SUGGESTIONS FOR IMPROVEMENTS IN TIMBER PORTAL FRAME DESIGN WITH SEMI-RIGID KNEE JOINTS

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Timber portal frames assembled on the construction site are the most suitable solution from the point of view of limitations of transportation options. However, the connections of the rafters and columns assembled at the construction site in the knee joints, using bolts, show a certain tendency to show plastic deformations under load. In addition, the transmitted shear forces at the knee joint form different angles with the fiber direction in the rafter and column elements. Service experience of timber portal frames shows that the vertical displacement of the apex point increases, also cracks appear in the rafter elements near the knee joints over time. Unfortunately, code design formats do not present specifications for timber structures incorporating L-shape joints with mechanical fasteners. This article presents the results of studies that confirm the need to supplement the design rules for wooden portal frames. It is recommended to implement the rotational spring constant when define rigidity of L-shape joints for RFEM model of structure. The Hoffman failure criterion has been chosen as the most appropriate of the known ones for evaluating the crack resistance of structural wooden elements, because this criterion includes more important specific properties affecting the development of plastic deformations and the formation of cracks in wood.

Keywords: Modeling of connections, Rotational stiffness, Creep, Tension perpendicular to the grain direction, Strength criterion for wood, Rotational stiffness modulus.

1 INTRODUCTION

A wooden portal frame is the best choice if the building requires additional space under the load-bearing structure, such as industrial buildings, sports halls and warehouses. Due to transport limitations of prefabricated units to construction site there are used semi-rigid connection with mechanical fasteners in the knee instead of fully rigid glued finger joints. Experience accumulated in the construction industry shows that for wooden portal frames with semi-rigid knee points, the horizontal displacements in the knee nodes and the vertical displacement at the apex point constantly increase depending on service loads and rotational movement. According to building codes, the moment capacity of the knee joint is usually designed basing on a simplified assumption of static balance, i.e., the sum of the reactive moments caused by the shear forces transmitted by the bolts about the geometric center of the connection must balance the moment caused by external forces in the knee section, see Figure 1. Real behavior of connection is more complicated due to non-linear embedment deformation of wood in bolt holes. Despite of known theory on elastic behavior of orthotropic materials (Bodig and Jayne 1993), as well as taking into account wood plasticity in low stages of loading and high localized stress...
concentrations around fasteners it is difficult to create a general analytical model for code applications.

![Figure 1. Timber portal frame with mechanical fasteners in a knee joint: illustration for variation of angle between shear force and grain direction.](image)

Wood is anisotropic material, it is important that angles between shear force and grain direction in rafter and column members change from zero to 90 degrees from bolt to bolt around the circle, more over these angles differ in middle and side members of the same fastener. It is thorough research done basing on beam-on-elastic foundation theory and it is found more adequate mathematical model for prediction of stiffness properties of bolted L-shape connections (Wang et al. 2021).

The rafter section near the knee joint is heavy loaded in bending, promoting both normal and tangential stresses, as well as tensile stresses perpendicular to the grain direction arise due to concentrated shear forces action transferred by the individual bolts. It has been observed that after several decades in service, cracks appear in the elements of portal frames, including the middle part of the rafter members made of glue laminated timber. That suggests that more comprehensive design assumptions are needed for safe and sustainable solutions of these connections than stated by codes now.

Modern software based on Finite Element Method enable to simulate stress-strain development of such complicated system as anisotropic viscoelastic wood material in conjunction with elastic steel dowels. It is proved by researchers the profit of finite element modelling takes into account both material properties in relevant directions and mechanical contact exposures in connections (Xu et al. 2008).

The design conditions provided in Eurocode 5 (2004) are not sufficient to predict the effect of plastic deformations of semi-rigid joints on the global deformations of the structure.

In this current study some aspects related to specifics of portal frame behavior are discussed, such as reduction of stiffness of L-shape bolted timber connections and splitting capacity of wood of rafter sections under combined loading, as well as wood tension strength perpendicular to the grain direction at the end sections of members beyond bolts.

