J-3 PIPE BRACING

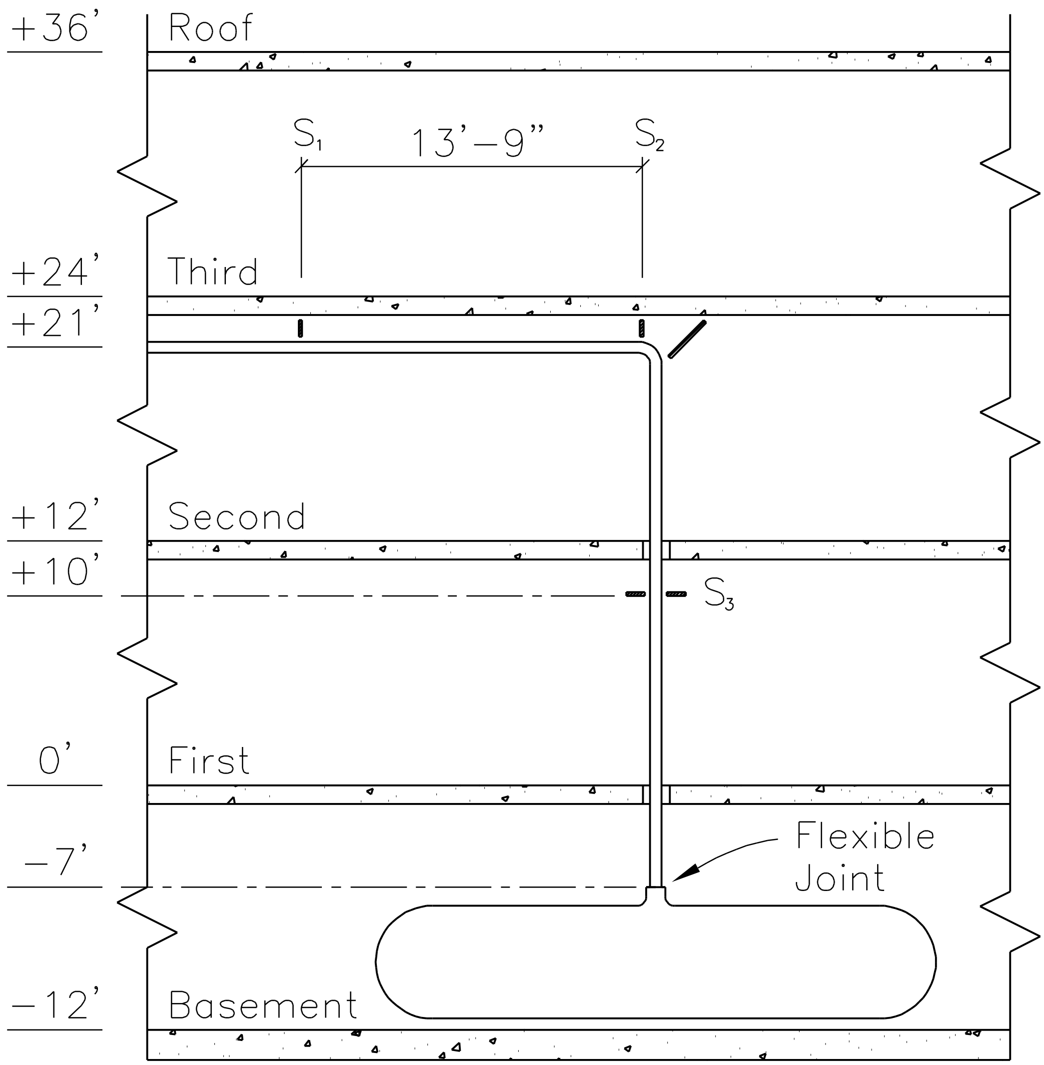
a. Introduction.

(1) Purpose. The purpose of this example problem is to illustrate the design of pipe bracing using Chapter 10 and Chapter 6 of FEMA 302 (Components).

(2) Scope. The problem generally follows the steps in Table 4-5 to analyze the pipe bracing and anchorage. Typical bracing details may be found in Figure 10-8

Component description.

The steel water pipe used in this example problem is a 6-inch (152.4mm) diameter standard wall pipe, extending from the basement to the second floor of a three story concrete building (see Figure J3-1). The piping is used to distribute chilled water for HVAC. The building and equipment performance objective is life safety (LS). Additionally, the equipment is not required to function after an earthquake.



