TFEC 1-2019

Standard for Design of Timber Frame Structures and Commentary

TIMBER FRAME ENGINEERING COUNCIL

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Timber Frame Engineering Council
Technical Activities Committee (TFEC-TAC)

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Standard for Design of Timber Frame Structures

1.0 General Requirements for Structural Design and Construction

1.1 Applicability and Scope

This Standard defines the engineering and design requirements for timber frame construction. A timber frame shall be regarded as a structural building frame system or a portion thereof that is composed of timber members in which connections between interlocking members are created principally by carpenter-style wood joinery, often using wood pegs and wood wedges, possibly supplemented with metal fasteners.

This Standard is not intended to preclude use of materials, assemblies, structures or designs not meeting the criteria herein, provided it is demonstrated by analysis based on recognized theory, full scale or prototype loading tests, studies of model analogues or extensive experience in use that the material, assembly, structure or design will perform satisfactorily in its intended end use.

This Standard is intended as a supplement to provisions of the National Design Specification for Wood Construction (ANSI/AWC NDS©, Ref. 4). In the event of conflicts or contradictory requirements between this Standard and the NDS©, the provisions of the latter specification shall apply.

1.2 Liability

It is intended that this document be used in conjunction with competent engineering design, accurate fabrication, and adequate supervision of construction. The Timber Framers Guild and the Timber Frame Engineering Council assume no responsibility for errors or omissions in this document, nor for engineering designs, plans, or construction prepared from it. Those using this Standard assume all liability arising from its 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.

1.3 General Requirements

1.3.1 Strength

Buildings and other structures shall be designed and constructed to safely support the anticipated loads that are likely to occur during the lifetime of the structure. In addition, assemblies and subassemblies shall be designed and constructed to safely support those loads that are likely to occur during construction, including but not limited to frame assembly and raising. Load types, magnitudes, and combinations shall conform to the building code under which the structure is designed, or where applicable, other recognized minimum design-load standards (see Ref. 10 and 11).

1.3.2 Serviceability

Structural systems and members thereof shall be designed to have adequate stiffness to limit deflections, lateral drift, vibration, or any other deformations that adversely affect the intended use and performance of the system. Limitations on deflections, lateral drift, vibration, and other deformations shall conform to the provisions of the building code under which the structure is designed.

1.3.3 General Structural Integrity

Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not damaged to an extent disproportional to the original damage location. This shall be accomplished by providing sufficient continuity, redundancy, energy-dissipating capacity or a combination thereof, in the members of the structure.

1.3.4 Conformance with Standards

The quality of wood products and fasteners and the design of load-supporting members and connections shall conform to the standards specified herein.

1.4 Design Loads

1.4.1 Governed by Codes

Minimum design loads shall be in accordance with the local building code under which the structure is designed. In the absence of a local building code, the minimum design loads specified in Minimum Design Loads for Buildings and Other Structures (SEI/ASCE 7; see Ref. 10) shall be used.

1.4.2 Loads Included

Where applicable, design loads shall include any or all of the following loads or forces: dead, live, snow, wind, earthquake, erection and other static and dynamic forces.

1.5 Construction Documents

1.5.1 Types of Documents

Construction documents shall be understood to include contracts, plans, specifications, shop drawings and other documents as agreed by the contracting parties intended to convey the construction requirements for the structure.

1.5.2 Material Selection

The construction documents shall indicate the species or species combination of the timber as well as the stress grade and grading rules for each structural load-carrying member used in construction. The construction documents shall also indicate the species or specific gravity of wood used for design of pegs and wedges in the structure.

1.5.3 Member Sizes

The construction documents shall indicate whether timber member sizes are stated in terms of standard nominal dimensions, standard net dimensions, or other designations.

1.5.4 Connection Details

The construction documents shall indicate the dimensions necessary for connection fabrication. Locations and sizes of tenons, mortises, housings, and other connection components shall be specified such that fabrication quality can be evaluated.

1.6 Materials

1.6.1 Sawn Timber

Design values for solid-sawn timbers used as structural load-carrying members shall be as specified for the species groups and grades defined in the National Design Specification for Wood Construction Supplement, Design Values for Wood Construction (Ref. 4). Alternatively, design values may be developed by other methods, such as those made available by ASTM Standards D245 (Ref. 5). Lumber shall be identified by the grade mark of, or certificate of inspection issued by, a certified grader, a lumber grading or inspection bureau, an agency recognized by the American Lumber Standards Committee or an individual qualified by education, experience or both to perform timber grading.

Guidelines for evaluation of timbers in existing buildings may be found in TFEC 3 (Ref. 12).

1.6.2 Structural Glued Laminated Timber

Design values for structural glued laminated timber (glulam) shall be as specified for the laminating combination as listed in the NDS® Supplement, American Institute of Timber Construction (AITC) Standard Specification AITC 117, or AITC 119 (see Ref. 1 and 2). Glulam shall bear a quality mark from an accredited inspection agency certifying conformance with ANSI/AITC A190.1 (see Ref. 3). Where significant amounts of the cross section will be removed to accommodate notches, mortises, or tenons, the structural effect of the removal of high-grade material shall be considered or glulam timbers of a uniform-grade lay-up shall be specified.

1.6.3 Wood Pegs

Wood pegs used as fasteners in connections shall be fabricated from clear, straight-grain, hardwood stock according to the provisions of ASTM D8023 (Ref. 7). Use of sawn, octagonal pegs or riven facetted pegs shall be permitted when they conform to the provisions of ASTM D8023 with the exception of their cross-section shape and when their use is approved by the engineer of record.

The oven-dry specific gravity of the peg shall not be less than that of the species or species group of the timber used in the connection, as assigned in the NDS®, but in no case shall the oven-dry specific gravity of the peg stock be less than 0.50. For the purposes of calculation in the provisions of this Standard, the specific gravity of the peg stock shall not be taken as greater than 0.86.

1.6.4 Wood Wedges

Wood wedges used to secure through-tenons or scarf joints, or used for other structural applications shall be fabricated from clear, straight-grain, hardwood stock. Wedges shall be fabricated to minimize slope of grain. The oven-dry specific gravity of the wedge shall not be less than that of the species or species group of the timber used in the connection as assigned in the NDS®, but in no case shall the oven-dry specific gravity of the wedge stock be less than 0.50.

1.6.5 Splines

Splines shall be formed from seasoned hardwood with specific gravity of at least 0.50 or from laminated veneer lumber.

1.7 Notation

Except where otherwise noted, the symbols used in this Standard have the following meanings.

C_D = load duration factor, see 3.4.9

C_M = wet service factor, see 3.4.9

C_g = group action factor for connections, see 3.4.9

C_t = temperature factor, see 3.4.9

C_Δ = geometry factor for connections, see 3.4.9

D = diameter of peg, in., see 3.4.6

F_{em} = dowel bearing strength of main member, psi, see 3.4.1

F_{es} = dowel bearing strength of side member, psi, see 3.4.1

F_{vp} = effective shear strength of peg, psi, see 3.4.1

$F_{e\theta}$ = dowel bearing strength at an angle to the grain, psi, see 3.4.3

F_{yb} = dowel bending yield strength of peg, psi, see 3.4.5

G_t, G_p = specific gravity of timber and of peg, dimensionless, see 3.4.1

R_e = ratio of specific gravities of main member and side member, see 3.4.1 and 3.4.9

Z, Z' = reference and adjusted lateral design value for a single fastener connection, lbs, see 3.4.1 and 3.4.9

b = breadth of rectangular bending member, in.

d = depth of bending member or least dimension of rectangular compression member, in.

d_n = depth of member remaining at a notch, in., see 2.3.3

l_e = end distance, in., see 3.1.1.2

l_m = dowel bearing length in the main member, or tenon breadth, in., see 3.4.1

l_s = dowel bearing length in the side member, or minimum mortise side wall thickness on one side of tenon, in., see 3.4.1

l_v = edge distance, in., see 3.1.1.1

w_1, w_2, w_3 = width of partial-width notch, in., see 2.3.4

w_m = width of mortise, see 3.4.11

w_s = width of side wall on either side of mortise, see 3.4.11

θ = maximum angle of load to grain for any member in a connection, deg, see 3.4.1

2.0 Structural Members

2.1 General

The provisions of the ANSI/AWC NDS© shall apply for design of wood bending members, compression members, tension members, members subjected to combined bending and axial loading, and members subjected to bearing.

