MOISTURE CONTENT CHANGES AND ASSOCIATED STRESS PREDICTIONS ON STRUCTURAL WOOD SCREWS

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Wood is a hygroscopic material composed of oriented, tube-like cells and cavities. Between a moisture content (MC) of 0% to ≈ 30%, water that is chemically bonded within the cell walls is continuously being exchanged with the surrounding air.

Changes in MC within this range will have an effect on mechanical properties such as strength and stiffness, as well as the weight and dimensions of a structural wood member. Above this range, additional water is stored in the cell cavity. Any further increase in MC above ≈ 30% will affect the weight, but not the mechanical properties, nor the volume of a wood member.

For design in North America, the influence of MC is addressed by the NDS as well as CSA O86 through the use of service condition factors, which are applicable to connections with self-tapping screws:

Table 1. Service Condition Factors for Connections

Building Code	Moisture Content		Factor	
	At Time of Fabrication	In Service		
NDS	≤ 19%	≤ 19%	C_M	1.0
	> 19%	≤ 19%		0.4[1]
	any	> 19%		0.7
CSA O86	≤ 19%	≤ 19%	K_{SF}	1.0
	≤ 19%	> 19%		0.67
	> 19%	≤ 19%		0.4[2]
	> 19%	> 19%		0.27[2]

Notes:
[1] Dependent on type of connection, see NDS-2015, table 11.3.3
[2] Dependent on type of connection, see CSA O86-2014, table 12.2.1.6

In both the NDS and CSA O86, an upper MC limit of 19% is specified for wood to conform to dry service conditions. Procedures for estimating current MC levels are relatively straightforward. Anticipating MC levels over the entire service life of a structure, however, can be more complicated. For example, the MC of an exterior structure can remain under 19% as long as the structural elements remain sheltered by a roof or overhang. This must be verified, however, through analysis of the relative humidity (RH) of the surrounding air and the overall site conditions.

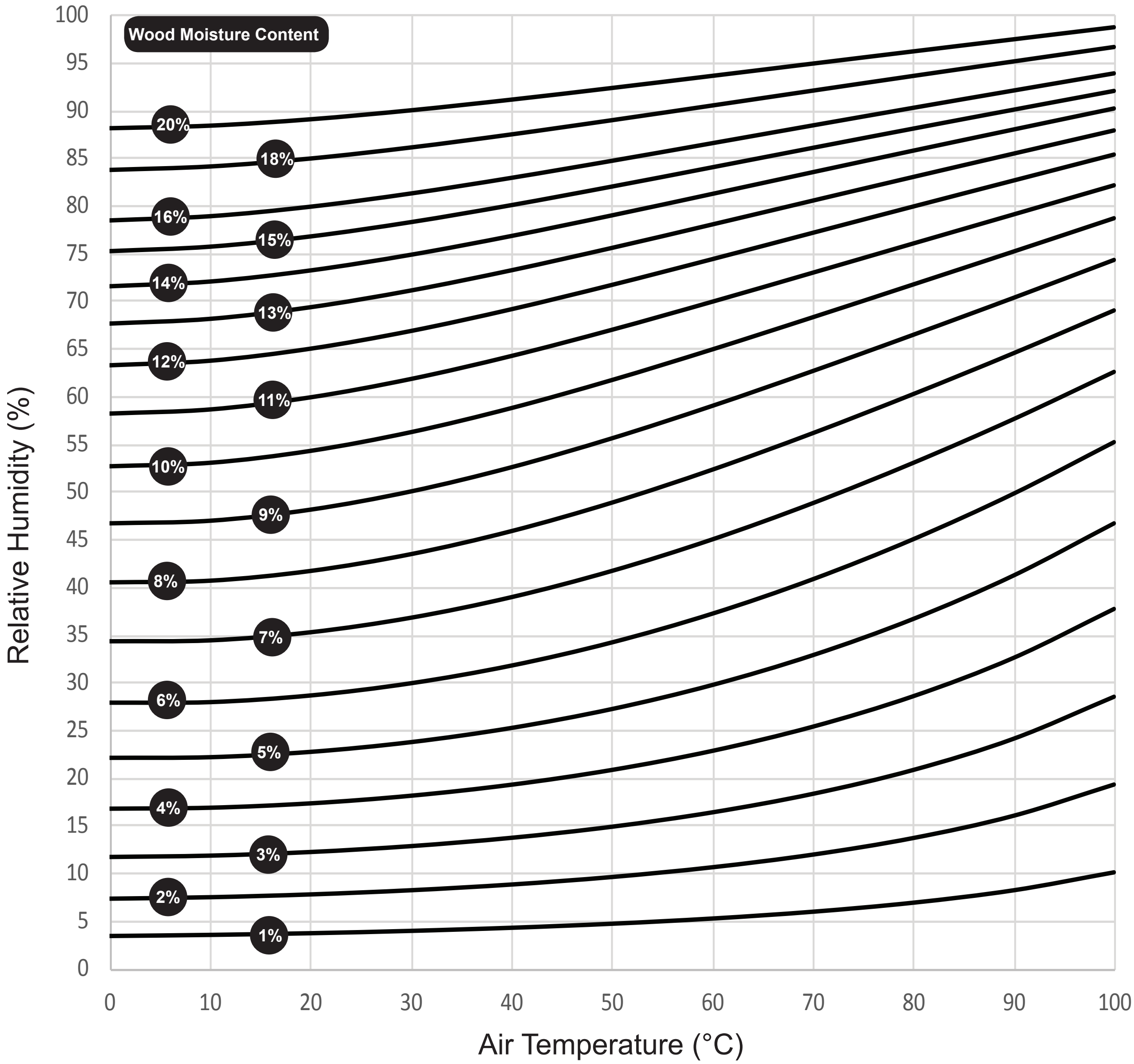
Overall, wet service conditions apply to connection design if:

