HiPAS Pole Failure Model

SLAC National Accelerator Laboratory
Last Update: June 2022

The pole failure model in GridLAB-D has been updated to support the extended Grid Resilience Intelligence Platform (GRIP) use case for the HiPAS Project (CEC EPC-17-046).

Failures Modes

The pole failure model in GridLAB-D is designed to examine multiple failure modes. However, given that ground-level structural failures are reported as the most frequent, the current implementation only supports these. Other failure modes may be provided in future versions of GridLAB-D.

Ground-level Failure

A pole can fail at or near the ground line due to excessive forces on the structure. The following forces are considered:

1. Pole loading due to pole weight and tilt angle
2. Mounted equipment loading due to pole tilt
3. Wire weight loading due to pole tilt angle
4. Wind pressure on pole
5. Wind loading due to wind pressure on mounted equipment
6. Wire loading due to wind pressure on wire
7. Wire ice loading (modeled as an increase in conductor diameter)
8. Loading due to wire tension asymmetry (does not account for wind pressure in increasing line tension)
9. Critical wind speed for pole failure
10. Pole failure probability under wind gust
11. Wire sag loading due to sag asymmetry - future work
12. Wire loading due to line sway - future work
13. Wire loading due to line gallop - future work

Superstructure Failure

Since the resisting moment for the utility pole superstructure will drop as the diameter of the pole decreases, a pole may fail above the ground owing to the reduced resisting moment. The SLAC team currently works on the development and validation of pole superstructure loading analysis considering pole shear force, bending moment and pole stress.

Other Failures

Other failure modes are possible, such as foundation failures and equipment malfunction. There can also be damage to the cross-arms and insulator pins. These are not considered at this time.

Methodology

The basic method of evaluating the condition of a pole relative to ground-line structural failure is to calculate the resisting moment at ground level and compare that with the total moment from the loads present.

The resisting moment for a wood pole at the ground line is computed as follows:

$$M_R = 0.008186\, S_f\, F_b\, D_0^{\ 3}$$

in ft.lb, where

- S_f is the NESC Table 261-1A safety factor (see Table 1)
- F_b is the fiber strength (see Table 2)
- D_0 is the ground-line diameter of the pole in inches

Pole degradation is modeled by computing the rate at which the interior is hollowed out by rot. The hollow interior diameter grows at the rate R such that the interior hollow diameter is given by $D_R = 2\,Y\,R$ where Y is the age of the pole. When considering pole degradation, the resisting moment is

$$M_R = 0.008186\, S_f\, F_b\, (D_0^{\ 3} - D_R^{\ 3})$$

Note that the ground line failure assumption ignores the possibility that the hollow interior diameter may lead to failure at the midpoint of the pole or at the pole top near the superstructure.

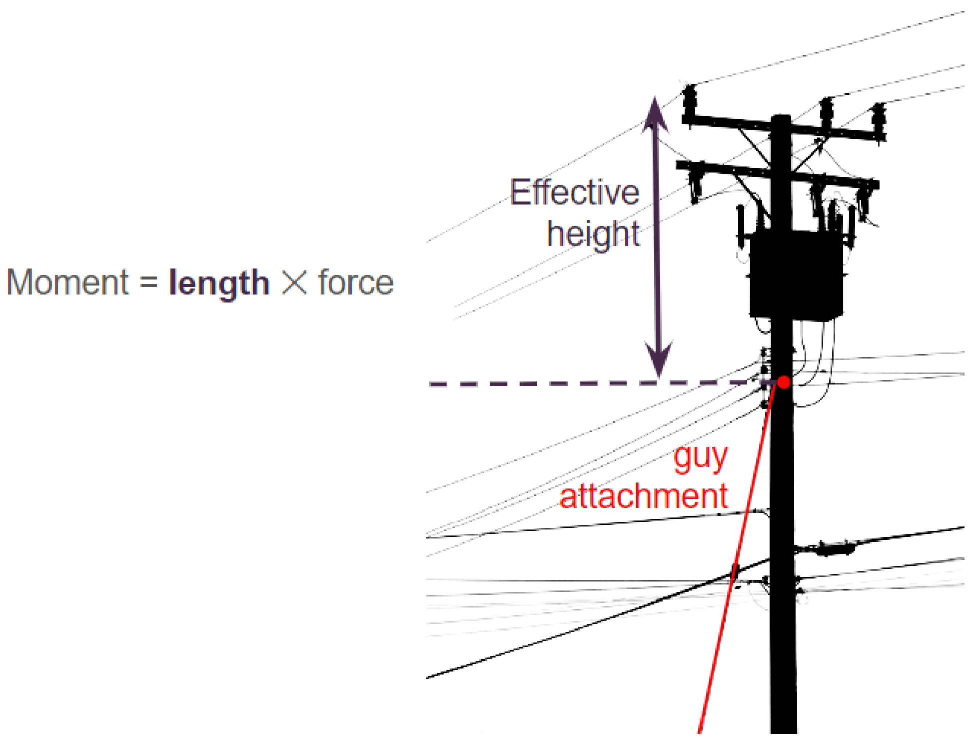
Table 1: NESC Table 261-1A Safety Factors (S_f)

Application	Grade B	Grade C
Rule 250B (normal conditions)		
Wood structures	0.65	0.85
Support structures	1.00	1.00
Rule 250C (extreme conditions)		
Wood structures	0.75	0.75
Support structures	1.00	1.00

Table 2: Ultimate Fiber Stress of Selected Wood Products (F_b)

Species	Fiber Stress in psi
Southern Yellow Pine	8,000
Douglas Fir	8,000
Lodgepole Pine	6,600
Western Larch	8,400
Western Red Cedar	6,000

When guy wires are present, the height at which the moments are calculated is determined by the attachment point of the guy wires rather than the ground line.