2.2 Seasoning Effects

Consideration shall be given to the potential effects of shrinkage and distortion due to changes in moisture content prior to and after assembly of the structure.

For timbers used in dry-service conditions, the design value for bending F_b shall be permitted to be adjusted by the factor C_M given in Table 2A. Such adjusted design values shall be applied to the actual cross section dimensions for the dry-service conditions.

Table 2A – F_b adjustment for dry service

Dry-service moisture content	C_M
19%	1.09
15%	1.15
10%	1.20

2.3 Notching

2.3.1 Effects on Member Stiffness

The effects of notching on member stiffness with respect to serviceability shall be considered.

2.3.2 Tension or Compression Face Notches

The provisions of the ANSI/AWC NDS© shall apply for the design of bending members that are notched across the full width of their tension or compression face. The provisions of Sections 2.3.3 and 2.3.4 of this Standard shall also apply.

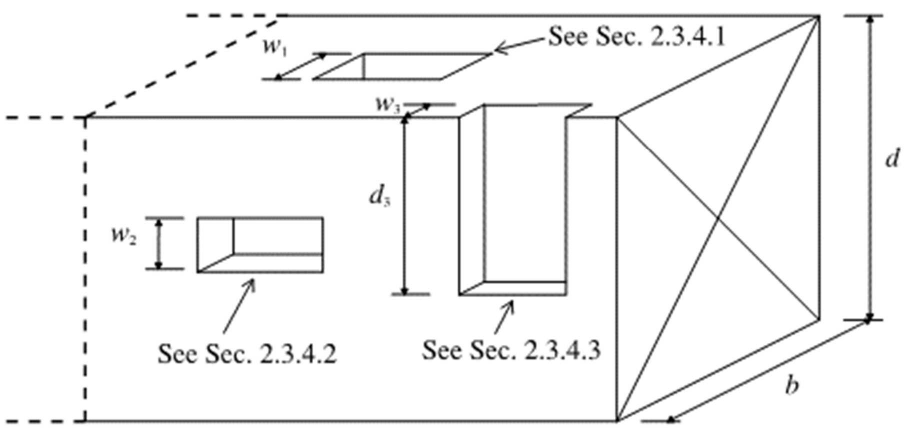
2.3.3 Coped Tension Face Notches

A gradual change in cross section compared with a square notch decreases the actual shear stress parallel to the grain nearly to that computed for an unnotched bending member with the same net depth d_n. Such a gradual change shall be achieved by providing smooth transitions between surfaces with no overcuts at reentrant corners.

2.3.4 Partial-width Notches

A partial-width notch is a notch on the face of a bending member that does not extend across the full width of the face (see Figure 2A).

Figure 2A Partial-width notches



2.3.4.1 The width w_1 of a partial-width notch on the tension or compression face of a bending member shall not exceed one-third the breadth b of the member. The flexural and shear capacities of the member shall be determined by the principles of engineering mechanics using the net cross section of the member at the notch.

2.3.4.2 A partial-width notch on the side of a bending member shall have width w_2 no greater than $d/2$ and the notch shall lie within the middle half of the depth of the member. The flexural and shear capacities of the member shall be determined by the principles of engineering mechanics using the net cross section of the member at the notch.

2.3.4.3 A partial-width notch extending from the compression face down the side of a bending member shall have a width w_3 not exceeding $b/4$. The flexural and shear capacities of the member shall be determined by the principles of engineering mechanics using the net cross sectional dimensions. If the clear distance parallel to grain between such notches on opposing sides of the member exceeds 6*b*, the notches shall be regarded as occurring at different cross sections. If the clear distance parallel to grain between notches on opposing sides of the member is less than 6*b*, the notches shall be regarded as occurring at the same cross section location. The clear distance parallel to grain between notches on the same side shall not be less than 6*b*.

3.0 Connections

3.1 General

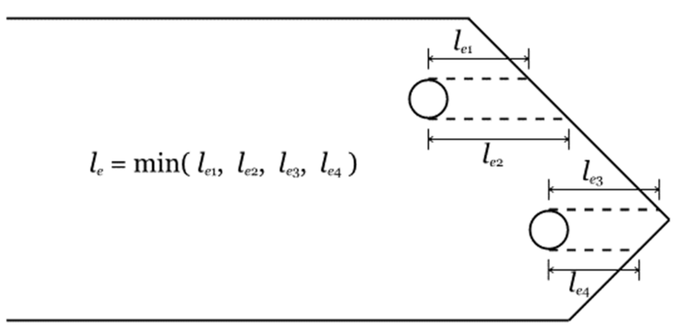
Chapter 3 applies to the engineering design of connections using wood-on-wood bearing and wood fasteners, including pegs and wedges, for load transfer. The provisions of the ANSI/AWC NDS© shall apply for the design of connections using metallic fasteners and metal connector plates.

3.1.1 Terminology

3.1.1.1 "Edge distance" is the distance l_v from the edge of a member or the inside face of a housing to the center of the nearest fastener, measured perpendicular to grain. When a member is loaded perpendicular to grain, the loaded edge shall be defined as the edge in the direction toward which the fastener is acting. The unloaded edge shall be defined as the edge opposite to the loaded edge.

3.1.1.2 "End distance" is the distance l_e measured parallel to grain from the square-cut end of a member to the center of the nearest fastener. For a member with a tapered-cut end, "end distance" is the minimum distance measured parallel to grain from the face of the cut end of a member to a diametrical line oriented perpendicular to grain through the center of the nearest fastener (see Figure 3A).

Figure 3A End distance for tapered member ends



3.1.1.3 "Spacing in a row" is the distance measured parallel to grain between the center of two fasteners in a row. "Spacing between rows" is the distance measured perpendicular to grain between two rows of fasteners.

3.1.2 Installation of Pegs

3.1.2.1 Holes for pegs shall be sized such that pegs are held securely by friction after installation, but pegs shall not be damaged by crushing, mushrooming, flexure, or splitting as they are driven into the hole.

3.1.2.2 Draw boring shall be permitted where it can be demonstrated by full-scale or prototype tests or by extensive experience in use that wood splitting in the tenon and damage to the peg do not occur and that the strength of the connection is not compromised.

3.1.3 Installation of Wedges

3.1.3.1 The opening in the receiving member for a wedge shall be sized such that the wedge is held in place by direct bearing of the wedge against endgrain inside the opening of the receiving member. Tension perpendicular to grain in the receiving member through direct bearing of the wedge shall not be permitted.

3.1.3.2 Joint detailing and assembly shall be as required to prevent splitting of the tenon, spline, or other joint material that receives the wedge as a result of wedge installation.

3.1.4 Connection Design

3.1.4.1 Design of mortise and tenon connections for shear or tension shall conform to the provisions of Sections 3.3 through 3.6 of this Standard.

3.1.4.2 Design of other connections (dovetails, scarfs, laps, etc.) shall be according to the principles of engineering mechanics with appropriate consideration for stress concentrations from notching.

3.2 Withdrawal

3.2.1 Prohibition of Withdrawal Loading

Joint detailing and assembly that may result in withdrawal loading of a peg or wedge is prohibited.

3.3 Mortise and Tenon Connections Loaded in Shear

3.3.1 Load Transfer by Direct Bearing

Transfer of shear load in a tenoned member to a mortised member shall be achieved by direct bearing of the tenon within the mortise or by direct bearing of the tenoned member on a mortise housing.

3.3.2 Shear Capacity

The shear capacity of the tenoned member shall be determined based on the breadth of the bearing surface of the tenoned member supported by the mortised member.

3.3.3 Strength Contribution of Pegs

Pegs shall not be considered to contribute to the shear strength of the tenoned member.

3.3.4 Connection Detailing

Pegs in connections in which the tenoned member is loaded in shear shall be located as close as practicable to the bearing surface.

Connections in general, and mortise and connections in particular, shall be detailed such that they do not entrap water when exposed to wet environments.

3.4 Mortise and Tenon Connections Loaded in Tension

3.4.1 Yield Limit Equations

Transfer of tension load in a tenoned member to a mortised member shall be permitted to be achieved by lateral-load transfer through one or more pegs. The nominal design value Z for one peg shall be permitted to be computed using the equations of Table 3A provided that:

(a) faces of the tenon and mortise are in close contact

(b) the load acts perpendicular to the axis of the peg

(c) the peg is loaded in double shear

(d) edge distance, end distance, and spacing are in accordance with provisions of Sec. 3.4.8

(e) the penetration length of the peg in the mortise side wall on each side of the tenon equals at least the thickness of the tenon

(f) the sizes and species of the pegs in a multiple-peg joint are identical

(g) the peg diameter is no less than 0.75 inches and no greater than 1.25 inches.

