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Title: Keyed Through Tenon Joints – Structural Design Guide	

Introduction

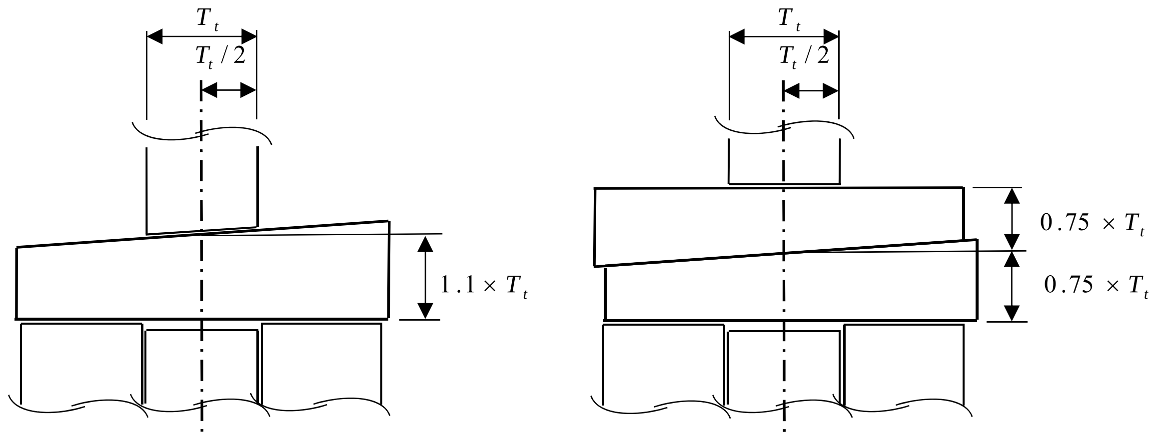
Both pegged joints and keyed through tenon (KTT) joints have been used in construction for many centuries. In current design practice, these joints have been designed solely on mechanics principles and knowledge of timber strength values. Several previous research projects have been conducted on pegged mortise and tenon joints since the 1980's. Until 2011, no known research has been conducted on KTT joints. This document provides design guidance for KTT joints based on test observations from research performed at Virginia Tech by Shields (2011) and should be used in conjunction with the provisions of the *National Design Specification for Wood Construction* (NDS) (AWC 2015) and TFEC Bulletin 2016-08 *Keyed Through Tenon Joints* (Hindman and DeStefano 2016). The information in this bulletin is general in nature and its application must be considered in the context of the unique circumstances of every design.

Design

Research conducted by Shields (2011) measured the strength of various KTT joints and developed prediction models based on NDS values and mechanics principles. Applicable limit states for KTT joints include key bearing, key bending, tenon row tear-out (relish), tenon net-section tension, and tenon block shear. Key bearing and key bending are ductile limit states and are preferable to governing joint design.

The design equations are written in ASD format only. The limit states are written as adjustable strength values per connection (Z'), which are based on combinations of adjusted strength properties (i.e. F_c', F_{cperp}', F_t', F_v') of the keys, tenon and mortise. Changes from applied standard adjustment values are bearing area factor, C_b, and size factor, C_F, for the keys.

TFEC-1 (TFEC 2010) defines wood wedges, or keys as "fabricated from straight-grain, hardwood stock." Stock with knots, checks, splits, shakes, delamination, wane or other defects should not be used. A maximum grain slope of 1:6 is prescribed, with an oven-dry specific gravity of the wood species being 0.57 or greater. Key taper is recommended at a maximum slope of 1:12. Based upon previous research, the key depth to tenon thickness ratio for joints with one key per slot should have a ratio of 1.1:1 or greater, while two keys per slot (folding keys) should have a ratio of 3:4 or greater (see Figure 1) to attain full key bearing strength prior to bending.