1) The connection may be exposed to direct wetting including rain, snow, splashing, dripping, or condensation such that it cannot dry out quickly and effectively.

2) The wood member is classified as “green” upon installation. For such members, wet service conditions apply at least until the wood dries to below 19% MC. This is accounted for in the NDS as well as CSA O86.

3) The equilibrium moisture content (EMC) exceeds 19% (according to the NDS) or 15% averaged over the year and/or 19% at any given time (according to CSA O86).

The relationship between air temperature, relative humidity, and EMC is illustrated below in Graph 1.



Graph 1. Equilibrium Moisture Content of Wood as Related to Environmental Conditions

Note: Graph 1 is a plot of the Hailwood-Horrobin equation

Designers should be aware that even in cases where dry service conditions apply, wood can still shrink or swell below a MC of 19% throughout its service life. Special attention will be given in this newsletter to cases where wood swelling may induce tensile forces on fasteners installed perpendicular to the grain.

The fact that wood swelling can develop considerable forces was exploited in ancient times in order to split stone with dried wooden wedges that were inserted into holes and then soaked with water. While modern fully threaded screws may be used to restrain wood against excessive swelling, improperly detailed connections may also have the potential to develop forces large enough to cause failure of the fasteners.

Since the resulting forces are influenced by moisture-dependent mechanical characteristics, estimating these forces accurately can be difficult. A simplified method, outlined below, allows the designer to approximate the resulting forces by assuming a linear elastic stress increase due to the change in wood member thickness:

$\sigma_r = E' \cdot \varepsilon_r$

where

E' = factored elastic modulus

= $E \cdot J_{angle} \cdot J_{MC}$

where

E = elastic modulus of the wood, GPa (Table 2)

J_{angle} = angle to grain reduction factor [1]

= 1.0 for force parallel to the grain

= 0.15 for force perpendicular to the grain

J_{MC} = moisture content reduction factor [2]

= 1.0 for moisture content ≤ 19%

= 0.75 for moisture content > 19%

ε_r = restrained strain, %

= $0.5 \cdot K_{MC} \cdot \Delta_{MC}$ [3]

where

K_{MC} = dimensional change coefficient (Table 2)

Δ_{MC} = moisture content variation, %

Notes: This calculation method should only be used for approximation purposes.
[1] reduction factor based on theoretical elastic modulus grain deviation of 90°, (Fracture and Fatigue in Wood, Smith, Landis and Gong, 2003)
[2] reduction factor based on theoretical elastic modulus of wet wood fiber, (Fracture and Fatigue in Wood, Smith, Landis and Gong, 2003)
[3] common European design literature suggests to half the respective values for restrained swelling, (Schneider Bautabellen Tafel 9.7a)

Unit conversion:

1 GPa	=	145,000 psi
1 GPa	=	1,000 MPa
1 GPa	=	1 kN/mm^2

The dimensional change coefficient, K_{MC}, is summarized in Table 2:

Table 2. Elastic Modulus and Dimensional Change Coefficient

Wood Species		E	K_{MC}	
		GPa	parallel to grain [1] %/%	perpendicular to grain [2] %/%
Western Cedar		9.10	0.00375	0.150
SPF	Black Spruce	12.30	0.00625	0.250
SPF	Grey Pine	10.50	0.00493	0.197
SPF	Balsam Fir	9.72	0.00625	0.250
Douglas Fir		13.60	0.00618	0.247

Notes:
1. Values are taken from FPInnovations Publication SP-0514F
2. Dimensional change coefficient based on a green wood state of 30% MC
3. The parallel to grain dimensional change coefficient is small and dimensional change in this direction is typically neglected (exceptions may apply).

