Bulletin No. 2018-13

First Release: December 2018	**Revised:**
Prepared by: Lance Shields, P.E.	
Title: Wedged Dovetail Tenon Joints – Structural Design Guide	

Introduction

Many variations of mortise and tenon joints have been used in construction for centuries. In current design practice, many of these joints have been designed solely on mechanics principles and knowledge of timber strength values. Although no known research has been performed on wedged dovetail tenons, this document provides design guidance for this type of mortise and tenon joint based on the provisions of the *National Design Specification for Wood Construction* (NDS) (AWC 2015).

Design

Wedged dovetail tenon (WDT) joints resist tension force primarily through bearing of the dovetail tenon and wedge against the mortise walls as the dovetail tenon tries to withdrawal from the mortise. The bearing limit-states are ductile and include Dovetail Tenon to Mortise Bearing, Dovetail Tenon Bearing at the Wedge, and Mortise Bearing at the Wedge. Only mortise and tenon bearing at the wedge is considered since the wedge is required to be at least as dense as the mortise and tenon members. The section of tenon at the shoulder resists tension force by tension parallel-to-grain (Tenon Tension at Shoulder) and the dovetail portion of the dovetail tenon resists tension force by shear parallel-to-grain (Tenon Shear at Dovetail). It may be preferable that Tenon Tension at Shoulder and Tenon Shear at Dovetail (non-ductile limit-states) do not govern joint design where life safety or substantial risk to public property is a concern. The use of screws in the dovetail tenon perpendicular to the shear plane may allow the Tenon Shear at Dovetail limit-state to be more ductile; the type and number of screws recommended for this are beyond the scope of this bulletin.

The following equations are written as tension capacity of the joint with respect to each limit-state and 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, $F'_{c\perp,}$, F'_t, F'_v) of the wedge, mortise member, and tenon member. Guidance for the design of wedged dovetail tenon joints is provided by the design example starting on page 3.

Basic Wedged Dovetail Tenon Joint Specification and Recommendations

1) Wedged dovetail tenon joints and their components shall be fabricated and assembled by craftsmen experienced in timber frame construction and timber frame carpentry techniques.
2) Wedges shall be fabricated from clear hardwood stock (TFEC 1).
3) Wedge slope of grain shall not exceed 1:6 on any face (TFEC 1).
4) Oven-dry specific gravity (SG) of wedges shall equal or exceed that of the species group (as assigned in the NDS) of the secured members and shall not be less than 0.57 (TFEC 1).
5) Joints shall be detailed and assembled as required to prevent mortise splitting resulting from installation (TFEC 1).
6) Mortise wall thickness shall equal or exceed mortise width (TFEC 1).
7) Excessive wedge width shall be avoided that would cause mortise splitting from seasoning effects (TFEC 1 Commentary and TFEC Bulletin 2016-08).
8) Wedge width and tenon thickness shall be equal (i.e. wedge shall not be wider or narrower than the tenon thickness).
9) Wedge length shall be greater than mortise depth.
10) Wedges shall be tightened as the timbers season to avoid slipping of the joint. The addition of pegs may also help prevent joint slipping.
11) All bearing surfaces of the wedge and tenon shall be in contact with each other and with the walls of the mortise along the entire length of each bearing interface (i.e. the mortise walls shall be cut to match the slope of the dovetail tenon and the wedge).
12) Wedged dovetail tenons better resist parallel-to-grain shear force when the tenon protrudes beyond the outer mortised member face opposite the tenon shoulder as shown in Figure 1 which increases the shear area. The ends of through tenons are often embellished making shear length determination more difficult than if the tenon end was square-cut. In Figure 1, tenon length (T_L) is based on the entire length of the tenon shear plane as a straight-line parallel to the grain from the tenon shoulder at the start of the dovetail to where it falls on the tenon embellishment.
13) Figure 1 below does not show a shoulder or housing for the tenon shoulder to bear on. Shoulders or housings may be required when the tenon member carries enough shear to require such and may not be required if the joint only carries tension with relatively little to no shear (such as queen post to bottom chord connection). Requirements for shoulders and housings are beyond the scope of this bulletin.