Singe Key Aspect Ratio **Double (Folding) Key Aspect Ratio**

Figure 1: Minimum Aspect Ratio for Ensuring Full Key Bearing Capacity

Limit States of Key Through Tenon (KTT) Joints

Key Bearing (Z'_B) is a ductile limit state that occurs when the key(s) or tenon keyholes crush at the bearing interface. Excessively short keys (i.e. less than the mortise width) should be checked for bearing capacity with respect to the mortise. Equation 1 is the bearing capacity considering keys ($Z'_{B,k}$) and tenon ($Z'_{B,t}$). Tenon keyhole bearing may govern in joints with relatively soft tenons or hard keys.

$$Z'_{B,k} = nK_wT_tF'_{c\perp,k}$$

or (1)

$$Z'_{B,t} = nK_wT_tF'_{c,t}$$

Where

$F'_{c\perp,k}$ = adjusted compression perpendicular to grain strength of key, psi

$F'_{c,t}$ = adjusted compression parallel to grain strength of tenon, psi

n = number of keys

K_w = width of key(s), in

T_t = tenon thickness, in

Key Bending (Z'_F) is a ductile limit state where bearing of the mortise and tenon against the key(s) produce capacity flexural stress in the key before the full bearing capacity is attained. Note that key bending can be ignored if the aspect ratios of Figure 1 are satisfied. Key bending rather than bearing is possible if the keys are relatively shallow due to the fact that keys are less constrained against flexure than pegs. Maximum moment of the key occurs near the center tenon thickness and the greatest flexural stress in the key is between the center tenon thickness and the tenon face with the lesser key thickness (depth).

The equation for key bending (Equation 2) was developed from Technical Report 12: General Dowel Equations for Calculating Lateral Connection Values (AWC 2015) considering a dowel in bending with gaps between the mortise and tenon elements.

$$Z'_F = 2n\frac{-g(q_m q_s)+\sqrt{q_m q_s(g^2 q_m q_s+2M_k(q_m+q_s))}}{q_m+q_s} \quad (2)$$

Where

q_m = [minimum $(F'_{c,t}, F'_{c\perp,k})$]*$K_w$, key-to-tenon bearing strength, lb/in

q_s = [minimum $(F'_{c\perp,m}, F'_{c\perp,k})$]*$K_w$, key-to-mortise bearing strength, lb/in

$F'_{c\perp,k}$ = adjusted compression perpendicular to grain strength of key, psi

$F'_{c,t}$ = adjusted compression parallel to grain strength of tenon, psi

$F'_{c\perp,m}$ = adjusted compression perpendicular to grain strength of mortise, psi

g = tolerance gap around mortise and tenon interface (assumed to be 1/16 inch)

$M_k = F'_{b,k} * K_W * K_d^2/6$, moment capacity of a single key, in-lb

Note: M_k applies to each key in joints with folding keys (two keys per keyhole)

$F'_{b,k}$= bending strength of key, psi

K_d = shallowest key depth at either face of tenon for single keys, in

= key depth at center tenon thickness for double (folding) keys, in

Tenon Row Tear-Our (Relish) (Z'_R) is a non-ductile limit state where the tenon shears along two shear planes at each key. NDS row tear-out uses one-half of the parallel-to-grain shear strength based on a triangular shear stress distribution assumption along shear planes. Through tenons with keys sometimes demonstrated a tendency to spread, creating splits in the tenon beyond the keys prior to a row tear-out (relish) failure. A more conservative factor than the NDS dowel row tear-out prediction was chosen. Based on testing from Shields (2011), a 40% (1/2.5) factor is applied for row tear-out giving a safety factor of approximately 3.0 to 4.8 against relish when compare to test values. Based on previous research the use of more than one key is recommended to prevent brittle joint behavior. Use of a several narrow keys allows the use of a shorter tenon length while still maintainingcapacity.

$$Z'_R = \frac{nT_t T_L F'_{v,t}}{1.25} \quad (3)$$

Where

$F'_{v,t}$= adjusted shear strength of tenon, psi

T_L = minimum tenon length beyond key holes, in

Tenon Net-Section Tension (Z'_T) is a non-ductile limit state where the tenon ruptures across the tenon width at the keyholes (net-section).

