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Stability of Tapered Wood Utility Poles under Extreme Loading

Cliff D. Bishop[1], Morgan Griffith[2], Brian M. McDonald[3], Joel M. Wolf[4]

Abstract
During a storm, a tree fell across a highway, downing utility lines on both sides of the road. County employees responded to clear the roadway encumbrance. A steel messenger wire that was pinned beneath the fallen tree, but still connected to its wood poles, was dragged along the ground as the fallen tree was towed from the roadway. At some point, the force exerted by the messenger wire on one of the poles to which it was attached caused the pole (which was otherwise undamaged) to fail and injure a utility worker as it fell. This paper explores the stability of the tapered wood utility pole subject to the changing forces imparted on it as the messenger wire was dragged. Catenary forces from utility lines in spans adjacent to the pinned messenger wire, as well as the effect of those forces on the failed wood utility pole, are also discussed herein. Additionally, modelling complications are addressed, such as determining the varying moment of inertia associated with the tapered pole's cross-section, and addressing the iterative nature of determining the P-Delta force on the wood pole associated with the changing position of the pinned messenger wire.

1. Introduction
This paper discusses the failure investigation of a Southern Pine Class 25/7 wood utility pole (subject pole) that occurred during removal of a fallen tree from a roadway. The investigation included review of incident specific documentation; review of industry codes, standards and literature; observation and documentation of conditions at the accident site; inspection of the subject pole and fallen tree sections; testing of exemplar messenger wire; and photogrammetric and engineering analyses.

2. Summary of Incident
During a windstorm, a large pine tree fell across a highway around 6:30 P.M. The tree, originally located on the north side of the highway, impacted communication and power lines along the north and south sides of the highway, respectively. Video documentation by the local sheriff's office shows taut communication lines below the fallen tree (Figure 1). According to information provided by the owner of the lines, these communication lines consisted of a Grade 6M steel messenger wire supporting two telecommunication cables (BHAA-50 and BHAA-100).

[1] Ph.D., S.E., P.E., Managing Engineer, Exponent Inc., Atlanta, GA, cbishop@exponent.com
[2] P.E., Managing Engineer, Exponent Inc., Menlo Park, CA, mgriffith@exponent.com
[3] Ph.D., S.E., P.E., Principal Engineer and Practice Director, Exponent Inc., Menlo Park, CA, mcdonald@exponent.com
[4] P.E., Principal Engineer, Exponent, Inc., Menlo Park, CA jwolf@exponent.com

Figure 1: Taught communication lines beneath fallen tree

Two county employees began to clear the fallen tree from the roadway around 8:00 P.M. Tree branches were first removed and then the main trunk was cut into several segments, which were dragged to the west, off the road, using a strap attached to the hitch of a pick-up truck. The fallen trunk was cut just south of the pinned communication lines, creating a trunk segment 14’-8” long, so that this trunk segment (south segment) could be removed from the road without disturbing the lines. Another cut was made through the trunk to the north of the lines, creating a trunk segment 5’-3” long (north segment). A nylon tow strap was then attached to the south end of the south segment and dragged to the west. Unbeknownst to the driver of the pick-up truck, the cut had not fully separated the south and north trunk segments and, as a result, both segments were dragged to the west. Post-incident photographs of the two displaced trunk segments indicate that the communication lines remained below the north segment as it was dragged to the west (Figure 2).


Figure 2: Communication lines still below tree segment that had been dragged from roadway

A county employee who was involved with the tree removal operations was standing to the west of the north segment when the two segments were dragged to the west. The county employee ran to the west and shouted to the driver of the pick-up truck when he realized that the south and north segments were being dragged together along with the communication lines that were snagged by the north segment. Subsequently, a sheriff's deputy reported hearing a "snap," caused by the failure of the wood utility pole to which the west end of the pinned messenger wire was attached. The subject pole fell toward the roadway, injuring the county employee. The pole in its failed position is shown in Figure 3. The accident was reported around 8:45 P.M.


