SECTION 5 – EXAMPLES

5.0 LATTICE SUSPENSION TOWER LOADS

This example shows calculations for wire and structure loads. The loads are based on the tower shown in Figure 5.0-1 and the design and wire data listed below.

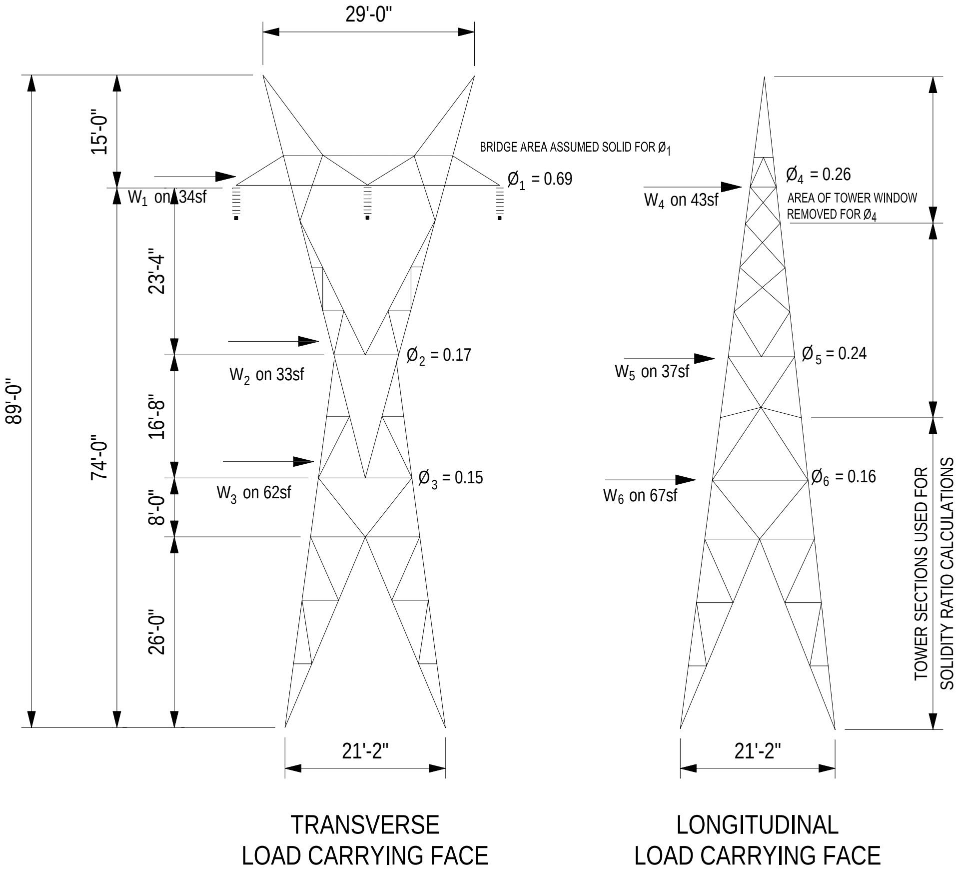


Figure 5.0-1 Suspension Tower

Design Data:
The transmission line is located in Utah.

Relative Reliability Factor = 1
Ruling Span = 1250 ft
Wind Span = 1500 ft
Weight Span = 1800 ft
Line Angle = 5 degrees
Length of Insulator Assembly = 6 ft
Weight of Insulator Assembly = 200 lbs
Weight of Ground Wire Assembly = 50 lbs

Wire Data:

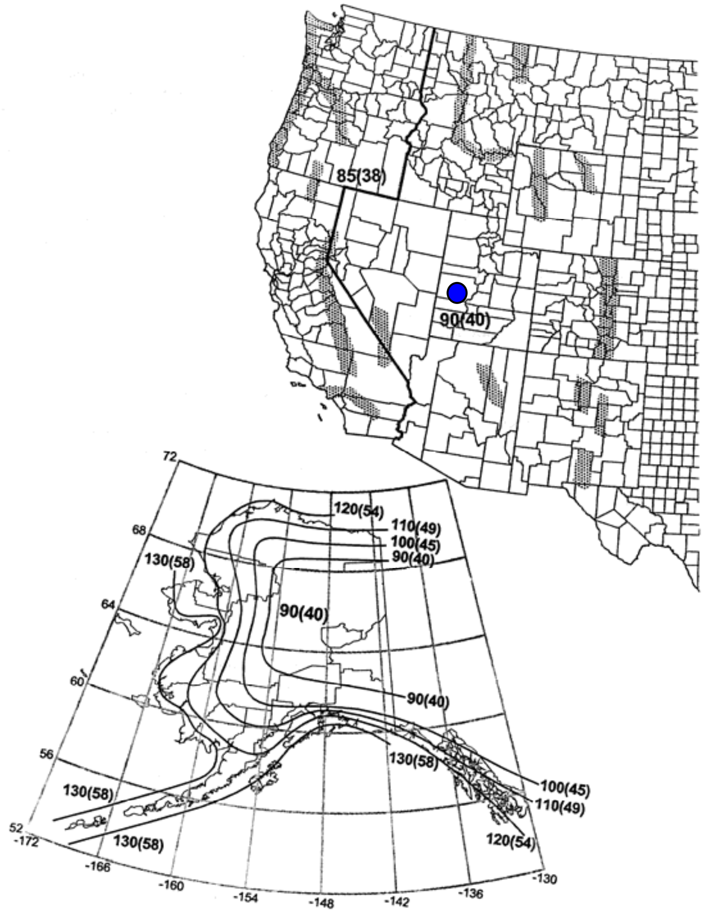
Loading Case	Temp (ºF)	Ice (in)	Wind (psf)	**954 kcmil 45/7 ACSR RAIL Conductor** (*d* = 1.165 in, *w* = 1.075 lbs/ft)		**7#8 Aluminum Clad Steel Ground Wire** (*d* = 0.385 in, *w* = 0.262 lbs/ft)	
				Initial Sag (ft)	**Initial Tension (lbs)**	**Initial Sag (ft)**	**Initial Tension (lbs)**
Wind	60	0	16.3	43.7	8598	39.0	2939
Wind @ 30	60	0	12.2	42.3	7428	37.2	2481
Wind and Ice	15	0.273	1.81	39.2	7921	35.8	2767
NESC	15	0.25	4	40.4	8800	39.5	3700
C&M	15	0	3	36.6	5961	31.2	1751
FC	30	0	0	37.5	5615	31.6	1623
No Wind	60	0	0	39.8	5302	33.2	1546

Wind pressures for the **Wind** and **Wind @ 30** loading cases are a function of the span length. They are generated using the wind span instead of the ruling span. However, for calculations of sags and tensions, the use of the ruling span is more appropriate.

Wind (Extreme Wind, Section 2.1)

Wind is normal to the ahead span, back span, and to the structure.
The structure is located on the perpendicular bisector of the line angle.

From the wind map (Figure 2.1.3-1), V_{50} equals 90 mph. The exposure category is C.



Wind on Wires:

Average wire height (z_h) = [3(74)+2(89)]/5 = 80 ft (Sect. 2.1.4.3)

$K_z = 2.01(z_h/z_g)^{2/\alpha} = 2.01(80/900)^{2/9.5} = 1.21$ (Eq. 2.1.4-1)

$E = 4.9(\kappa)^{1/2}(33/z_h)^{1/\alpha_{FM}} = 4.9\ (0.005)^{1/2}(33/80)^{1/7} = 0.305$ (Eq. 2.1.5-3)
$B_w = 1/(1+0.8L/L_s) = 1/(1+0.8(1500)/220) = 0.155$ (Eq. 2.1.5-4)
$G_w = [1+2.7E(B_w)^{1/2}]/k_v^2 = [1+2.7(0.305)(0.155)^{1/2}]/1.43^2 = 0.648$ (Eq. 2.1.5-1)

Wind pressure = $\gamma_w Q K_z (V_{50})^2 G_w C_f$ (Eq. 2.1-1a)
$= 1.0(0.00256)(1.21)(90)^2(0.648)1.0 = 16.3$ psf

Ground Wire Loads:

V = 0.262(1800)+50 = 522 lbs = 0.5 kips
T = 16.3(0.385/12)(1500)+2939 sin(5/2)(2) = 1041 lbs = 1.0 kips

Conductor Loads:

V = 1.075(1800)+200 = 2135 lbs = 2.1 kips
T = 16.3(1.165/12)(1500)+8598 sin(5/2)(2) = 3124 lbs = 3.1 kips

Wind on Structure:

Two thirds of the structure height (z_h) = 2(89)/3 = 59.3 ft (Sect. 2.1.4.3)

$K_z = 2.01(z_h/z_g)^{2/\alpha} = 2.01(59.3/900)^{2/9.5} = 1.13$ (Eq. 2.1.4-1)

$E = 4.9(\kappa)^{1/2}(33/z_h)^{1/\alpha_{FM}} = 4.9\ (0.005)^{1/2}(33/59.3)^{1/7} = 0.319$ (Eq. 2.1.5-3)
$B_t = 1/(1+0.56z_h/L_s) = 1/(1+0.56(59.3)/220) = 0.869$ (Eq. 2.1.5-5)
$G_t = [1+2.7E(B_t)^{1/2}]/k_v^2 = [1+2.7(0.319)(0.869)^{1/2}]/1.43^2 = 0.882$ (Eq. 2.1.5-2)

Wind pressure = $\gamma_w Q K_z (V_{50})^2 G_t$ (Eq. 2.1-1a)
$= 1.0(0.00256)(1.13)(90)^2\ 0.882 = 20.7$ psf

Figure 5.0-1 shows tower areas and solidity ratios.

Transverse Wind Loads:

For $\Phi_1 = 0.69$, $C_{f1} = 1.8$, and $A_1 = 34$ ft^2
For $\Phi_2 = 0.17$, $C_{f2} = 4.1-5.2\Phi = 4.1-5.2(0.17) = 3.22$, and $A_2 = 33$ ft^2
For $\Phi_3 = 0.15$, $C_{f3} = 4.1-5.2\Phi = 4.1-5.2(0.15) = 3.32$, and $A_3 = 62$ ft^2
where force coefficient equations are from Table 2.1.6-1.

$W_1 = 20.7(1.8)(34) = 1267$ lbs = 1.3 kips
$W_2 = 20.7(3.22)(33) = 2200$ lbs = 2.2 kips
$W_3 = 20.7(3.32)(62) = 4261$ lbs = 4.3 kips

Wind @30 (Extreme Wind @ 30º Yaw Angle, Section 2.1)

Wind is at a 30 degree yaw angle.

Wind on Wires:

From the **Wind** load case, the wind pressure normal to the wires equals 16.3 psf.

Wind pressure = $16.3 \cos^2\Psi = 16.3 \cos^2(30) = 12.2$ psf (Eq. 2.1.6-4)

Ground Wire Loads:

V = 0.262(1800)+50 = 522 lbs = 0.5 kips
T = 12.2(0.385/12)(1500)+2481 sin(5/2)(2) = 804 lbs = 0.8 kips

Conductor Loads:

V = 1.075(1800)+200 = 2135 lbs = 2.1 kips
T = 12.2(1.165/12)(1500)+7428 sin(5/2)(2) = 2425 lbs = 2.4 kips

Wind on Structure:

From the **Wind** load case, the structure wind pressure equals 20.7 psf.
Use the first alternative in Section 2.1.6.2.3.

Transverse Wind Loads:

Wind pressure = 20.7 cosΨ = 20.7 cos(30) = 17.9 psf (Eq. 2.1.6-5a)
Force coefficients and areas are provided in the **Wind** loading case.

W_1 = 17.9(1.8)(34) = 1096 lbs = 1.1 kips
W_2 = 17.9(3.22)(33) = 1902 lbs = 1.9 kips
W_3 = 17.9(3.32)(62) = 3684 lbs = 3.7 kips

Longitudinal Wind Loads:

Wind pressure = 20.7 sin Ψ = 20.7 sin(30) = 10.4 psf (Eq. 2.1.6-5b)

For Φ_4 = 0.26, C_{f4} = 4.1-5.2Φ = 4.1-5.2(0.26) = 2.75, and A_4 = 43 ft^2
For Φ_5 = 0.24, C_{f5} = 4.1-5.2Φ = 4.1-5.2(0.24) = 2.85, and A_5 = 37 ft^2
For Φ_6 = 0.16, C_{f6} = 4.1-5.2Φ = 4.1-5.2(0.16) = 3.27, and A_6 = 67 ft^2
where force coefficient equations are from Table 2.1.6-1.