$$Z'_T = F'_{t,t}T_t(T_w - nK_h) \qquad (4)$$

Where

$F'_{t,t}$ = adjusted tension strength of tenon, psi

T_w = tenon width, in

K_h = width of tenon key holes (slightly larger than K_w)

Tenon Block Shear (Z'_G) is a non-ductile limit state where a combination of tenon row tear-out (relish) and tenon net-section tension occur simultaneously. This limit state only applies to tenons with two or more key holes. Two block shear limit states apply (Figure 2). The first limit state occurs where the tenon ruptures (relishes) beyond the outer keys and pieces of tenon remain only between keys (Figure 2A). The other limit state occurs where only outer portions of tenon remain and a larger center piece of tenon ruptures (relishes) beyond the keys (Figure 2B). Two equations, $Z'_{G,A}$ and $Z'_{G,B}$ are presented for the corresponding limit states. The minimum Z'_G value should be used. The block shear limit state equations assume that keys are of uniform width and spacing. Where tenon width is limited, tenons may be lengthened to increase shear plane capacity and allow tenon net-section tension to govern over the block shear limit states.

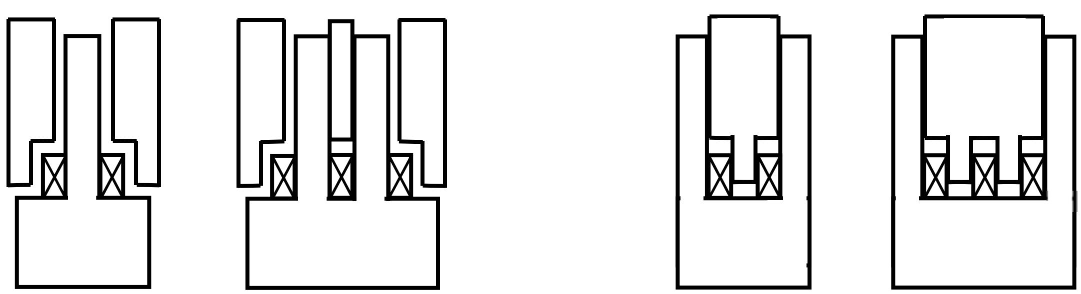


Figure 2: Block Shear Limit States A (left) and B (right) for KTT Joint with Two and Three Keys

$$Z'_{G,A} = 2F'_{t,t}T_tT_o + \frac{(n-1)F'_{v,t}T_tT_L}{1.25}$$

Or (5)

$$Z'_{G,B} = (n-1)F'_{t,t}T_tK_S + \frac{F'_{v,t}T_tT_L}{1.25}$$

Where

T_o = width of tenon beyond outer keyholes (key slots), in

K_s = spacing between key slots, in

Example 1: Anchor Beam Connection to Post

Given Information:

- Anchor Beam: 8x14 Southern Pine, No.1
- Column: 12x12 Southern Pine, No.1
- Keys: Red Oak, Select Structural (SS)
- All NDS Adjustment Factors other than C_D can be assumed to be 1.0

Detail a KTT joint for a maximum tension load of 11,500 lbs generated by wind only.

Solution:

Try (4) 1 ½" wide keys with uniform spacing and thickness:

<u>Key Bearing Capacity (Equation 1)</u>:

Key bearing based on key bearing strength: $Z'_{B,k} = nK_wT_tF'_{c\perp,k}$

$C_b = (T_t + 0.375)/T_t = (2 + 0.375)/2 = 1.188$

$F'_{c\perp,k} = C_b * F_{c\perp,k} = 1.188*820 = 974$psi (*Note: keys must be long enough to use* C_b)