Figure 3: Failed utility pole

3. Site Observations

A site visit was conducted at the location of the pole failure. Prior to the site visit, a replacement utility pole had been installed near the location of the subject pole. The associated communication lines ran approximately parallel to the road. The locations of the poles to the east (designated P18½) and west (designated P19½) of the failed utility pole (designated P19) were documented, as well as the location of the fallen tree stump. A short segment of the fallen tree remained on-site, just north of the fence along the north side of the road (Figure 4). The site was extensively photo-documented and measurements were taken of key features (e.g., span lengths, pole sizes, location relative to roadway, etc.). In addition, dimensions of several objects and features were measured for later use in a photogrammetric analysis. These included roadway widths, and lengths and location of broken yellow lane lines.

Figure 4: Segment of fallen tree

A variety of sources were utilized to determine sizes, geometries and positions of various utility elements prior to the tree fall, after the tree fall (but prior to tree cutting and removal), and at the time of the accident (during tree removal activities). These included photogrammetric analysis of incident video documentation and site photographs; field measurements of the accident site, accident pole and fallen tree segments; and publicly-available photographs taken along the roadway depicting the catenary geometry of the messenger wire. Field photographs of the butt end of the subject pole, which was removed from the ground on the day of the site visit, were also utilized.

4. Structural Member and Material Properties

One of the initial modeling tasks was determining the properties of the subject pole; specifically, characterization of the pole's taper was of paramount importance, because the poles capacity in bending is a function of the changing cross-section along its height. Therefore, three available sections of the pole were measured and documented during the site visit:

1. A butt section approximately 6’ long that included the ground-line fracture;
2. An approximately 12’-10” long section that included the other side of the ground-line fracture at one end and a saw cut at a through-bolt hole near the top of the pole at the other end; and
3. An approximately 2’-9” long segment that exhibited saw cuts at both ends including the matching face of the cut at the through-bolt hole.

The bottom of the pole butt was stamped with information indicating it was a Class 7 pole, 25 feet long, Southern Pine species, treated with creosote in 1958.

Pole Taper

Using the diameter of the pole at the three segments discussed above, the varying moment of inertia along the height of the pole were calculated. For modeling purposes, the pole was divided into 6 equal segments along its height from the ground-line to the attachment of the messenger wire; approximately 18’-6” in total. The diameter at the bottom was measured as 7.32 inches and the diameter at the point of messenger wire attachment was measured as 6.21 inches. Table 1 provides the diameter and average moment of inertia calculated at the mid-height between segments.

Table 1: Pole Characteristics

Segment	Height (ft)	Diameter (in.)	Average Moment of Inertia (in.^{4})
1	0	7.321	134.13
	3.08	7.135	
2	3.08	7.135	120.87
	6.17	6.95	
3	6.17	6.95	108.63
	9.25	6.764	
4	9.25	6.764	97.34
	12.33	6.578	
5	12.33	6.578	86.95
	15.42	6.393	
6	15.42	6.393	77.42
	18.5	6.207	

Pole Capacity

Due to restrictions associated with evidence preservation, the modulus of rupture of the pole could not be determined through testing. Per ANSI O5.1 (1987), the nominal modulus of rupture for a Southern Pine wood pole is 8,000 pounds per square inch (psi). It is widely recognized that the actual capacity varies between poles, and varies over the life of an individual pole. For purposes of the analyses described below, analysis results are compared with the nominal modulus of rupture of 8000 psi for reference.

Messenger Wire Properties

As discussed previously, the communication lines were supported by a steel messenger wire. The messenger wire was 6M Utilities Grade wire with a weight of 0.225 pounds per linear foot, with additional load associated with the supported telecommunication cables. Typical 6M wire is 5/16-inches in diameter and has a 1x7 strand configuration. The properties of this wire are described in ASTM A475 (2003) which specifies a minimum breaking strength of 6,000 pounds.

In order to better understand the force-deformation behavior of the messenger wire, and therefore the forces imparted by the wire to the subject pole, testing on exemplar samples of the wire were performed. Results of the testing indicated a breaking strength ranging from 7,680 to 7,730 pounds, and a modulus of elasticity ranging from 15,800,000 to 16,900,000 pounds per square inch. Failure of the exemplar samples was associated with fracture and unraveling of the strands forming the messenger wires. A photograph of one such failure is shown in Figure 5. Given the relatively close grouping of the results, the average test data was used to create the messenger wire tension-strain relationship shown in Figure 6. This relationship was used in the analyses described below.

