to traditional design the most important conclusions read:

- The shear force from the crossbeam is transferred to the rear post for the largest part through the tenon. A 3D effect is present in the joint whereby the shear force from the tenon is transferred to the sides of the mortise and is then transferred to the seal strip via the full section of the rear post.

- Due to the 3D effect the line of action of the reaction force on the tenon lies closer to the pit of the tenon than the line of action of the reaction force at the seal strip support does. Therefore a negative moment is present in the rear post which is counteracted by a frictional force at the back of the rear post.

- Appearing stresses throughout the joint satisfy design strength values.
  Based on the test program the tenon strength can be extrapolated to dimensions applied in practice. Comparison of these tenon strength with the force transferred through the tenon calculated with the FEM model can be concluded that the tenon joint in lock gates is capable to meet the strength requirements

- Eurocode 5 design rules are not applicable on tenon joints. The current design rules may be modified by introducing two types of modification factors, one for the strength ratio between tenon joints and notched joints and a second factor to take into account the wood species. On the basis of the test results, this second factor could be around 2.67 or around the ratio of the wood densities, whereas the first factor has a value of around 2, on the basis of the two geometries tested. The current clause in Eurocode 5 should state that it is applicable to softwood.

- For the latter proposal to be introduced in Eurocode 5, additional testing is recommended with medium and dense hardwood species that have less interlocked grain than azobé.

ACKNOWLEDGEMENT

The company Wijma Kampen BV in Kampen, the Netherlands is greatly acknowledged for their support.

REFERENCES

[1] Van de Kuilen, J.W.G. & Blass, H.J. Mechanical properties of azobé (*Lophira alata*), Holz als Roh- und Werkstoff, 2005, 63: 1-10.

[2] EN 338 Structural timber – Strength classes (2003, 2010)

[3] Blass, H. J., & Görlacher, R. (2000). Rolling shear in structural bonded timber elements (pp. 327–337). Stuttgart: Universität Stuttgart.

[4] Ehlbeck, J., & Kromer, M. (1995). Carpentry joints. Timber Engineering STEP 1 (pp. C12/15 - C12/17). Almere: Centrum Hout.

[5] Gustafsson, P. J. (1988). A study of strength of notched beams. CIB-W18 Timber Structures, Paper 21-10-1, Vancouver Island, Canada.

[6] Larsen, H. J., Gustafsson, P. J. (1990). The fracture energy of wood in tension perpendicular to the grain. CIB-W18 Timber Structures Paper 23-19-2, Lisbon, Portugal.

[7] Larsen, H. J., & Gustafsson, P. J. (1992). Annex to paper CIB-W18/25-102-1. Eurocode 5 - Design of notched beams. CIB-W18 Timber Structures, Åhus, Sweden.

[8] EN 408 Structural timber – Test methods

[9] Sandhaas, C. Mechanical behavior of timber joints with slotted-in steel plates. Ph.D. Thesis. Technische Universiteit Delft. ISBN 978-90-8570-837- www.library.tudelft.nl.

[10] Wood Handbook, Forest Products Laboratory, Madison, Wisconsin.

[11] Vermeij, D. A. A. N. De pen-gat verbinding in houten sluisdeuren: een onderzoek naar de bruikbaarheid van de rekenregels voor nokken uit de eurocode. BSc Thesis, TU Delft, NL (in Dutch).

[12] Van Otterloo, J. Force distribution and connection strength in timber lock gates. MSc Thesis, TU Delft, NL.