Note: For metric equivalent; 1-ft = 0.30m
Figure J3-1. Water pipe and bracing elevation

b. *Component design.*

A.1 *Determine appropriate Seismic Use Group*

Because the equipment is not required to be functional after an earthquake, the water pipe bracing is given a performance level of life safety (LS). The Seismic Use Group and other performance parameters are determined from Table 4-4, as follows;

Performance Level:	LS	(per problem statement)
Seismic Use Group:	I	(Table 4-4)
Ground Motion:	2/3 MCE (A)	(Table 4-4)
Performance Objective:	1A	(Table 4-4)

A.2 *Determine site seismicity.*

The following values are assumed for this example:

$S_S = 1.20g$ (MCE Maps)

A.3 *Determine site characteristics.*

Soil type D is assumed for this problem

Soil type: D (Table 3-1)

A.4 *Determine site coefficients.*

$F_a = 1.02$ (interpolated) (Table 3.2a)

A.5 *Determine adjusted MCE spectral response accelerations.*

$S_{MS} = F_aS_S = 1.02(1.20)g = 1.22g$ (EQ. 3-1)

A.6 *Determine design spectral response accelerations.*

$S_{DS} = 2/3\ S_{MS} = 2/3(1.22) = 0.81g$ (EQ. 3-23)

A.7 *Bracing system.*

The bracing system will consist of structural steel bracing assumed to be installed using low deformability anchor bolts in concrete. To ensure rigidity, the pipe spans are limited to values shown if Figures 10-6 of this document.

A.8 *Select R_p, a_p, and I_p factors.*

$a_p = 1.0$ (Table 10-1)

$R_p = 1.25$ (Table 10-1)

$I_p = 1.0$ (per paragraph 10-1d)

A.10 *Determine member sizes for gravity load effects.*

Note: Only supports S_1 and S_2 support gravity loads. Additionally, connection design will be postponed until the seismic analysis is complete.

Dead load acting at supports is determined as follows;

a. Determine unit weight of pipe;

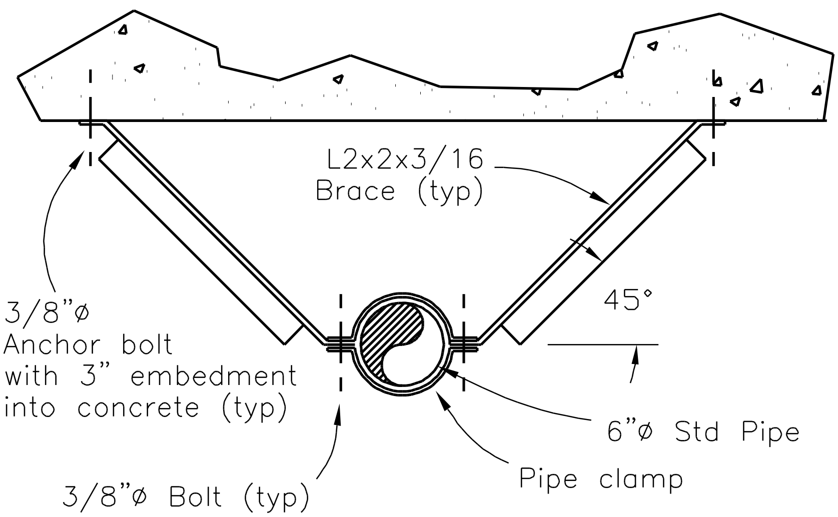
6" ϕ pipe;	19plf
Flanges;	4plf
Supports;	2plf
Water;	20plf
Total =	45plf (0.66KN/m)

b. Determine required support spacing;
Use 13'-9" (4.19m) for a pinned-pinned rigid pipe per Figure 10-5.

c. Determine dead loads;
$W_{P@S1}$ = 13.75'(45plf) = 619-lbs (2.75KN) (typical for horizontal spans)
$W_{P@S2}$ = (13.75' + 28')(1/2)45plf = 939-lbs (4.18KN) (governs for gravity load design)

Therefore, one design, based on the worst case loading at location S_2, will be used throughout for gravity loads.