The remainder of the methodology requires computing the contributions of the various loads to the total pole moment.

Note that wind induced moments may not be in the same direction as the pole tilt. The incident angle of the wind must be considered with respect to the pole tilt angle such that $\beta = \beta_T - \beta_W$. The vector sum of the moments must be used, e.g.,

$$M = \sqrt{(M_T + M_P \cos\beta)^2 + (M_P \sin\beta)^2}$$

In some cases, the wind pressure may reduce the tilt moment and in other cases it may increase it.

1. Pole Loading Due to Pole Tilt Angle

A tilted pole is illustrated in Figure 1, where H is measured in ft, D_0, and D_1 are measured in inch and M is measured in ft.lb.

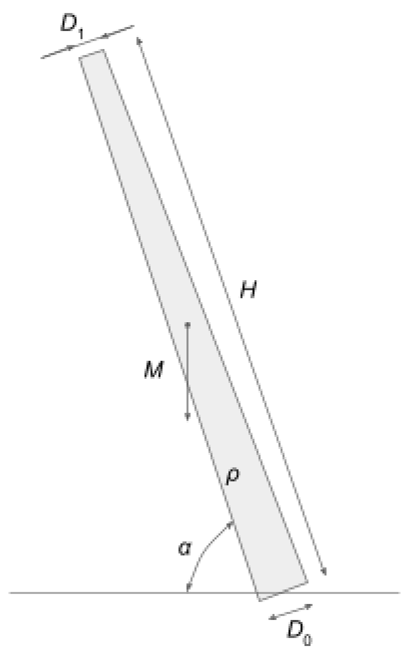


Figure 1: Tilted pole

For small angles α, the moment resulting from the tilt of a pole of uniform diameter D and height $H$is

$$M_{PT} = 0.5\, m\, H \sin\alpha$$

where m is the mass of the pole in lbs. The mass m of the pole can be calculated using the density ρ of the material, e.g., 35 lb/ft[3], such that $m = \pi\,(D/2/12)^2\,H\,\rho = 0.001736\,\pi\,D^2\,H\,\rho$.

However, the taper of the pole must be considered, in which case the moment is

$$M_{PT} = \sin\alpha \int_0^H h\,m(h)\,dh$$

where $m(h)\,dh$ is the mass at the height h, such that $m(h) = \rho\,\pi\,r(h)^2$ with $r(h)$ measured in ft. The resulting moment is

$$r(h) = 0.5\,[D_0 - (D_0 - D_1)\,h/H]$$

$$M_{PT} = 0.125\rho\,\pi H^2\left[\frac{1}{6}(D_0 + D_1)^2 + \frac{1}{3}D_1^2\right]\sin\alpha$$

2. Mounted equipment loading due to pole tilt

Equipment mounted on a tilted pole may induce small changes in the moment depending on the position relative to the pole's centerline and the tilt direction. The moment of equipment mounted offset from the pole's centerline is

$$M_{ET} = W\,X_E$$

where W is the weight of the equipment in lbs and X_E is the offset distance in ft. Denote the equipment mounted direction as β_E and mounted height as H_E, when the pole is tilted at an angle α and the pole tilt direction is β_T, the tilt equipment offset distance is

$$X_{E\_x} = (cos^2(\beta_T) * cos(\alpha) + sin^2(\beta_T)) * X_E * cos(\beta_E)$$
$$+ (cos(\beta_T) * sin(\beta_T) * cos(\alpha) - cos(\beta_T) * sin(\beta_T)) * X_E * sin(\beta_E) + cos(\beta_T) * sin(\alpha) * H_E$$

$$X_{E\_y} = (cos(\beta_T) * sin(\beta_T) * cos(\alpha) - cos(\beta_T) * sin\ (\beta_T)) * X_E * cos(\beta_E)$$
$$+ (sin^2(\beta_T) * cos(\alpha) + cos^2(\beta_T)) * X_E * sin(\beta_E) + sin(\beta_T) * sin(\alpha) * H_E$$

Then the moment M_O and tilt mounted height H_{E_T} is

$$M_{ET} = W\sqrt{{X_{E\_x}}^2 + {X_{E\_y}}^2}$$

$$H_{E\_T} = - sin(\alpha) * X_E * (cos(\beta_T) * cos(\beta_E) + sin(\beta_T) * sin(\beta_E)) + cos(\alpha) * H_E$$

3. Wire weight loading due to pole tilt angle

The moment due to cable weight loading is computed as follows:

$$M_{CW} = W_C X_C$$

where W_C is the cable weight and W_C is calculated by multiplying the cable unit weight w_C with the cable length L_C. X_C is the cable mounted distance from the pole centerline and it can be calculated using pole ground-line diameter, top diameter, and the cable mounted height.