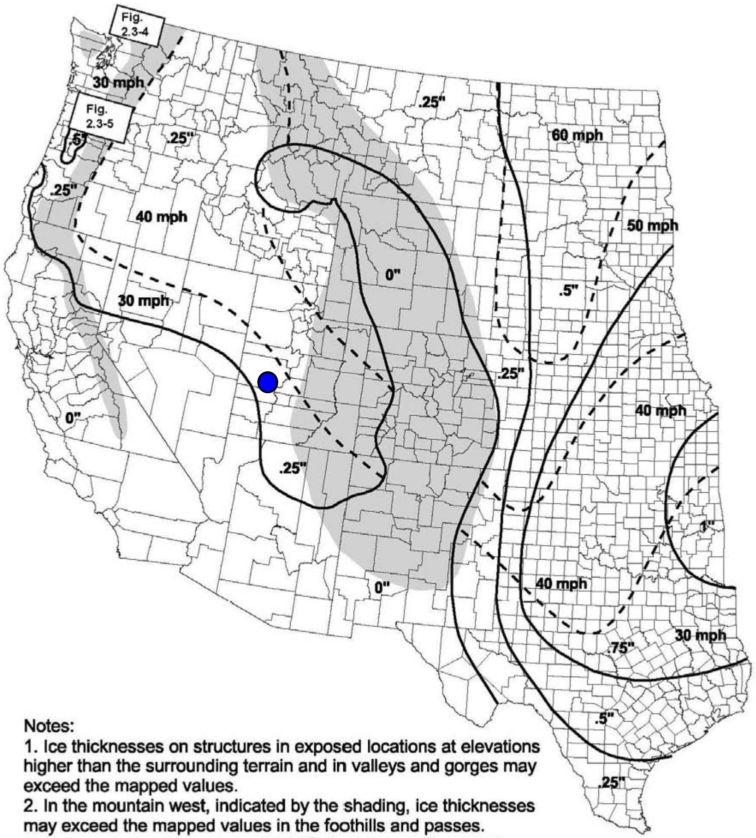
W_4 = 10.4(2.75)(43) = 1230 lbs = 1.2 kips
W_5 = 10.4(2.85)(37) = 1097 lbs = 1.1 kips
W_6 = 10.4(3.27)(67) = 2279 lbs = 2.3 kips
where force coefficient equations are from Table 2.1.6-1.

Wind and Ice (Extreme Radial Glaze Ice with Wind, Section 2.3)

Wind on Wires:

From the **Wind** load case, K_z equals 1.21 and G_w equals 0.648.

From the wind and ice map (Figure 2.3-1a), I_{50} equals 0.25 in and V_I equals 30 mph.



Notes:
1. Ice thicknesses on structures in exposed locations at elevations higher than the surrounding terrain and in valleys and gorges may exceed the mapped values.
2. In the mountain west, indicated by the shading, ice thicknesses may exceed the mapped values in the foothills and passes. However, at elevations above 5,000 ft, freezing rain is unlikely.
3. In the Appalachian Mountains, indicated by the shading, ice thicknesses may vary significantly over short distances.

Wind pressure $= Q\, K_z\, (V_I)^2\, G_w C_f$ (Eq. 2.1-1a)

$= 0.00256(1.21)(30)^2(0.648)1.0 = 1.81$ psf

$I_z = I(z_h/33)^{0.10}$ (Eq. 2.3-1)

$= 0.25(80/33)^{0.10} = 0.273$ in

Ground Wire Loads:

$W_i = 1.24(d + I_z)I_z$ (Eq. 2.3-3)

$= 1.24(0.385+0.273)0.273 = 0.223$ lbs/ft

$d_i = 2(0.273)+0.385 = 0.931$ in

V = 1800(0.262+0.223)+50 = 923 lbs = 0.9 kips

T = 1.81(0.931/12)(1500)+2767 sin(5/2)(2) = 452 lbs = 0.5 kips

Conductor Loads:

$W_i = 1.24(d + I_z)I_z$ (Eq. 2.3-3)

$= 1.24(1.165+0.273)0.273 = 0.487$ lbs/ft

$d_i = 2(0.273)+1.165 = 1.711$ in

$V = 1800(1.075+0.487)+200 = 3012$ lbs $= 3.0$ kips
$T = 1.81(1.711/12)(1500)+7921 \sin(5/2)(2) = 1078$ lbs $= 1.1$ kips

Wind on Structure:

From the **Wind** loading case, K_z equals 1.13 and G_t equals 0.882.

