Appendix D Example 16 – Diagonal Bracing of Multi-Tiered Framed Bents – Two Posts

Refer to *Falsework Manual,* Section 6-3, *Diagonal Bracing* and Section 5-3, *Timber Fasteners*. This example demonstrates how to determine if the bracing system of a multi-tiered framed bent is adequate. The tiers are different heights. The brace to post connections are bolted, and the mid brace connections are nailed.

Given Information

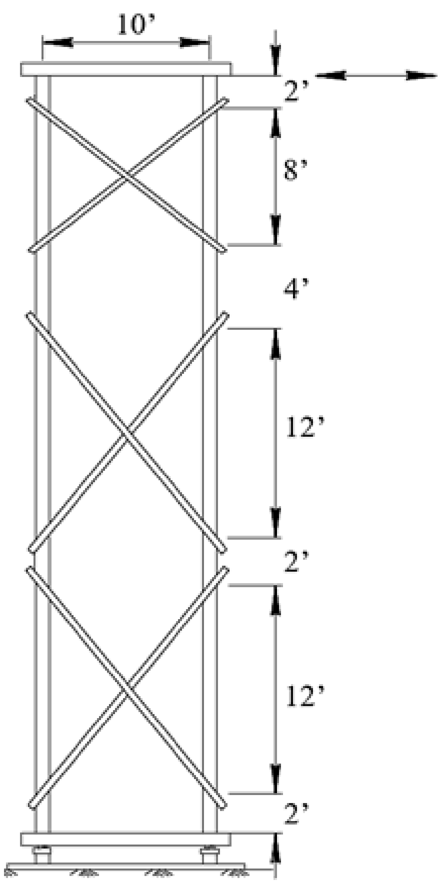


Figure D-16-1. Multi-Tiered Framed Bent

2% Dead load = 2700 lb
Wind load = 2800 lb

Posts:
12 x 12 Rough Douglas Fir-Larch #1 (G=0.50)

Diagonal Braces:
2x8 S4S Douglas Fir-Larch #2 (G=0.50)

Connectors:
Brace to Post (Top Brace): 1 x 7/8″ Ø Bolt
Brace to Post (Middle Brace): 1 x 1″ Ø Bolt
Brace to Post (Bottom Brace): 1 x 1″ Ø Bolt
Mid Brace Connections (All): 4 - 16d common nails
(All bolts in single shear)

Determine if the Bracing System is Adequate

ANALYZE THE TOP TIER

1. **Determine the connection capacity between brace and post:**

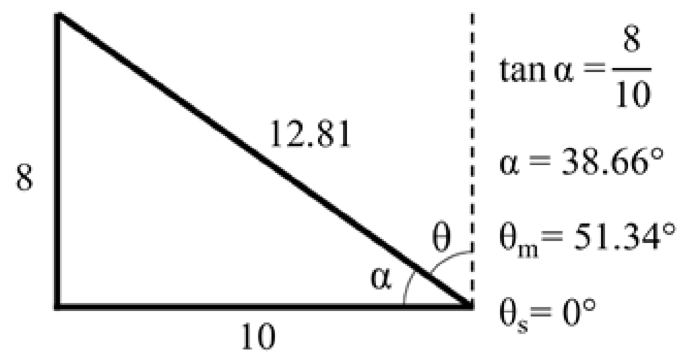


Figure D-16-2. Top Tier Member Lengths and Orientation

Main Member Properties

l_m = 12 in *thickness (12x12)*

$t_m = l_m$ = 12 in

θ_m= 51.34° *angle between direction of loading & direction of grain*

G = 0.50 *Specific Gravity NDS Table 12.3.3*

Side Member Properties

l_s = 1.5 in *thickness (2x8)*

$t_s = l_s$ = 1.5 in

θ_s= 0° *angle between direction of loading & direction of grain*

Connector Properties

D = 0.875 in	*connector diameter*
F_{yb} = 45000 psi	*Yield Strength (See Footnote #2 NDS table 12A)*
$F_{e.pll}$ = 11200G psi = 5600 psi	*Dowel Bearing Strength Parallel to Grain (NDS table 12.3.3 footnote 2)*
$F_{e.perp} = \dfrac{6100G^{1.45}}{\sqrt{D}}$ = 2387 psi	*Dowel Bearing Strength Perpendicular to Grain (NDS table 12.3.3 Footnote 2)*

Compare values to NDS Table 12.3.3:

