Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2025.000086

ORIGINAL ARTICLE

Addressing the challenges of electric pole design and material selection: A review of current practices and future directions

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Abstract: Electricity is vital for everyday human activities yet meeting the escalating demand for reliable energy presents significant challenges. The government has undertaken efforts to extend electricity access to remote areas; however, the transmission process from generating stations to end-users faces obstacles related to design, material selection, and protection. This overview evaluates the advantages and limitations of concrete, steel, and timber poles commonly used in power distribution networks. Various factors impact the performance of these materials, including steel corrosion, concrete reinforcement, prestress loss, insect infestations, adverse weather conditions, seismic events, and construction methods. Despite efforts to reinforce poles and extend their service life, the mechanisms underlying pole failure remain inadequately understood. Strengthening measures are frequently employed to mitigate deterioration, yet the fatigue effects on existing poles have not been thoroughly investigated, exacerbating their susceptibility to environmental stressors. Consequently, it is imperative to consider the specific environmental and geographical factors influencing pole performance during the design phase to ensure the reliability and longevity of electricity distribution systems.

Keywords: Electric poles, steel, concrete, timber, design and erection, failure mode

1 Introduction

Every nation's socioeconomic and technological development is heavily reliant on electricity, and global electricity demand today is increasing exponentially daily as population and economic activities grow. Fire was essential to early man's ability to cook, stay warm, and enjoy the light, but we take these conveniences for granted. There is an instant presence of power at the flick of a switch or turn of a knob. Electricity is not just crucial for our immediate surroundings but also essential for various aspects of modern life, including industries we depend on and communication methods such as radio, television, email, and the Internet. Additionally, electricity also influences the modern-day transportation [1]. As the power is generated from the generating station, there is a need to convey it to the end users, in this case power distribution network is essential. The electric power distribution network functions similarly to human cardiovascular mechanisms, with connecting links between the generating station and the distribution system resembling arteries in the human body. Capillaries are analogous to distribution systems, which connect all separate loads to transmission lines at substations that perform voltage conversion and regulation. They play an important role in supplying viable life-giving blood of civilization electricity to users at various ends [2].

Received: 24 November 2024; Received in revised form: 4 April 2025; Accepted: 29 August 2025

Three different materials; steel, wood, and concrete have often been used to transport/distribute electricity from the generating station to the end consumers. Although other innovative materials (hybrid composite) have also been adopted, this investigation only considers these three traditional materials for transporting electricity to the final users. Steel towers and steel poles have been employed to transfer electricity, the former **Fig. 1** (a, b) has been adopted to transmit high voltage (100 KV and higher) where service dependability and continuity are required [3]. However, as the electricity demand grows, the availability of right-of-way becomes more critical in terms of cost and space. The demand for steel pole-type structures Figure 1c, particularly in cities, is also growing tangentially. Steel poles are considered more advantageous than steel towers because they can be erected in a much smaller area. Hence, less expensive and more efficient than towers in cities, where the limited right of way is costly [4]. Also, they are subjected to less wind loads than towers due to their lower aerodynamic coefficient, allowing them to be used more efficiently.