Figure 5: Fracture and unraveling of messenger wire during testing

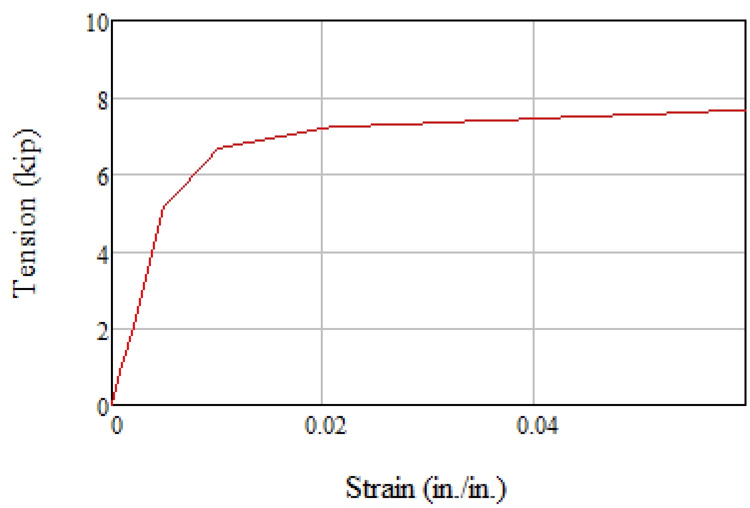

Figure 6: Messenger Wire Tension-Strain Relationship

5. Rigorous Hand Calculations

The investigation included analyses of pole stresses both immediately after the tree fall, and as the communication lines were dragged to the west along the roadway with the tree segments. The initial length of the messenger wire and the tension in the messenger wire prior to the tree fall were determined based on the sag of the line depicted in publicly-available photographs along the roadway, and the principles of elastic catenary behavior. The analyses incorporated the bending stiffness of the subject pole, as well as the restoring force applied to the subject pole by the messenger wire span to the west (which applied a force to the subject pole that was generally opposite in direction of the force applied to the pole by the pinned messenger wire). For comparison purposes, the bending stresses associated with design loads applicable to wood utility poles were also computed.

Forces on the Pole due to the Tree Fall

In order to determine the forces imparted to the subject pole as a result of the fallen tree pinning the messenger wire, it was first necessary to determine the tension in the wire prior to the tree fall. In this case specifically, the messenger wire tension was determined for the span between the subject pole and the pole to the east (i.e., the span upon which the tree fell). However, as discussed previously, a restoring force is imparted to the subject pole by the messenger wire span to the east of the subject pole. For this reason, the tension in this span prior to the tree fall was also determined. The tension in a cable element such as the messenger wire is determined based on the weight, axial stiffness, and un-stretched length of the element; the un-stretched length is related to the sag of the cable element based on the following equations of elastic catenary (Pevrot 1979):

$$H = -F_1 * \left[\frac{L_u}{EA} + \frac{1}{w} * \ln\frac{F_4+T_J}{T_I-F_2}\right] \tag{1}$$

$$V = \frac{1}{2*EA*w} * \left(T_J^2 - T_I^2\right) + \frac{T_J-T_I}{w} \tag{2}$$

$$L = L_u + \frac{1}{2*EA*w} * \left[F_4 * T_J + F_2 * T_I + F_1^2 * \ln\frac{F_4+T_J}{T_I-F_2}\right] \tag{3}$$

where H and V are the horizontal and vertical positions of a point on the catenary; L is the total "stretched" length of the messenger wire; F_1 and F_2 are the forces at each end of the messenger wire in the Cartesian plane; F_4 is the weight of the messenger wire less the end force, F_2; T_I and T_J are the tensile forces in the wire at each end; L_u is the un-stretched length of the messenger wire; w is the weight of the messenger wire and any other supported cables; and EA is the axial strength of the messenger wire.

