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Study of Alternatives to Mitigate the Domino Effect on Concrete Pole Failures Resulting from a High-Category Hurricane

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***Abstract*— The recent hurricanes that impacted Puerto Rico have highlighted the fragility of the electrical system, resulting in long-term power outages. This study focuses on the distribution poles failure, which posed a significant challenge to the recovery of the island's electrical system after Hurricane Maria. An analysis was conducted to estimate the wind load on a typical H4 concrete type pole configuration. The results show that wind loads would not exceed the breaking strength of the pole structure. The Broms method was employed to estimate the lateral load that a pole can sustain, as well as the procedure described in the international building code (IBC) 2018, which relates the minimum required embedment depth with the applied lateral load. The analysis shows that the embedment depth of the poles could not provide adequate support to sustain lateral load. The use of guy wires and dead-end breakaway connectors was evaluated to protect the distribution system. Guys wires could provide lateral support, while breakaway connectors are intended to break before the pole falls. Further analysis is necessary to evaluate the feasibility of implementing a protection system to improve the resiliency of the electrical distribution network.**

Keywords*— Hurricane, Pole Failure, Dominoes Effect, Mitigate Blackout, Lateral Support, Breakaway Connectors.

I. Introduction

Puerto Rico and other Caribbean islands have suffered direct and indirect impacts from atmospheric phenomena such as hurricanes. Global warming is one of the factors contributing to the increased activity of these events. For reference, Florida has been one of the states that have experienced hurricanes of categories 4 and 5. To have understand how hurricanes arise in the Caribbean, it is important to note that they typically form in the Lesser Antilles region between latitude 10N and 18N. These hurricanes often originate from the west coast of Africa but are known for their disorganization and the long time they take to develop [1].

To determine the category of a hurricane, the National Hurricane Center (NHC) uses the Saffir Simpson Hurricane Scale. This scale estimates potential property damage based on the maximum sustained. wind speed. It ranges from 1 to 5. Category 5 on the scale is associated with catastrophic damage and is defined by wind speeds of 157 mph or more. A high percentage of framed homes would be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months [2,3].

DE, a web page on international news, published a headline titled: "Central America and the Caribbean: Devastating Hurricanes of the Centuries." They made a representation of the trajectory lines of the last 4 strongest hurricanes, which have caused severe damage to essential services, homes and life. [4].

Fig. 1. Strongest hurricanes paths through the Caribbean

A. *Four hurricanes that caused the most damage.*

Hurricane Felix caused significant damage in Nicaragua on September 4, 2007. As category 5, it destroyed homes and resulted in 130 deaths. [5].

Hurricane Dorian became category 5 when it made landfall on the Abaco Islands and Bahamas. With winds reaching 185mph, many residential areas were torn and destroyed. The high wind speeds affected electrical lines, leaving 95% of the population incommunicado and without essential services such as water and electricity [6].

Hurricane Irma was cataloged by Noa as a very dangerous hurricane due to its period of irregularity, but its strength increased once it becomes organized. As it approached the Caribbean, its potential increased to Category 5. Irma only had a slight approach to the northeast of Puerto Rico, but residents in the area could still feel its effects. There was also a near-total loss of electricity and water supply for several days [7].

Hurricane Maria occurred on September 20, 2017. It made landfall as a Category 4 hurricane with sustained winds of 155 mph. The National Hurricane Center reported different wind speeds across the island: 150 mph on the southeast coast where it made landfall, 145 mph in mountain towns, and 140 mph in the north. The hurricane intensity decreased from 140`mph to 115 mph as it exited north. Maria caused major damage to the electrical infrastructure, resulting in power outages that lasted up to 200 days. Many residents were without electrical service for periods ranging from 2 months to 1 year. This atmospheric phenomenon knocked down 80 percent of Puerto Rico's utility poles and all transmission lines, resulting in the loss of power to nearly the entire island [8].

Considering the events that occurred in Puerto Rico with the passage of Hurricane Maria, it's evident how critical the recovery of essential services is. It requires attention, maintenance, and preparation, which could help reduce blackouts.