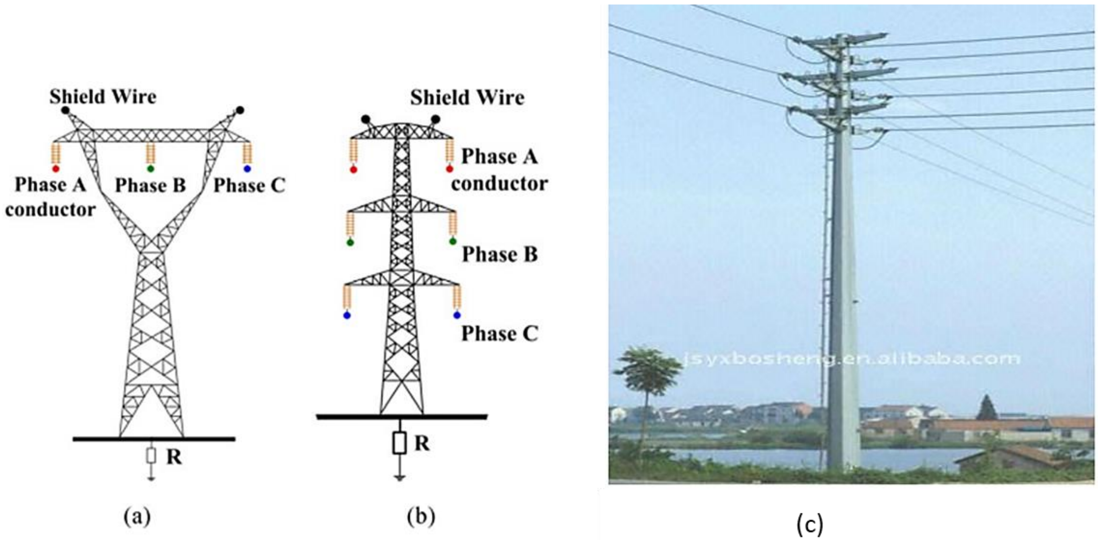
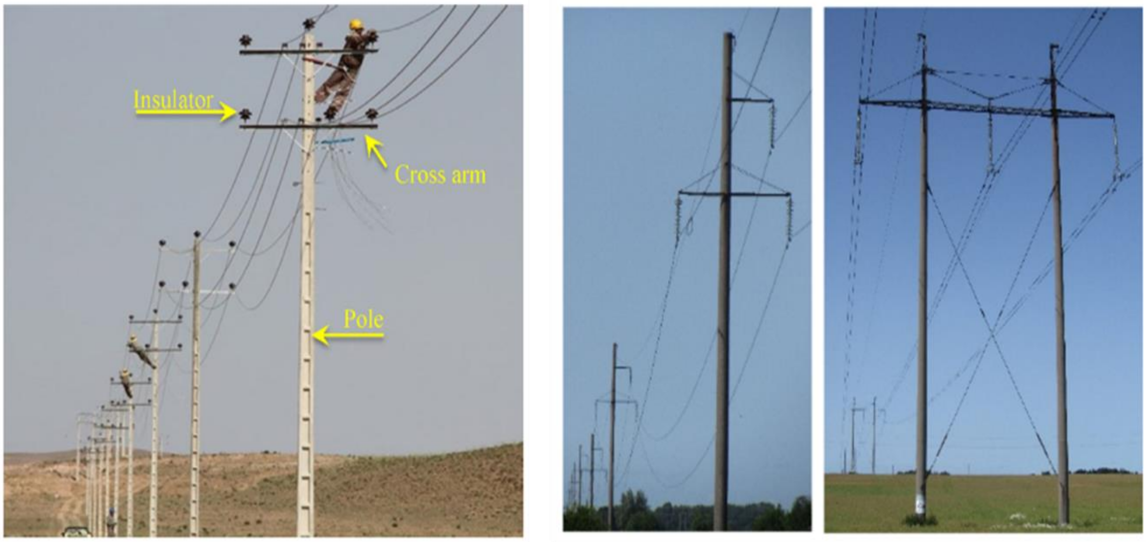


Fig. 1 (a, b) Steel tower [5], (c) electric distribution steel pole [6]

Due to an increase in demand for forest wood for urban-rural electrification, the world has recently seen unprecedented growth in farm forests in various configurations. Preservative-treated Eucalyptus wood has long been used as a power transmission pole in Kenya, Ghana, Nigeria, and Brazil among other countries [7–10]. The demand for treated wooden poles has continued to rise as a result of the government's efforts to connect more people to electricity, which has been matched by increased investment in the species' growth. It is thus estimated that each country requires 400,000-500,000 poles per year for rural electrification. Wooden pole **Fig. 2** is considered environmentally friendly since it is harvested from nature and its renewability can continue for a long period, as such, harvesting wood for electricity does not pose much threat to the environment. Treated woods contribute significantly to the gross domestic product of a nation [11].