The catenary equations were solved in an iterative manner, until the shape of the messenger wire along the span to the west of the subject pole (noted as W to 0) and along the span to the east of the subject pole (noted as 0 to E) matched the shape of the spans as depicted in publicly-available photographs taken prior to the tree fall. The results are shown in Figure 7 for the west and east spans, respectively. Messenger wire tensions associated with these shapes were applied to the subject pole to determine its stress state prior to the tree fall. Note that in the pre-tree fall configuration, the tension in the spans west and east of the subject pole are approximately equal and opposite, resulting in minimal bending moment on the pole, and therefore minimal deflection of the pole.

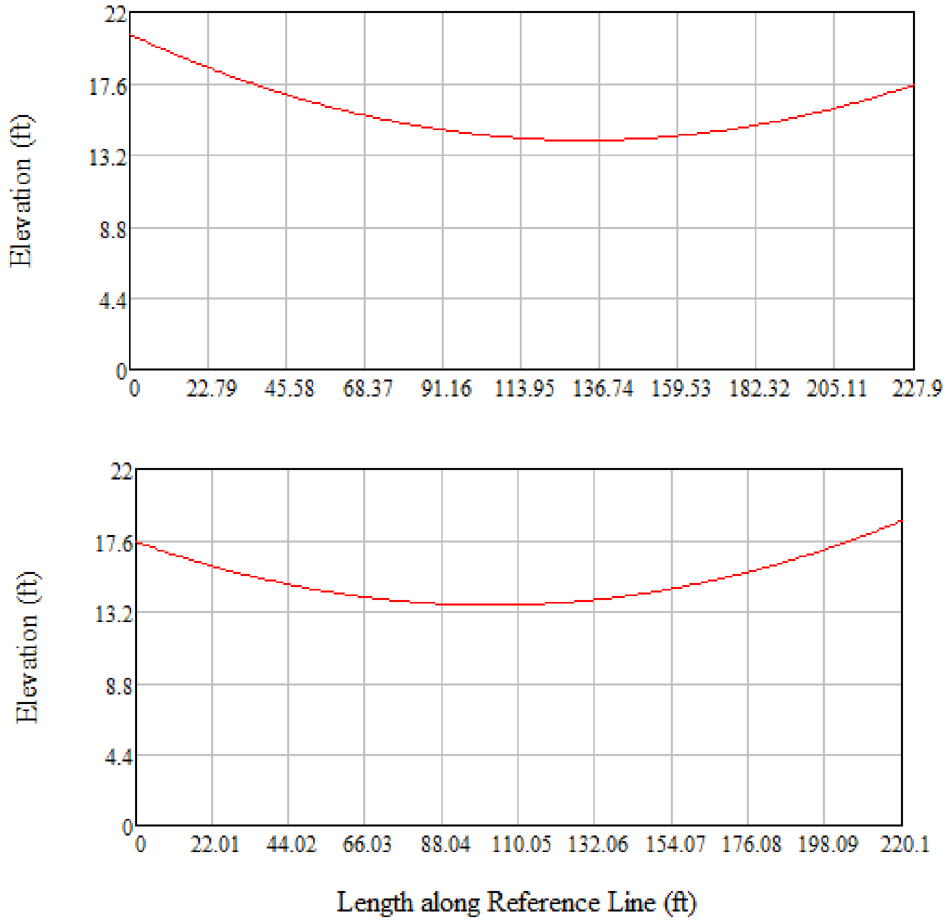

Figure 7: Elevation of Messenger Wires from W to 0 (top) and 0 to E (bottom)

Now that the pre-tree fall characteristics of the messenger wire had been determined, an iterative procedure was used to determine the tension in, and shape of, the pinned messenger wire for any given condition following the tree fall. First, the procedure was used to determine the state of the messenger wire immediately after the tree fall. Next, the procedure was used to track the change in the state of the messenger wire as it is dragged to the west by the tree segments. An iterative procedure was necessary because, as the messenger wire is displaced, a force imbalance is created relative to the messenger wire span to the west of the subject pole, both parallel and perpendicular to the general direction of the line. This imbalance causes the top of the subject pole to displace, altering the geometry of the pinned messenger wire. Therefore each state of the messenger wire was determined as follows:

1. Approximate the tension in the messenger wire using the un-deformed pole configuration.
2. Determine the three-dimensional force components at the subject pole imparted by the tension in the pinned messenger wire.
3. Determine the deformation of the pole subject to the forces from Step 2, including P-Delta effects, as well as the change in tension of the messenger wire span west of the subject pole.
4. Update the state of the messenger wire based on Step 3, resulting in a refined messenger wire tension.