Wind pressure = Q K_z $(V_I)^2$ G_t (Eq. 2.1-1a)
$= 0.00256(1.13)(30)^2\ 0.882 = 2.30$ psf

Transverse Wind Loads:

Force coefficients and areas are provided in the **Wind** loading case.

$W_1 = 2.3(1.8)(34) = 141$ lbs $= 0.1$ kips
$W_2 = 2.3(3.22)(33) = 244$ lbs $= 0.2$ kips
$W_3 = 2.3(3.32)(62) = 473$ lbs $= 0.5$ kips

HIW (High Intensity Wind, Section 2.2)

Eighty-six percent of the tornadoes are F2 or smaller (Table 2.2.1-2). This rating corresponds to a wind speed of 157 mph. Wind is applied on the structure and wire loads are assumed to be zero.

F-scale (gust wind speed range)	Number of Tornadoes	Percentage	Cumulative percentage
F0 (40-72 mph)	5718	22.9	22.9
FI (73-112 mph)	8645	34.7	57.6
F2 (113-**157** mph)	7102	28.5	86.1
F3 (158-206 mph)	2665	10.7	96.8
F4 (207-260 mph)	673	2.7	99.5
F5 (261-318 mph)	127	0.5	100.0
Total	24,930	100.0	

Three loading cases are calculated, 0, 90, and 45 degree yaw angles.

Wind on Structure:

$K_z = G_t = 1.0$

Wind pressure = Q K_z $(V)^2$ $G_t = 0.00256(1.0)(157)^2\ (1.0) = 63.1$ psf

0 degree yaw angle:

Transverse Wind Loads:

Force coefficients and areas are provided in the **Wind** loading case.

$W_1 = 63.1(1.8)(34) = 3862$ lbs $= 3.9$ kips
$W_2 = 63.1(3.22)(33) = 6705$ lbs $= 6.7$ kips
$W_3 = 63.1(3.32)(62) = 12989$ lbs $= 13.0$ kips

90 degree yaw angle:

Longitudinal Wind Loads:

Force coefficients and areas are provided in the **Wind@30** loading case.

$W_4 = 63.1(2.75)(43) = 7461$ lbs $= 7.5$ kips
$W_5 = 63.1(2.85)(37) = 6654$ lbs $= 6.7$ kips
$W_6 = 63.1(3.27)(67) = 13825$ lbs $= 13.8$ kips

45 degree yaw angle:

Transverse Wind Loads:

Wind pressure = 63.1 cosΨ = 63.1 cos(45) = 44.6 psf (Eq. 2.1.6-5a)

Force coefficients and areas are provided in the **Wind** loading case.

W_1 = 44.6(1.8)(34) = 2730 lbs = 2.7 kips
W_2 = 44.6(3.22)(33) = 4739 lbs = 4.7 kips
W_3 = 44.6(3.32)(62) = 9180 lbs = 9.2 kips

Longitudinal Wind Loads:

Wind pressure = 63.1 sinΨ = 63.1 sin(30) = 44.6 psf (Eq. 2.1.6-5b)

Force coefficients and areas are provided in the **Wind@30**loading case.

W_4 = 44.6(2.75)(43) = 5274 lbs = 5.3 kips
W_5 = 44.6(2.85)(37) = 4703 lbs = 4.7 kips
W_6 = 44.6(3.27)(67) = 9771 lbs = 9.8 kips

NESC

From the NESC General Loading Map of the United States (Fig. 250-1), Utah is in the medium loading district. Rule 250C (Extreme Wind) is not included in this example.