While steel and wooden poles are made of homogeneous materials, reinforced concrete poles are made of heterogeneous materials from different stone aggregates bonded together by substantial water-cement proportion, and reinforcing bars to resist tensile forces under loads since concrete is weak in tension [12]. They are available in a variety of shapes, including H-shape tapered, round tapered, and uniformly round, because concrete at the plastic stage can occupy the shape of any designed formwork. Reinforced concrete (RC) and prestressed concrete (PC) poles, **Fig. 3**, are commonly used for electricity distribution; the latter is more durable, less in weight, has a longer life span, requires less maintenance, and has a wider range of heights, especially when centrifugally spun. Normal RC poles could fail after a thousand load repetition under fatigue, PC poles can withstand up to 500,000 cycles without failure, moreover, RC are susceptible to steel corrosion leading to spalling of concrete under fatigue problems. Due to the prestressing process, PC exhibit reduced cracking minimizing ingress of moisture and consequent corrosion [13]. PC poles also demonstrate excellent performance under vehicular impact conditions than RC suggesting enhanced durability [14]. Furthermore, compared to RC, PC are more cost-effective in the long-term usage and a reduced in the need for maintenance can give significant cost saving over the life span of the poles.

Fig. 2 Wooden poles from wind farms in Kiowa County Oklahoma [15]



(a) Reinforced concrete poles (b) Prestressed concrete poles

Fig. 3 Electric concrete pole (a) reinforced type [16], (b) prestressed type [17]

Following this backdrop, a comprehensive review study on the challenges of electric pole design and material (wood, steel, and concrete) selection is imperative for several reasons. Firstly, the critical roles played by electric poles in supporting overhead power lines and distributing electricity to communities, industries, and infrastructure, cannot be overemphasized. Therefore, ensuring their structural integrity and resilience is paramount to public safety and maintaining reliable electrical infrastructure. Secondly, the selection of materials, steel, concrete, and wood for electric pole construction involves trade-offs between factors such as cost, durability, environmental impact, and maintenance requirements. Understanding the advantages and limitations of each material type is crucial for making informed decisions in pole design and material selection. Additionally, advancements in material science and engineering techniques may offer innovative solutions to address longstanding challenges in electric pole design, making a comprehensive review study timely and beneficial for the industry as a whole.

2 Pros and Cons of these three materials used for electricity distribution

2.1 Electric wooden/timber poles

Wooden poles made from eucalyptus and other viable trees have been widely used to support electrical lines in some parts of the world [18,19]. Wood is strong, pliable, and lightweight. A preservative-impregnated wooden pole can have a specific gravity of up to 700 Kg/m^3. A ten-meter-high pole with a top flexural strength of 8.2 kN would be less than 300 kg in weight, increasing the truck loading accordingly and lowering transportation and installation costs significantly. Thus, heavy machinery is not required to install the wooden poles. Due to their elastic properties and the homogeneity of their material constituents, preserved wooden poles on high-voltage lines can achieve the goal of increasing stability in the event of wind loads. Yu et al. [20] considered numerically the wind load effect on timber poles and the different types of damage. Since the current standards do not highlight the wind capacity consequence of the damage mode of timber poles, external and internal damage due to wind action was simulated. According to the findings, external damage reduced the timber pole capacity, while internal damage only led to a small loss of capacity within a positive range. A pole with mid-to-large size damage tends to fail due to the damage under design wind loading, whereas a pole with internal damage will still have large enough strength to withstand wind effects. In addition, although cables attached to wooden poles play an important part in determining their capacity under wind effect, wooden poles will support strung wires, reducing the number of outages on the lines.

Due to the obvious lack of leakage currents, wood has exceptional dialect properties. When transferring electric power over a long distance, the use of wooden poles saves a significant amount of energy [21,22]. They provide a significant isolation distance from impulse over-voltages and can extinguish the power overlap, providing high earth fault circuit resistance. These properties can reduce the number of transmission line lightning outages and thus increase safety [9,23]Meanwhile, the readily available market for eucalyptus poles has motivated farmers to plant the trees as a cash crop. Langat et al. [24] reported from a field survey that, according to market prices and current economic conditions, growing eucalyptus-grandis was more profitable for medium power transmission poles than firewood. The internal rate of return can vary between about 5% and 28% for firewood and medium power transmission poles, respectively. Furthermore, the use of wooden poles is a step in the right direction toward reducing the carbon footprint. Wooden poles are sourced from sustainable forests, where three trees are planted for every one harvested. Besides, the wood used to make the poles is renewable, and the waste rate is low. In the event of damage, wooden poles are returned to the factory for recycling.