Steps 2 through 4 continue until, for a given messenger wire location on the ground, the deflection of the subject pole does not cause a significant adjustment of the messenger wire tension.

Once the tension in the messenger wire was known and the deflected shape of the pole was known, the resultant bending stress at the base of the pole was calculated as follows:

$$f_{b0} = \sqrt{f_{bx0}^2 + f_{by0}^2} \tag{4}$$

where f_{bx0} and f_{by0} are the x-direction and y-direction components of bending stress, respectively, which are a function of the first and second-order moments induced on the pole by the messenger wires.

This set of iterations and bending stress calculations was performed at discrete locations along the path of the messenger wire as it was dragged by the tree segments attached to the truck.

Design Pole Stresses, Including Wind Loads

Design loading on utility poles is defined in ANSI C2. Specifically, design loading due to ice, wind, and temperature effects are provided in maps and corresponding tables, based on the geographic location of the pole. The pole would be subject to a design horizontal wind pressure of 9 pounds per square foot (psf) and no ice load based on its location. When taking into account the overturning moment induced in the pole due to the horizontal wind load, coupled with the axial forces associated with the weight of the pole and the supported components, the maximum induced bending stress at the base of the pole is approximately 2,600 psi. Therefore, the factor of safety associated with the nominal modulus of rupture and the design wind load is 8,000psi divided by 2,600psi, or 3.08.

6. Refined Computer-based Analysis

The analysis described above provides a good approximation of the stress state of the subject pole for various messenger wire configurations. However, the analysis does not account for the deformation of adjacent poles associated with the force imbalance caused by the pinned messenger wire. As the subject pole deflects, the adjacent poles will also deflect, changing the tension in their associated messenger wires. In theory, the ripple effect of this phenomenon will extend to every pole within the line until some means for counteracting the force imbalance is encountered, such as a guy wire at a so-called dead end pole. In practice, the effect will diminish with increasing distance from the pinned messenger wire. The influence of this effect on the stress state of the subject pole was introduced using a refined computer model with a sufficient number of adjacent poles.[5]

The layout of the adjacent poles/spans to the west and east of the subject pole are detailed in Table 2 and Table 3, respectively. The dimensions of each class of pole are detailed in Table 4. As indicated in the tables, seven poles on either side of the subject pole were sufficient to capture the effect described above.

[5] A "sufficient number of adjacent poles" was determined by adding additional poles to the model until the effect on the stress state of the subject pole was insignificant.

Table 2: Spans west of the subject pole

Pole	Dist. to Next Pole (ft)	Dist. to Subject pole (ft)	Class
0	227.9	0.0	Measured
1	226	227.9	Measured
2	222	453.9	25/7
3	233	675.9	30/7
4	230	908.9	25/7
5	233	1138.9	30/7
6	113	1371.9	25/7
7	161	1484.9	30/7
8	-	1645.9	25/7

Table 3: Spans east of the subject pole

Pole	Dist. to Next Pole (ft)	Dist. to Subject pole (ft)	Class
0	220.1	0.0	Measured
1	108	220.1	Measured
2	176	328.1	35/5
3	176	504.1	25/7
4	233	680.1	30/7
5	199	913.1	25/7
6	203	1112.1	30/7
7	Unknown	1315.1	Unknown
8	-	-	Unknown

