Mortise and tenon joints secured with wood pegs (Figure 1) are perhaps the most common connection type found in traditional timber frame structures. They are relatively easy to fabricate, enable efficient frame assembly, and are effective in transferring shear forces.

Design for transfer of shear forces can be based on the provisions of the National Design Specification® for Wood Construction (NDS®) (AF&PA 2005) and relies on direct bearing between the bottom of the tenoned member and the inside of the mortise. To increase bearing area, a housing (recess) can be cut in the mortised member to provide bearing support over the full width of the tenoned member.

In some cases, such as during frame erection or to resist wind loads in frames without shear walls, it might be necessary for the joint to resist tension loading. Tension load tends to withdraw the tenon from the mortise. The focus of this article is on considerations for design of a mortise and tenon joint loaded in tension. Considerations for strength, detailing, and long-term performance are discussed.

## Joint Strength

The tensile strength of a mortise and tenon joint secured with one or more wood pegs can be predicted by using the yield model approach found in the NDS. In this case the tenon is regarded as the main member and the mortise side walls are treated as the side members of the connection. However, some adjustment to the yield model approach is needed to account for details of mortise and tenon joints. First, dowel bearing strength of the tenon must account for the fact that load is transferred through a wood peg rather than a steel dowel. Thus, the wood peg experiences compression perpendicular to the grain in series with the dowel bearing action inside the hole of the mortised member and the tenon. The result is likely a decrease in the values of $F_n$ and $F_{wm}$ used in the yield model equations. Second, a value for $F_{wm}$ must be selected to describe the flexural yield strength of the wood peg. Third, an additional yield mode, that of peg shear, must be considered. Finally, yield mode IV, which involves two plastic hinges in the fastener at each shear plane, should be removed from consideration, as this mode has not been observed in practice or in laboratory testing. Details of the first three of these issues follow.

### Dowel Bearing Strength

In a pegged mortise and tenon connection under tension, the peg and the mortise side walls are loaded in bearing perpendicular to the grain, whereas the tenon is loaded in bearing parallel to the grain. Dowel bearing strength for a pegged connection depends upon the combined deformation of the peg and the timber. Two approaches are available for determining dowel bearing strengths $F_n$ and $F_{wm}$ for a peg bearing in the mortise side wall and a peg bearing in the tenon.

In the first approach, strength data is taken directly from physical tests following ASTM D5764 (ASTM 1997) but with the steel dowel required by the standard replaced with a wood peg of the same species, quality and diameter as that used in the prototype connection. In these tests, the wood peg must be supported such that it is not crushed or bent during the test. Procedures for two different versions of this modified test are found in Church & Tew (1997) and Schmidt & MacKay (1997).

In the second approach, dowel bearing strength can be determined by combining load-displacement records from separate bearing tests of the timber and the peg. In this approach, dowel bearing tests of the timber are performed according to ASTM D5764. Then a bearing test is performed on the peg in which, in effect, the wood block specified in ASTM D5764 is replaced by a metallic load block with a semicylindrical slot across one face. In this test, the metallic load block is pressed into the side of a peg while the peg is supported along its full length to prevent crushing and bending under load. Load-displacement records from these two tests are then combined assuming that combined behavior corresponds to a “springs in series” model (Figure 2). Dowel bearing strength is determined from the combined load-displacement records using the conventional 5% diameter (0.05D) offset method described in ASTM D5764. The approach for combining load-displacement records from the separate timber and peg tests is presented in Schmidt & Daniels (1999) and Schmidt & Scholl (2000).
Yield Strength in Bending of a Peg

Dowel bending yield strength $F_{yd}$ for wood pegs is normally derived from results of tests according to ASTM F 1575 (ASTM, 2003). In the absence of physical test data, $F_{yd}$ for wood pegs may be taken as the value of modulus of rupture at 12% moisture content contained in the Wood Handbook (FPL, 1999).

Values of modulus of rupture (MOR) in the Wood Handbook were developed from small, clear, straight-grain specimens and represent average values for a given species. Based on bending tests of pegs commonly used in timber frame construction (Schmidt & MacKay, 1997), average values of $F_{yd}$ using the 5% diameter $(0.05D)$ offset method for pegs are consistently higher than the values of MOR in the Wood Handbook. The higher flexural strength of the wood peg can be attributed to the form factor associated with round pegs, the smaller size of the peg compared to the ASTM D143 (ASTM, 1994) standard test specimen, and possibly lower moisture content in the pegs. Nevertheless, the values of MOR at 12% MC in the Wood Handbook appear to be conservative estimates of $F_{yd}$ for wood pegs used in timber frame construction. When the specific subspecies of wood used in the peg is not known, the smallest value of MOR for the species group should be selected.