The simplified approach is demonstrated in the following example in which a rigid (relative to wood) steel plate is fastened to a Black Spruce beam with an original MC of 12% and a final MC of 30%. The fastener is a 12 mm x 200 mm (1/2” x 7-7/8”) ASSY® SK partially threaded screw installed perpendicular to the grain:

$$E' = 12.30 \cdot 0.15 \cdot 0.75$$
$$= 1.38 \text{ GPa}$$

$$\varepsilon_r = 0.5 \cdot 0.250 \cdot (30\text{-}12)$$
$$= 2.25\ \%$$

$$\sigma_r = 1.38 \cdot 0.0225$$
$$= \mathbf{31.05\ MPa}$$

The specified ASSY® SK screw has a head diameter (D_{HEAD}) of 29 mm (1.14“) and a shank diameter (D_S) of 8.2 mm (0.323”), resulting in an effective bearing area under the head of 608 mm^2. Therefore, the tensile force on the screw due to expansion of the wood can be estimated as follows:

$$F_r = 31.05 \cdot 608$$
$$= \mathbf{18.88\ kN}$$

The resulting force is compared to the relevant factored fastener resistances according to Canadian Limit States Design:

- Factored withdrawal resistance = 8.01kN < **18.88 kN [LSD req. not satisfied]**
- Factored head pull-through resistance = 6.42 kN < **18.88 kN [LSD req. not satisfied]**
- Factored fastener tensile strength = **24 kN** > 18.88 kN

As this example shows, a large change in MC has the potential to introduce stresses that can lead to various failure modes if not considered early on in the design stage.

In similar cases where the fastener is a fully threaded screw (see detail in Figure 1), the longer effective thread length has the potential to develop withdrawal resistance that exceeds the tensile strength of the screw. This type of detail deserves special consideration when large variations in MC are expected. Since the steel plate increases the effective bearing area, a fastener tensile failure mode can occur in advance of wood crushing under significant MC changes and wood swelling.

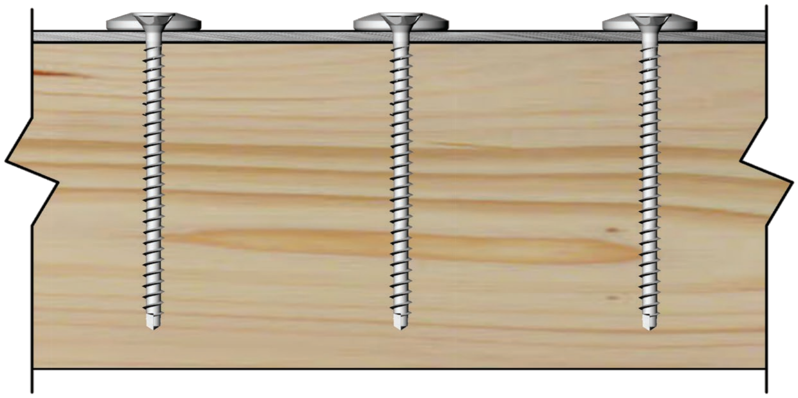


Figure 1 Fully threaded screws with steel side plate.

Detailing for rigid side members must ensure that unintentional large strains are not generated in the screw if excessive wood swelling is anticipated. Detailing shown in Figure 2, Detail A may cause concern since any elongation generated by the long thread penetration lengths is distributed over short side member lengths. A design alternative shown in Detail B may lower the anticipated strains in the screws due to the shorter thread penetration lengths. In Detail C, long side member lengths may also reduce the strains in the screws, as any elongation is distributed over greater lengths.