In the presence of pole tilt, the tilt cable offset distance can be calculated similar to the process when calculating the offset for mount equipment:

$$X_{C\_x} = (cos^2(\beta_T) * cos(\alpha) + sin^2(\beta_T)) * X_C * cos(\beta_C)$$
$$+ (cos(\beta_T) * sin(\beta_T) * cos(\alpha) - cos(\beta_T) * sin(\beta_T)) * X_C * sin(\beta_C) + cos(\beta_T) * sin(\alpha) * H_C$$

$$X_{C\_y} = (cos(\beta_T) * sin(\beta_T) * cos(\alpha) - cos(\beta_T) * sin(\beta_T)) * X_C * cos(\beta_C)$$
$$+ (sin^2(\beta_T) * cos(\alpha) + cos^2(\beta_T)) * X_C * sin(\beta_C) + sin(\beta_T) * sin(\alpha) * H_C$$

Where β_C is the cable mounted offset direction and H_C is the cable mounted height.

Thus the moment due to cable weight loading is recalculated as

$$M_{CW} = W_C \sqrt{{X_{C\_x}}^2 + {X_{C\_y}}^2}$$

$$H_{C\_T} =- sin(\alpha) * X_C * (cos(\beta_T) * cos(\beta_C) + sin(\beta_T) * sin(\beta_C)) + cos(\alpha) * H_C$$

In the presence of pole tilt, the tension in the wires can significantly increase the load on the pole. To calculate the moment on the pole due to the angle of the conductors, the follow formula can be used:

$$M_{CT} = D_T F_{TW} * H_{C\_T}$$

where $D_T = B_C P_T$ is the breaking strength B_C multiplied by the percent design tension P_T in lbs, F_{TW} is the overload capacity factor for transverse wires, as given in Table 3.

4. Wind pressure on pole

Wind pressure is the main source of moments on poles. The formula for calculating the moments due to wind on the pole face is

$$M_{PW} = \frac{1}{6} W\, H^2\, (D_{base} + 2D_{top})/12 \; * F_W$$

where W is the wind pressure in lb/sf, H is the pole height, D_{base} is the diameter at the pole base, D_{top} is the diameter at the pole top, and F_W is the overload capacity factor for transverse wind given in Table 3. The wind pressure is calculated as

$$W = 0.00256\, V^2$$

where V is the wind speed in mph. See Appendix: *Derivation of coefficient 0.00256 in wind pressure equation.*

Note: there was considerable discussion as to whether to include a correction for pole tilt, see Appendix.

A. What the equation represents:

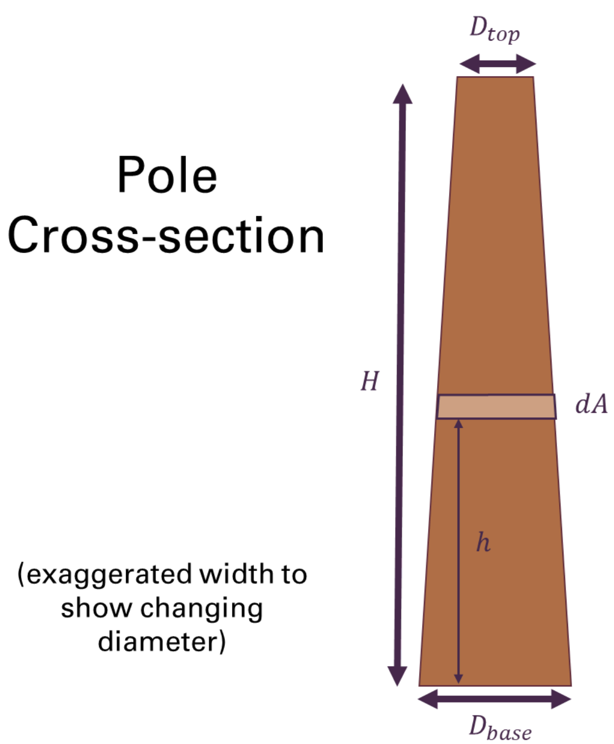
The equation for moment due to wind on the pole face comes from the Pole Structural Loading Model, linked in References. It approximates the area presented to incoming wind as a tall trapezoid, and integrates over height. We start with:

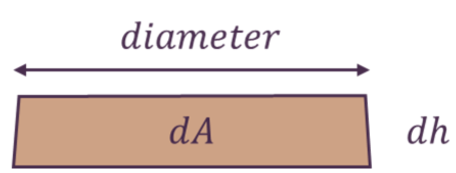
moment = force * moment arm

Pole moment = wind pressure * cross-sectional area * height from supported point

$$dM \quad = \quad W \quad * \quad dA \quad * \quad h$$

and $\quad dA = (diameter)\, dh = (D_{base} - h\, \frac{D_{base} - D_{top}}{H})\, dh$





When we integrate to sum up the contribution to moment from every slice, we get:

Pole moment = $\frac{1}{6} W\, H^2\, (D_{base} + 2D_{top})$

- A factor of 1/12 converts diameter from inches to feet.