II. Impact on the Electrical System

The electrical system provides one of the most important services for a modern society and life. That is why such a system should be reliable against accidental or deliberate events that can cause long blackouts, with severe social and economic consequences. Therefore, it's important to identify failures or vulnerabilities in a power system and provide resources to support reliable power system operation. One of the main problems related to the electrical system due to the passage of Hurricane Maria over Puerto Rico was the failure of utility poles, which leaf the power lines on the ground.

Considering specifically the electrical distribution system, poles may fail for different reasons due to the impact of a high energy storm, such as.

- Construction issues
- Installation issues
- Domino Effect: "Cascade Effect"
- Atmospheric phenomena
- Overloads by electrical and communications lines
- Debris load
- Soil/foundation failure

This work reference category 5 hurricane reports, as well as some newspapers, which compiled images of the coverage after Hurricane Maria. These images illustrate several distribution poles on the ground, showing a domino effect. For instance, Hurricane María caused over 40 poles to fall to the ground, in the PR-2 area in Quebradillas [9].

III. The Dominoes Effect

When the strength of the pole systems is exceeded due to overload in the cables or the pole itself, the pole may fall. Once a pole falls, it applies additional load to the system through the cables, pulling the adjacent poles and resulting in a cascade or domino effect that causes several poles to fall. This effect worsens the situation as it increases the efforts required to reestablish the electrical infrastructure.

The long-term blackout is associated with the domino effect. As a reference, the image on Figure 2., taken the day after Maria passed through the island, shows a clear example of the domino effect on concrete poles of the electrical system. A blackout affects facilities, technology, and networks, as well as services, health and economic development. An eventual failure can cause major problems, leading to social and economic consequences, including deaths.

Fig. 2. An example of Domino Effect on Power line poles, which were knocked down to the ground on the highway, in the municipality of Luquillo. Source: LAPRENSA/AFP [10].

The "Build Back Better" report, prepared by several power authorities, public agencies and private consultants, along with the Grid Modernization Plan for Puerto Rico by the Central Office for Recovery, Reconstruction and Resiliency, recognized that long sections of line failed under a domino effect due to the limited use of dead-end breakaways on poles. This report also established that the distribution systems were not originally designed to withstand a Category 4 hurricane [11,12].

IV. Distribution Poles

Distribution poles are crucial to the operation of electrical grids, allowing for the efficient distribution of electricity to end-users. Their design, placement, and maintenance are paramount to the overall stability and resilience of the electrical infrastructure, particularly in regions susceptible to extreme weather events. Pre-stressed Concrete Poles of types H3 and H4 are designed for direct ground installation. Types H-6, H8 and H10 poles are designed to be installed in a precast concrete foundation, which allows for the complete utilization of the pole's strength [13]. As a reference, the H4 concrete square type pole, characterized by Power Precast Inc., has a height of 40 feet, a weight of 6,100 pounds, a base width of 15.5 inches, and a top width of 9 inches.

Design specifications for distribution poles are a set of criteria and requirements that govern the construction, installation, and use of these essential components in electrical distribution systems. These specifications are established to ensure safety, reliability, and compliance with industry standards. PREPA uses wooden, prestressed concrete and galvanized steel poles for its sub-transmission lines and distribution. Steel poles are sourced from outside vendors in the US. However, most of the prestressed concrete poles currently in use were obtained from three manufacturers on the island, of which only two remain operational.

The companies are: Moca Concrete Poles, Inc." (formerly Pepino Concrete Poles, Inc.), Power Precast Products, Corp and Caribbean Poles, Inc, which is not operational. These design specifications are crucial in ensuring that distribution poles meet safety, structural, and operational requirements for electrical distribution networks. They serve as a blueprint for manufacturers, engineers, and installers to follow, contributing to the overall reliability and safety of the electrical infrastructure [14].

The grade of constructions generally determines different margins of safety. Higher grades of construction translate to a higher level of structural reliability and safety to withstand the environmental conditions. The NESC defined construction grades are:

Grade B: Provides the highest margin of safety and is required when the pole supports spans that cross limited access highways, railroads, and waterways.