(h) the tension capacity of the tenon at its net cross section (see NDS® Section 3.1.2) is sufficient to resist the applied load.

The nominal design value *Z* for one peg shall be the minimum computed yield value using equations in Table 3A. The capacity of the connection shall be the capacity of one peg times the number of pegs in the connection.

Table 3A Yield Limit Equations, Double Shear

Yield Mode	Capacity		Yield Mode	Capacity	
I_m	$Z = \frac{D\ l_m F_{em}}{R_d}$	(3.4-1)	III_s	$Z = \frac{2\ k_3\ D\ l_s F_{em}}{(2+R_e)R_d}$	(3.4-3)
I_s	$Z = \frac{2\ D\ l_s F_{es}}{R_d}$	(3.4-2)	V	$Z = \frac{\pi D^2\ F_{yv}}{2\ R_d}$	(3.4-4)

Notes:

$R_d = 4.0\ K_\theta$ (Modes I_m and I_s)

$= 3.2\ K_\theta$ (Mode III_s) (3.4-5)

$= 3.5$ (Mode V)

$$K_\theta = 1 + \left(\frac{\theta}{360}\right) \quad (3.4\text{-}6)$$

$$k_3 = -1 + \sqrt{\frac{2(1+R_e)}{R_e} + \frac{2F_{yb}(2+R_e)D^2}{3F_{em}l_s^2}} \quad (3.4\text{-}7)$$

$$F_{yv} = 4850 G_p G_t^{0.75} \quad (3.4\text{-}8)$$

$$R_e = F_{em}/F_{es} \quad (3.4\text{-}9)$$

3.4.2 Dowel Bearing Strength

Dowel bearing strength F_{es} and F_{em} used in the yield limit equations shall be determined as follows. For tenons in a mortise and tenon connection with the tenon loaded in tension, $F_{em} = F_{e||}$ given by

$$F_{e\parallel} = 4770 G_p^{1.32} \qquad (3.4\text{-}10)$$

For mortised members in a mortise and tenon connection with the tenon loaded in tension, $F_{es} = F_{e\perp}$ given by

$$F_{e\perp} = 4900 G_p G_t^{0.50} \qquad (3.4\text{-}11)$$

3.4.3 Dowel Bearing Strength at an Angle to Grain

When a mortised member is loaded at an angle to the grain, the dowel bearing strength $F_{e\theta}$ for the member shall be determined as follows:

$$F_{e\theta} = \frac{F_{e\parallel} F_{e\perp}}{F_{e\parallel} \sin^2\theta + F_{e\perp} \cos^2\theta} \qquad (3.4\text{-}12)$$

3.4.4 Dowel Bearing Length

3.4.4.1 Dowel bearing length in the main member and side member(s) represent the length of dowel bearing perpendicular to the applied load. The length of dowel bearing shall not include the tapered tip of a peg.

3.4.4.2 Dowel bearing length l_m in the main member shall be taken as the thickness of the tenon.

3.4.4.3 Dowel bearing length l_s in the side member shall be taken as the minimum of the two penetration lengths in the side walls of the mortise.

3.4.5 Bending Yield Strength of Pegs

3.4.5.1 Bending yield strength F_{yb} for wood pegs shall be determined as follows:

$$F_{yb} = 22{,}200\ G_p \qquad (3.4\text{-}13)$$

Alternatively, bending yield strength shall be permitted to be determined using methods provided in ASTM F1575 (Ref. 8). Table 3B contains values of bending yield strength for pegs formed from the species so listed.

Table 3B – Bending yield strength of pegs per ASTM F1575

Species	F_{yb} (psi)
Black Locust	18,200
Hard Maple	14,500
Red Oak	14,300
White Oak	12,300

3.4.6 Peg Diameter

3.4.6.1 For nominally round pegs, peg diameter *D* shall be taken as the mean diameter of the peg.

3.4.6.2 For octagonal or other faceted cross-section pegs, peg diameter *D* shall be the minimum dimension measured across the peg between two parallel faceted faces.

3.4.6.3 The diameter of a peg shall not exceed two-thirds of the thickness of the tenon that it joins to the mortise.

3.4.7 Seasoning and Creep Effects

The effects of seasoning and creep on the serviceability of mortise and tenon connections loaded in tension shall be considered. The possible redistribution of forces due to long-term deflection of connections shall be examined.

3.4.8 Edge Distance, End Distance and Spacing

Mortise and tenon joints loaded in tension shall be proportioned such that splitting of the wood members does not occur.

In the absence of connection details shown to produce satisfactory performance in their intended end use, end distance, edge distance and spacing of pegs shall meet the provisions of Table 3C.

Table 3C – End Distance, Edge Distance and Spacing Requirements			
Detailing Dimension	Loading Direction	Minimum value for $C_\Delta = 0.5$	Minimum value for $C_\Delta = 1.0$
End Distance	Perpendicular to grain	2.0 *D*	2.5 *D*
End Distance	Parallel to grain, compression	2.0 *D*	2.5 *D*
End Distance, Softwoods	Parallel to grain, tension	2.0 *D*	4.0 *D*
End Distance, Hardwoods	Parallel to grain, tension	2.0 *D*	3.0 *D*
Edge Distance	Parallel to grain	--	1.5 *D*
Edge Distance, Loaded edge	Perpendicular to grain	--	2.5 *D*
Edge Distance, Unloaded Edge	Perpendicular to grain	--	1.5 *D*
Spacing in a row	Any	3.0 *D*	4.0 *D*
Spacing between rows	Parallel to grain	1.5 *D*	2.5 *D*
Spacing between rows	Perpendicular to grain	1.5 *D*	3.0 *D*

3.4.9 Adjustment Factors for Peg Connections

The nominal design capacity *Z* for a connection shall be multiplied by all applicable adjustment factors to determine the allowable design value *Z′*. Equation (3.4-14) specifies the adjustment factors that apply to the nominal design value *Z*.

$$Z' = Z \times \left[C_D C_M C_t C_g C_\Delta \right] \tag{3.4-14}$$

The actual load applied to a connection shall not exceed the allowable design value *Z′* for the connection.

3.4.9.1 The load duration factor C_D, the temperature factor C_t, and the group action factor C_g shall be selected according to the provisions in Chapter 11 of the ANSI/AWC NDS©. The load duration factor shall not exceed 1.6.

3.4.9.2 Wet Service Factor, C_M: Nominal design values for timber are for material in the unseasoned condition. Hence, design values shall be permitted to remain unadjusted for timber exposed to wet service conditions at a moisture content above 19%. C_M is equal to 1.0 when a single peg is used in the connection or pegs are placed in a single row parallel to grain in the tenon or spline. In other cases, consideration shall be given to any potential strength reduction caused by restraint of shrinkage in pegged connections when moisture content at the time of assembly exceeds 19% and the in-service moisture content will be less than or equal to 19%.

3.4.9.3 Geometry Factor, C_Δ: When the end distance or spacing provided for peg connections is less than that required for full design value, but greater than the minimum required for reduced design value, nominal design values shall be multiplied by the smallest applicable geometry factor determined from the end distance and spacing requirements, where for each detailing dimension, the corresponding geometry factor, C_Δ, shall be determined as follows:

$$C_\Delta = \frac{\text{actual detailing dimension}}{\text{minimum dimension for } C_\Delta\text{=1.0}} \qquad (3.4\text{-}15)$$

The smallest geometry factor determined from Eq. (3.4-15) for any peg in a group shall apply to all pegs in the group.

3.4.10 Tenon Size and Quality

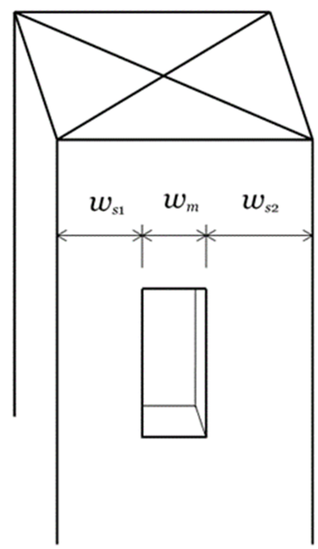
3.4.10.1 Tenon Size: The thickness of a tenon shall not exceed one-third the breadth of the face of the mortised member that receives the tenon.