Member design (see Figure J3-2);



Note: For metric equivalent; 1-in = 25.4mm

Figure J3-2. Transverse pipe restraint

Factored dead load acting at support; $P_u = 1.4W_{S2}$ =1.4(939-lbs) = 1,315-lbs, or 1.32^k (5.85KN)

For two braces inclined at 45 degrees (one on either side of pipe), the ultimate load per brace is determined as;

$$P_u = \frac{(1.32^k)\sqrt{2}}{2} = 0.93^{k/brace} \quad (4.14KN/brace)$$

Try L2x2x3/16 (L50.8mmX50.8mmX4.8mm) (Area = 0.715-in^2 (461.2mm^2)) attached using one 3/8" (9.53mm) ϕ bolt per connection;

Check yielding on the gross area;

$$f_t P_n = f_t F_y A_g \qquad \text{where;} \quad f_t = 0.90 \qquad \text{(EQ. D1-1 AISC LRFD)}$$

$\phi_t P_n = 0.90 F_y A_g = 0.9(36ksi)0.715 - in^2 = 23.2^k > 0.93^k = P_u$ (103.2KN > 4.14KN) **O.K.**

Check fracture on the effective net area;

$\phi_t P_n = \phi_t F_u A_e$ where; $\phi_t = 0.75$ (EQ. D1-2 AISC LRFD)

$A_e = 2"(3/16") - (1/8" + 3/8")(3/16") = 0.281\text{-}in^2$ ($181.2mm^2$)

$\phi_t P_n = 0.75 F_u A_e = 0.75(58ksi)0.281 - in^2 = 12.2^k > 0.93^k = P_u$ (54.3KN > 4.14KN) **O.K.**

Use 2-L2x2x3/16 (L50.8mmX50.8mmX4.8mm) braces

Note: The following steps do not have a one to one correspondence to steps as listed in table 4-6.

F.1 *Determine seismic force effects.*

Seismic forces (F_p) shall be determined at each pipe location (i.e., S_1, S_2, and S_3) in accordance with chapter 10 as follows:

$$F_p = \frac{0.4 a_p S_{DS} W_p}{R_p / I_p}\left(1 + 2\frac{z}{h}\right) \quad \text{(EQ. 10-1)}$$

where; z/h = 21/36 = 0.58 (Figure J3-1)

W_P: $W_{P@S1}$ = 619-lbs or 0.619^k (2.75KN) (as previously calculated)

$W_{P@S2}$ = 939-lbs or 0.939^k (4.18KN) (as previously calculated)

$W_{P@S3}$ = (21' + 7')(1/2)45plf = 630lb or 0.630k (2.80KN)

F_p is not required to be taken greater than:

$$F_p = 1.6 S_{DS} I_p W_p \quad \text{(EQ. 10-2)}$$

nor less than:

$$F_p = 0.3 S_{DS} I_p W_p \quad \text{(EQ. 10-3)}$$

Seismic load at location S_1;

$$F_{p1} = \frac{0.4(1.0)0.81(0.619^k)}{1.25/1.0}(1 + 2(0.58)) = 0.56(0.619^k) = 0.347^k \quad (1.54KN)$$

Note: The seismic coefficient is 0.56 and is applicable at all locations along the pipe.

$(F_{p1})_{max} = 1.6(0.81)1.0(0.619^k) = 0.802^k > 0.347^k = F_{p1}$ (3.57KN > 1.54KN) **O.K.**

$(F_{p1})_{min} = 0.3(0.81)1.0(0.619^k) = 0.150^k < 0.347^k = F_{p1}$ (0.67KN < 1.54KN) **O.K.**

Seismic load at location S_2;

$F_{p2} = 0.56(0.939^k) = 0.526^k$ (2.34KN)

$(F_{p2})_{max} = 1.6(0.81)1.0(0.939^k) = 1.22^k > 0.526^k = F_{p2}$ (5.43 > 2.34KN) **O.K.**

$(F_{p2})_{min} = 0.3(0.81)1.0(0.939^k) = 0.228^k < 0.526^k = F_{p2}$ (1.01KN < 2.34KN) **O.K.**

Seismic load at location S_3;

$F_{p3} = 0.56(0.636^k) = 0.356^k$ (1.58KN)

$(F_{p3})_{max} = 1.6(0.81)1.0(0.630^k) = 0.817^k > 0.356^k = F_{p3}$ (3.63KN > 1.58KN) **O.K.**

$(F_{p3})_{min} = 0.3(0.81)1.0(0.630^k) = 0.153^k < 0.356^k = F_{p3}$ (0.68KN < 1.58KN) **O.K.**