$F_{e.pll\ (NDS\ Table\ 12.3.3)}$ = 5600 psi

$F_{e.perp\ (NDS\ Table\ 12.3.3)}$ = 2400 psi

Use calculated value for F_{perp} = 2387 psi

Find Dowel Bearing Strength at an Angle to Grain (NDS Section 12.3.4):

$$F_{em} = \frac{F_{e.pll}F_{perp}}{F_{e.pll}(\sin(\theta_m))^2 + F_{perp}(\cos(\theta_m))^2} = 3076 \text{ psi}$$

$$F_{es} = \frac{F_{e.pll}F_{perp}}{F_{e.pll}(\sin(\theta_s))^2 + F_{perp}(\cos(\theta_s))^2} = 5600 \text{ psi}$$

Find Reduction Term, R_d (NDS Table 12.3.1B):

$\theta = \max(\theta_m, \theta_s) = 51.34°$ *Maximum angle between direction of load and direction of grain for any member in connection (See Table 12.3.1B)*

$$K_\theta = 1 + 0.25\frac{\theta}{90 \text{ deg}} = 1.1426$$

$R_{d\_I} = 4\ K_\theta = 4.57$ *Reduction Term for Yield Mode I_m and I_s*

$R_{d\_II} = 3.6\ K_\theta = 4.11$ *Reduction Term for Yield Mode II*

$R_{d\_III.IV} = 3.2\ K_\theta = 3.66$ *Reduction Term for Yield Mode III_m, III_s, and IV*

Find Yield Limit Equations for Single Shear (NDS Table 12.3.1A):

$$R_e = \frac{F_{em}}{F_{es}} = 0.5492$$

$$R_t = \frac{l_m}{l_s} = 8$$

$$k_1 = \frac{\sqrt{R_e + 2R_e^2\left(1 + R_t + R_t^2\right) + R_t^2R_e^3} - R_e(1 + R_t)}{(1 + R_e)} = 1.6047$$

$$k_2 = -1 + \sqrt{2(1 + R_e) + \frac{2F_{yb}(1 + 2R_e)D^2}{3F_{em}l_m^2}} = 0.7909$$

$$k_3 = -1 + \sqrt{\frac{2(1 + R_e)}{R_e} + \frac{2F_{yb}(2 + R_e)D^2}{3F_{em}l_s^2}} = 2.7554$$

$$Z_{Im} = \frac{Dl_mF_{em}}{R_{d\_I}} = 7066 \text{ lb}$$ *NDS Eqn 12.3-1*

$Z_{Is} = \dfrac{DI_sF_{es}}{R_{d\_I}}$ = 1608 lb *NDS Eqn 12.3-2*

$Z_{II} = \dfrac{k_1DI_sF_{es}}{R_{d\_II}}$ = 2867 lb *NDS Eqn 12.3-3*

$Z_{IIIm} = \dfrac{k_2DI_mF_{em}}{(1 + 2R_e)R_{d\_III.IV}}$ = 3329 lb *NDS Eqn 12.3-4*

$Z_{IIIs} = \dfrac{k_3DI_sF_{em}}{(2 + R_e)R_{d\_III.IV}}$ = 1193 lb *NDS Eqn 12.3-5*

$Z_{IV} = \dfrac{D^2}{R_{d\_III.IV}}\sqrt{\dfrac{2F_{em}F_{yb}}{3(1 + R_e)}}$ = 1616 lb *NDS Eqn 12.3-6*

The controlling value is the minimum single shear capacity from the above equations.

$Z_{control}$ = min (Z_{Im}, Z_{Is}, Z_{II}, Z_{IIIm}, Z_{IIIs}, Z_{IV}) = 1193 lb *(Yield Mode IIIs controls)*

Adjustment factors from NDS Table 11.3.1:

C_D = 1.25 *Duration Factor for 2% lateral loading*
C_M = 1.0 *Wet Service Factor NDS 11.3.3 (Assume < 19% moisture content)*
C_t = 1.0 *Temperature Factor NDS 11.3.4 (Temp up to 100ºF)*
C_g = 1.0 *Group Action Factor NDS 11.3.6 (Single Fastener)*
C_Δ = 1.0 *Geometry Factor NDS 12.5.1 (Assume End Dist. & spacing meet Tables 12.5.1A and 12.5.1B)*
C_{eg} = 1.0 *End Grain Factor NDS 12.5.2 (Does not apply)*
C_{di} = 1.0 *Diaphragm Factor NDS 12.5.3 (Does not apply)*
C_{tn} = 1.0 *Toe Nail Factor NDS 12.5.4 (Does not apply)*