- An overload capacity factor increases the modeled force on the pole. For reliability, the National Electrical Safety Code requires that these overload factors be used when calculating the maximum force a pole must withstand.

-

Table 3: Overload Capacity Factors (F_W)

Condition	**Grade B**	**Grade C**	**Extreme Wind**
Vertical	1.50	1.90	1.00
Transverse Wind			
General	2.50	1.75	1.00
Crossings	2.50	2.20	1.00
Transverse Wire	1.65	1.65	1.00
Longitudinal			
General	1.10	N/A	1.00
Dead Ends	1.65	1.30	1.00

5. Wind loading due to wind pressure on mounted equipment

Voltage regulators, capacitor banks, and transformers can induce large wind moments on poles. The formula for calculating the moment

$$M_{EW} = A\, H_E\, W\, F_W$$

where A is the cross-sectional area of the equipment in sf, and H_E is the height at which the equipment is mounted on the pole.

Note: the moment only captures the direct force, and not the twisting action due to the perpendicular forces.

6. Wire loading due to wind pressure on wire

Wind pressure on conductors constitutes a significant part of the load on pole structures. The formula for calculating the wire loading due to wind pressure is

$$M_{CW} = C_L * H_C * F_W$$

where M_{CW} is the moment on the pole due to wind on conductors, C_L is the wind load (formula found below) in lbs/ft, H_C is the height of the conductor, and F_W is the Overload Capacity Factor for transverse wind given in Table 3.

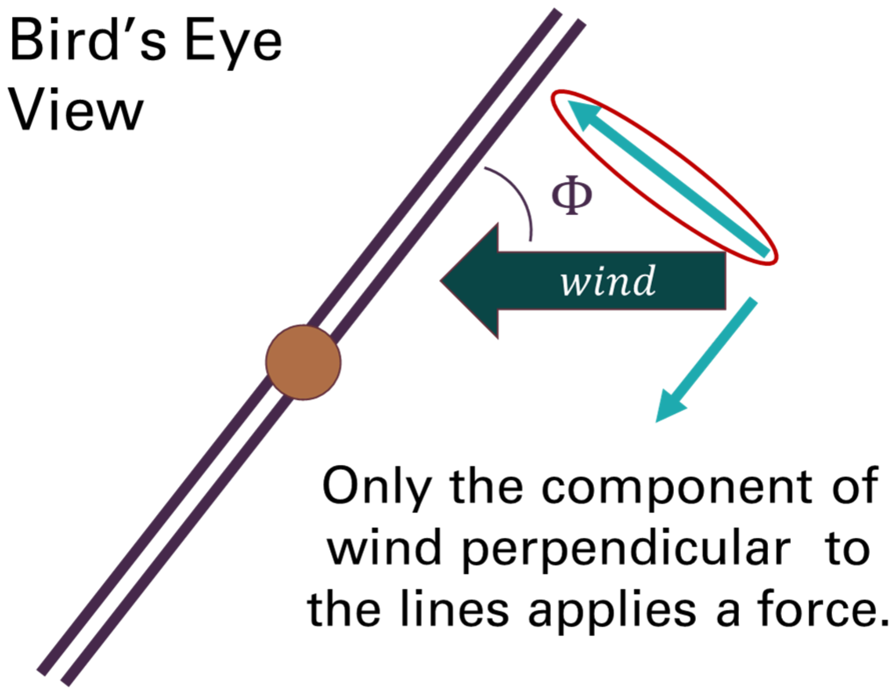
In the presence of ice on the conductors, the wire loading due to wind pressure will significantly increase. However, in the absence of ice, this formula is still used to calculate the intermediate value for wire loading due to wind pressure on wire

$$C_L = W * sin(\phi) * L_C * D_C / 12 * cos(\theta)$$

where W is the wind load in lbs/ft², ϕ is the angle between the lines and the wind direction, L_C is cable length measured in ft, D_C is the conductor diameter in inches with common sizes in table 4, , and θ is the degree of pole tilt.

L_C is currently set as a constant, pole_spacing, which comes from the pole_mount glm object and is assumed to be the same on both sides of the pole. The true wind span should be half of the cable length on one side plus half that on the other side.

The diagrams below explain the use of the $sin(\phi)$ and $cos(\theta)$ terms:



ϕ is calculated as the absolute difference between the wind direction (which comes from the weather object) and the direction of the lines (a property of a pole_mount object in glm). <u>This part of the model cannot handle an angle in the lines at the pole.</u>