F.2 *Design members.*

Design for loads transverse to pipe axis (see Figure J3-2);
Note: Supports for loads transverse to pipe axis are located at locations S_1, S_2, and S_3.
At location S_1;
Seismic load per brace;

$$P_u = \frac{(0.347^k)\sqrt{2}}{2} = 0.245^{k/brace} \quad (1.09KN/brace)$$

Dead load per brace;

$$P_u = \frac{(0.619^k)\sqrt{2}}{2} = 0.438^{k/brace} \quad (1.99KN/brace)$$

Load combinations;

U = 1.4D; $P_u = 1.4(0.438^{k/brace}) = 0.61^{k/brace}$ (2.71KN/brace)

U = 1.2D + E; $P_u = 1.2(0.438^{k/brace}) + 0.245^{k/brace} = 0.77^{k/brace}$ (3.42KN/brace)

U = 0.9D – E; $P_u = 0.9(0.438^{k/brace}) - 0.245^{k/brace} = 0.15^{k/brace}$ (0.67KN/brace)

At location S_2;

Seismic load per brace;

$$P_u = \frac{(0.526^k)\sqrt{2}}{2} = 0.372^{k/brace} \quad (1.65KN/brace)$$

Dead load per brace;

$$P_u = \frac{(0.939^k)\sqrt{2}}{2} = 0.664^{k/brace} \quad (2.95KN/brace)$$

Load combinations;

U = 1.4D; $P_u = 1.4(0.664^{k/brace)} = 0.93^{k/brace}$ (4.14KN/brace)

U = 1.2D + E; $P_u = 1.2(0.664^{k/brace}) + 0.372^{k/brace} = 1.17^{k/brace}$ (5.20KN/brace) (governs)

U = 0.9D – E; $P_u = 0.9(0.664^{k/brace}) - 0.372^{k/brace} = 0.23^{k/brace}$ (1.02KN/brace)

At location S_3;

Note: No dead load acts at location S_3.

Seismic load per brace;

$$P_u = \frac{(0.356^k)\sqrt{2}}{2} = 0.25^{k/brace} \quad (1.11KN/brace)$$

Load combinations;

U = E; $P_u = 0.25^{k/brace}$ (1.11KN/brace)

Note: Braces always act in tension.

Check capacity of angle braces;

Check yielding on the gross area;

$$f_t P_n = 0.90 F_y A_g = 0.9(36ksi)0.715 - in^2 = 23.2^k > 1.17^k = P_u \quad (103.2KN > 5.20KN)$$ **O.K.**

Check fracture on the effective net area;

$$f_t P_n = 0.75 F_u A_e = 0.75(58ksi)0.281 - in^2 = 12.2^k > 1.17^k = P_u \quad (54.3KN > 5.20KN)$$ **O.K.**

Use 2-L2x2x3/16 (2-L50.8mmX50.8mmX4.8mm) braces

Design connections to pipe;

Determine design loads;

$$T_u = V_u = \frac{1.17^{k/brace}}{\sqrt{2}} = 0.83^{k/connection} \quad (3.69KN/connection)$$

Try a single 3/8" ϕ A307 bolt in a bearing type connection;

Check shear;

$f R_n = f F_n A_b$ where; $f_t = 0.75$ (per AISC LRFD section J3.6)

$F_n = 24ksi$ (per AISC LRFD Table J3.2)

$$A_b = \frac{p(3/8")^2}{4} = 0.11 - in^2 \quad (71.0mm^2)$$

$$f R_n = f F_n A_b = 0.75(24ksi)0.11 - in^2 = 1.98^k > 0.83^k = V_u \quad (8.81KN > 3.69KN)$$ **O.K.**

Check bearing;

By inspection, $L_e > 1.5d$;

$R_n = 2.4dtF_u$ with; $f = 0.75$ (EQ. J3-1a AISC LRFD)

$fR_n = 0.75(2.4(3/8")3/16"(58ksi)) = 7.35^k > 0.83^k = V_u$ (32.7KN > 3.69KN) **O.K.**

Check combined tension and shear;
The tension limit stress is;

$59 - 1.9f_v \leq 45\,ksi$ (310.3MPa) (per AISC LRFD Table J3.5)

Therefore,

$$f_v = \frac{P_u}{A_b} = \frac{0.83^k}{0.11 - in^2} = 7.55ksi \quad (52.1MPa)$$

$59ksi - 1.9(7.55ksi) = 44.7ksi < 45ksi$ Therefore, $F_t = 44.7ksi$ (308.2MPa)