3.4.10.2 Tenon Quality: Tenons shall be fabricated in a manner and location such that the strength of the tenon is not disproportionately reduced from that of the member due to the presence, size, and location of knots, shakes, slope of grain, pith, and other defects.

3.4.11 Mortise Placement

Mortises shall be placed such that the widths w_{s1} and w_{s2} of sidewalls adjacent to the mortise are each equal to or greater than the width w_m of the mortise (see Figure 3B).

Figure 3B Mortise placement



3.5 Seasoning Effects

For connections fabricated from unseasoned lumber, consideration shall be given to the potential effects of distortion due to shrinkage or warping prior to and after assembly of the structure. In addition, the potential effects of seasoning on the assembled connection shall be considered. In particular the possible loss of bearing contact between two members and the change in orientation of bearing surfaces shall be considered.

3.6 Bearing Connections Inducing Block Shear

Where connections transfer load through wood-on-wood bearing, the capacity of the connection may be limited by wood failure in block shear. In such cases, the block shear capacity of the member receiving the load shall be calculated as follows:

$$Z' = F_v' A_v / 2 \qquad (3.6\text{-}1)$$

where:

Z' = adjusted block shear capacity

F_v' = adjusted shear design value parallel to grain, but with C_M = 1.0.

A_v = block-shear area parallel to grain

4.0 Design for Lateral Loads

4.1 Stand-Alone Timber Frames

Stand-alone timber frames are those frames in which lateral-load resistance is provided solely by traditional knee braces or long braces using mortise and tenon connections with wood pegs. Where stand-alone frames are designed with braces capable of resisting only compression, braces shall be provided in pairs, with the braces resisting lateral load from opposing directions. Connections for compression-only braces shall be designed to transmit forces through wood-to-wood bearing.

4.1.1 Serviceability Considerations

Stand-alone timber frames in which mortise and tenon joints on braces are subjected to tension have been shown to have limited stiffness under lateral loads due to the relatively low stiffness of wood-pegged joints. Hence, the effects of joint stiffness shall be considered in the structural analysis of stand-alone timber frames to assure that the strength and serviceability of the structural system are adequate for the intended end use.

4.1.2 Seismic Design Criteria

4.1.2.1 For knee-braced frames used as the seismic force-resisting system in a structure, the following seismic design coefficients shall be used.

Response modification coefficient, $R = 3.0$

Overstrength Factor, $\Omega_0 = 3.0$

Deflection amplification factor, $C_d = 4.0$

These coefficients are applicable to frames designed to withstand the maximum ground shaking in seismic design categories A, B, C and D.

4.1.2.2 For knee-braced frames used as the seismic force-resisting system in a structure, the pegs used in connections shall conform to the provisions of ASTM D8023.

4.2 Timber Frames and Diaphragm/Shearwall Systems

The strength and stiffness of timber frames constructed with diaphragms and shearwalls to resist lateral load shall be determined by one of the following methods.

4.2.1 Coupled Timber Frame and Diaphragm/Shearwall Systems

Timber frames and their jointed connections that resist lateral loads shall be designed for strength based on allowable stresses for the frame members and connections. Designated shearwalls and diaphragms shall be designed for strength based on the allowable shear load for the individual shearwalls and diaphragms. Design forces in the timber frames, shearwalls, and diaphragms shall be determined by the use of a diaphragm-frame interaction structural model that includes the relative effects of shearwall stiffness and roof diaphragm stiffness on the lateral load distribution to the lateral-load-resisting components.

4.2.2 Timber Frame Gravity-Only Systems

For timber frames that are intended to resist only gravity loading, additional structural systems, such as diaphragm/shearwall systems (consisting of sheathing, chord elements, drag struts and anchorage), shall be designed to resist all lateral loads on the structure. In addition, connections between the timber frame and the lateral-force resisting system shall be adequate to maintain displacement compatibility between the timber frame and the lateral-force resisting system. The timber frame must be designed to safely resist the forces associated with maintaining displacement compatibility.

Appendix A Glossary

COPE – a notch cut on the tension face of a bending member at the member's bearing surface.

DRAW BORING – traditional framing technique in which the peg hole in the tenon is deliberately offset from the peg hole in the mortise to draw a joint tight when assembled and fastened with a tapered pin or peg, and to hold the joint tight after shrinkage of the mortised member occurs.

EDGE DISTANCE –The distance from the center of a peg hole to the edge of the member, or to the edge of the housing, in a mortised member measured perpendicular to the grain direction.

END DISTANCE –The distance from the center of a peg hole to the end of the member, measured parallel to the grain direction.

HOUSING – a recess in a supporting member to permit the full width of an adjoining member to bear on the supporting member.

LATERAL FACE – a face of a structural member that is parallel to the plane of the loads on the bending member. The lateral face is perpendicular to the tension and compression faces.

MOISTURE CONTENT – the weight of water in the cell walls and cavities of wood, expressed as a percentage of oven-dry weight.

MORTISE – a rectangular notch, slot, or hole cut into a structural component that will accept a corresponding tenon or spline.

MORTISE AND TENON (M&T) – a joint in which a projection (tenon) on one end of a piece is inserted into a notch, slot or hole (mortise) in another piece.

MORTISE SIDE WALL – the portion of the mortised member between the inside face of the mortise and the outside face of the member.

NOTCH – an area in a timber where a portion of the cross-section has been cut away, typically as part of joinery between two intersecting members.

NOTCH, FULL-WIDTH – a notch on the tension or compression face of a bending member that extends across the full width of the face.

NOTCH, PARTIAL-WIDTH – a notch on the tension or compression face of a bending member that does not extend across the full width of the face.

PEG – a cylindrical or slightly tapered wooden dowel or pin with round, octagonal, or other faceted cross section.

SCARF JOINT – a joint made by notching and lapping two timbers such that the longitudinal axes of the timbers are collinear.

SPECIFIC GRAVITY (G) – the ratio of the oven-dry weight of a sample of wood to the weight of a volume of water equal to the volume of the sample of wood at a specified moisture content.

SPLINE (aka: FREE TENON) – a lumber or engineered wood element placed in slot cuts, grooves, dados, etc. to secure joints between two components.

STAND-ALONE TIMBER FRAME – a timber frame structure designed to resist lateral loads without the use of shear walls or other supplementary structural systems.

TENON – a projecting square or rectangular end on a timber that fits into a mortise to complete the connection of two pieces.

TIMBER FRAME – a structural building frame system or portion thereof that is composed of heavy timber members in which connections between interlocking members are typically created by carpenter-style joinery using wood pegs and wood wedges but may be supplemented with some metallic fastener components.

WEDGE – a tapered wood element with rectangular cross section used to secure through-tenons, through-splines and scarf joints.

References

1. AITC 117-2004 - Standard Specifications for Structural Glued Laminated Timber of Softwood Species, AITC, Centennial, CO.
2. AITC 119-96 – Standard Specifications for Structural Glued Laminated Timber of Hardwood Species, AITC, Centennial, CO.
3. AITC Standard A190.1-2017, Structural Glued Laminated Timber, AITC, Centennial, CO.
4. ANSI/AWC, NDS©-2018, National Design Specification for Wood Construction, AWC, Washington, D. C.
5. ASTM Standard D245, Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber, ASTM, West Conshohocken, PA.
6. ASTM Standard D5764-97a, Test Method for Evaluating Dowel Bearing Strength of Wood and Wood Base Products, ASTM, West Conshohocken, PA.
7. ASTM Standard D8023, Standard Specification for Round Wood Dowels (Pegs) for Use in Wood Construction, ASTM, West Conshohocken, PA.
8. ASTM Standard F1575-17, Standard Test Method for Determining Bending Yield Moment of Nails, ASTM, Conshohocken, PA.
9. National Institute of Standards and Technology Voluntary Product Standard PS 20-15, American Softwood Lumber Standard, Washington, DC.
10. SEI/ASCE Standard 7-16, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA.
11. SEI/ASCE Standard 37-02, Design Loads on Structures During Construction, American Society of Civil Engineers, Reston, VA.
12. TFEC 3 (2018) Guide to Structural Evaluation of Existing Timber Structures, Timber Frame Engineering Council, November.