2 STIFFNESS PROPERTIES OF L-SHAPE BOLTED CONNECTION

Development of rotational deformation of L-shape moment connections appears more intensively than predicted by conventional design rules. It is phenomenon of natural wood materials that effects of stiffness anisotropy differ essentially from those characterized the strength anisotropy. In the simplest way this phenomenon is demonstrated by ratio between wood characteristic
compression strength at longitudinal and cross grain loading. For example, longitudinal and cross grain embedment strength values predicted for bolt shear capacity calculations varies in the range of $f_{h,0,k}/f_{h,90,k}= 1.47 - 1.71$ for diameters 8-24 mm, but ratio of modulus of elasticity values is $E_{0,05}/E_{90,05}= 11600/2500=4.6$. This phenomenon causes unexpected deformations in L-shaped joints, where the angle between the shear force and the fiber direction changes depending on the location of the bolt on the circle line, and the specified angle differs significantly in the rafter and column elements. It is underlined by researchers that it is important for L-shape connections to control stiffness in design (Shu et al. 2019).

L-shape test model was defined for experimental and numerical test with purpose to study stiffness reduction effects. A total of eight spruce wood models were made, half of them - with strength class C20, half - from C30, see Figure 2. Models were tested by universal testing machine INSTRON following the loading procedure according to EN 26891:1991 and adopting the maximum value $F_{\text{max}}=1.15 \text{ kN}$ equal to design shear force capacity.

![Figure 2. L-shape model for simulation of bolted knee joint behavior.](image)

![Figure 3. Rigid, semi-rigid RFEM models and experimental test setup.](image)
The test results of the L-shaped model obtained in this study, as well as the results of previous long-term tests, prove the need to define the initial rotational stiffness (or spring constant) $K_y$, the value of which can be determined as the ratio of the design moment to the angle of rotation in radians, determined on the basis of the assumption that the bolts placed in an external circle can move by $(1+\Delta)$ millimeters in the tangent direction producing much more displacement in apex point, see Figure 3. Displacement component 1 mm may develop due to tolerance in bolt hole, but component $\Delta$ develops due to embedment and depends on the loading level and the angle between force and fiber directions. Both results of experiment and numerical test by RFEM show the similar results. The slip value under design load is $\Delta=0.33$-$0.42$ mm. Both the numerical and experimental test results include some uncertainty in the borehole tolerance, which varies between 0.7 and 1 mm in the experimental models, but is not taken into account at all in the RFEM model. It is preferred to stay in the range of $\Delta \leq 1$ for design purposes in any case, but no more than calculated $\Delta$ value corresponding to an allowable displacement of apex point.

3 SPLITTING CAPACITY PROBLEM IN COMBINED LOADING

As a result of serious research work (Bouchaïr et al. 2007) it was recognized that the use of expected embedment deformation as the only criteria for predicting the capacity of bolts may lead to an unsafe solution. Due to the lack of knowledge about the effects of damage resulting from the adverse interaction between shear and tensile stresses in different angles to the fiber direction. The constitutive law incorporating the hill yield criterion (Xu et al. 2015) serves reasonably well while representing damage evolution in timber members as the modulus of elasticity decreases. The parameter study conducted by the research group (Hochreiner et al. 2016) proved that the distribution of stresses in anisotropic wood material around the joint area is significantly dependent on the boundary conditions, the geometric arrangement of fasteners and the mechanical properties of the dowels. In general, ductility in joint behavior is preferably justified as a benefit due to failure modes demonstrated by large deformations as well as stress redistribution in the cross-sections of members in the joint area (Jorissen and Fragiacommo 2011).

In this study obtained illustrations for distribution of normal stresses in orthotropic surfaces are shown in Figure 4.