Adjusted lateral design value Z’ = $Z(C_D)(C_M)(C_t)(C_g)(C_\Delta)$ = 1492 lb

2. **Determine the capacity of the diagonal brace in tension:**

Reference design value in tension F_t = 575 psi (NDS supplement table 4A)

Adjustment factors from NDS table 4.3.1:

C_D = 1.25 *Duration Factor for 2% lateral loading*
C_M = 1.0 *Wet Service Factor NDS table 4A (Assume < 19% moisture content)*

C_t = 1.0 *Temperature Factor NDS table 2.3.3 (Temp up to 100ºF)*
C_F = 1.2 *Size Factor NDS Table 4A*
C_i = 1.0 *Incising Factor NDS 4.3.8*

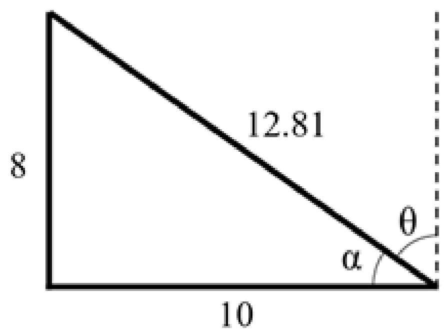
Adjusted design value $F_t' = F_t$ (CD)(CM)(Ct)(CF)(Ci) = 863 psi

Tension capacity = 863 psi(1.5")(7.25") = 9385 lb

3. **Determine the strength value of the tension members:**

9385 lb > 1492 lb ∴ Connection strength controls

4. **Calculate the horizontal component of the strength value for the tension members:**



$T = 1492 \cos\alpha = 1165$ lb

Figure D-16-3. Geometric Components of Tension Strength Value for Top Tier

5. **Determine the capacity of diagonal brace in compression:**

First check adequacy of the connection to reduce the unsupported length of compression member (See Section 6-3.02, *Wood Cross Bracing*):

(See Example Problem #14 Step 5 for additional information)

Connection capacity = 300 lb > 250 lb (minimum required per section 6-3.02)

Check cross brace capacity in compression:

Reference design value in compression F_c = 1350 psi (NDS supplement table 4A)

Adjustment factors from NDS table 4.3.1:

C_D = 1.25 *Duration Factor for 2% lateral loading*

C_M = 1.0 *Wet Service Factor NDS table 4A (Assume < 19% moisture content)*

C_t = 1.0 *Temperature Factor NDS table 2.3.3 (Temp up to 100ºF)*

C_F = 1.05 *Size Factor NDS Table 4A*

C_i = 1.0 *Incising Factor NDS 4.3.8*

$$C_p = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + (F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}} = 0.1003$$

Column Stability Factor NDS Eqn. 3.7-1

where:

l_e = (12.81 ft/2) = 6.405 ft = 76.86 in *unsupported length*

d = 1.5 in *member width, weak direction*

E_{min} = 580,000 psi *NDS supplement table 4A*

$$F_{cE} = \frac{0.822E_{min}'}{(l_e/d)^2} = 182$$ *NDS 3.7.1*

F_c^* = F_c $(C_D)(C_M)(C_t)(C_F)(C_i)$ = 1772 psi *Adjusted design compression value except C_p*

c = 0.8 for sawn lumber *NDS 3.7.1*

Adjusted design compression value F_c' = F_c $(C_D)(C_M)(C_t)(C_F)(C_i)(C_p)$ = 177.7 psi

Compression brace capacity = 177.7 psi (1.5”)(7.25”) = 1932 lb

6. Determine the strength value of the compression members:

Connection capacity = 1492 lb

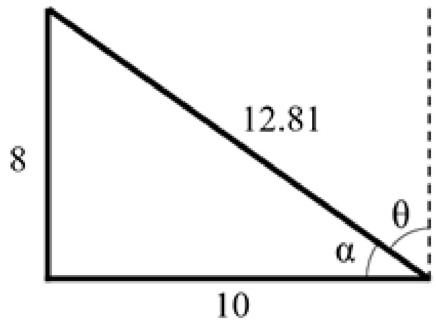
(See step 1. Capacity in tension and compression are the same)

1932 lb > 1492 lb ∴ connection controls compression

Limit to ½ theoretical strength for compression values: See Section 6-3.02, *Wood Cross Bracing.*

Reduced compression brace capacity = $\frac{1492 \text{ lb}}{2}$ = 746 lb

7. **Calculate the horizontal component of the strength value for the compression member:**