Commentary to TFEC 1-2019
Standard for Design of Timber Frame Structures

C1.0 General Requirements for Structural Design and Construction

C1.1 Applicability and Scope

The Standard defines the standard of practice for the structural design of timber frame construction, which is typified by use of carpenter-style joinery to connect members. Carpenter-style joinery includes, but is not limited to, use of mortise and tenon joints, dovetails, fork and tongue joints, and scarf joints. These joints are normally secured with wood pegs or wedges.

The Standard is intended as a supplement to provisions of the NDS©, not as an alternative or replacement. For instance, design of connections for heavy timber members using steel side plates and bolts is adequately defined in the NDS©; thus, the Standard does not address this aspect of timber design.

The provisions of the Standard are not intended to limit or prohibit use of alternative materials and methods for structural design and construction. Practices and procedures that have been shown to be safe and effective are not restricted. Alternative design approaches based on reliability-based concepts or other recognized approaches are also not restricted.

C1.3 General Requirements

C1.3.1 Strength

The loads applied during assembly and raising of a timber frame can differ substantially in character and magnitude from those that act on a completed frame. Supplemental strengthening and bracing may be needed to protect the integrity of the frame during construction. Structural analysis and design of these supplemental systems may be necessary.

C1.3.2 Serviceability

As with all structures, the appropriate serviceability limits are dependent on the conditions and use of the building. Limits on deflections or drift are not defined in the Standard. Local building codes normally include appropriate deflection and drift limits.

C1.3.3 General Structural Integrity

The requirement for general structural integrity is intended to assure that a building can sustain local damage under unanticipated loads without progressive, catastrophic collapse of the remainder of the structure. Statically determinate systems without multiple load paths are particularly vulnerable.

C1.5 Construction Documents

C1.5.2 Material Selection

Design values vary with the species of timber as well as the geographic source of the material. For instance, design values for Douglas fir produced in the United States differ from those for Douglas fir produced in Canada. To assure accurate account of both strength and stiffness of members, the specific material, source, stress grade and grading rules must be identified.

C1.5.3 Member Sizes

There is no definitive relationship between nominal size and actual size of timbers used in timber framing. Mill conventions as well as joinery practices influence the size of timber actually produced. To assure accurate account of both strength and stiffness of members, the actual member sizes must be identified.

C1.5.4 Connection Details

Design values for connections are dependent upon use of accurate joinery details, including tenon thickness, width and length; mortise width, height and depth; and peg hole size and placement.

C1.6 Materials

C1.6.1 Sawn Timber

Normally, timber used in structural applications is visually graded based on rules approved by the American Lumber Standards Committee (Ref. 19), such that reference design values in the NDS Supplement – Design Values for Wood Construction (Ref. 6) – may be used. However, reference design values are not available for all species of timber that might be used in a timber frame structure. In particular, timber produced from a particular species may exhibit properties significantly different from those for the corresponding species combination. In these cases, the building official may permit use of such material in a structural application based on visual examination, nondestructive testing, or other rationale provided by the engineer of record.

The methods of ASTM D245 (Ref. 5 of the Standard) may be applied to those timber species for which mechanical test results in accordance with ASTM D143 (Ref. 3) are available. This approach allows for assignment of reference design values other than those corresponding to the stress grades established by the grading agencies, to reflect the quality of the material and seasoning. TFEC Technical Bulletin 11 (Ref. 2) provides guidance on this approach.

Grading rules and reference design values are not available for reclaimed, recycled or remanufactured material. Nevertheless, use of these materials is not restricted by the Standard.

C1.6.3 Wood Pegs

Experience suggests that wood pegs used in structural applications must contain sound, straight-grain, defect-free material. Presence of defects or slope-of-grain can lead to failure of the peg during installation. Research results on the strength of pegged connections are based on the use of hardwood pegs with specific gravity of the peg stock equal to or exceeding that of the timber stock. A minimum peg specific gravity of 0.50 is established based on past performance. A maximum peg specific gravity of 0.86, corresponding to the value for black locust pegs tested in Ref. 15, is selected as an upper limit for use in the provisions of the Standard. Pegs with higher specific gravity may be used in frame construction, but their design capacities may not exceed that of material with $G = 0.86$. The NDS© supplement *Design Values for Wood Construction* should not be used to assign design values to pegs.

C1.6.4 Wood Wedges

Experience suggests that wood wedges used in structural applications must contain sound, straight-grain, defect-free material. Presence of defects or slope-of-grain can lead to failure of the wedge during installation. Use of hardwood wedge stock with specific gravity equal to or exceeding that of the timber stock is required to reduce the likelihood of wedge failure by bending or compression perpendicular to the grain.

C1.6.5 Splines

Splines are generally used as alternatives to tenons to provide greater flexibility when detailing connections. No known research is available on their design and performance requirements, but common practice is to use material with a higher specific gravity for splines than that of the connected members. Detailing of splines (thickness, width, peg spacing, etc.) is left to the judgement of the design professional.

C2.0 Structural Members

C2.1 General

The Standard stands as a supplement to the ANSI/AWC NDS©. Hence, the Standard contains provisions for timber frame design not included in the NDS©. The NDS© remains the primary governing design document for structural design of wood buildings.

C2.2 Seasoning Effects

Timber frame structures are often cut and assembled using unseasoned timbers. Seasoning in place can lead to shrinkage, 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.

Research reviewed in Ref. 1 demonstrates that timbers used in dry-service conditions experience an increase in strength and stiffness relative to those in the unseasoned condition. Since design values are assigned to timbers in the unseasoned condition, it is reasonable to exploit that increase in strength due to seasoning so long as the changes in cross section dimensions due to drying shrinkage are also determined. The permitted adjustment is limited to the design value for bending, due to a lack of supporting evidence for other design values.

C2.3 Notching

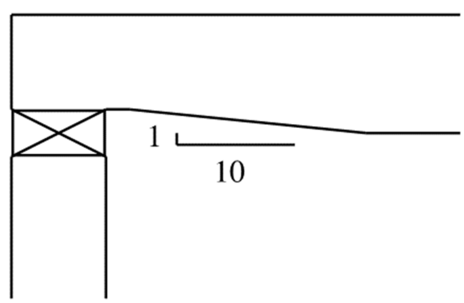
The effects of notching on member stiffness will vary, as there are no standard limits on notch geometry and placement. Hence, each situation must be evaluated on a case-by-case basis by the engineer of record. The NDS suggests that stiffness is practically unaffected by a notch when notch depth does not exceed 1/6 of the beam depth and notch width does not exceed 1/3 the beam depth. The stiffness of a member with multiple notches may require special consideration. Two examples in which notch effects may impact stiffness are:

- Closely spaced joist housings along the length of a carrying beam
- Multiple housings in a post for a three-way or four-way connection

The provisions of the NDS© are applicable to design of bending members that are notched across the full width of their tension or compression faces. Such notches often occur when beam ends are tapered or coped at their bearing surfaces. According to NDS© Section 3.4.3.2(d), the stress concentration can be eliminated with a suitable "gradual change in cross section." When such a notch is provided, the shear capacity of the bending member may be taken as that of an unnotched member with a depth of d_n.

Any number of approaches may be used to achieve this condition. One such approach, as recognized in Eurocode 5 (Ref. 12), is to provide a linear taper with a slope not steeper than 1:10 (see Figure C-2A), in which case the stress concentration may be disregarded.

Figure C-2A Linear taper notch



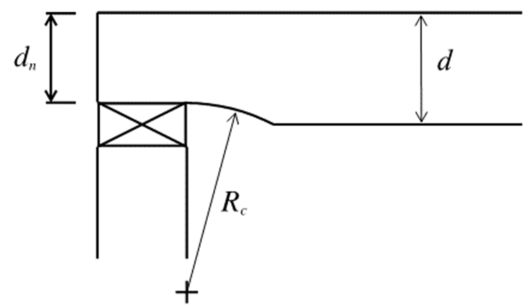
Another approach is to provide a notch geometry in the form of a circular arc that is tangent to the bearing surface at the end of the member and intersects the tension face of the member at a distance of $4(d - d_n)$ from the bearing surface. When such gradual change is achieved by coping to a circular arc of radius R_c given by

$$R_c = 8.5(d - d_n) \qquad \text{(C2.3-1)}$$

where the arc is tangent to the bearing surface at the end of the member (see Figure C-2B), then the allowable design shear V_r' may be calculated as

$$V_r' = \frac{2}{3} F_v' b d_n \qquad \text{(C2.3-2)}$$

Figure C-2B Coped notch



Partial-width notches are common in timber frame structures and typically consist of mortises, housings, and beam pockets. Partial-width notches occur when a mortise is cut to receive a tenon. Partial-width notches also occur in, among others, ridge beams, purlins, and wall plates that support rafters. The provisions for bending strength and shear strength of members with partial-width notches are based on judgement and limited experimental results of similar notches cut in dimension lumber bending members.