Grade C: The most common grade, providing a basic margin of safety. It is often utilized for typical power and joint-use distribution poles.

Grade N: The lowest grade of construction, most often used for emergency and temporary construction.[4].

In Puerto Rico, poles most commonly have a grade C rating.

V. Wind Pressure

Wind pressure is indeed a critical factor in the design and analysis of structures, especially those exposed to outdoor environments. For distribution poles in electrical service, wind pressure significantly impacts their structural integrity and stability, particularly during extreme weather events like hurricanes. The wind pressure can be estimated as follows [15]:

$$p = \frac{q \cdot v^2 \cdot Cf \cdot Cl}{2 \cdot g} \quad (1)$$

where,

p: wind pressure.

q: volumetric weight of air (1.225 kgf / m³).

v: wind speed (m/s).

g: is the gravity (m / s²).

Cf and CL: are constants that depend on the shape factor of the cable and the span, for cylindrical cables these are 1.45 and 0.55, respectively [15].

After Hurricane Maria, the design wind speed in Puerto Rico increased from 145 mph to 165 mph. However, considering high category hurricanes, the wind speed could be even higher. For the analysis in this work, the maximum wind speed is assumed to be 185 mph, which is 20 mph higher than the design speed. Thus, the wind pressure is calculated to be 3343 N/m^2 or 69.76 lbf/ft^2.

VI. Wind Force on Pole

The wind pressure acts on the cables and insulators, and those elements transfer the load to the poles. For example, for a pole with a line span of 100 ft, the wind load on the cables, can be calculated as follows: [14]:

$$F_{WC} = P \cdot D \cdot L \cdot N_C \quad (2)$$

where,

F_{WC}: wind load on cables.

P: wind pressure

D: diameter of cable.

L: cable length or span.

N_C: number of conductors per phase

Considering distribution wire gauges are between #12 and 4/0, the 2/0 AWG was selected for analysis, with an insulation outside diameter of 0.576 in [16]. Thus, for three conductors, the lateral load on the pole due to wind load on cables is estimated to be 1004 lbf. Considering a H4 type pole, the wind force over the pole structure (32 ft from ground base) could be approximated to 2100 lbf and the wind load is under the pole design rupture load, specified by Power Precast Products Inc. as 4350 lbf. This suggests that the pole rupture is not a consequence of the wind load on the cables only. For instance, Acosta et.al concluded that many poles made from previous designs failed by design deficiencies and improper construction practices, while poles manufactured under updated codes failed mostly due to foundation issues and structural overload [14].

An analysis in SAP2000 for a 40 ft H4 type pole with a span of 100 ft and wind pressure of 69.76 lbf/ft^2 resulted in a maximum moment at the base of 77.8 k-ft. The analysis was carried out assuming the pole in a cantilever configuration with fixed support at the base. For reference, Fig. 3 illustrates the results. Communication equipment was not considered in the analysis.

Overload may also be caused by debris (plates, trees or tree branches), which can impact the pole system. For the analysis, the effect of a typical roof zinc sheet (8ft x 3 ft) was considered. To estimate the increase in the wind load, the authors approximated the area of the sheet facing the wind pressure to 8ft x 1.5ft. This increases the wind force on the pole, resulting in a maximum moment at the base of 105.5 k-ft. This is an increment of 27.7 k-ft due to debris and the load is still under the moment of rupture specified as 141 k-ft.

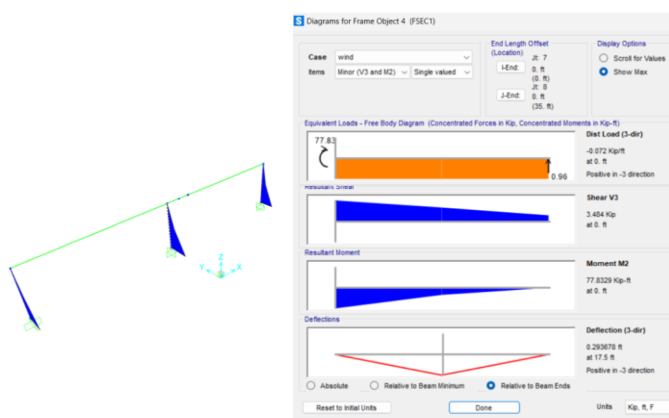


Fig. 3. Results from analysis in SAP2000.