Wedged Dovetail Tenon Joint Diagram with Notation of Dimension Variables

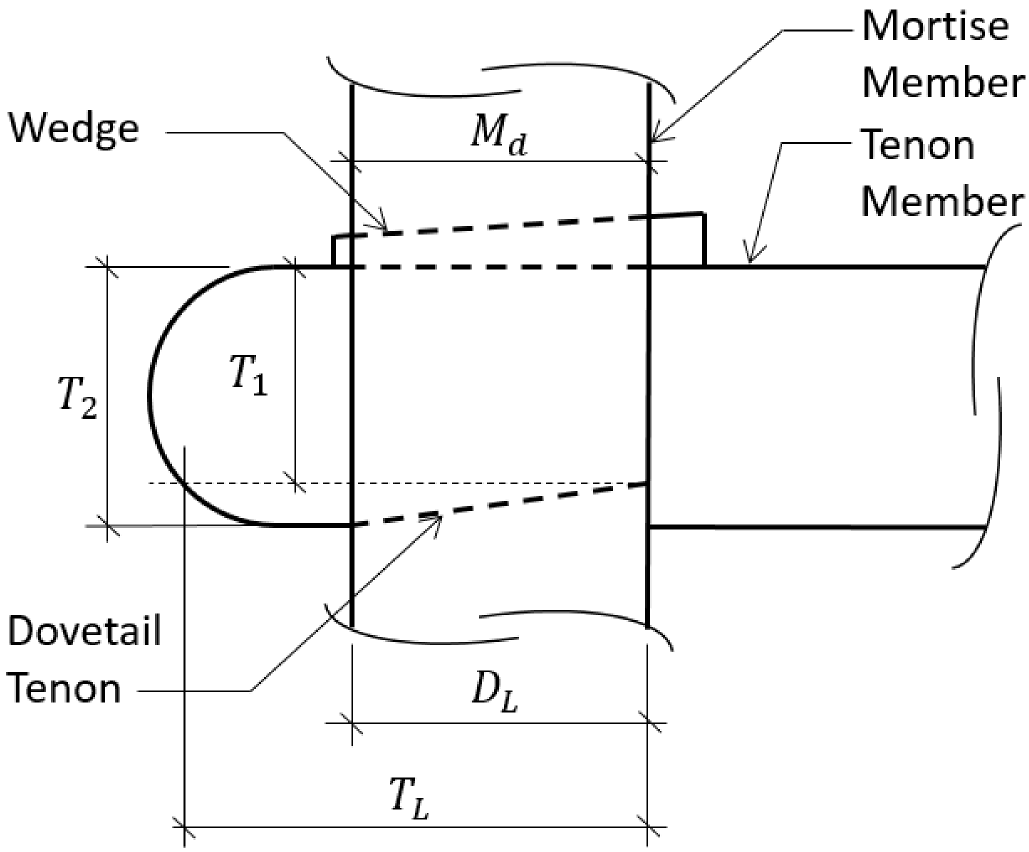


Figure 1: Wedged Dovetail Tenon Joint Dimensions

See "Basic Wedged Dovetail Tenon Joint Specifications" on Page 2 for other details. Joint can also exist in the vertical orientation as a king or queen post.

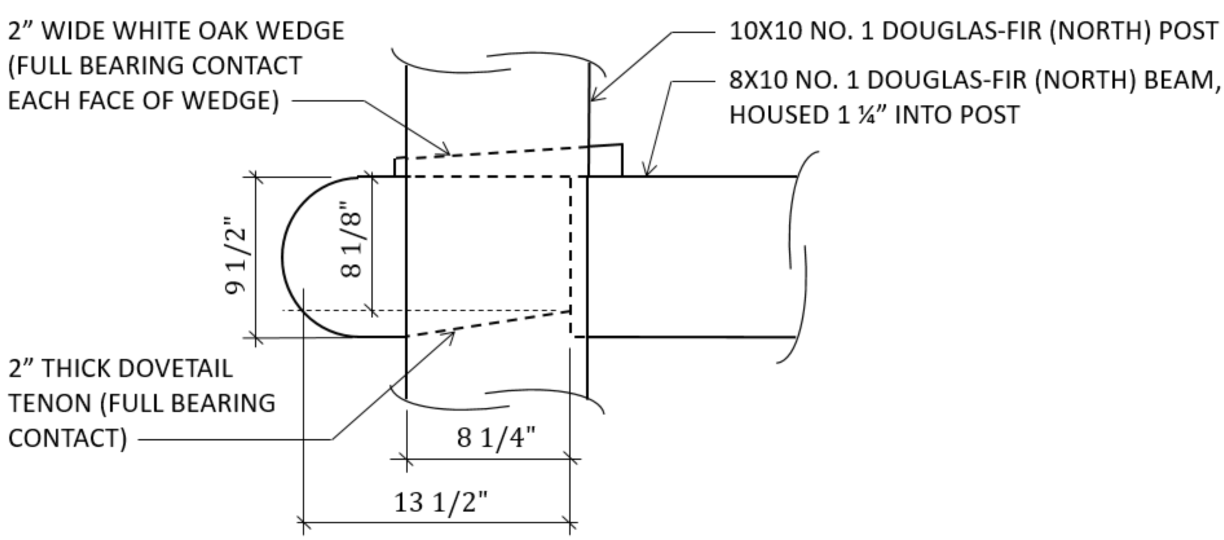
Example: Beam Tension Member with Dovetailed Tenon into Post secured with Wedge