Partial-width notches on the sides of bending members that extend below mid-depth of the member from the compression face, such as those in Sec. 2.3.4.2 and 2.3.4.3 of the Standard, are common in timber framing. For example, these notches are used where joists frame into the sides of carrying beams. In such instances, bearing of the joist on the bottom surface of the notch induces a complex stress state including tension perpendicular to grain, horizontal shear, rolling shear and flexure. Tests reported in Ref. 18 indicate that load-bearing capacity of the notch increases with increasing clear distance to the tension face. This behavior suggests that light loads may be safely supported by smaller net depths than for heavy loads. As yet, however, capacity-based design equations have not been developed to define the relationships among the notch dimensions, clear distance to the tension face, mechanical properties of the wood in the notched timber, spacing of the notches, and safe load-carrying capacity of the notch. Nevertheless, some guidance from practice in Germany is available; in particular DIN 1052 2004-08 (Ref. 11) specifies a minimum net depth of $d/3$ below the side notch discussed in Section 2.3.4.2 of the Standard.

Where partial width notches in the side of a bending member occur on opposite lateral faces at the same cross section of the member, the limit on width w_3 applies individually to each notch. The flexural and shear capacities of the member can be determined in accordance with Section 2.3.4.3 of the Standard.

Housings may consist of relatively shallow partial-width or full-width notches in a member to receive the end of a joining member. Similarly, fabrication of joinery by the square-rule method also involves small reductions on the faces of the receiving member. The provisions in this standard for partial-width notches are not intended to apply to or restrict the use of shallow, partial-width housings or reductions. Rather determination of the effects of housings and reductions on the strength and stiffness of a timber member is left to the judgement of the engineer of record. Full-width housing are covered by provisions of the NDS©, Sec. 4.4.3 and Sec. 5.4.5.

C3.0 Connections

C3.1 General

The provisions of the NDS© apply to a broad range of connections using metallic fasteners. However, explicit provisions to guide the design of connections using non-standard fasteners are not included. Rather, Section 12.1.8 of the NDS© permits other dowel-type fasteners, including wood pegs, to be used to transfer lateral load in connections, provided that the variation in connection type is accounted for and detailing dimensions are sufficient to prevent splitting. The Standard addresses use of wood pegs and wedges as fasteners in connections.

C3.1.2 Installation of Pegs

Normally, holes for round pegs are drilled to the same diameter as the pegs. Hole size for pegs of noncircular cross section should be determined by trial.

Draw boring has the potential to cause damage to the peg and to the tenon if the offset in the peg hole is too great. Successful draw boring can measurably increase initial stiffness of a mortise and tenon connection under tension and can reduce long-term deflections of the joint due to seasoning and sustained load effects (see Ref. 22). In such cases, the tensile strength of the joint is not compromised. For connections using 3/4" diameter pegs, typical values of peg hole offset between the tenon and the mortised member are 1/16-inch for hardwood timbers and 1/8-inch for softwood timbers.

C3.1.3 Installation of Wedges

Wedges must be sized and installed to apply only tension load parallel to the grain of the member that receives the wedge. If a wedge is too wide (in the dimension between the two parallel faces), it will cause tension perpendicular to the grain of the receiving member. This tension can subsequently increase due to shrinkage of the member and lead to splitting.

C3.1.4 Connection Design

Sufficient research on the performance of mortise and tenon connections has been performed to support development of specification provisions. Similar research for other joinery-type connections, including dovetails, scarfs, and laps, is not available. Hence, design of these connections must be based on the principles of engineering mechanics and the judgement of the engineer of record.

C3.2 Withdrawal

C3.2.1 Prohibition of Withdrawal Loading

It might be argued that a wood peg has some nominal withdrawal capacity, similar to that for drift pins (see Ref. 24). However, since both the timber member and wood peg are subject to size variation due to moisture cycling, the variability in withdrawal capacity of a wood peg would be significantly larger than that of a drift pin. Also, accepted timber framing practice is to avoid withdrawal loading of pegs. Hence, no withdrawal design value is assigned.

C3.3 Mortise and Tenon Connections Loaded in Shear

C3.3.1 Load Transfer by Direct Bearing

Pegs used to secure a tenon within a mortise may not be relied upon for transfer of shear loads. Such a load path produces tension perpendicular to the grain of the tenon, which can lead to brittle failure at relatively low loads (see Ref. 23). In addition, transverse shear loading of the tenon by the pegs can result in rolling shear failure of the tenoned member. Hence, transfer of shear load through a mortise and tenon connection must be by direct bearing of the tenon on the mortise housing.

C3.3.2 Shear Capacity

Shear load in a beam may be transferred to the mortised member through direct bearing across the width of the tenon for a beam that is not housed, or across the full width of the beam for a fully housed beam.

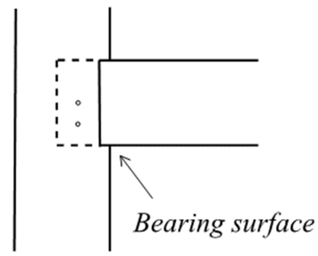
C3.3.3 Strength Contribution of Pegs

Direct bearing between a tenon and a mortise housing provides a load path with substantial stiffness, relative to that of a pegged connection. Hence, virtually all of the shear load in the joint will be transferred through the bearing surface. Pegs may be needed to carry some short-term load during assembly and erection of the frame, before the bearing surfaces come into full contact.

C3.3.4 Connection Detailing

The effects of shrinkage after joint assembly must be considered such that direct bearing between members is maintained. Placement of pegs close to the bearing surface is one effective means to control shrinkage effects (see Figure C-3A).

Figure C-3A Peg placement to control shrinkage effects



Entrapment of water in and around connections may lead to loss of durability due to decay. Proper detailing is essential to protect connections from collecting and retaining water. Blind mortises with upward-facing openings are particularly vulnerable, as any water that enters them will not freely drain away, preventing the mortise from drying out quickly.

C3.4 Mortise and Tenon Connections Loaded in Tension

C3.4.1 Yield Limit Equations

The yield model approach can be used to predict the tensile strength of pegged mortise and tenon connections. With this approach, the tenon is regarded as the main member and the mortise side walls are regarded as side members in a double-shear connection. Yield modes that have been observed in pegged mortise and tenon connections include:

Mode I_m – crushing in the main member and peg material due to bearing action

Mode I_s – crushing in the side member and peg material due to bearing action

Mode III_s – combined flexure of the peg and crushing of the timber due to bearing

Mode V – double shear failure of the peg

Modes II and III_m in the NDS© are not applicable due to geometric constraints of a double shear connection. Mode IV has not been observed in pegged mortise and tenon connections due to the restraint (confinement) placed on the pegs in the connection. For connections with relatively large diameter pegs, Mode III_s failure occurs with a single flexural hinge in the peg. For connections with relatively small diameter pegs, Mode V failure is observed. In some cases, pegs exhibit evidence of both flexural (Mode III_s) and shear (Mode V) failure.

The effective shear strength F_{vp} of a peg for Mode V failure is related to the values of specific gravity G_t and G_p for the timber and peg, respectively. The expression for F_{vp} in Table 3A of the Standard was developed from research presented in Ref. 17.

The majority of research available on the behavior of pegged mortise and tenon joints utilizes 1-inch diameter pegs. Some test results are available for joints with 0.75-inch and 1.25-inch pegs. Hence, the provisions of the Standard are limited to pegs in this range of sizes.