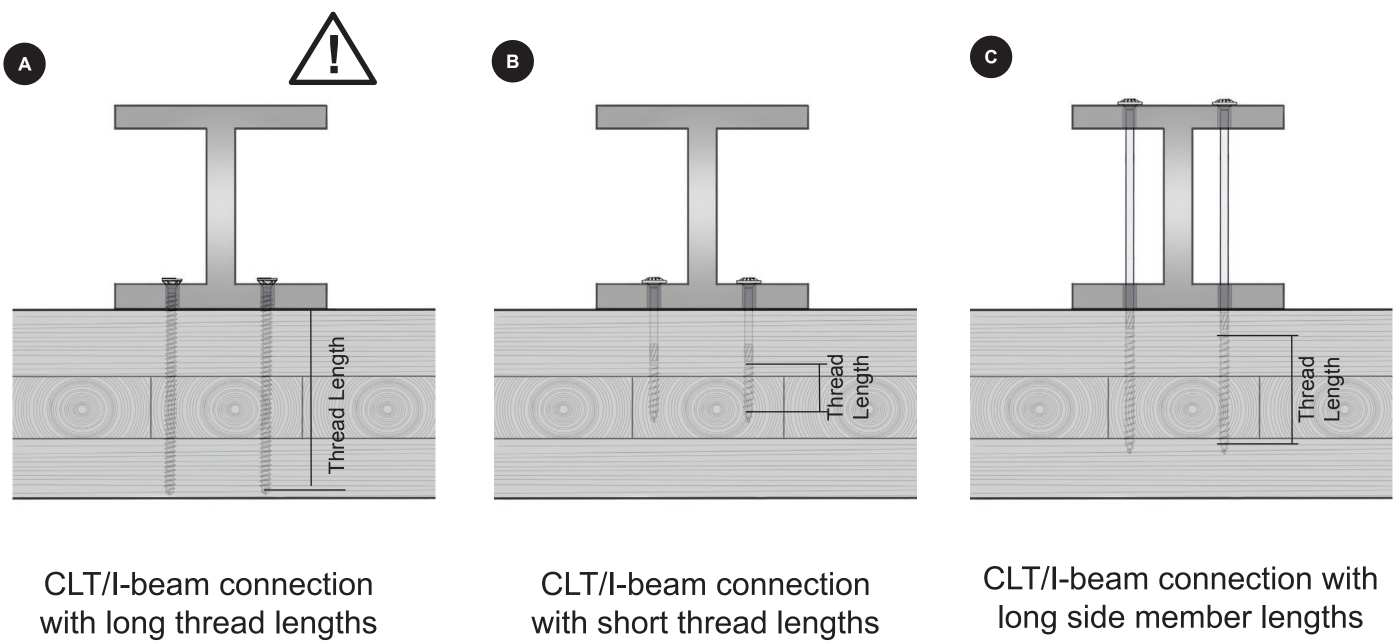


Figure 2 Details with rigid side members.

Another concern regarding MC in connection design has to do with differential drying in heavy timber members, which can cause checking and splitting (see Figure 3, D, E). The possibility of checks and splits running along the grain is one of the reasons that most building codes have special considerations regarding screws installed in the end grain at 0°. In some cases, the fastener axis may run parallel to these voids, resulting in decreased capacity. Detail F shows how fasteners installed at an angle ≥ 30° to the grain can avoid problems associated with end grain application, since they are installed across checks and splits.