Wind on Wires:

Wind pressure = 4 psf

Ground Wire Loads:

$W_i = 1.24(d + I_z)I_z$ (Eq. 2.3-3)
= 1.24(0.385+0.25)0.25 = 0.197 lbs/ft

d_i = 2(0.25)+0.385 = 0.885 in

V = 1800(0.262+0.197)(1.5)+50(1.5) = 1314 lbs = 1.3 kips
T = 4(0.885/12)(1500)(2.5)+3700 sin(5/2)(2)(1.65) = 1638 lbs = 1.6 kips

Conductor Loads:

$W_i = 1.24(d + I_z)I_z$ (Eq. 2.3-3)
= 1.24(1.165+0.25)0.25 = 0.439 lbs/ft

d_i = 2(0.25)+1.165 = 1.665 in

V = 1800(1.075+0.439)(1.5)+200(1.5) = 4388 lbs = 4.4 kips
T = 4(1.665/12)(1500)(2.5)+8800 sin(5/2)(2)(1.65) = 3348 lbs = 3.3 kips

Wind on Structure:

Transverse Wind Loads:

Wind pressure = 4(2.5) = 10 psf
Areas are provided in the **Wind** loading case.
The NESC force coefficient is 3.2.

W_1 = 10(3.2)(34) = 1088 lbs = 1.1 kips
W_2 = 10(3.2)(33) = 1056 lbs = 1.1 kips
W_3 = 10(3.2)(62) = 1984 lbs = 2.0 kips

C&M (Construction and Maintenance, Section 3.1)

Wind on Wires:

Wind pressure = 3 psf

Ground Wire Loads:

Alt. A :..Snubbing Wires - the pulling slope is 3 horizontal to 1 vertical.
Alt. B: Two times the weight span.

V = 1.5(1751)(1/3)+0.262(1800)(1.5)/2+50(1.5)= 1304 lbs = 1.3 kips (Alt. A controls)
V = 0.262(1800)(2)+50(2) = 1043 lbs = 1.1 kips (Alt. B)
T = 3(0.385/12)(1500)1.5+1751 sin(5/2)(2)1.5 = 446 lbs = 0.5 kips

Conductor Loads:

V = 1.5(5961)(1/3)+1.075(1800)(1.5)/2+200(1.5)= 4732 lbs = 4.7 kips (Alt. A controls)
V = 1.075(1800)2+200(2) = 4270 lbs = 4.3 kips (Alt. B)
T = 3(1.165/12)(1500)1.5+5961 sin(5/2)(2)1.5 = 1435 lbs = 1.4 kips

Wind on Structure:

Transverse Wind Loads:

Wind pressure = 3(1.5) = 4.5 psf
Force coefficients and areas are provided in the **Wind** loading case.

W_1 = 4.5(1.8)(34) = 275 lbs = 0.3 kips
W_2 = 4.5(3.22)(33) = 478 lbs = 0.5 kips
W_3 = 4.5(3.32)(62) = 926 lbs = 0.9 kips

FC (Failure Containment, Section 3.3.2)

This loading case is based on the residual static load of a broken conductor or ground wire (0 psf wind and 0 inches of radial ice at 30ºF).

Ground Wire Loads:

The RSL load factor for a broken ground wire is 1.0.

Broken Wire:

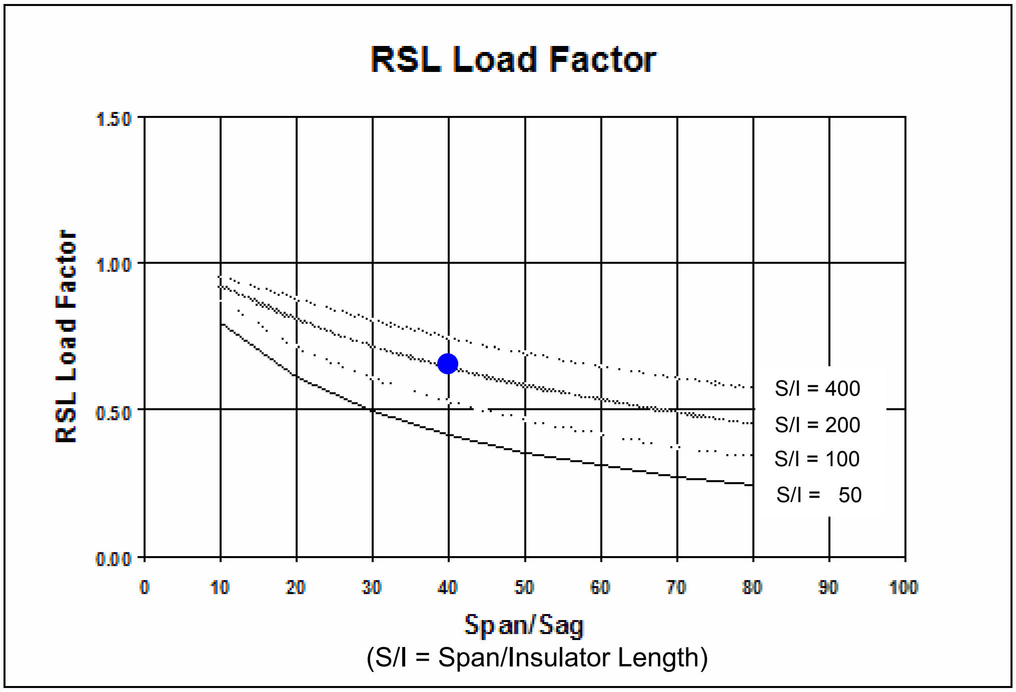
V = 0.262(1800)/2+50 = 286 lbs = 0.3 kips
T = 1623 sin(5/2)(1.0) = 71 lbs = 0.1 kips
L = 1623 cos(5/2)(1.0) = 1621 lbs = 1.6 kips