Peg Shear Strength

A new yield mode, Mode V – peg shear, is proposed to represent a common failure mode observed in mortise and tenon joints. In mode V, shear failure of the peg develops at the mortise-to-tenon interfaces. A failed peg removed from a white oak frame is shown in Figure 3. The two shear planes are evident in the photograph along with damage due to flexure. The flexural damage is a secondary response that develops following shear failure through the peg cross section at the shear planes.

The shear strength $F_{ps}$ of a peg for Mode V failure is related to the values of specific gravity for the timber and peg. Compared to low specific gravity materials, pegs with higher specific gravity have greater shear strength and timber material with a higher specific gravity provides greater confinement of the peg, restricting the length of the shear link (Figure 4) and hence increasing joint strength.

A suitable mechanics-based theoretical equation for mode V capacity, similar to those for the other yield modes, has not yet been developed. Hence, use of a regression equation based on test results and finite element analyses (Schmidt & Miller, 2004) is proposed.

The allowable working-level shear stress $F_{py}$ in a wood peg is given by

$$ F_{py} = 1365 \frac{G_p^{0.826}}{G_t^{0.778}} $$

Eq. (1)

where $G_p$ and $G_t$ are the values of specific gravity for the timber and peg, respectively. The corresponding mode V allowable load is

$$ Z = \frac{\pi D^2}{2} F_{py} $$

Eq. (2)

where $D$ is the diameter of a peg that passes through two shear planes in the joint. Equation (1) is based the 5% offset yield load for all joints used in the study. A factor of safety of 2.2 and a load duration factor of 1.6 have been applied to the regression equation to achieve the allowable stress formula in Equation (1).

The majority of tests involved joint specimens with 1-inch diameter pegs. Some tests were performed on joints with 0.75-inch and others had 1.25-inch pegs. Also the regression equation was developed for joints with $G_p > G_t$. Use of Equation 1 for joints beyond these ranges of peg sizes and densities is not recommended.

Detailing Requirements

Specification of appropriate end distance $l_e$, edge distance $l_v$, and spacing $l_s$ of pegs in a mortise and tenon connection (Figure 5) is critical to prevent brittle timber failure under tension load. NDS detailing requirements for dowel-type fasteners are based on performance with steel fasteners, which of course have higher capacity than wood pegs. Hence, detailing requirements for joints with wood pegs can reasonably be adjusted.

![Figure 3: Shear failure of peg](image)

Figure 3: Shear failure of peg

![Figure 4: Shear links in failed pegs](image)

Figure 4: Shear links in failed pegs

![Figure 5: Joint detailing](image)

Figure 5: Joint detailing
Long-term Performance

Timber frame structures are often cut and assembled while timbers are still green (unseasoned). Seasoning in place can lead to checking, cross section distortion, and other effects that may influence the integrity of joinery-style connections. In particular, member shrinkage can lead to loss of bearing at the ends of beams and changes in contact surfaces for members joined at non-orthogonal orientations. Cross section distortion due to shrinkage can cause tenons to be pushed out of their mortise, resulting in distress to the pegs that secure the joint. These effects can be avoided or minimized through proper detailing and cutting of joinery.

A pegged mortise and tenon joint assembled from unseasoned timber and loaded in tension will experience significant long-term deflection due to creep and shrinkage. Joint deflection increases beyond the initial elastic deflection due to shrinkage of the pegs and timbers, flexural and shear creep in the peg, and localized compression creep in the timbers around the peg hole. Joint deflection tends to stabilize at some maximum value after timbers reach equilibrium moisture content (EMC). Maximum deflection at EMC can be 3 to 8 times larger than the initial elastic deflection, depending on initial moisture content, load history, and joinery details. This creep behavior does not appear to negatively influence joint load capacity (Schmidt & Scholl, 2000). One approach to controlling creep behavior is to avoid subjecting pegged mortise and tenon joints to long-term tension loads.

Summary

Mortise and tenon connections secured with wood pegs have a predictable strength and can be used with confidence to resist short-term, moderate tensile loads. Design capacity can be determined by methods based on NDS requirements, but modified to account for particular characteristics of these joints.

Table 1: Minimum Detailing Dimensions

<table>
<thead>
<tr>
<th>Timber Species</th>
<th>End Distance</th>
<th>Edge Distance</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas Fir</td>
<td>2D</td>
<td>2.5D</td>
<td>2.5D</td>
</tr>
<tr>
<td>Eastern White Pine</td>
<td>4D</td>
<td>4D</td>
<td>3D</td>
</tr>
<tr>
<td>Red &amp; White Oak</td>
<td>3D</td>
<td>2D</td>
<td>2.5D</td>
</tr>
<tr>
<td>Southern Yellow Pine</td>
<td>2D</td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Yellow Poplar</td>
<td>2.5D</td>
<td>2.5D</td>
<td>3D</td>
</tr>
</tbody>
</table>

Research on behavior of traditional joinery connections continues and code-recognized design provisions are expected to become available in the not-too-distant future.

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For a complete list of references, please see next page.
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