$Z'_{B,k} = (4)*1.5*2*974 = 11,685$ lbs

Key bearing based on tenon bearing strength: $Z'_{B,t} = nK_wT_tF'_{c,t}$

$F'_{c,t} = C_D * F_{c,t} = 1.6*825 = 1,320$psi

$Z'_{B,t} = (4)*1.5*2*1,320 = 15,840$ lbs

Therefore, bearing capacity is governed by the keys at $Z'_{B,k}$ = <u>11,685 lbs</u> (> 11,500 lbs, OK)

<u>Key Bending Check (Figure 1 or Equation 2)</u>:

Note that key bending, in Equation 2, does not need to be checked if KTT joints with single keys (one key per keyhole) have a key depth at center tenon thickness equal to 1.1 times the tenon thickness or greater or at least ¾ of the tenon thickness per key if using double (folding) keys, per Figure 1. Therefore, keys in this joint need to be 2¼" deep at the center of the two inch tenon thickness if using single keys and 1½" deep if using double (folding) keys.

<u>Tenon Row Tear-out (Equation 3)</u>:

Solve for minimum tenon length beyond keys for the required load of 11,500lbs:

$$T_L = \frac{1.25*Z'_R}{nT_tF'_{v,t}} = \frac{1.25*11,500}{(4)*2*1.6*165} = 6.81\text{in}$$

TFEC Bulletin 2016-08 *Keyed Through Tenon Joints* (Hindman and DeStefano 2016) states that tenons should extend at least 10 inches beyond the keys. Therefore, T_L = <u>10in</u>.

Tenon Net-Section Tension (Equation 4):

$Z'_T = F'_{t,t}T_t(T_w - nK_h)$ = 1.6*900*2*[13.5 - (4)*1.5] = 21,600 lbs (> 11,500 lbs, OK)

Tenon Block Shear (Equation 5):

$$Z'_{G,A} = 2F'_{t,t}T_tT_o + \frac{(n-1)F'_{v,t}T_tT_L}{1.25}$$

= 2*1.6*900*2*1.5 + [((4)-1)*1.6*165*2*10]/1.25 = 21,312 lbs

$$Z'_{G,B} = (n-1)F'_{t,t}T_tK_S + \frac{F'_{v,t}T_tT_L}{1.25}$$

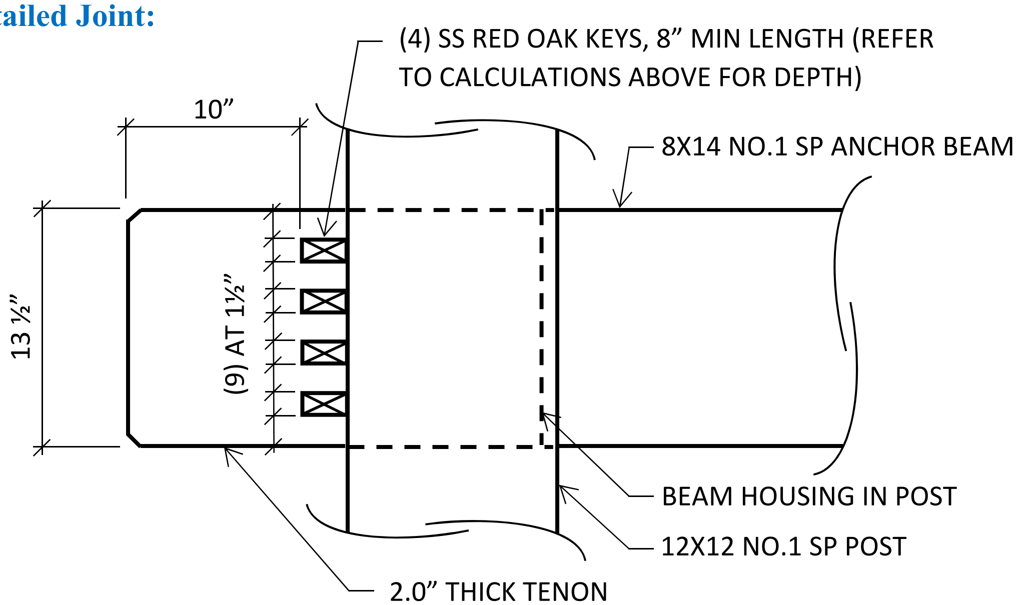
= ((4)-1)*1.6*900*2*1.5 + [1.6*165*2*10]/1.25 = 17,184 lbs