$\underline{C = 746 \cos \alpha = 582 \text{ lb}}$

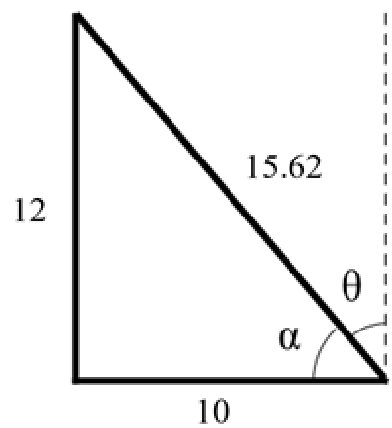
Figure D-16-4. Geometric Components of Compression Strength Value for Top Tier

8. **Calculate the total resisting capacity of the top tier of bracing:**

   Total resisting capacity = Σ(C+T) = 582 + 1165 = 1747 lb

ANALYZE THE MIDDLE TIER

1. **Determine the connection capacity between brace and post:**



$$\tan \alpha = \frac{12}{10}$$

$$\alpha = 50.1944°$$

$$\theta_m = 39.806°$$

$$\theta_s = 0°$$

Figure D-16-5. Middle Tier Member Lengths and Orientation

Main Member Properties		Side Member Properties	
l_m = 12 in	*thickness (12x12)*	l_s = 1.5 in	*thickness (2x8)*
$t_m = l_m$ = 12 in		$t_s = l_s$ = 1.5 in	
θ_m= 39.806°	*angle between direction of loading & direction of grain*	θ_s= 0°	*angle between direction of loading & direction of grain*
G = 0.50	*Specific Gravity NDS Table 12.3.3*		

Connector Properties

$D = 1$ in	*connector diameter*
$F_{yb} = 45000$ psi	*Yield Strength (See Footnote #2 NDS table 12A)*
$F_{e.pll} = 11200G$ psi $= 5600$ psi	*Dowel Bearing Strength Parallel to Grain*
$F_{e.perp} = \dfrac{6100G^{1.45}}{\sqrt{\frac{D}{in}}} = 2233$ psi	*Dowel Bearing Strength Perpendicular to Grain (See Footnote #2 NDS table 12A)*

Compare values to NDS Table 12.3.3:

$F_{e.pll\ (NDS\ Table\ 12.3.3)} = 5600$ psi

$F_{e.perp\ (NDS\ Table\ 12.3.3)} = 2400$ psi

Use calculated value for $F_{perp} = 2233$ psi

Find Dowel Bearing Strength at an Angle to Grain (NDS Section 12.3.4):

$$F_{em} = \frac{F_{e.pll}F_{perp}}{F_{e.pll}(\sin(\theta_m))^2 + F_{perp}(\cos(\theta_m))^2} = 3461 \text{ psi}$$

$$F_{es} = \frac{F_{e.pll}F_{perp}}{F_{e.pll}(\sin(\theta_s))^2 + F_{perp}(\cos(\theta_s))^2} = 5600 \text{ psi}$$

Use same methodology as top tier to find controlling yield mode and adjusted lateral design value:

$Z_{control} = \min(Z_{Im}, Z_{Is}, Z_{II}, Z_{IIIm}, Z_{IIIs}, Z_{IV}) = 1626$ lb *(Yield Mode IIIs controls)*

Adjusted lateral design value $Z' = Z(C_D)(C_M)(C_t)(C_g)(C_\Delta) = 1626\ (1.25) = 2033$ lb

2. **Determine the capacity of the diagonal brace in tension**

   By inspection, same as top tier. See top tier, step #2.

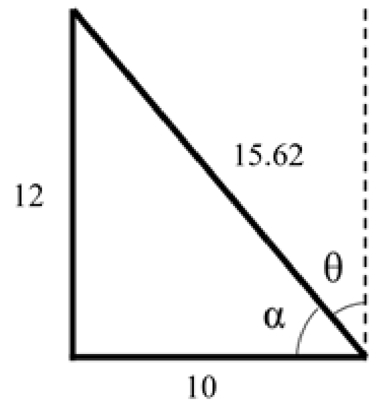
   Adjusted design value $F_t' = F_t\ (C_D)(C_M)(C_t)(C_F)(C_i) = 863$ psi

   Tension capacity = 863 psi(1.5")(7.25") = 9385 lb

3. **Determine the strength value of the tension members**

   9385 lb > 2033 lb ∴ Connection strength controls

4. **Calculate the horizontal component of the strength value for the tension members**



T = 2033 cos α = 1301 lb

Figure D-16-6. Geometric Components of Tension Strength Value for Middle Tier

5. **Determine the capacity of diagonal brace in compression:**

Adequacy of connection to reduce unsupported length of compression member was checked previously, see Step 5 of Top Tier.