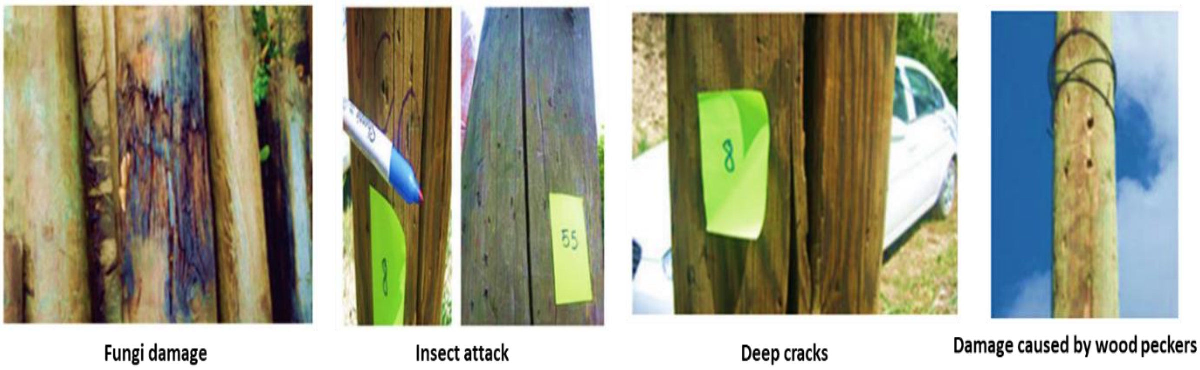


Fig. 4 Damage and defects on wooden poles [20]

Unfortunately, wood deteriorates as a result of physical, chemical, and biological factors. The most imperative decay factor is biological agents. Bacteria, insects, fungi, and marine drill attacks are common to wooden poles. Fungi, organisms whose system and existences differ from simple yeast, receive special attention in Southern Brazil [25]. This deterioration drastically affects its service life and may have a significant impact on its capacities which might fail with serious consequences such as loss of life and high cost. According to Gezer et al. [26] approximately 20,000 wooden poles are placed across four cities in Turkey each year, with treated poles having a life span of up to 50 years. However, in the sea region, the life span can reduce to 10 years. They determine the deterioration and degradation of the poles by adopting visual inspection using a guideline for the physical inspection of poles in service standard method AWPA M13-01 [27], and nondestructive test methods using resistograph and micro hammer to determine internal decay of 150 poles to improve the service life around these major cities. They concluded that fungi, insects, inadequate impregnation, and deep cracks and splits were the most critical factors influencing pole service life. Some of the highlighted defects and damage are presented in **Fig. 4**. Wooden poles are also not suitable for high-tension power lines due to power surges and can easily catch fire [28], especially during the dry season; they only gain value in remote areas to carry step-down power lines into buildings; and they are unsuitable for busy areas because collapse does not give any warning during heavy wind and can lead to serious accidents or loss of life in the event of a possible fall on vehicles on traffic road and electrocution [29].

Wooden poles that are faster grown, weak wood, combined with the condition of fungi growth can cause wooden poles to fail easily under extreme weather conditions such as hurricanes, tornados, and high-temperature areas during summer may experience fire in untreated wood. It is necessary to assess the condition of an area before installing wooden poles [30]. Humidity and temperatures have been reported to affect the durability of wood [31]. Wood poles' moisture content rises when they are exposed to damp environments. When wood's moisture content rises above the fiber saturation point, a favorable environment for the formation of fungal is established [32].

2.2 Electric steel poles

The use of steel poles provides several benefits, including competitive purchase prices, less weight, pre-drilled notches at the factory, reduced installation costs, cheaper grounding costs (where copper down-lead is essential), and improved aesthetics. Removable pole steps can also be used to quickly and easily ascend steel poles [33]. The mechanical strength property of steel, especially the response to external loads in tension, has been deployed for steel towers to convey long-span transmission at high voltage. The truss connection of the steel rod for a tower, Figure 1(a, b), allows for substantial height and systematic distribution of load across the truss member. Steel towers can withstand extreme weather and natural disasters. The risk of service interruption due to broken or punctured insulation is significantly reduced due to the obvious longer spans. The weight of the tower that supports the conductor, and thus its cost, is determined by tower height, which is the maximum sag at the design span and the minimum ground clearance between the charged line and the ground [34]. Typically, tower footings are grounded by driving rods into the ground, which reduces lightning problems because each tower acts as a lightning conductor.