Therefore, block shear capacity is governed by $Z'_{G,B}$ = 17,184 lbs (> 11,500 lbs, OK)

Conclusion:

The KTT joint is adequate to support the new design load. Note that key bearing and bending design values are lower than (govern over) the tenon limit state design values, which is preferable in the design of KTT joints.

Detailed Joint:



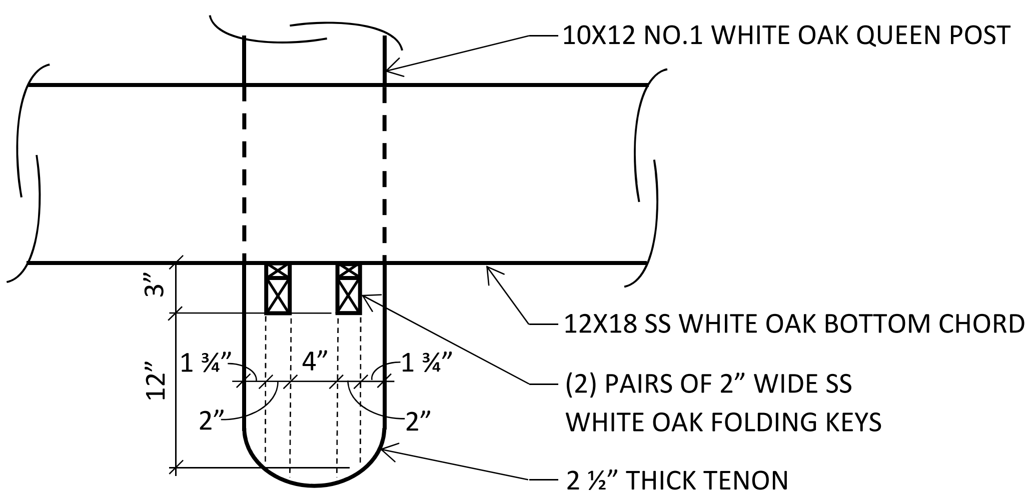
Example 2: Existing Queen Post and Bottom Chord KTT Joint Check

Given Information:

A twenty-year old barn is to be converted in to a residence. The structure is one-story with a gable roof. Roof framing is composed of uniformly spaced timber framed double queen post trusses forming a central isle along the entire length of the structure. The space between the queen posts and height between the bottom chord and collar beam allow for bedrooms, bathrooms and other living spaces. All roof trusses are constructed of the same geometry, timber size, and species. Field investigations provided the following information:

- Queen Posts: 10x12 white oak, No.1 (oriented so that tenon is 12 inches wide)
- Queen Post Tenon Length: 12 in (beyond keys)
- Queen Post Tenon Thickness: 2.5 in
- Key Species: white oak (Select Structural)
- Number of Keys: (2) per joint (with enough length to allow use of C_b)
- Key Width: 2.0 in
- Key Depth: 1.5 in at center tenon thickness per key (3.0 in total – folding keys)
- Bottom Chord: 12x18 white oak, SS
- Total Demand after Renovation: 7,600 lbs Dead and Live Load (each Queen Post)

Given that all members and other connections in the trusses were determined adequate or in need of additional support, determine if existing KTT joints of the queen posts into the bottom chords are adequate or if additional reinforcing is required. Below is the illustrated KTT joint:



Solution:

Check Key Bearing Capacity (Equation 1):