Given Information:

- Floor and Tie Beam: 8x10 Douglas-fir (North), No.1
- Tenon thickness: 2”
- Tenon length: 8.25” (see detail below)
- Dovetail Taper: 2”/12” (1/6)
- Column: 10x10 Douglas-fir (North), No.1
- Wedge: White Oak (matches tenon thickness) – Select Structural properties may be assumed
- Conditions allow for NDS adjustment factors other than C_D to be 1.0.

The joint only goes into tension during wind events (C_D = 1.6). Calculate the maximum capacity of the joint.

Detailed Joint: **(Not to Scale)**



Applicable Limit States:

- Dovetail Tenon to Mortise Bearing (Ductile)
- Dovetail Tenon Bearing at Wedge[1] (top flat portion) - (Ductile)
- Mortise Bearing at Wedge[1] (Ductile)
- Tenon Shear at Dovetail (Non-ductile)
- Tenon Tension at Shoulder (Non-ductile)

1. Only mortise and tenon bearing at the wedge is considered since the wedge is required to be at least as dense as the mortise and tenon members.

Solution:

Note 1: The following bearing limit state design equations assume full bearing contact along the entire length of bearing interfaces including, dovetail tenon-to-mortise, wedge-to-dovetail tenon, and wedge-to-mortise bearing limit states. Friction resistance between components is not quantifiable and is therefore neglected.

Note 2: The 1 ¼" beam housing (shown on the previous page) is used since this is a floor beam with significant end shear (not part of this problem). Shouldering the beam would be acceptable if the post and beam were the same width. Housing or shouldering the beam (or tenon member) may not be necessary in cases where there is tension only or relatively small shear force.

Note 3: NDS Table 4D Posts and Timbers strength values are used for 10x10 post and 4D Beams and Stringers strength values are used for 8x10 beam.

Dovetail Tenon-to-Mortise Bearing, ZB'_{tm} (Ductile):

Note that bearing at this interface is normal to the inclined surface:

Dovetail Length, D_L: $8.25in$

Dovetail Tenon Width at Shoulder, T_1: $8.125in$

End Width of Dovetail Tenon, T_2: $9.5in$

Dovetail Width, $T_2 - T_1$: $9.5in - 8.125in = 1.375in$

Dovetail Bearing Length, $\sqrt{(D_L)^2 + (T_2 - T_1)^2}$: $\sqrt{8.25^2 + 1.375^2} = 8.36in$

Mortise Parallel-to-grain Bearing Strength:

$$F^*_{cm} = C_D F_C = 1.6 \times 1{,}000psi = 1{,}600psi$$

Dovetail Tenon Perpendicular-to-grain Bearing:

$$F'_{c\perp t} = 625psi$$

Dovetail Tenon Angle-to-grain Bearing:

$$\emptyset_{DT} = 90° - \tan^{-1}((T_2 - T_1)/T_L)$$

$$\emptyset_{DT} = 90° - \tan^{-1}(1.375in/8.25in) = 80.538°$$

Bearing Strength:

$$F'_{\emptyset DT} = \frac{F^*_{cm} F'_{c\perp t}}{F^*_{cm}(\sin\emptyset_{DT})^2 + F'_{c\perp t}(\cos\emptyset_{DT})^2} = 635\text{psi}$$