VII. Soil Considerations

The structure, texture, mineralogy, water content, and chemical composition define the characteristics of the soil. For this reason, among the determining factors in its formation are climate, bedrock (underlying rock), biological activities and organisms that develop in the area, relief and time. The following table illustrates the different types of soil [17].

TABLE I Types of soil

Soils	Compound
Clay	Hydrated aluminum silicates, rocks that contain feldspar and granite.
Gravel	Sedimentary deposits formed by clasts with a size between 2 and 64 millimeters.
Loam	Loam soil is usually called the superficial parts of the terrain.
Peat	Problematic soils in the fields of civil and environmental engineering is formed by organic materials under the waterlogged environment.
Sand	Mainly of sand (more than 70%) with very little clay (less than 15%) and/or silt.
Silt	Incoherent clastic sediment transported in suspension by rivers and by the wind.

Puerto Rico has different types of soil. Some of them are good for construction, which requires that the soil have good drainage. As a reference, Gutierrez in 2010 carried out a study of soils in the municipality of Humacao. It presents the municipal map of Humacao with zones identified by colors and uses a table to relates the colors with the corresponding type of soil, i.e. S_C, S_D, S_E and S_F type of soil [17].

In general, to analyze the pole foundation/soil interaction, soil was considered in a saturated condition. However, the soil could be in a worse condition since the storm system can result in flooding, a common situation in areas impacted by tropical storms in the Caribbean. This weakens the pole system, making it more vulnerable to wind load and debris.

VIII. FOUNDATION

The foundation is the structural element designed to safely transfer construction loads to the underlying soil. It must satisfy the bearing load, and the soil should ensure the integrity of the foundation. It cannot experience displacement, and settlement should be within tolerable limits [18].

Loading or soil issues may result in the tilting of a pole making it vulnerable to wind forces. The analysis of foundation/soil failure due to wind action involves several factors. Therefore, this work presents a case analysis for a typical distribution pole configuration. It is a H4 type pole with three lines, a 100 ft span, and exposure to a storm with 185 mph wind speed, which results in an equivalent force of 2100 lbf at two feet from the top of the pole. It considers the wind load on the cables and the force due to wind pressure over the pole structure acting on the centroid of the pole.

An approach of the reaction in the soil can be obtained by employing a simplified analysis presented by Acosta et. All and illustrated in Fig. 4. Thus, the reactions in the top R_t and the bottom R_b are [14]:

$$R_t = P_u[7(H/L) + 1] = 13{,}970\ lbf \quad (3)$$

and

$$R_b = 7P_u(H/L) = 11{,}869\ lbf \quad (4)$$

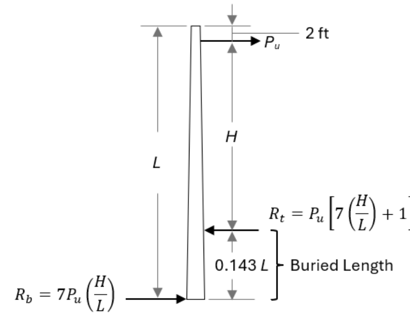


Fig. 4 Simplified Analysis

R_t and R_b: simplifications of the reactions coupled that develop underground.
P_u: ultimate force concentrated at the top.
H: heigh of the exposed part of pole = 32.28 ft
L: total length of pole = 40 ft

The requirement of a pole foundation depends on the soil type and condition. In general, most poles are embedded into the soil. The deep each pole has underground (embedment length) is associated to the pole length and is controlled to ensure stability and safety. For instance, Table II shows the recommended penetration of the pole in the soil for different pole lengths [19].