Key bearing based on key bearing strength: $Z'_{B,k} = nK_w T_t F'_{c\perp,k}$

$C_b = (T_t + 0.375)/T_t$ = (2.5 + 0.375)/2.5 = 1.15

$F'_{c\perp,k} = C_b * F_{c\perp,k}$ = 1.15*800 = 920psi

$Z'_{B,k}$ = (2)*2*2.5*920 = 9,200 lbs

Key bearing based on tenon bearing strength: $Z'_{B,t} = nK_w T_t F'_{c,t}$

$F'_{c,t} = C_D * F_{c,t}$ = 1.0*825 = 825psi

$Z'_{B,t}$ = (2)*2*2.5*825 = 8,250 lbs

Therefore, bearing capacity is governed by the tenon at $Z'_{B,t}$ = 8,250 lbs (> 7,600 lbs, OK)

Check Key Bending Capacity (Figure 1 or Equation 2):

Note that key bending, in Equation 2, does not need to be checked if KTT joints with double keys (two keys per keyhole) have a key depth at center tenon thickness equal to ¾ of the tenon thickness or greater for each key. Therefore, keys in this joint need to be **(3/4) *2.5" = 1 7/8"** deep at the center of the tenon thickness. Key bending must be checked since the keys do not satisfy the aspect ratio of Figure 1 **(3"/2 = 1½" key depth at tenon center)**:

q_m = [minimum ($F'_{c,t}$, $F'_{c\perp,k}$)]*K_w:

= min(1.0*825,1.15*800)*2.0 = 1,650 lbs/in

q_s = [minimum ($F'_{c\perp,m}$, $F'_{c\perp,k}$)]*K_w:

= min(800,1.15*800)*2.0 = 1,600 lbs/in

g = tolerance gap around mortise and tenon interface (assumed to be 1/16 inch)

$M_k = F'_{b,k} * K_W * K_d^2/6$:

= (2)*1.0*1.5*1,200*2*(1.5^2)/6 = 2,700 in-lb per pair of folding keys

Note:

NDS Size Factor C_F of 1.5 applies to $F_{b,k}$ for most keys
M_k is doubled for folding keys (two keys per keyhole)
K_d is equal to the key depth at center tenon thickness for double (folding) keys

$$Z'_F = 2n\frac{-g(q_m q_s)+\sqrt{q_m q_s\left(g^2 q_m q_s + 2M_k(q_m+q_s)\right)}}{q_m+q_s}$$ = 8,177 lbs (> 7,600 lbs, OK)

Tenon Row Tear-out (Equation 3):

$$Z'_R = \frac{nT_tT_LF'_{v,t}}{1.25} = \frac{(2)*2.5*12*1.0*205}{1.25}$$ = 9,840 lbs (> 7,600 lbs, OK)

Tenon Net-Section Tension (Equation 4):

$Z'_T = F'_{t,t}T_t(T_w - nK_h)$ = 1.0*700*2.5*[11.5 - (2)*2] = 13,125 lbs (> 7,600lbs, OK)

Tenon Block Shear (Equation 5):

$$Z'_{G,A} = 2F'_{t,t}T_tT_o + \frac{(n-1)F'_{v,t}T_tT_L}{1.25}$$

= 2*1.0*700*2.5*1.75 + [((2)-1)*1.0*205*2.5*12]/1.25 = 11,045 lbs

$$Z'_{G,B} = (n-1)F'_{t,t}T_tK_S + \frac{F'_{v,t}T_tT_L}{1.25}$$

= ((2)-1)*1.0*700*2.5*4 + [1.0*205*2.5*12]/1.25 = 11,920 lbs

Therefore, block shear capacity is governed by $Z'_{G,A}$ = 11,045 lbs (> 7,600 lbs, OK)

Conclusion:

The KTT joint is adequate to support the new design load. Note that key bearing and bending design values are lower than (govern over) the tenon limit state design values, which is preferable in the design of KTT joints.

Reference

American Wood Council (AWC). 2015. **National Specification for Wood Construction**. American Wood Council, Leesburg, VA.

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