Mortise Angle-to-grain Bearing at Tenon Dovetail:

$$\emptyset_{DM} = \tan^{-1}((T_2 - T_1)/T_L)$$

$$\emptyset_{DM} = \tan^{-1}(1.375in/8.25in) = 9.4623°$$

Bearing Strength of Dovetail Mortise:

$$F'_{\emptyset DM} = \frac{F^*_{cm} F'_{c\perp t}}{F^*_{cm}(\sin \emptyset_{DM})^2 + F'_{c\perp t}(\cos \emptyset_{DM})^2} = 1{,}535\text{psi}$$

Minimum Bearing Capacity of Tenon Dovetail and Adjacent Mortise Surface:

$$min(F'_{\emptyset DT}, F'_{\emptyset DM}) \times T_t \times \sqrt{(T_L)^2 + (T_2 - T_1)^2}$$

Where:

T_t = tenon thickness, in
T_L = tenon length, in
T_2 = end width of dovetail tenon, in
T_1 = dovetail tenon width at shoulder, in
$\sqrt{(T_L)^2 + (T_2 - T_1)^2}$ = dovetail bearing length, in

Note that the bearing capacity of the dovetail tenon and adjacent mortise surface act normal to the inclined bearing interface. Joint tension capacity for this limit-state is the horizontal component of the minimum bearing capacity of dovetail tenon or adjacent mortise surface which is calculated as follows:

$$ZB'_{tm} = min(F'_{\emptyset DT}, F'_{\emptyset DM}) \times T_t \times \sqrt{(T_L)^2 + (T_2 - T_1)^2} \times \left[(T_2 - T_1)/\sqrt{(T_L)^2 + (T_2 - T_1)^2}\right]$$

Or, more simply:

$$ZB'_{tm} = min(F'_{\emptyset DT}, F'_{\emptyset DM}) \times T_t \times (T_2 - T_1)$$

$$ZB'_{tm} = min(635psi, 1{,}535psi) \times 2.00in \times (6.375in - 5.00in) = \underline{1{,}746 \text{ lbs}}$$

Dovetail Tenon Bearing at Wedge (top flat portion), ZB'_{tw} (Ductile):

Note that bearing at this interface is normal to the flat (non-dovetail) portion of the tenon and is generated by the vertical component of the bearing force normal to the inclined dovetail tenon-to-mortise bearing interface as tension force is applied to the joint.

Bearing Length (equal to Mortise Depth), M_d: $9.50in$:

Tenon Perpendicular-to-grain Bearing Strength:

$$F'_{c\perp t} = 625psi$$

Tenon Bearing Capacity adjacent to Wedge:

$$F'_{c\perp t} \times T_t \times M_d$$

Where:
T_t = tenon thickness, in
M_d = mortise depth, in

The joint tension required to generate tenon bearing capacity adjacent to the wedge is a function of the tenon dovetail slope and is calculated in the equation below. Joint tension is the horizontal component of the force at the inclined dovetail tenon-to-mortise bearing interface generated by joint tension. Tenon bearing adjacent to the wedge is the vertical component of the force at the inclined dovetail tenon-to-mortise bearing interface generated by joint tension.

$$ZB'_{tw} = F'_{c\perp t} \times T_t \times M_d \times [(T_2 - T_1)/T_L]$$

Where:
T_L = tenon length, in
T_2 = end width of dovetail tenon, in
T_1 = dovetail tenon width at shoulder, in

$$ZB'_{tw} = 625psi \times 2.00in \times 9.50in \times [(9.5in - 8.125in)/8.25in]$$

= <u>1,979 lbs</u>

Mortise Bearing at Wedge, ZB'_{mw} (Ductile):

Note that bearing at this interface is normal to the flat (non-dovetail) portion of the tenon and is generated by the vertical component of the bearing force normal to the inclined dovetail tenon-to-mortise bearing interface as tension force is applied to the joint.