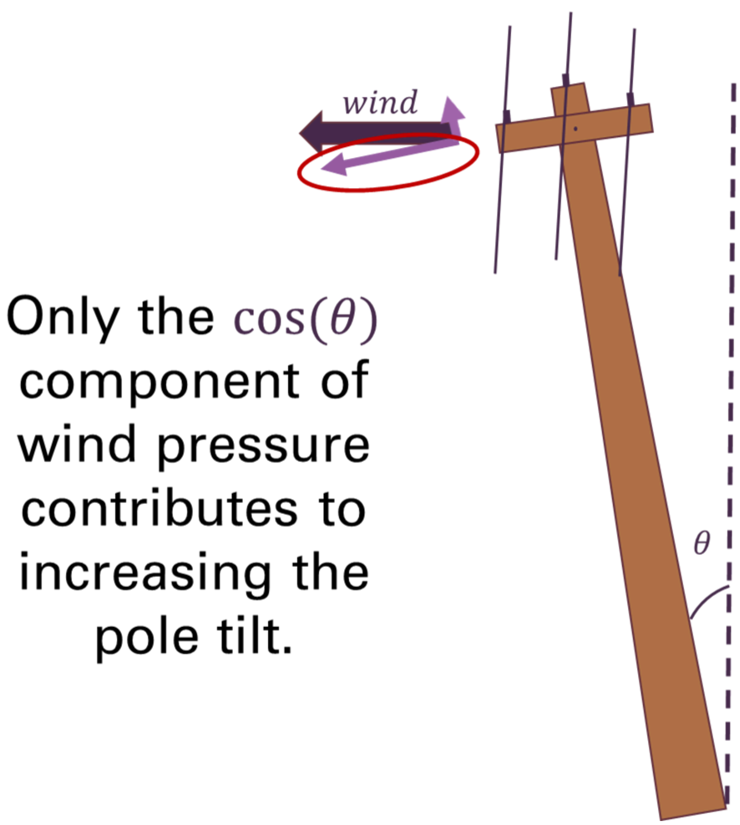


Table 4: Common Conductor Diameters

Size	Code	Diameter (inches)
#4 ACSR	Swante	0.257
#2 ACSR	Sparrow	0.316
1/0 ACSR	Raven	0.398
4/0 ACSR	Penguin	0.563
266 ACSR	Patridge	0.642
336 ACSR	Merlin	0.684
397 ACSR	Ibis	0.783
636 ACSR	Grosbeak	0.990
795 ACSR	Drake	1.108
266 AAC	Daisy	0.586
336 AAC	Tulip	0.666
556 AAC	Mistletoe	0.858
795 AAC	Arbutus	1.026

7. Wire ice loading

In the presence of ice on the conductors, the wire loading due to wind pressure (6) will significantly increase. However, in the absence of ice, this formula is still used to calculate the intermediate value for wire loading due to wind pressure on wire

$$C_L = W * sin(\phi) * L_C * (D_C + 2 * I_R) / 12 * cos(\theta)$$

This is the above equation with ice added. I_R is the radial ice thickness as given in table 5.

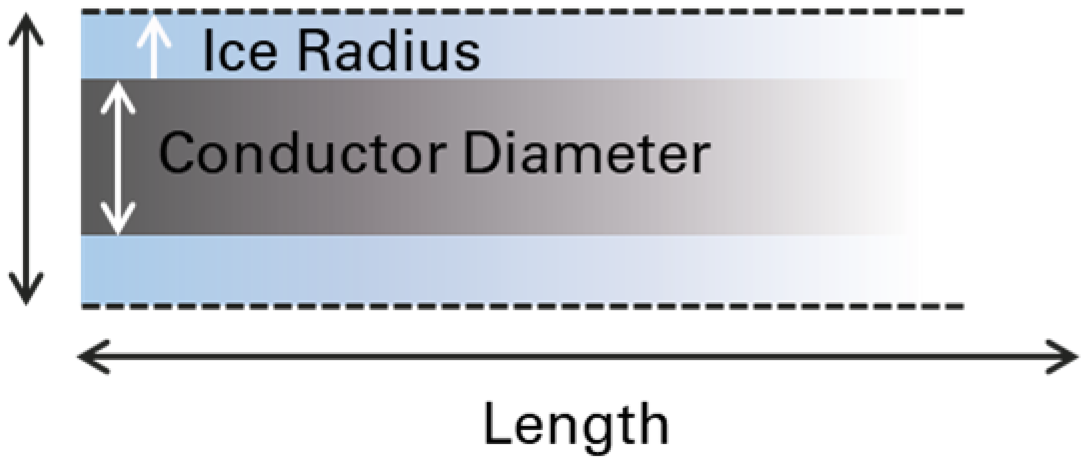


Table 5: NESC Table 250-1 Ice and Wind Loads of Loading Districts

	Light	Medium	Heavy
Ice radial in.	0.0”	0.25”	0.5”
Wind lbs/ft²	9	4	4
Temperature ℉	30	15	0

This model does not include a drag coefficient to account for the surface roughness of ice on the lines.

8. Loading due to wire tension asymmetry

When multiple cables are mounted to a pole, the total moment caused by the cable weight loading and tension should be calculated as the vector sum considering the cable mounted offset direction β_C and cable heading direction θ at which departures away from the pole.