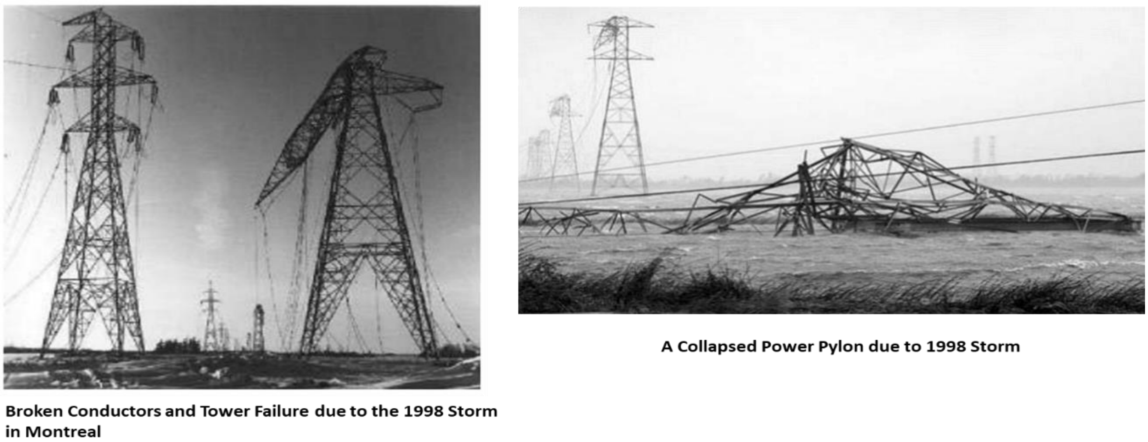


Fig. 5 Typical collapse of steel tower in Canada due to heavy ice storm [38]

Failure of components of steel towers, such as conductors, is common; the conductors are connected to the insulator strings, which are attached to the cross arms of the supporting towers. Damage due to the accumulation of ice storms can disrupt the flow of electricity, causing power outages [35]. There is a significant amount of strain energy when a transmission tower experiences a heavy load due to a storm. The strain energy causes dynamic problems affecting the weakest area of the truss member; a case of collapse in Canada is shown in **Fig. 5**. Li et al. [36] investigated the failure of transmission tower line systems induced by ice shedding through finite element analysis. The uniform method was adopted in the modeling process to present the initial defects, and the failure caused by ice shedding and its influencing constraints are studied on ANSYS. According to the findings, the more the ice-shedding height, the more the threat to the system; additionally, the longer the span, the shorter the insulator length, and the higher the dynamic response of the line. The cross arm connected to the ice-shedding conductor, the tower body, and the tower head are susceptible to ice storms. Additionally, Natural disasters, particularly hurricanes, can lead to the failure of electricity distribution systems. Hurricanes can damage the distribution system, resulting in power outages that are costly in loss of revenue and restoration expenses [37].