Check cross brace capacity in compression:

Reference design value in compression F_c = 1350 psi (NDS supplement table 4A)

Adjustment factors from NDS table 4.3.1:

C_D = 1.25 *Duration Factor for 2% lateral loading*

C_M = 1.0 *Wet Service Factor NDS table 4A (Assume < 19% moisture content)*

C_t = 1.0 *Temperature Factor NDS table 2.3.3 (Temp up to 100ºF)*

C_F = 1.05 *Size Factor NDS Table 4A*

C_i = 1.0 *Incising Factor NDS 4.3.8*

$$C_p = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + (F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}} = 0.0679$$

Column Stability Factor NDS Eqn. 3.7-1

where:

l_e = (15.62'/2) = 7.81 ft = 93.72 in *unsupported length*

d = 1.5 in *member width, weak direction*

E_{min} = 580,000 psi *NDS supplement table 4A*

$F_{cE} = \dfrac{0.822E_{min}'}{(l_e/d)^2} = 122$ *NDS 3.7.1*

$F_c^* = F_c\,(C_D)(C_M)(C_t)(C_F)(C_i) = 1772$ psi *Adjusted design compression value except C_p*

c = 0.8 for sawn lumber *NDS 3.7.1*

Adjusted design compression value $F_c' = F_c\,(C_D)(C_M)(C_t)(C_F)(C_i)(C_p) = 120.4$ psi

Compression brace capacity = 120.4 psi (1.5")(7.25") = 1309 lb

6. Determine the strength value of the compression members:

Connection capacity = 2033 lb

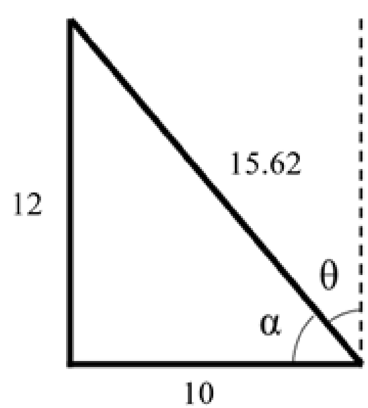
(See step 1. Capacity in tension and compression are the same)

1309 lb < 2033 lb ∴ member controls compression

Limit to 1/2 theoretical strength for compression values: See section 6-3.02, *Wood Cross Bracing.*

Reduced compression brace capacity = $\dfrac{1309 \text{ lb}}{2}$ = 655 lb

7. Calculate the horizontal component of the strength value for the compression member:



C = 655 cos α = 419 lb

Figure D-16-7. Geometric Components of Compression Strength Value for Middle Tier

8. Calculate the total resisting capacity of the middle tier of bracing:

Total resisting capacity = Σ(C+T) = 419 + 1301 = 1720 lb

ANALYZE THE BOTTOM TIER

Since the bottom tier is identical to the middle tier, the resisting capacity is equal to the middle tier. By inspection, Σ(C+T) = 1720 lb.

Summary

Summarize Results for 2% Dead Load:

Tier	Resisting Capacity	Collapsing Force = 2700 lb
Top	1747 lb	No Good
Middle	1720 lb	No Good
Bottom	1720 lb	No Good

Summarize Results for Wind Load:

Repeat above process for wind load to calculate the Resisting Capacity, using C_D = 1.6 rather than 1.25. All other factors are the same.

The Resisting Capacity for wind load can also be derived by multiplying the resisting capacity for 2% Dead Load (above table) by the factor $\frac{C_D \text{ wind}}{C_D \text{ 2\%}} = \frac{1.6}{1.25}$

$$\Sigma(C+T) \text{ Top Tier} = 1747 \text{ lb} \left(\frac{1.6}{1.25}\right) = 2236 \text{ lb}$$

$$\Sigma(C+T) \text{ Middle \& Bottom Tiers} = 1720 \text{ lb} \left(\frac{1.6}{1.25}\right) = 2202 \text{ lb}$$

Tier	Resisting Capacity	Collapsing Force = 2800 lb
Top	2236 lb	No Good
Middle	2202 lb	No Good
Bottom	2202 lb	No Good

Bracing system is inadequate.