C3.4.2 Dowel Bearing Strength

In a pegged mortise and tenon connection under tension load, the peg and the mortise side walls are loaded in bearing perpendicular to grain, whereas the tenon is loaded in bearing parallel to grain. Hence, dowel bearing strength for a pegged connection depends upon the deformation of both the peg and the timber. Equations (3.4-9) and (3.4-10) for $F_{e||}$ and $F_{e\perp}$ respectively account for the deformation of both the wood peg and the timber base material under dowel bearing load. These equations were developed from a regression analysis of physical test results and a numerical study to generate dowel bearing strength data for 48 combinations of peg species, timber base material species, and load direction (Ref. 17). Good correlations between dowel bearing strength and material specific gravity were found. The coefficients of determination were $R^2 = 0.65$ and $R^2 = 0.77$ for Equations (3.4-9) and (3.4-10) respectively.

In situations for which use of Equations (3.4-9) and (3.4-10) is not appropriate, alternative approaches may be used to determine dowel bearing strengths for a pegged mortise and tenon connection.

In the first approach, strength data is taken directly from physical tests following ASTM D5764 (see Ref. 5) but with the steel dowel required by the test 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 Ref. 10 and 20.

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. 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 semi-cylindrical slot across one face matching the peg diameter. 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. Dowel bearing strength is determined from the combined load-displacement record 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 Ref. 21 and 22.

The third approach to finding dowel bearing strength is simply to choose the minimum value of F_e for the materials used in a connection. F_e for the timber material may be taken from tabulated data or empirical equations based on physical tests according to ASTM D5764. F_e for the peg is similarly determined by tests on pegs following ASTM D5764, but with the wood block replaced by a metallic load block with a semi-cylindrical slot matching the peg diameter across one face. Such data is available in Table 12.3.3 of the NDS©.

C3.4.5 Bending Yield Strength of Pegs

The expression for bending yield strength for pegs F_{yb} was developed through a testing program reported in Ref. 15. A linear regression provides satisfactory correlation between bending yield strength of pegs and peg specific gravity. For situations in which a particular species of peg material is used, results from direct physical tests according to ASTM F 1575 (Ref. 8 of the Standard) are permitted to be used.

As an alternative to use of Eq. 3.4-12 or physical testing, it is conservative to use the average modulus of rupture for the peg material, as listed in ASTM D2555 (Ref. 4) or the Wood Handbook (Ref. 24), as the value for bending yield strength, F_{yb}. Adjustment of the modulus of rupture to account for in-service moisture content, as provided in ASTM D245, may be advantageous.

C3.4.6 Peg Diameter

Peg diameter is limited to two-thirds of the thickness of the tenon in a mortise and tenon connection. This limit reflects good practice and helps maintain balance in the various limit states of the connection.

C3.4.7 Seasoning and Creep Effects

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 after the timbers reach equilibrium moisture content (EMC). The stabilized 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 (see Ref. 22). One approach to controlling creep behavior is to avoid subjecting pegged mortise and tenon joints to long-term tension loads.

C3.4.8 Edge Distance, End Distance and Spacing

Previous versions of TFEC 1 contained provisions for edge distance, end distance and spacing using the concept of an equivalent steel bolt as a surrogate for the wood peg in applying NDS© provisions for detailing dimensions. Subsequent numerical studies for typical mortise and tenon connections indicate that it is simpler and conservative to use detailing dimensions from the NDS©, with some of the values adjusted by a factor of 0.6 and then suitably rounded. The values in Table 3C of the Standard represent the updated requirements.

The detailing dimensions in Table C3A have been shown by physical tests to develop the full design value of a pegged mortise and tenon connection without splitting of the timber (see Ref. 22 and 23). Use of the provisions of Section 3.4.8 of the Standard may result in end and edge distances smaller than those in Table C3A and may be used accordingly.

Table C3A –Detailing Dimensions Based on Physical Tests

Timber Species	End Distance	Edge Distance	Spacing
Douglas Fir	2*D*	2.5*D*	2.5*D*
Eastern White Pine	4*D*	4*D*	3*D*
Red & White Oak	3*D*	2*D*	2.5*D*
Southern Yellow Pine	2*D*	2*D*	3*D*
Yellow Poplar	2.5*D*	2.5*D*	3*D*

C3.4.9 Adjustment Factors for Peg Connections

The applicability of the various adjustment factors to peg connections has not been satisfactorily determined. Some research on the duration of load effects has been conducted (see Ref. 22) and it appears that duration of load has no discernable effect on connection capacity. Nevertheless, use of the load duration factor C_D is permitted until its applicability is resolved. The flexibility of wood pegs might be sufficient to permit transverse shrinkage strains to develop without causing splitting of timbers. Hence, this flexibility could eliminate the applicability of the wet service factor for joints assembled from unseasoned timber that seasons naturally in service. Even if transverse shrinkage cracks were to develop in the tenoned member, the tenon in such connections is typically confined within the mortise such that spreading of the tenon is restrained. Also, the pegs are of sufficient diameter that the shear planes in the relish are little affected by a shrinkage crack, and so the connection retains both strength and ductility.

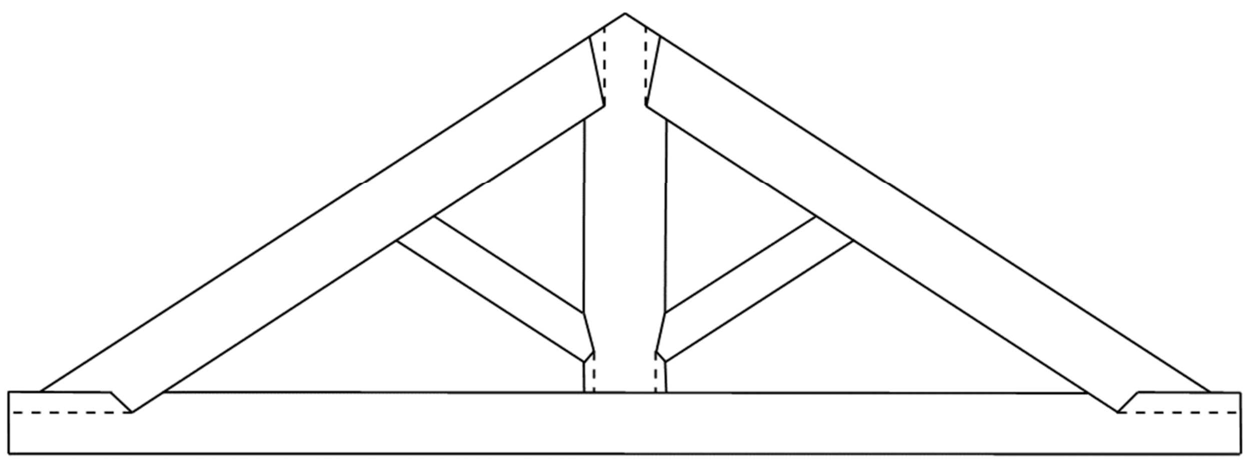
C3.5 Seasoning Effects

Timber frame structures are often cut and assembled while the timbers are unseasoned. Seasoning in place can lead to shrinkage, 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.

C3.6 Bearing Connections Inducing Block Shear

Joinery-style connections that rely on wood-on-wood bearing for load transfer often involve notching the member receiving the load. A king-post truss, such as that shown in Figure C-3B, may have notched connections at the heel joint, at the strut to king post joint, and at the rafter to king post joint. In each of these cases, as well as many others, the shear stress along the block-shear failure plane (shown dashed in the figure) is not uniform. Instead, it has a peak value at the notch and must be zero at the free surface. Equation (3.6-1) of the Standard represents this behavior, which is similar to the row tear-out capacity in Section E.3 of the NDS. Shear stress is assumed to vary linearly from a peak value of F_v' at the notch to 0 at the free surface, resulting in a triangular shear-stress distribution.

Figure C-3B King-post truss with bearing connections



Design values for shear stress given in the NDS Supplement have been developed for beam shear rather than block shear, and they contain a built-in strength ratio of 0.5 to account for the worst-case effect of checks, splits and shakes on beam bending capacity. Use of the NDS shear design values for connection design would appear to be conservative for connections in unchecked timber, whereas these values do provide some hedge against possible strength reducing effects of fractures in or near the critical shear plane, should they develop. They also provide an additional factor of safety against brittle shear failure, even if not explicitly considered as such.