TABLE II
DEEP IN THE SOIL OF THE FOUNDATION OF THE POLE [19]

Length (Ft)	Depth (Ft)
35	5'-6"
40	6'-0"
45	6'-6"
50	7'-0"
55	7'-9"
60	8'-5"
65	9'-1"

Soil is mostly heterogeneous and changes with depth, however, it is modelled as an elastic media. For instance, the Winkler elastic model considers the soil as a series of independent elastic springs [18]. Thus, the embedded pole can be modelled as a short pile with a free head (see Fig. 5), for which different models consider the pressure, friction angle, horizontal reaction, and properties of the pile. The simplified Broms method was used to estimate the ultimate lateral load $Q_{u(g)}$, for a H4 type pole [18].

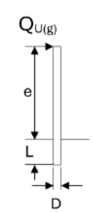


Fig. 5 Pile with Free Head

with,

φ'=26°	friction coefficient
$k_p = tan^2\left(45 + \frac{\varphi'}{2}\right)$	Rankine passive pressure coefficient
q_u=200 kN/m^2	Simple compression strength
γ=18 kN/m^3	

c_u=0.375·q_u=75 kN/m^2 non drained cohesion
L= 6.6 ft
D= 1.25 ft
e=31.4 ft
L/D=5.249
e/L=4.785
e/D=25.12

The analysis resulted in values of $Q_{u(g)}$ of 1.72 kips and 2.45 kips for Sand and Clay soil types, respectively. It is less than the estimated reaction on the soil.

On the other hand, the minimum embedment depth to support the lateral load on the pole can be estimated by using the procedure described in the International Building Code (IBC) 2018 [20]. The analysis is iterative, and it considers the soil in a saturated condition. The IBC 2018 provides presumptive lateral load-bearing values for different types of soil. Assuming class 3 (Sandy gravel and gravel), the presumptive lateral bearing pressure is 200 psf/ft below natural grade. If the lateral load is applied at 2 ft from top of the pole, the embedment depth can be estimated as follows:

Pres=200 psf/ft Presumptive lateral bearing pressure
P=2100 lbf Applied lateral force
b=1.826 ft Diagonal of square pole
E_d=11.8 ft Embedment depth
h=26.2 ft Distance from ground surface to point of application of P

$S_1 = Pres \cdot \frac{E_d}{3} = 786.67\ psf$ Allowable soil-bearing pressure

$A = 2.34 \cdot \frac{P}{S_1 \cdot b} = 3.421\ ft$

Depth of embedment

$$d = 0.5 \cdot A \cdot \left(1 + \left(1 + 4.36 \cdot \left(\frac{h}{A}\right)\right)^{1/2}\right) = 11.741\ ft \quad (5)$$

This analysis shows that a lateral force produced by a 185 mph wind speed on the pole requires around 11.8 ft of embedment depth, a length higher than 6'-0", the value established in Table II for a pole of 40 ft in length.

IX. Protection System

The Grid Modernization Plan for Puerto Rico suggests that during Hurricane Maria, long sections of line failed in a domino effect due to the limited use of dead-end breakaways on poles [12]. Moreover, dead-end devices available in the market are intended to sustain the cable attached to the insulator on the pole and to protect the cables. These are designed to fail under the cable tensile load capacity. For example, a series of Automatic Dead End provides a quick and secure method of deadening conductors. Several bail types are available to meet application needs, rated to hold a minimum of 95% of RBS of the strands used. Figure 6. illustrates an Automatic Dead-End Device, produced by MacLean Power Systems [21]

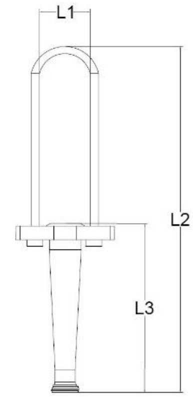


Fig. 6. Automatic Dead End Design Class FDS.

To mitigate the domino effect caused by a high category hurricane, it is important to consider a protection system that could enhance the resiliency of the electrical distribution system. In this work, two alternatives were considered: providing lateral support to withstand wind load and using breakaway connectors to release the load on the pole.