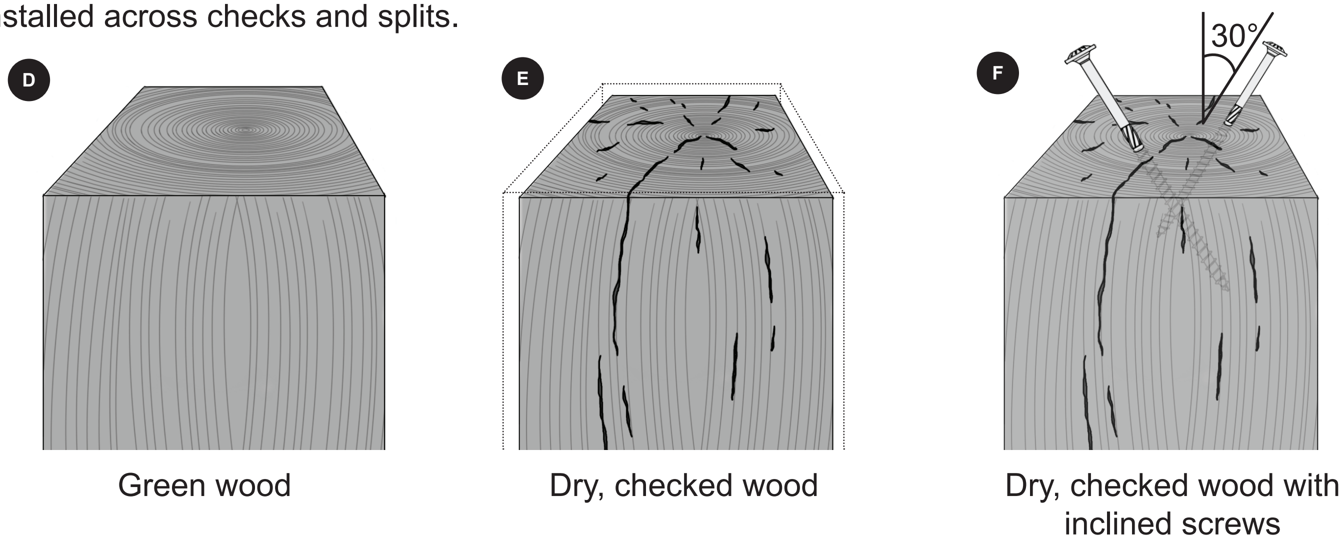


Figure 3 End grain application in dry, checked heavy timber members.

Since changes in MC can cause significant dimensional changes perpendicular to the grain, the design of steel plate connections on a typical slender beam like those shown in Detail G in Figure 4 must consider swelling and shrinking in this direction. For rigid, large diameter fasteners like bolts, the NDS and CSA O86 specify a maximum distance of 125 mm (5") between the outer rows, measured perpendicular to the grain [1]. As typical beam cross-sections are narrow and deep, top and bottom steel plate as shown in Detail H may reduce the impact of MC changes stress.

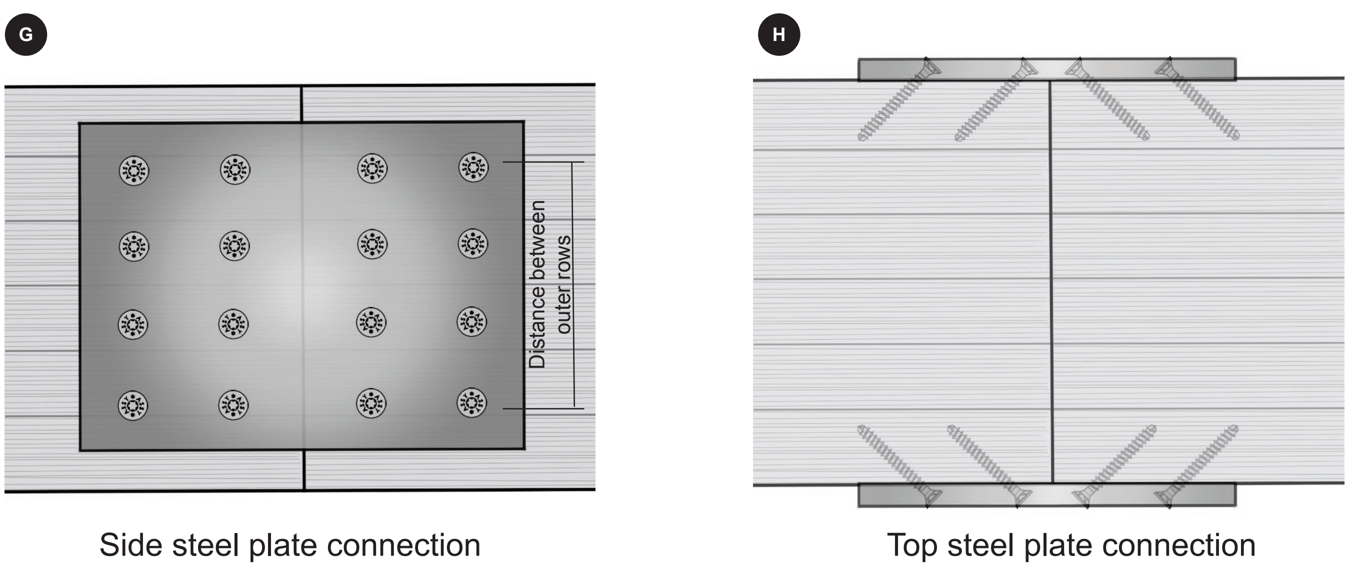


Figure 4 Steel plate connections

[1] This limitation does not apply to many modern pre-engineered hanger plates fastened with self-tapping screws, which rely on custom testing.

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