Intact Wires:

V = 0.262(1,800)+50 = 522 lbs = 0.5 kips
T = 1623 sin(5/2)(2) = 142 lbs = 0.1 kips
L = = 0.0 kips

Conductor Loads:

Ratio of the span to insulator length = 1250/6 = 208
Ratio of the span to sag = 1250/31.6 = 40
From Figure 3.3-2, the RSL load factor is 0.7.



Broken Wire:

V = 1.075(1800)/2+200 = 1168 lbs = 1.2 kips
T = 5615 sin(5/2)(0.7) = 171 lbs = 0.2 kips
L = 5615 cos(5/2)(0.7) = 3927 lbs = 3.9 kips

Intact Wires:

V = 1.075(1800)+200 = 2135 lbs = 2.2 kips
T = 5615 sin(5/2)(2) = 490 lbs = 0.5 kips
L = = 0.0 kips

Load Summary

All loads are in kips.

Loading Case	Ground Wire			Conductor			Transverse Wind on Structure			Longitudinal Wind on Structure		
	V	T	L	V	T	L	W_1	W_2	W_3	W_4	W_5	W_6
Wind	0.5	1.0		2.1	3.1		1.3	2.2	4.3			
Wind @ 30	0.5	0.8		2.1	2.4		1.1	1.9	3.7	1.2	1.1	2.3
Wind and Ice	0.9	0.5		3.0	1.1		0.1	0.2	0.5			
HIW @ 0 deg							3.9	6.7	13.0			
HIW @ 90 deg										7.5	6.7	13.8
HIW @ 45 deg							2.7	4.7	9.2	5.3	4.7	9.8
NESC	1.3	1.6		4.4	3.3		1.1	1.1	2.0			
C&M	1.3	0.5		4.7	1.4		0.3	0.5	0.9			
FC (Broken Wire)	0.3	0.1	1.6	1.2	0.2	3.9						
FC (Intact)	0.5	0.1		2.2	0.5							

5.1 WEIGHT SPAN CHANGE WITH BLOWOUT ON INCLINED SPANS

This example compares weight spans with and without wind for the center tower shown in Figure 5.1-1. The equations are shown in Section 4.5.1.1. Wire data is from Section 5.0.