Like transmission towers, where suspension towers are weaker and dead-end towers are reinforced and strategically placed to withstand critical loads and prevent cascading tower failures [22], reinforce specific dead-end distribution poles to support the impact of a high energy storm could help mitigate the domino effect. Typically, the cable load is balanced in a pole by using the lines or wire guys, but most poles do not have lateral support in the direction transverse to the lines (week direction). In fact, the National Electric Code requires provisions for extreme wind load only when the top of a pole is 60 feet or more above ground [23]. Lateral support could be provided by using wire guys, push pole bracing, or wedge clamping. On the other hand, dead-end breakaways connectors could be used to work as weak links on specific poles. Thus, before the first pole collapses, the connectors would break, and damage could be localized within a few poles.

X. Lateral Support

In general, concrete distribution poles often have inherent strength and durability, which can influence the choice of lateral support systems to balance the loading conditions. The selection depends on the type of load and pole/distribution configuration. The overhead electrical distribution system manual, published by Luma Energy in April of 2024, identifies guys as an indispensable element for the structural strength of the pole. For example, to support the loads imposed by wind, when the load is greater than the pole can support on its own. This manual establishes that at least one of every five poles shall have a concrete base and a higher pole classification to prevent the poles from experience a domino effect if they fall [19]. A concrete base would also be required for soil classification 6 to 8, per 1724 E-153 RUS bulletin [24].

Considering wind load, the experience with Hurricane Maria showed that electrical distribution poles with heights lower than 60 ft may fail due to wind-related loads, and the domino effect was evident in different areas of Puerto Rico.

In this work, the analysis was limited to concrete H4 type distribution poles, which are produced by Power Precast Inc. [11]. As a reference, Table III illustrates properties of a 40ft H4 concrete type pole, which was used for calculation.

TABLE III
POLE INFORMATION

Pole Detail	Value and Units
Dimension Top	9 in
Dimension Base	15.5 in
Weight	6,100 lbs
Maximum Moment	141 k-ft-lbs
Breaking Strength	4,350 lbf
Class Pole	H4

Although wind load on cables is critical, there are different approaches to estimate the wind load on the power lines. For example, the method described in ASCE 7, NESC, variations included by electrical companies and other methods like IEC 826 and JEC 127, described in the Assessment of Wind Loads on Power Lines report, published by the Electrical Power Research Institute (EPRI) [13].

Considering a wind speed of 185 mph, which corresponds to a wind pressure of 69.76 psf, the equivalent wind load at 2 ft from the top of the pole, due to the load on cables (3 cables) and pole structure (32 ft over ground level), was estimated to be 2100 lbf. Additionally, if load due to debris is considered, in example, an aluminum laminate on a cable with an area estimated of 8 ft by 3 ft, the load would increase by 1674 lbf, reaching a total of 3774 lbf. In absence of a concrete base and a higher pole classification every five poles, guys could be an alternative to reinforce the electrical distribution system, improving the resiliency to hurricane events.

The standard E5 of the Overhead Electrical Distribution System Manual establishes the guy selection tables for grade B construction. The guy is composed of the guy wire, which shall be galvanized steel with a ½ inch diameter, a guy marker (which shall be PVC and yellow), a guy grip to attach the wire to the other elements, fiberglass insulators at a lower height than the lowest primary electrical circuit to prevent voltage transfer to other facilities on the pole. To install the guy, a 10-foot-long galvanized steel rod is used. The steel rod is installed in a straight line with the guy and ends with an anchor (See figure 7). The type of rod and anchor depends on the type of terrain [19]. This manual indicates that the guy strand could support up to 26700 lbf. The permitted load is 24030 lbf, which is obtained by applying a load factor of 0.9. An additional tension factor is applied, considering the height of the guy attachment and the distance from the pole to the anchor. For wind, an overload factor of 2.5 shall be used, as well as a grade B safety factor of 1.65. As established in the manual, a ½ single guy is intended to allow up to 5000 lbf of horizontal load, as per the E-1-2-3 LUMA standard [19].