Therefore, the total moment on x-axis and y-axis are

$$M_{C\_x} = \sum_i ((C_L H_C F_W + D_T F_{TW} H_{C\_T}) * cos(\theta) + W_C X_{C\_x})$$

$$M_{C\_y} = \sum_i ((C_L H_C F_W + D_T F_{TW} H_{C\_T}) * sin(\theta) + W_C X_{C\_y})$$

where i is the index of cable while M_{C_x} and M_{C_y} represent the total moment on x-axis and y-axis for all cable connected to the pole. Thus, the total moment of pole due to wire loading is

$$M_{C\_TOTAL} = \sqrt{{M_{C\_x}}^2 + {M_{C\_y}}^2}$$

9. Critical wind speed for pole failure

To estimate the pole withstand wind speed is a critical step as the wind pressure is the main source of moments on poles. The critical wind pressure W_F for pole failure is

$$W_F = \frac{\sqrt{{M_R}^2(1+F_O)^2-(M_{PT}+M_{ET}+M_{CW})^2}}{0.01389*(D_0+2D_1)\,H^2\,F_W+A\,H_E\,F_W+H_C\,F_W L_C(D_C+2\,I_R)\,/\,12}$$

Where $F_O \geq 1$ is the design margin factor for pole resisting moment. Note that this formulation assumes the wind blows from the worst angle and the resulting critical wind pressure is conservative. It also ignores the pole moment due to the line tension because such loads will be canceled by each other when multiple lines are connected to a pole. A design margin factor is set up so that the user can properly configure their computation. Then the critical wind speed V_F in mph is

$$V_F = \sqrt{W_F/0.00256}$$

10. Pole failure probability under wind gust

In the case of wood strength, the bending moment resistance of the pole is calculated using the median wood fiber strength; as a result, there is a 50% chance that the pole is weaker than the utilities assume. Moreover, the design software used by utilities (e.g., SPIDAcalc and Osmose O-Calc) have a major flaw: safety factors by the design software obfuscate the actual windspeed that a pole should be able to withstand. For example, a very clear result such as “this wood pole can withstand a 112 mile per hour wind gust with a 95% probability of success” is not achievable via the existing software. In GRIP, a probabilistic assessment is developed for wind gusting based on the z-score of normal distribution. Denote the wind gust as V_G, then the pole failure is

$$P_F = 1 - {Z_{sorec}}^{-1}(ln(V_G/V_F))$$

Where ${Z_{sorec}}^{-1}$ is function that maps the z-score to cumulative percentage in a normal distribution and the $ln()$ maps the wind speed ratio from $[0, +\infty)$ to $(-\infty, +\infty)$.

11. Wire sag loading due to sag asymmetry

Future work

12. Wire loading due to line sway

Future work

13. Wire loading due to line gallop

Future work

14. Pole superstructure analysis

As shown in previous calculations, the pole resisting moment will drop when the pole diameter decreases, thus, the pole may fail at its superstructure. We divide the pole structure on the z-axis into multiple segments and the loading condition for each segment will be analyzed using finite element analysis and considering different forces including self-weight, wind loads, and cable tension. With this effort, GridLAB-D and GRIP can conduct similar analysis compared to SPIDAcalc, such as the computation of the worst wind load angle and the critical pole withstand wind speed. Initial example results are depicted in the following figures. However, the team still works on the benchmark and validation of the proposed pole finite element analysis and final results will be attached to future project reports.