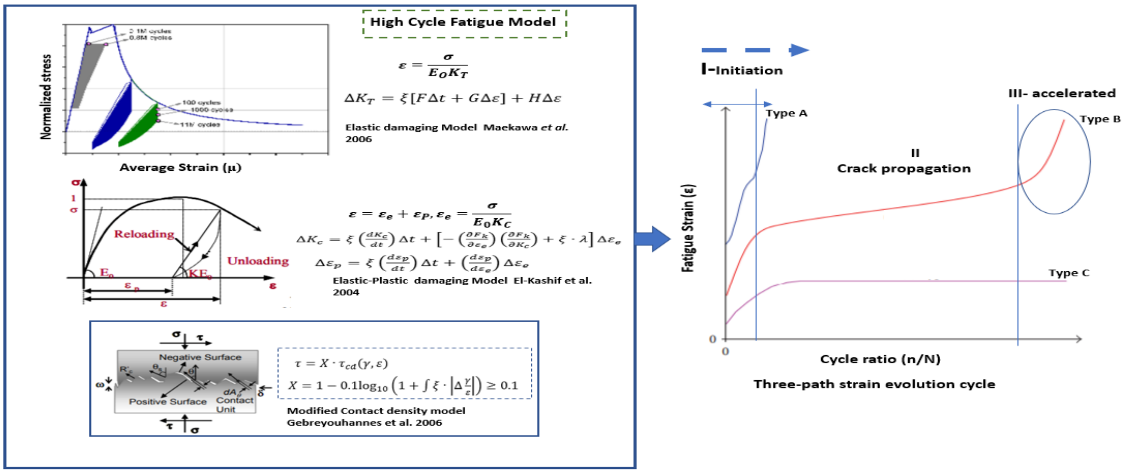


Fig. 6 Fundamental high-fatigue strain evolution [41]

Steel is susceptible to chemical and corrosive effects. Early in the production of steel utility poles, metallurgical processes produced corrosion-resistant steel. Later, their lifespan decreased as the galvanized zinc coat on the poles became thinner. Corrosion fatigue, the combination of cyclic stress and corrosive environment, is also common to steel poles. In electrical transmission, corrosion fatigue happens because of repeated mechanical loading from winds, vibrations, or thermal expansion in the presence of moisture pollutants or salts [39,40]. Quadri and Ali [41] identified three stages of fatigue evolution under high-fatigue loading, as shown in **Fig. 6**. The initiation stage is where a micro crack is formed; here, the steel poles may experience cyclic loading from wind, temperature changes, or mechanical loads. Stresses usually concentrate at an area of surface imperfection. Corrosive agents may weaken the steel surface [42].The second stage is the point where crack propagation accelerates by attacking the steel at the crack tip due to the presence of a corrosive environment. Metal undergoes an electrochemical reaction at the anode and cathode. Oxidation of steel is expressed as;

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

Reduction occurs at the cathode area and is expressed as

$$O_2 + 4e^{-} + 2H_2O \rightarrow 4OH^{-} \quad (2)$$

The third stage is where the fracture of steel occurs. As the crack deepens, the area of the steel pole becomes thinner, reducing the load-bearing capacity. If cyclic loading progresses, the pole experiences catastrophic failure even at a reduced stress level than its normal tensile strength [43].

It has also become expensive to inspect and maintain these poles regularly. Corrosion control deficiencies, improper coatings, the pH level of the soil, the water table, and failure to consider soil corrosivity are all common causes of galvanized steel pole member corrosion [44]. Steel poles are sensitive below the earth, and the degree of soil permeability, as well as the presence of air and water, are important factors in determining the extent of corrosion. Soils with fines, such as clays and silts, have low aeration rates and poor drainage, which can delay a speedy corrosion rate; however, coarse sand and gravels allow air circulation, which resembles a corrosion rate equivalent to atmospheric exposure. A galvanized steel pole with zinc requires a passive layer at all times to avoid the formation of zinc oxide. Another important corrosion control is to keep the surface free of moisture and air to preserve the passive film.

Byrd [45], tested some electric steel poles, **Fig. 7** (left), according to the International Association of Corrosion Engineers Standards [46], "Miller LC4 high resistance test meter, and a copper sulfate cell". A 0.2-volt was typically compared to a corrosion-protected value of higher than 0.85 volts. This infers that the pole is heavily corroded, with little discrepancy between copper and steel materials as observed in the electromotive series. The lower-in-grade steel is predominantly corroded oxide with slight mechanical significance. Liu et al. [47] investigated the strain clamp steel-anchored corrosion damage of a 500 kV transmission line, a part shown in **Fig. 7** (right), by adopting a mechanical properties test, macroscopic observation, composite analysis, and SEM analysis. It was observed that the corroded clamps had complex shapes, which are not convenient for anticorrosion coating since the components are welded. The tensile stresses were cumulated at the corroded part. It was pointed out that the gradual corrosion of the steel anchorage for over 30 years without attention resulted in the natural corrosion damaging the galvanic layer. According to an investigation by [48], steel poles kept for a long time underwent a different type of corrosion mechanism than when they were in use. When the poles were exposed to field conditions three years later, extensive red rust had formed at a part below the ground level and had spread outside, resulting in mechanical damage that was not what would have been expected under normal circumstances.

Corrosion of anchored members in electric steel tower

Corroded steel pole

Fig. 7 Corroded steel poles and tower investigated [45,47].