$fR_n = fF_tA_b = 0.75(44.7ksi)0.11 - in^2 = 3.69^k > 0.83^k = T_u$ (16.4KN > 3.69KN) **O.K.**

Use a single 3/8" f bolt for connections to pipe

Design connections to concrete;

Note: For anchors in concrete without special inspection, Section 9.2.1 in FEMA 302 requires an additional load factor of 2.0. Therefore;

$P_u = V_u = 2(0.83^k) = 1.66^k$ (7.38KN)

Try a single 3/8" (9.53mm) ϕ A307 bolt in a bearing type connection;
Check capacity in shear;
Steel;

$V_s = (0.75A_bF_u)n$ (EQ. 9.2.4.2-1 FEMA 302)

For 3/8" (9.53mm) ϕ bolt (A 307)

where; $A_b = 0.11\text{-}in^2$ ($71.0mm^2$)
$F_u = 60ksi$ (413.7MPa)
n = 1-bolt

$V_s = 0.75(0.11 - in^2)60ksi(1.0 - bolt) = 4.95^k > 1.66^k = V_u$ (22.0KN > 7.38KN) **O.K.**

Concrete;

$fV_c = (f800A_b\,l\sqrt{f_c'})n$ (EQ. 9.2.4.2-2 FEMA 302)

where; $\phi = 0.65$
$\lambda = 1.0$ (normal weight concrete)
$f_c' = 4,000psi$ (27.6MPa)
n = 1-bolt

$\therefore fV_c = 0.65(800)0.11 - in^2(1.0)\sqrt{4,000psi} = 0.65(5.57^k) = 3.62^k$ (16.1KN)

$fV_c = 3.62^k > 1.66^k = V_u$ (16.1KN > 7.38KN) **O.K.**

Check capacity in tension;
Steel;

$P_s = (0.9A_bF_u)n$ (EQ. 9.2.4.1-1 FEMA 302)

where; $A_b = 0.11\text{-}in^2$ ($71.0mm^2$)
$F_u = 60ksi$ (413.7MPa)
n = 1-bolt

$\therefore P_s = 0.9(0.11 - in^2)60ksi(1 - bolt) = 5.94^k > 1.66^k = P_u$ (26.4KN > 7.38KN) **O.K.**

Concrete;

$fP_c = f\,l\sqrt{f_c'}(2.8A_s)n$ (EQ. 9.2.4.1-2 FEMA 302)

where; $\phi = 0.65$
$\lambda = 1.0$ (normal weight concrete)
$f_c' = 4,000psi$ (27.6MPa)
$A_s = \pi(3")3" = 28.3\text{-}in^2$ ($18.25X10^3\ mm^2$) (for a 3-in. (76.2mm) embedment)

$\therefore \phi P_c = 0.65(1.0)\sqrt{4{,}000\text{psi}}(2.8(28.3-\text{in}^2))(1-\text{bolt}) = 0.65(5.01^k) = 3.26^k > 1.66^k = P_u$

(14.5KN > 7.38KN) **O.K.**

Check combined tension and shear;

Per section 9.2.4.3 of FEMA 302 , all of the following conditions shall be met;

condition (a) $\frac{1}{\phi}\left(\frac{V_u}{V_c}\right) \leq 1.0$ (EQ. 9.2.4.3-1a FEMA 302)

$\frac{1}{0.65}\left(\frac{1.66^k}{5.57^k}\right) = 0.46 \leq 1.0$ **O.K.**

condition (b) $\frac{1}{\phi}\left(\frac{P_u}{P_c}\right) \leq 1.0$ (EQ. 9.2.4.3-1b FEMA 302)

$\frac{1}{0.65}\left(\frac{1.66^k}{5.01^k}\right) = 0.51 \leq 1.0$ **O.K.**

condition (c) $\frac{1}{\phi}\left[\left(\frac{P_u}{P_c}\right)^2 + \left(\frac{V_u}{V_c}\right)^2\right] \leq 1.0$ (EQ. 9.2.4.3-1c FEMA 302)