Using guys to reinforce a pole to sustain hurricane conditions requires installing guys on the sides perpendicular to the lines, when no guys are required to balance the lines. Thus, the initial tension of the guys can be as low as zero. The guys will resist tensile load only when lateral load is applied to the pole.

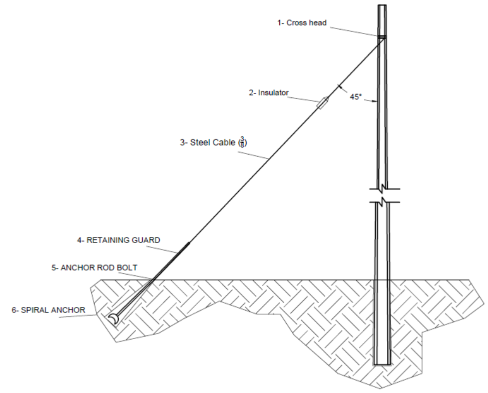


Fig. 7. Guy components illustration

This alternative has a restriction, since guy wires shall not be installed on roadways [19]. This significant because many poles failed during Hurricane Maria in these locations.

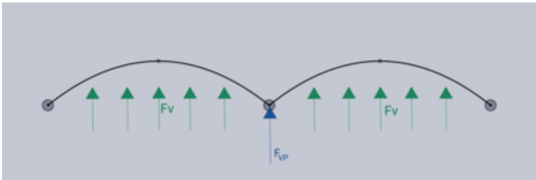
XI. Breakaway Connectors

Breakaway connectors are devices designed to load in tension and break once they have achieved an overload. These have applications in various industries such as: naval, marine, aerospace, telecommunications and aviation. They can be used in utility poles when spooling or lashing cable and installing aerial insert wires. The connectors are also viable in locations with harsh weather conditions that can tear cables down. Thus, this system allows to faster repairs.

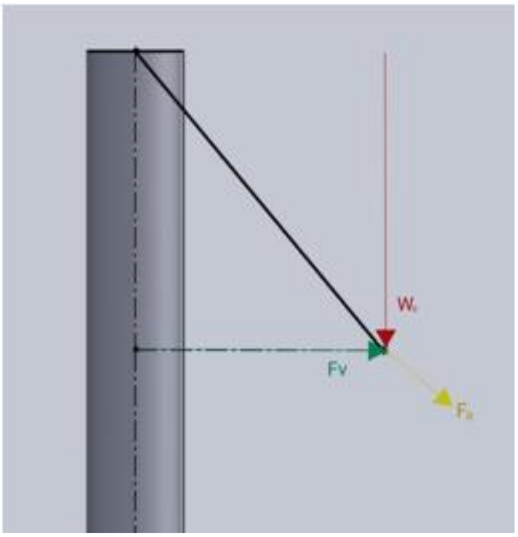
A load analysis allows determining which model of connector suits the needs. It requires estimating the pole failure load, which could be defined by the pole breaking load or pole/foundation capacity. The first is reported by power precast for a H4 type pole as 4350 lbf, and the second is limited by the pole/foundation condition, i.e. foundation type, soil type and its condition. It can be estimated by using the procedure described in the International Building Code (IBC) 2018, which relates the minimum required embedment depth with the applied lateral load on the pole. For instance, considering sandy gravel and gravel, a presumptive lateral bearing pressure of 200 psf/ft, a square concrete H4 type pole and 6 ft of embedment depth for a 40 ft pole length (see Table II), the lateral force that the pole system could support is 550 lbf. In fact, a limitation note in section 1807.3.1 of IBC 2018 indicates that posts embedded in earth shall not be used to provide lateral support unless bracing is provided [20].