Bearing Length (equal to Mortise Depth), M_d: $9.50in$:

Mortise Parallel-to-grain Bearing Strength:

$$F'_{cm} = C_D F_C = 1.6 \times 1{,}000psi = 1{,}600psi$$

Mortise Bearing Capacity adjacent to Wedge:

$$F'_{cm} \times T_t \times M_d$$

Where:

T_t = tenon thickness, in
M_d = mortise depth, in

The joint tension required to generate mortise bearing capacity adjacent to the wedge is a function of the tenon dovetail slope and is calculated in the equation below. Joint tension is the horizontal component of the force at the inclined dovetail tenon-to-mortise bearing interface generated by joint tension. Mortise bearing adjacent to the wedge is the vertical component of the force at the inclined dovetail tenon-to-mortise bearing interface generated by joint tension.

$$ZB'_{mw} = F'_{cm} \times T_t \times M_d \times [(T_2 - T_1)/T_L]$$

Where:

T_L = tenon length, in
T_2 = end width of dovetail tenon, in
T_1 = dovetail tenon width at shoulder, in

$$ZB'_{mw} = 1{,}600psi \times 2.00in \times 9.50in \times [(9.5in - 8.125in)/8.25in]$$

= 5,067 lbs

Tenon Shear at Dovetail, ZR_t' (Non-ductile):

Note that tension force acting on the joint creates parallel-to-grain shear stress along the line where the dovetail portion of the tenon is connected to the rest of the tenon:

Length of Shear Plane (Tenon Length), T_L: $13.5in$

Width of Shear Plane (Tenon Thickness), T_t: $2.00in$

Parallel-to-grain Shear Strength of Tenon:

$$F_v' = C_D F_v = 1.6 \times 170psi = 272psi$$

Joint Tension Capacity based on Shear Capacity of Dovetail portion of Tenon:

$$ZR_t' = F_v' \times T_t \times T_L = (272psi/2) \times 2.00in \times 13.5in = \underline{3{,}672\ lbs}$$

Note that dividing the shear strength by two (as shown above) is done because of the assumption of triangular shear stress distributions along shear planes per NDS Appendix E. Future research may show that this reduction is not required and that full F_v' could be used.

Tenon Tension at Shoulder, ZT_t' (Non-ductile):

Note that the dovetail being only on one side of the tenon (instead of both sides) would normally create eccentricity and therefore a combination of tension and flexural stress in the tenon section at the shoulder. However, this limit state can be designed for concentric tension of the tenon cross-section since the dovetail tenon is restrained from rotation within the mortise due the presence of the wedge. Also note that it is recommended that the T_2 dimension remain the entire depth of the tenon member to maximize the Tenon Tension at Shoulder limit-state strength which will also minimize the amount of tenon material removed to make the joint.

Dovetail Tenon Width at Shoulder, T_1: $8.125in$

Tenon Thickness, T_t: $2.00in$

Parallel-to-grain Tension Strength of Tenon:

$$F_t' = C_D F_t = 1.6 \times 675psi = 1{,}080psi$$

Joint Tension Capacity based on Tension Capacity of Tenon Section at Shoulder:

$$ZT_t' = F_t' \times T_t \times T_1 = (1{,}080psi) \times 2.00in \times 8.125in = \underline{17{,}550lbs}$$

Summary:

• Dovetail Tenon to Mortise Bearing (Ductile)	**1,746 lbs - Governs**
• Dovetail Tenon Bearing at Wedge (top flat portion) - (Ductile)	1,979 lbs
• Mortise Bearing at Wedge (Ductile)	5,067 lbs
• Tenon Shear at Dovetail (Non-ductile)	3,672 lbs
• Tenon Tension at Shoulder (Non-ductile)	17,550 lbs

Conclusion:

The governing joint design limit state is Dovetail Tenon-to-Mortise Bearing at a capacity of 1,746 lbs. Note that the governing limit state is ductile, which is preferred where life safety or substantial risk to public property is a concern.

Liability

The information in this example is general in nature and its application must be considered in the context of the unique circumstances of every design. It is intended that timber frame joints (such as the joint in this design example) be analyzed and design with competent engineering, constructed with accurate fabrication, and have adequate supervision of construction. The authors, Timber Frame Business Council, Timber Frame Engineering Council, the Timber Framers Guild, and any other associated organization do not assume any responsibility for errors or omissions in information presented in this bulletin, nor for engineering designs, plans, or construction prepared from it. Those applying the principals of design from this example assume all liability arising from their use. The design of engineered structures is within the scope of expertise of licensed engineers, architects, or other licensed professionals for applications to a particular structure.

References

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

Timber Frame Engineering Council (TFEC). 2010. Standard for Design of Timber Frame Structures and Commentary, TFEC 1-2010. Timber Frame Engineering Council, Becket, MA.

Lance Shields, P.E. is an associate at Dunbar Milby Williams Pittman & Vaughan, PLLC., Richmond, VA.