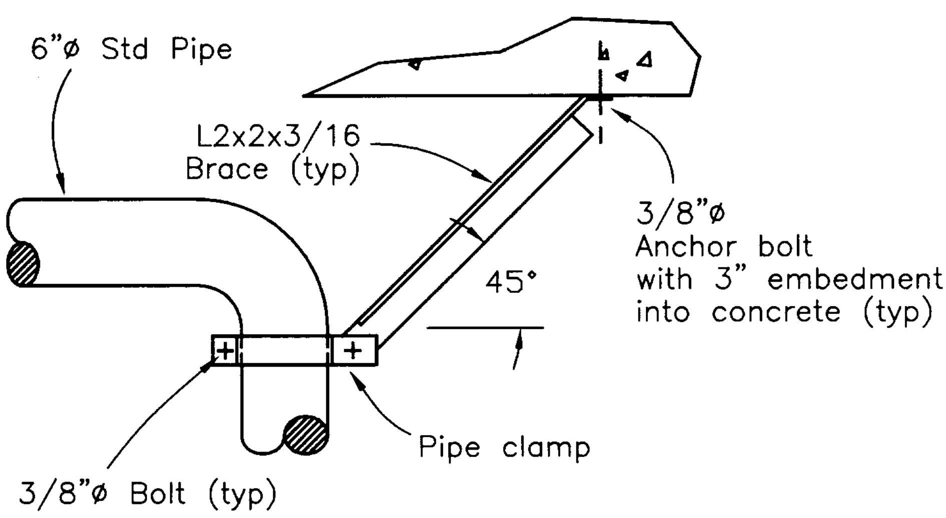
$\frac{1}{0.65}\left[\left(\frac{1.66^k}{5.57^k}\right)^2 + \left(\frac{1.66^k}{5.01^k}\right)^2\right] = \frac{1}{0.65}(0.089 + 0.11) = 0.31 \leq 1.0$ **O.K.**

condition (d) $\left(\frac{P_u}{P_s}\right)^2 + \left(\frac{V_u}{V_s}\right)^2 \leq 1.0$ (EQ. 9.2.4.3-1d FEMA 302)

$\left(\frac{1.66^k}{5.94^k}\right)^2 + \left(\frac{1.66^k}{4.95^k}\right)^2 = (0.078 + 0.112) = 0.19 \leq 1.0$ **O.K.**

Use a single 3/8" (9.53mm) ϕ A307 bolt to concrete

Design for loads longitudinal to pipe axis (see Figure J3-3);



Note: For metric equivalents; 1-in = 25.4mm

Figure J3-3. Longitudinal pipe restraint and force diagram

Note: Supports for loads longitudinal to pipe axis are located at location S_2 only. Assume that the horizontal section of pipe at the 3rd floor has longitudinal braces spaced at 60-ft (18.3m). on center.

Therefore; $(W_{P@S2})_{long}$ = (60' + 11')(1/2)45plf = 1,598-lbs or 1.60^k (7.11KN)

$F_p = 0.56(1.60^k) = 0.896^k$ (3.99KN)

Seismic load per brace;

$$P_u = \pm\frac{(0.896^k)\sqrt{2}}{2} = \pm 0.633^{k/brace}\ (2.82KN/brace)$$

Note: Brace acts in both tension and compression.

Try a single L2x2x3/16 (L50.8mmX50.8mmX4.8mm) brace.

Check capacity of brace;

Note: By inspection, the brace is adequate in tension. Also, the brace is a singly symmetric shape that is susceptible to flexural-torsional buckling. Therefore, equations from Appendix E3 of AISC LRFD are invoked.

Compare slenderness ratios;

The length of brace is established from Figure J3-1. Assume floor slab is 6-in. (152.4mm) thick, and that attachment to the pipe is made one pipe diameter below the horizontal pipe centerline.

$$L = \sqrt{2}(24'-21'-0.5'+0.5') = 4.24'\ \ (1.29m)$$

$$\frac{KL_y}{r_y} = \frac{KL_x}{r_x} = \frac{1.0(4.24')(12''/1')}{0.617''} = 82.5$$

$$\frac{KL_z}{r_z} = \frac{1.0(4.24')(12''/1')}{0.394''} = 129.1 \qquad \text{(governs)}$$

Check flexural buckling;

$$\phi_c P_n = \phi_c A_g F_{cr} \qquad \text{with;} \quad \phi_c = 0.85 \qquad \text{(EQ. E2-1 AISC LRFD)}$$

From Table 3-36 of AISC LRFD;

$$\phi_c F_{cr} = 12.72\text{ksi}\ \ (87.7\text{MPa}) \qquad \text{(interpolated)}$$

and

$$\phi_c P_n = \phi_c A_g F_{cr} = (12.72\text{ksi})0.715-\text{in}^2 = 9.1^k\ \ (40.5\text{KN})$$