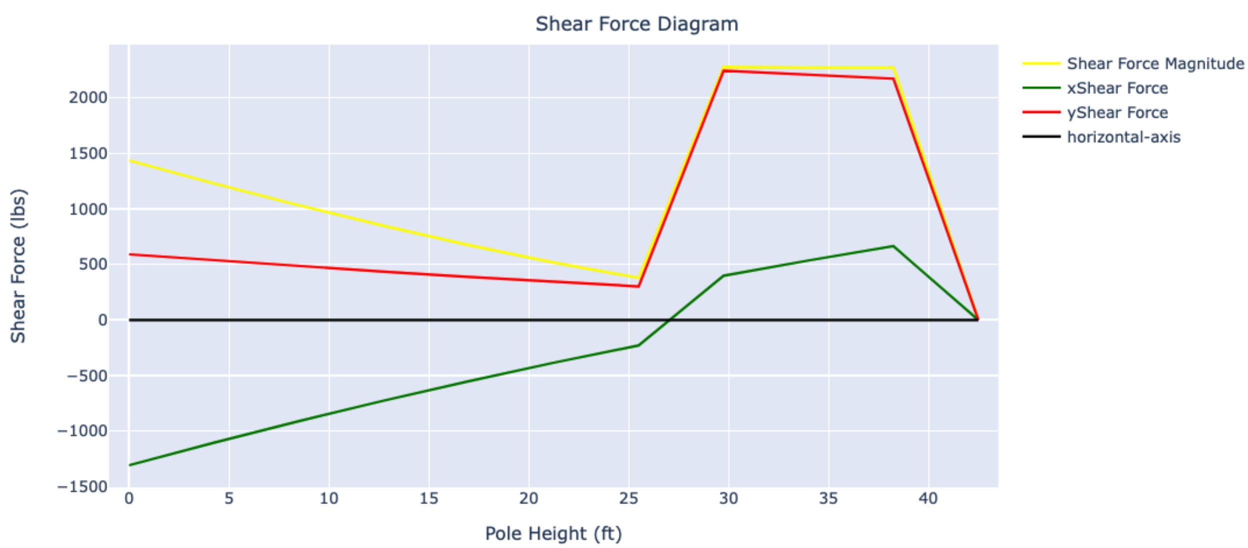


Figure. 1. Shear force curve along with the pole height

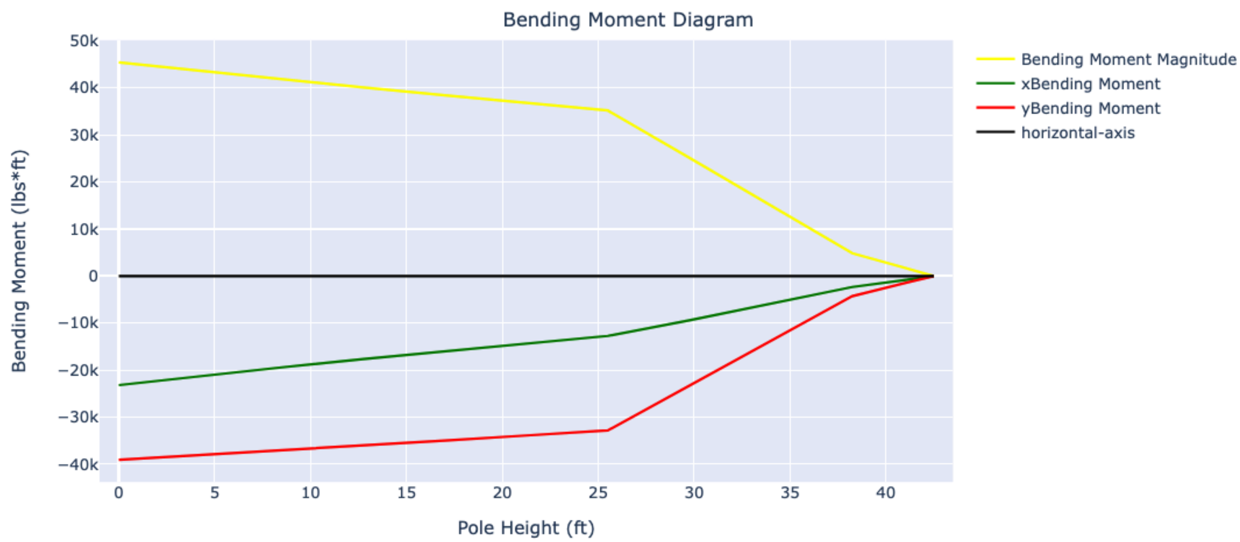


Figure. 2. Bending moment curve along with the pole height

Figure. 3. Pole stress curve along with the pole height

References

- "Pole Structural Loading", RedVector.com.
- National Electric Safety Code

Appendix

Derivation of coefficient 0.00256 in wind pressure equation

$$W = 0.00256\,V^2$$

Wind pressure (W) is equal to $\frac{1}{2}\,\rho\,V^2$,

where ρ is the density of air, V is the wind speed. It incorporates the momentum of air particles hitting a given area (density, speed) and the rate at which they arrive (speed again).

In SI units, that's $W = \frac{1}{2}\,(1.28\,kg/m^3)\,V^2 = (0.64\,kg/m^3)\,V^2$

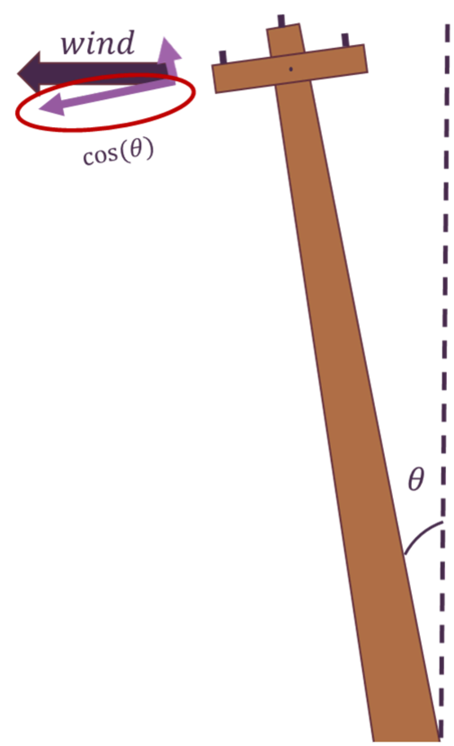
- To accept wind speeds in mph instead of m/s, we throw in a factor of 0.447 squared — because 0.447 m/s = 1 mph
- Multiplying by 0.02 converts pascals to pounds per square foot:

So W in psf $= (0.02\frac{psf}{Pa})\,(0.447\,\frac{m/s}{mph})^2\,(0.64\,kg/m^3)\,V^2 = (0.00256\,\frac{psf}{mph^2})\,V^2$

Decision not to include pole tilt angle in calculations of moment due to wind on pole face