Table 4: Pole properties

Pole Type	Ground Dia. (in.)	Attachment Dia. (in.)	Attachment Mom. of Inertia (in.^{4})	Effective Mom. of Inertia (in.^{4})	Effective Dia. (in.)
Subject pole	7.2	5.8	55.5	106.3	6.8
West Pole	8.6	6.9	112.8	215.7	8.1
East Pole	9.4	7.5	158.0	302.3	8.9
25/7 Pole	6.8	5.5	45.3	86.7	6.5
30/7 Pole	7.5	6.0	64.7	123.8	7.1
35/5 Pole	9.2	7.4	150.1	287.1	8.7

A computer model was created in SAP2000 (2012). The poles were assigned properties based on Table 2 and Table 3 and were considered fixed at their base. The messenger wires were modeled in a manner similar to that of the pinned messenger wire in the pre-tree fall configuration described above, using the cable element capabilities of SAP2000. Gravity load was also applied to all messenger wires and poles. A unit displacement to the east was applied to the subject pole at the messenger wire attachment height, and then a unit displacement to the west was applied to the pole east of the subject pole. A second order analysis was performed for each of these unit displacements, accounting for both material and geometric non-linearity (including large displacements). The resulting forces on the subject pole were used to calculate the stiffness provided by the east and west spans.

The scaled deformed shape (including a silhouette of the un-deformed shape) of the east and west spans subject to these unit displacements are shown in Figure 8 and Figure 9. A plot of the west and east span stiffness effect on the subject pole is shown in Figure 10. As indicated in the figure, the effect is essentially linear within the relevant range of pole behavior, and could therefore be easily incorporated into the rigorous hand calculations described above.

Figure 8: East span deformed shape

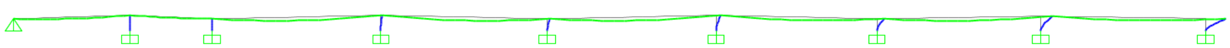

Figure 9: West span deformed shape

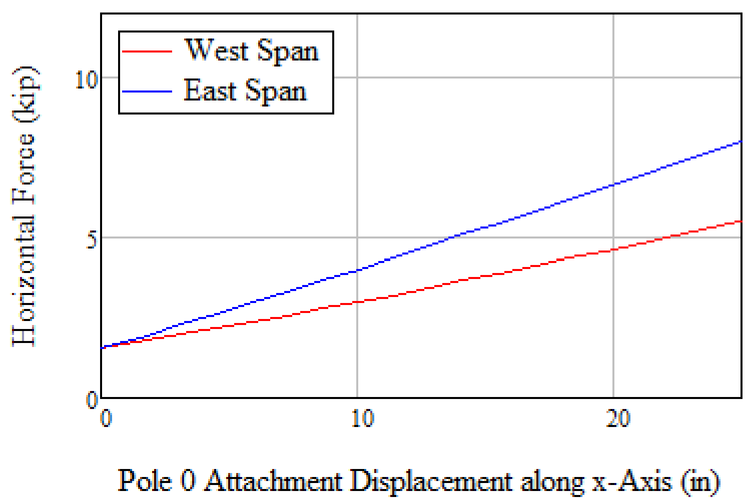

Figure 10: East span and west span stiffness

7. Results and Discussion

The results of the rigorous hand analysis, including the contribution from the east and west spans as determined from the computer model, are shown in Figure 11. The results indicate that just after the communication lines were pinned by the fallen tree, the bending stress on the pole was approximately 7.6ksi. This is 95% of the nominal modulus of rupture for the pole and almost 3 times the stress associated with the design wind load. The pole remained upright and intact despite the stress state associated with the initial tree fall.

As the tree was dragged along the ground (represented as total distance from the initial messenger wire position in Figure 11), the stresses increased at the base of the pole, quickly exceeding the nominal pole capacity. In the final position of the messenger wire (i.e., when the truck finally stopped), the bending stress on the pole would have been approximately 16.7ksi, which is more than double the nominal modulus of rupture of the pole, and approximately 6.5 times the stress associated with the design wind load.