On the other hand, assuming the foundation/soil condition provide adequate strength to support the lateral load, estimating the increase in cable tensile load due to wind force action alone requires a wind load analysis. Figure 8a and 8b illustrates the wind force acting on consecutive poles and resultant force on a cable due to the combined action of weight and wind load. The cable's weight and wind load are treated as distributed loads. By multiplying the wind pressure by the cable's diameter, the distributed load on one cable (F_V) is 3.35 lbf/ft. The 2-0 wire gauge weight is 0.376 lbf/ft, and the resultant force on one cable (F_R) can be estimated from the action of each component using equation 6. Thus, F_R is 3.371 lbf/ft

$$F_R = \sqrt{{F_V}^2 + {W_g}^2} \tag{6}$$



(a)



(b)

Fig. 8. Load on cables and Pole. a) Lateral load on cables and pole (Top View), b) Acting forces on cables (Right View)

To estimate the tension on a cable, the parabolic model was used [25].

$$T \cdot \sin\theta = W_0 \cdot x \tag{7}$$

Where:
T= Cable tensile load
W_0= weight of cable (distributed load)
x= half of span length

Once applied the initial or installation tension (650 lbf), the angle θ is computed as follows:

$$\theta = sin^{-1}\left(\frac{W_0 \cdot x}{T}\right) = sin^{-1}\left(\frac{18.8\ lbf}{650\ lbf}\right) = 1.657° \tag{8}$$

Using F_R as the distributed load to include the wind effect and neglecting the cable deformation, the tension in the cable can be estimated using equation 7, resulting in 5828.94 lbf:

On the other hand, considering the lateral load is limited to 550 lbf, as estimated for a H4 concrete type pole and soil condition studied in this work, the increase in the cable's tension can be computed in the same way. For three cables, the lateral distributed load on each cable is:

$$\frac{550\ lbf}{\#cable \cdot L} = \frac{550\ lbf}{3 \cdot 100\ ft} = 1.83\ \frac{lbf}{ft} \tag{9}$$

Using W_g = 0.376 lbf/ft and the lateral distributed load, F_R is computed using equation 6. Thus F_R=1.87 lbf/ft and the tension in the cable is estimated by using equation 7, resulting in T= 3233.5 lbf.

Assuming this tensile load will cause the pole system to fail by exceeding the capacity of the pole foundation, the breaking load for the breakaway connector must be set to a lower value, i.e. 80% of the breaking load. Thus, the breakaway connector will break before the pole falls. In the case studied in this work, the breakaway design load is 2586.8 lbf, which could be conservatively rounded to 2500 lbf.

Currently, there are models of breakaway connectors available in the market that could meet the requirements. The company DCD Design offers a catalog of breakaway pin connector kits that use pins of specific tensile strength, varying from 125 lbf to 4000 lbf. For instance, the model 0555-027 from Group C, a 5 pins kit, offers a tensile breaking strength of 2700 lbf (+/- 10%) [26]. The breakaway connectors would be installed in the dead-end assembly, between the pole and the electrical insulator.

XII. Conclusion

The wind load does not exceed the breaking strength of the pole structure; therefore, pole rupture would be caused by construction defects or impact of debris [14].

The Broms method allowed to identify that the capacity of soil could be exceeded by wind lateral load in some saturated soil conditions.

Lateral load caused by a 185 mph wind speed could require an embedment depth higher than the employed by the power authority. This could be because the standard does not consider wind load on poles with lengths less than 60 ft.

The LUMA standard considers reinforcing the system every five poles, by using concrete foundation and higher-grade construction. However, this has proven to be insufficient. The use of guy wires could provide adequate lateral support to wind loads, but it's restricted in roadways.

There are breakaway connectors available on the market that could meet the requirements to protect the distribution system. Implementing breakaway connectors will require further analysis to consider the economic impact, safety concerns, and improvements in recovery time periods.

Authors recommend considering wind load analysis even on poles with lengths under 60 ft in zones exposed to hurricanes and making provisions to improve the reliability of the distribution system.

Further investigation is necessary to study the impact of debris on the electrical system.

XIII. Future Work

Study the implementation of lateral support and breakaway connectors to protect the electrical distribution system, considering economic and safety analyses. Continue studying the pole foundation/soil interaction to identify pole design alternatives to improve the resistant to pole overturning due to lateral loads.

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