Check flexural-torsional buckling;

$$\phi_c P_n = \phi_c A_g F_{cr} \qquad \text{with;} \quad \phi_c = 0.85 \qquad \text{(EQ. A-E3-1 AISC LRFD)}$$

$$F_e = \frac{F_{ey}+F_{ez}}{2H}\left(1+\sqrt{1-\frac{4F_{ey}F_{ez}H}{(F_{ey}+F_{ez})^2}}\right) \qquad \text{(EQ. A-E3-6 AISC LRFD)}$$

$$F_{ey} = \frac{\pi^2 E}{(K_y l/r_y)^2} \qquad \text{(EQ. A-E3-11 AISC LRFD)}$$

$$F_{ez} = \left(\frac{\pi^2 EC_w}{(K_z l)^2} + GJ\right)\frac{1}{A\bar{r}_o^2} \qquad \text{(EQ. A-E3-12 AISC LRFD)}$$

where; $A = 0.715\text{-in}^2$ (461.2mm^2)

$l = 4.24'(12''/1') = 50.9\text{-in}^2$ ($32.8\text{X}10^3\ \text{mm}^2$)

$K_y = 1.0$ (no sway)

$K_z = 1.0$ (ends are rotationally restrained)

$r_y = 0.617$-in (15.67mm) (from AISC LRFD properties tables)

$\bar{r}_o = 1.10$-in (27.94mm) (from AISC LRFD torsional properties tables)

$C_w = 0.00254\text{-in}^6$ ($682.1\text{X}10^3\ \text{mm}^6$)(from AISC LRFD torsional properties tables)

E = 29,000ksi ($200\text{X}10^3$ MPa)

G = 11,200ksi ($77.2\text{X}10^3$ MPa)

$J = 0.00880\text{-in}^4$ ($3.67\text{X}10^3\ \text{mm}^4$) (from AISC LRFD torsional properties tables)

H = 0.628 (from AISC LRFD torsional properties tables)

$$F_{ey} = \frac{\pi^2(29{,}000\text{ksi})}{(82.5)^2} = 42.1\text{ksi} \quad (290.3\text{MPa})$$

$$F_{ez} = \left(\frac{\pi^2(29{,}000\text{ksi})0.00254-\text{in}^6}{(1.0(4.24'(12''/1')))^2} + 11{,}200\text{ksi}(0.00880-\text{in}^4)\right)\frac{1}{0.715-\text{in}^2(1.10-\text{in})^2} = 125.7\text{ksi}$$

(866.7MPa)

$$F_{ey} + F_{ez} = 42.1\text{ksi} + 125.7\text{ksi} = 168\text{ksi} \quad (1.16X10^3\text{ MPa})$$

$$F_e = \frac{168\text{ksi}}{2(0.628)}\left(1+\sqrt{1-\frac{4(42.1\text{ksi})114\text{ksi}(0.628)}{(173)^2}}\right) = 237\text{ksi} \quad (1.63X10^3\text{ MPa})$$

Check local buckling;

$$\frac{b}{t} = \frac{2.0}{3/16} = 10.67 < 12.67 = \frac{76}{\sqrt{F_y}} \Rightarrow Q = 1.0$$ (per paragraph E3 of Appendix E of AISC LRFD)

Determine which equation to use;

$$\lambda_e = \sqrt{F_y / F_e}$$ (EQ. A-E3-4 AISC LRFD)

$$\lambda_e = \sqrt{36\text{ksi}/237\text{ksi}} = 0.39 < 1.5$$

$$F_{cr} = Q\left(0.658^{Q\lambda_e^2}\right)F_y$$ (EQ. A-E3-2 AISC LRFD)

$$F_{cr} = 1.0\left(0.658^{1.0(0.39)^2}\right)36\text{ksi} = 33.8\text{ksi} \quad (233.1\text{MPa})$$

$$\therefore \phi_c P_n = \phi_c A_g F_{cr} = 0.85(0.715-\text{in}^2)33.8\text{ksi} = 20.5^k \quad (91.2\text{KN})$$

Therefore, flexural buckling controls.

$$\phi_c P_n = 7.73^k > 0.633^k = P_u \quad (33.4\text{KN} > 282\text{KN})$$ **O.K.**

Use L2x2x3/16 (L50.8mmX50.8mmX4.8mm) brace