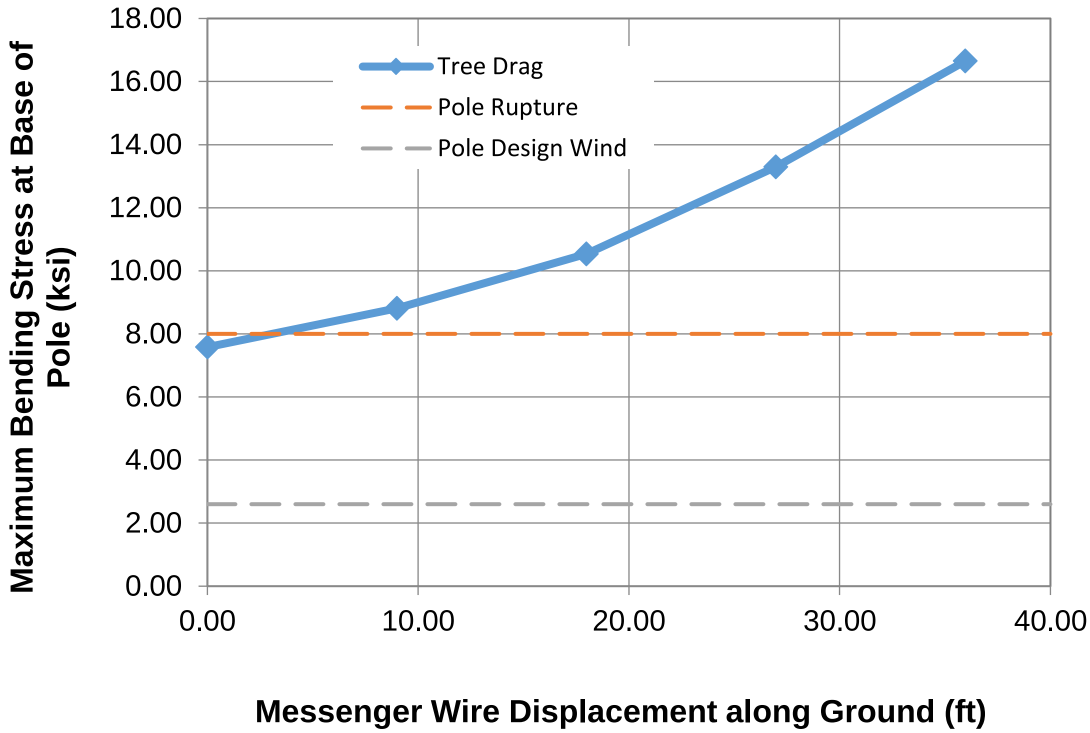

Figure 11: Results from hand calculations of tree drag

8. Conclusions

Based on the methodology and analyses discussed herein, the following conclusions can be drawn:

1. A complex, non-linear loading scenario associated with pinning and dragging a messenger wire attached to wood utility poles was analyzed using rigorous hand calculations; a refined computer model allowed the contribution of adjacent pole/span behavior to be incorporated into the analysis. Because the tension in the messenger wire is highly sensitive to deformation of the poles to which it is attached, and visa-versa, an iterative approach was needed.

2. Calculations show that, while pinning of the messenger wire to the ground by the fallen tree resulted in very high bending stress at the base of the subject pole, dragging the messenger wire to the west resulted in a significant increase in that bending stress. The

force associated with the messenger wire in its final position corresponds to a bending stress at the base of the subject pole that is more than double the nominal modulus of rupture of a new Southern Pine utility pole. As the tree segment was dragged to the west, the subject pole could not withstand these increased stresses and eventually failed in bending at the ground-line.

3. Tragically, the subject pole was likely very near a state of failure when the messenger wire was first pinned by the fallen tree. Had the pole broke at this time, the accident would not have occurred.

4. Had the cut been complete between the north and south sections of the tree, the messenger wire would not have been dragged to the west and the accident would not have occurred.

5. Calculations show that even if the subject pole had been replaced with a new Southern Pine Class 25/7 pole prior to the accident, the new pole would have likely failed at the ground-line in a similar manner when the messenger wire was dragged to the west.

Disclaimer

The views expressed herein are solely those of the authors and do not necessarily represent the position(s) of Exponent, Inc. or any other individuals.

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