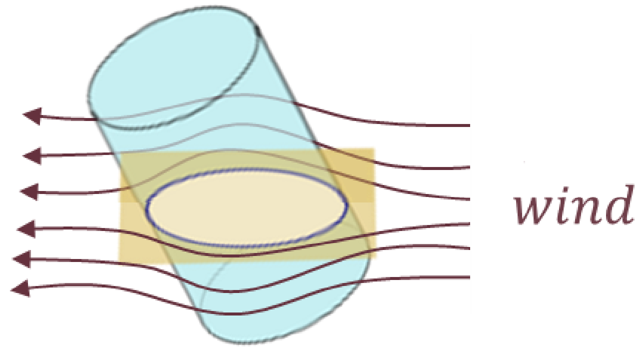
There are three effects that pole tilt can have on the moment due to wind on the pole face. (1) It changes the angle of the moment arm, (2) it could alter the direction of the force imparted by wind pressure, and (3) it could decrease the magnitude of wind drag.

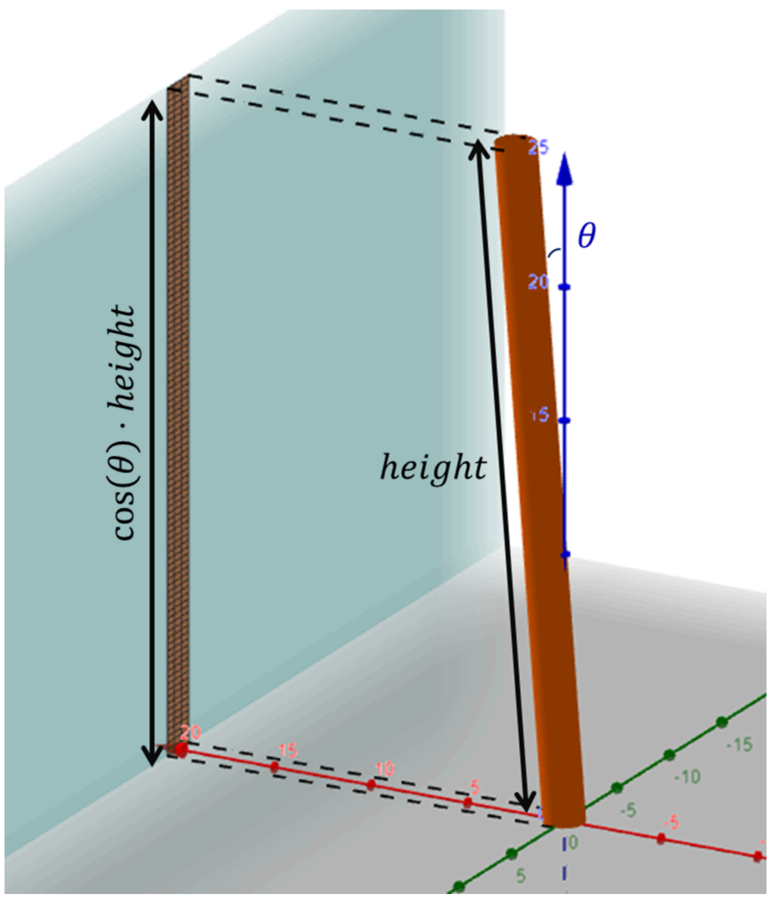
1. Only forces perpendicular to the moment arm act to rotate an object. Assuming the wind wind force is still parallel to the plane of the ground, if the wind is in the same direction as the pole's lean then only the $cos(\theta)$ component of that wind force acts to rotate the pole. θ is the degree of pole tilt. If the wind is oriented differently, the correction is more complicated and more minor. (I imagine representing the wind direction and pole moment arm as unit vectors and taking the cross product to get the magnitude of the correction.)



2. The above assumes that the force due to wind on the pole is still aligned with the direction of wind (i.e. that it's just drag). Lift is the component of force applied perpendicular to wind flow. With the pole tilted, some of the air will be deflected to travel up the pole, adding a downward component to the force on the pole. If this is significant, then both the magnitude and direction of the wind force would differ from that assumed in the correction above.

3. If the pole's lean is in a direction parallel to wind flow, the magnitude of drag force may be reduced. Firstly, the cross section presented to the wind is shortened by a factor $cos(\theta)$ (θ still being the degree of pole tilt). Secondly, horizontal wind flow will encounter an oblique cross section of the pole. This oval shape produces less form drag than the circular cross section of a non-leaning pole. If the wind flow is perpendicular to the direction of pole lean, then neither of these effects come into play.





These corrections are difficult to represent accurately. There is uncertainty in the true magnitude and direction of the applied force. The data we have on wind speeds and direction has low resolution on the scale of pole locations. It doesn't account for a potential vertical component to the wind. (The ground isn't always flat.) There is no point in carefully accounting for the direction of the wind if the uncertainty in its direction swamps our corrections. Our model of wind interactions with the pole would need to get much more complex to account for lift, changes in form drag, and the relative angle between the pole lean direction and wind flow.

The corrections scale with $cos(\theta)$. While the pole is still stable, the tilt angle will be no more than about 5 or 10 degrees - $cos(10^{o}) = 0.985$. The corrections are tiny at most.

➔ We concluded that it is not worth the added complication to account for pole tilt in our calculations of moment due to wind on the pole face.