C4.0 Design for Lateral Loads

C4.1 Stand-Alone Timber Frames

Traditional knee braces are diagonal braces with leg lengths that are less than half the story height and less than half the adjacent beam span. Long braces are diagonal braces with a vertical leg length at least 2/3 of the story height. Long braces may be used individually or in pairs with an X, V, or chevron (inverted V) configuration. Long-braced frames are more effective than knee-braced frames in resisting lateral load, resulting in less drift and lower brace forces.

Analysis models for lateral-load performance of stand-alone frames should account for the difference in strength and stiffness between tension and compression brace connections.

C4.1.1 Serviceability Considerations

Stiffness of pegged mortise and tenon joints is sufficiently low that substantial drift (lateral displacement) has been observed in frames that rely only on knee braces for lateral stability. Conventional structural analysis programs can accurately predict the behavior of stand-alone frames when the stiffness of pegged joints is included in the analysis models. Appropriate modeling techniques are presented in Ref. 7, 8 and 13. Based on tests of individual joints, the axial stiffness k (lb/in) of a mortise and tenon joint loaded in tension and secured with two 1-inch diameter oak pegs may be approximated by $k = 110{,}000\, G_t$, where G_t is the specific gravity of the timber (see Ref. 14). Stiffness under compression loading depends upon direct bearing contact, rather than peg stiffness, between the connected elements after any gaps in joinery are closed. Complicating factors including shrinkage and joint fit-up contribute to the challenge of predicting frame deflections.

Guidance on serviceability limit states is available in Appendix C of ASCE 7 (Ref. 10 of the Standard). Local building codes may also specify limits on deflections and drift applicable to stand-alone frames.

C4.1.2 Seismic Design Criteria

Research by Judd, et. al (Ref. 16) involved physical testing of knee-brace frame subassemblages and nonlinear collapse simulations of prototypical stand-alone frame structures. That research provides the basis of the seismic design parameters given in the Standard. A value of R equal to 3 is recommended as consistent with the quality ratings determined in the FEMA P-695 process. The static pushover results indicate that timber frame structures designed based on the tensile capacity of the brace exhibit significant system overstrength, in which the overstrength factor Ω_0 varied from approximately 5 to 6. However, for practical considerations (e.g., design of connecting elements to the frame), Ω_0 equal to 3 is recommended. The nonlinear response history results indicate that the maximum story drift under the design basis earthquake (DBE) level ground motions is in the range of 3 to 4 times the elastic drift produced by reduced design forces based on R. Given the uncertainty inherent in predicting the drift of wood systems, it is recommended to use, as a minimum, C_d equal to 4. Approved use of these seismic response coefficients is subject to review by an independent peer review panel and the authority having jurisdiction.

The physical tests of the knee-braced frame subassemblages was limited to Douglas fir timber with 1”-diameter oak pegs. However, results of the research are expected to apply equally well to frames constructed with timber of other species and other pegs confirming to the requirements of the Standard. Although the research program was limited to knee-brace configurations, the specified seismic design coefficients for frames with long braces are expected to be in the same range.

When the allowable stress design methodology is used, provisions in Section 2.4.5 of ASCE 7 permit the allowable stresses for members and connections subject to load combinations containing the over strength factor, Ω_0, to be increased by a factor of 1.2 in addition to application of the load duration factor $C_D = 1.6$ for seismic loading as well as other adjustment factors specified in the NDS.

C4.2 Timber Frames and Diaphragm - Shear Wall Systems

In a structure that couples the timber frame to the diaphragm/shear wall system for lateral-load resistance, the members of the timber frame may be used as components, such as chord and strut elements, of the lateral-load resisting system. The stiffness of a timber frame sheathed with structural insulated panels (SIPs) can be an order of magnitude higher than that of the stand-alone frame (see Ref. 9 and 13). Hence, in coupled timber frame and diaphragm/shear wall systems, the timber frame is not likely to carry significant lateral load. A diaphragm-frame interaction structural analysis such as that described in Ref. 9 is recommended. In timber frame systems designed to carry only gravity load, all lateral load must be transferred to and resisted by the shear wall system. Continuity of load path through the timber frame to the shear wall system and ultimately to the foundation is essential.

CA Glossary

For a more complete glossary of terms related to timber framing, refer to:

Rower, K., editor (2012) *TIMBER FRAMING FUNDAMENTALS*, Timber Framers Guild.

References

1. Anthony, R. and DeStefano, J. (2018) Effect of Moisture Content on Bending Strength of Timber, Technical Bulletin 2018-11, Timber Frame Engineering Council.

2. Anthony, R. and Nehil, T. (2018) Determining Allowable Design Stresses for Timber Using ASTM Standards D2555 and D245, Technical Bulletin 2018-11, Timber Frame Engineering Council.

3. ASTM Standard D143, Standard Methods of Testing Small Clear Specimens of Timber, ASTM, West Conshohocken, PA, 1997.
4. ASTM Standard D2555, Standard Practice for Establishing Clear Wood Strength Values, ASTM, West Conshohocken, PA.

5. ASTM Standard D5764, Test Method for Evaluating Dowel Bearing Strength of Wood and Wood Base Products, ASTM, West Conshohocken, PA, 1997.

6. AWC (2018) National Design Specification for Wood Construction with Commentary, American Wood Council, Leesburg, VA.

7. Bulleit, W. M., Sandberg, L. B., O'Bryant, T. L., Weaver, D. A., and Pattison, W. E., (1996). "Analysis of Frames with Traditional Timber Connections," Proceedings, International Wood Engineering Conference, New Orleans, LA. 4, 232-239

8. Bulleit, W. M., Sandberg, L. B., Drewek, M. W., and O'Bryant, T. L., (1999). "Behavior and Modeling of Wood-Pegged Timber Frames," *Journal of Structural Engineering*, 125(1), 3-9.

9. Carradine, D. M, Woeste, F. E., Dolan, J. D., and Loferski, J. R. (2004) Utilizing diaphragm action for wind load design of timber frame and structural insulated panel buildings," *Forest Products Journal*, 54(5): 73-80, May.

10. Church, J. R. and Tew, B. W. (1997). "Characterization of Bearing Strength Factors in Pegged Timber Connections," Journal of Structural Engineering, March 1997, 326-332.

11. DIN 1052 (2004) Design of timber structures – general rules and rules for buildings, German Institute for Standards, Berlin (in German).

12. EN 1995-1-1:2004 (E), Eurocode 5 – Design of Timber Structures, Part 1-1: General – Common Rules and Rules for Buildings, Technical Committee CEN/TC250
13. Erikson, R. G. and Schmidt, R. J. (2003) Behavior of Traditional Timber Frame Structures Subjected to Lateral Load, Research Report, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY
14. Erikson, R. E. and Schmidt, R. J. (2004) "Lateral Load Response of Full-Scale Traditional Timber Frame Structures, "*Wood Design Focus*, American Forest and Paper Association, Third Quarter.
15. Hindman, D. (2017) Measuring the Bending Yield Strength of Timber Frame Pegs, Research Report to the Timber Frame Engineering Council, Dept. of Sustainable Biomaterials, Virginia Tech.
16. Judd J. P., Fonseca F. S., Leidy J. (2018) Seismic Performance Factors for Stand-Alone Timber Frame Structures. Structural Engineering and Materials Report No. 18/05, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, Wyoming.
17. Miller, J. F., Schmidt, R. J. and Bulleit, W. M. (2010), Journal of Structural Engineering, v. 136, n. 10, pp. 1255-1261, ASCE
18. Nehil, T. (2013) Capacity of Load-Bearing Housings: Preliminary Results from Load Testing, Research Report 2013-01, Timber Frame Engineering Council.
19. PS 20 (2010) Voluntary Product Standard PS 20-10 - American Softwood Lumber Standard, American Lumber Standards Committee and National Institute of Standards & Technology, Washington, D. C.
20. Schmidt, R. J. and MacKay, R. B., (1997) Timber Frame Tension Joinery, Research Report, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY
21. Schmidt, R. J. and Daniels, C. E., (1999) Design Considerations for Mortise and Tenon Connections, Research Report, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY

22. Schmidt, R. J. and Scholl, G. F. (2000), Load Duration and Seasoning Effects on Mortise and Tenon Joints, Research Report, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY

23. Schmidt, R. J. and Miller, J. F. (2004) Capacity of Pegged Mortise and Tenon Joinery, Research Report, Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY

24. Wood Handbook: Wood as an Engineering Material, General Technical Report 113, Forest Products Laboratory, U. S. Department of Agriculture, 2010.