![Figure 4. Illustration for principal stress distribution in orthotropic members.](image-url)
The Hoffman failure criterion (Xu et al. 2015) is treated in this study for examination of wood strength and failure capacity in multiaxial loading. This criterion (see Eq. (1)) allows to take into account the different tensile and compressive strength properties of wood, it also includes the effect of plastic behavior of the material in combination with the formation of cracks.

\[
C_1 (\sigma_y - \sigma_z)^2 + C_2 (\sigma_z - \sigma_x)^2 + C_3 (\sigma_x - \sigma_y)^2 + C_4 \sigma_z + C_5 \sigma_x + C_6 z + C_7 \tau_{yz}^2 + C_8 \tau_{xz}^2 + C_9 \tau_{xy}^2 = 1
\]

where constants \(C_1\) to \(C_9\) represent the resistance side:

\[
C_1 = \frac{1}{f_{t,0} f_{c,0}} - \frac{1}{2 f_{t,0} f_{c,0}}; C_2 = C_3 = \frac{1}{2 f_{t,0} f_{c,0}}; C_4 = \frac{1}{f_{c,90}} - \frac{1}{f_{c,0}}; C_5 = C_6 = \frac{1}{f_{c,90}} - \frac{1}{f_{c,0}}; C_7 = C_8 = C_9 = \frac{1}{f_v^2}
\]

where \(f_{t,0}\) and \(f_{c,0}\) are the strength values of wood in the direction of the grain in tension and compression correspondingly; \(f_{c,90}\) and \(f_{c,0}\) are wood strength values perpendicular to the grain direction in compression and tension correspondingly, and \(f_v\) is wood strength in shear. The glulam used corresponds to the strength class Gl28h according to EN 14080:2013, and the characteristic strength values are: \(f_{t,0}=22.3\) MPa, \(f_{c,0}=0.5\) MPa, \(f_{c,90}=28\) MPa, \(f_{c,90}=2.5\), \(f_v=3.5\) MPa.

For example, if the normal stresses \(\sigma_x\) acting in the fiber direction account for 75% of the load-bearing capacity, at the same time only about 24% of the shear capacity and only 40% of the tensile capacity perpendicular to the fiber direction can safely be used (see Figure 5).

4 RESULTS

Some of the most important results of this study are summarized in Table 1.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Simplified design</th>
<th>RFEM model</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical displacement of apex point, mm</td>
<td>1.02</td>
<td>3.83*</td>
<td>12.3**</td>
</tr>
<tr>
<td>(\sum M_{\text{Rx}}/\sum M_{\text{Rx,0}})</td>
<td>(r_{ex}/r_{ex}=2)</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Maximum principal stresses (\sigma_1), MPa</td>
<td>Unknown</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>Maximum principal stresses (\sigma_2), MPa</td>
<td>Unknown</td>
<td>6.5</td>
<td>-</td>
</tr>
</tbody>
</table>

* excluding borehole tolerance; ** including borehole tolerance
5 CONCLUSIONS

On the bases of numerical modelling and experimental tests it is concluded:

- It is adequate RFEM model found for stress-strain development analysis in system constituted of orthotropic surfaces (timber members) and mechanical fasteners (dowels) representing embedment pressure actions on hole surfaces by fictive beam type members.
- The rotational stiffness parameter of the semi-rigid timber connection can be determined as the ratio between the design moment capacity and the permissible rotation value in radians, which is determined correspondingly to the permissible linear displacement at the apex point of the L-shaped model or, respectively, at the ridge point of the wooden portal frame.
- Based on the results of this and previous studies, it can be concluded that the set of design conditions for wooden structural elements heavily loaded in bending and shear, such as portal frame rafter members, should be supplemented with particular requirements to avoid the crack formation.
- It is suggested the best choice between wood failure criterions listed according different research results, such as Hoffman criterion, applicable for the examination of failure capacity of structural timber elements since this criterion incorporates the most important expressions of mechanical behavior of wood material.
- It is recommended to reduce the load level, i.e., not to use the full structural design capacity of the dowel-type fastener, if the shear force transmitted by them causes tensile stresses perpendicular to the grain direction in the connected wooden elements.

References