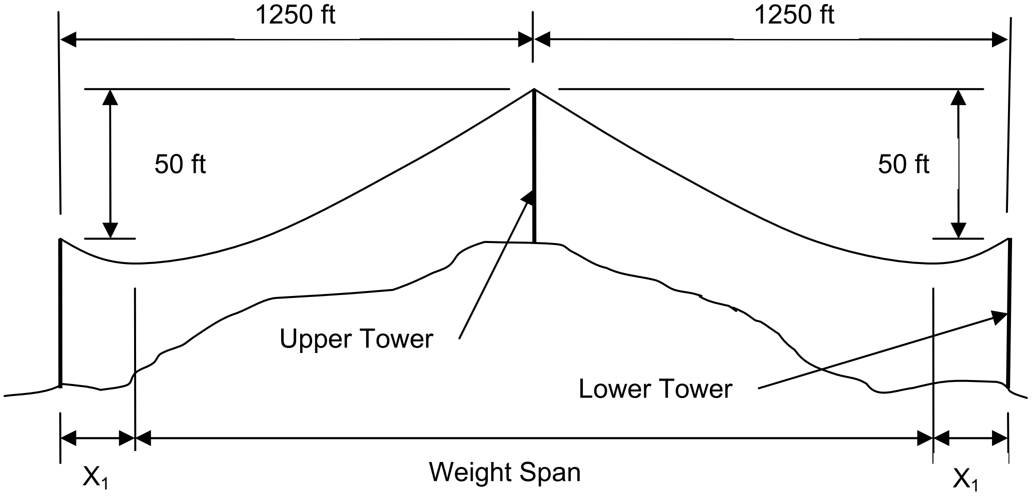


Figure 5.1-1. Weight Span for Center Tower with Inclined Spans

Ground Wire:

No Wind:

C_v = H/w_v = 1546/0.262 = 5901 ft (Eq. 4-7)

X_1 = L/2-$C_v$sinh^{-1}[(B/2)/$C_v$sinh(L/2C_v)] (Eq. 4-5)
= 1250/2 – 5901sinh^{-1}[(50/2)/5901sinh(1250/2(5901))] = 390 ft

Weight span = 2(1250 – 390) = 1720 ft

16.3 psf Wind:

C_v = 2939/0.262 = 11218 ft (Eq. 4-7)

X_1 = 1250/2 – 11218sinh^{-1}[(50/2)/11218sinh(1250/2(11218))] = 177 ft (Eq. 4-5)

Weight span = 2(1250 – 177) = 2146 ft **25% increase**

Conductor:

No Wind:

C_v = 5302/1.075 = 4932 ft

X_1 = 1250/2 – 4932sinh^{-1}[(50/2)/4932sinh(1250/2(4932))] = 428 ft

Weight span = 2(1250 – 428) = 1644 ft

16.3 psf Wind:

C_v = 8598/1.075 = 7998 ft

X_1 = 1250/2 – 7998sinh^{-1}[(50/2)/7998sinh(1250/2(7998))] = 306 ft

Weight span = 2(1250 – 306) = 1888 ft **15% increase**

5.2 TRADITIONAL CATENARY CONSTANT

This example compares weight spans to those in Section 5.1 using the traditional catenary constant. The traditional catenary constant is based on the resultant unit weight (w_r). The catenary constant in Section 5.1 is based on the vertical unit weight (w_v).

Figure 5.1-1 shows the upper and lower towers and spans.

Ground Wire:

16.3 psf Wind:

$w_v =$ $= 0.262$ lbs/ft
$w_t = 16.3(0.385/12)$ $= 0.523$ lbs/ft
$w_r = (0.262^2 + 0.523^2)^{1/2}$ $= 0.585$ lbs/ft

$C_r = H/w_r = 2939/0.585 = 5025$ ft (Eq. 4-6)

$X_1 = L/2 - C_r\sinh^{-1}[(B/2)/C_r\sinh(L/2C_r)]$ (Eq. 4-5)
$= 1250/2 – 5025\sinh^{-1}[(50/2)/5025\sinh(1250/2(5025))] = 425$ ft

Weight span = 2(1250 – 425) = 1650 ft

Conductor:

16.3 psf Wind:

$w_v =$ $= 1.075$ lbs/ft
$w_t = 16.3(1.165/12)$ $= 1.582$ lbs/ft
$w_r = (1.075^2 + 1.582^2)^{1/2}$ $= 1.913$ lbs/ft

$C_r = 8598/1.913 = 4494$ ft (Eq. 4-6)

$X_1 = 1250/2 – 4494\sinh^{-1}[(50/2)/4494\sinh(1250/2(4494))] = 446$ ft (Eq. 4-5)

Weight span = 2(1250 – 446) = 1608 ft

Weight Span Summary:

Wire	C	Upper Tower		Lower Tower	
		Weight Span (ft)	Difference	Weight Span (ft)	Difference
Ground Wire	Traditional	1650	23%	425	140%
	Section 5.1	2146		177	
Conductor	Traditional	1608	15%	446	45%
	Section 5.1	1888		306	

The traditional catenary constant under estimates the vertical load on the upper tower and over estimates the vertical load on the lower tower.