2.3 Electric concrete poles

Utility companies have been looking into more affordable materials to distribute electricity among houses because of durability issues, high maintenance costs, and the need for better aesthetics. Pozzolanic cements have improved the durability of concrete poles in marshy and waterlogged areas and areas prone to chemical and soil contamination. Prestressed concrete has also enhanced the quasi-brittle damage of normal reinforced concrete, allowing for heights of up to 15 meters and enabling heavy vehicles to pass easily [13,49]. With fiber-reinforced concrete, the ductility of the pole has been substantially improved [50].

Distribution concrete poles collapsing under simultaneous wind and ice loads is a fundamental issue in the electric power distribution network that usually occurs in regions with severe weather conditions (regions that experience snow and hurricane like Japan, Russia, USA, etc.), **Fig. 8a**. This causes a power outage, which can result in severe human and financial losses [16,51]. Kliukas et al. [52], have revealed that the main causes of structural degradation are damage and loss of cover concrete, as well as longitudinal cracks (**Fig.8b**). It is primarily caused by reinforcement corrosion, which is affected by the quality (density) of the concrete and the cover depth. According to Kuebler [53], unexpected applied forces on electrical lines caused by wind action can cause cracks and spalls in the cement paste microstructure, and then the prestressing strands can crack into the hollow section of the concrete pole, resulting in a loss of flexural stiffness and pole stability. Inappropriate foundation embedment and vehicle impacts can result in shear failure, (**Fig. 8c**) [54,55]. Dilger et al. [56], reported that the damage of prestressed concrete can be attributed to differential shrinkage between the inner and outer layers, (**Fig. 8d**) resulting in longitudinal cracks in the weaker cement paste layer. Many durability issues for poles can be caused by poor concrete handling; concrete segregation and poor concrete mixtures. Water infiltration leads to corrosion of the reinforcement, resulting in several cracks, which causes some pole failures.

Fig. 8 Electric concrete pole failure (a) damage of concrete poles under instantaneous severe wind and snow loads [16], (b) damages in RC supports of overhead power distribution lines [52]. (c) Shear damage of concrete pole due to a vehicle impact [54]. (d) Longitudinal cracking, corrosion of reinforcement, and spalling of concrete caused by differential shrinkage and segregation [56]

It should be noted that besides the right of way, materials for distributing electricity depend on the nature of the area where the poles are installed. In extreme wind areas, taller poles (above 10 m) with larger cross-sections may be vulnerable under high wind load. Steel poles and composite poles with enhanced strength and flexibility may be desirable. Ice accumulation aggregates weight on poles, increasing the bending stress [57,58]. Steel and concrete poles may be desired however, they may face durability issues due to fatigue problems, corrosion, and freezing and thawing. In the region with high humidity, electric wooden poles and accessories can be prone to corrosion which can affect their performance in service, in this case, concrete poles maybe desirable however, quality control must be ensured to prevent development of cracks due to moisture absorption [59]. Extreme temperature is another factor that influences the performance of electric poles in service. Extreme heat can cause thermal expansion in steel poles resulting in structural stress. Cold weather can increase the risk of cracks in concrete, while wooden poles may expand or contract needing proper seasoning to prevent warping [60,61].

3 Electric pole maintenance- repair and protection

Electric pole maintenance and repair are critical to ensuring an uninterrupted power supply and avoiding premature pole replacement. Increasing the service loads to keep the structure on target, investigating and correcting defects or damage, corrosion issues, and seismic strengthening are all essential engineering issues that necessitate the strengthening of existing electric poles. If increasing capacity is a viable option for extending service life, complete replacement of existing poles will be inefficient and will almost certainly increase the financial burden. Electricity poles that have been damaged or are in a high-risk area can often be treated or repaired with materials that help maintain or replenish their integrity. Because electric pole components can be damaged at any time, it is critical to be proactive rather than reactive to save money. Regular inspection of components such as insulators, cross arms, restringing lines, and the body of the poles is required before and after natural disasters for more reliable performance.

3.1Repair and protection of wooden poles

The most important parameters influencing the performance of timber pole structures are abiotic and biotic [62]. Bacteria, insects, and fungi which constitute the biotic influence, have a significant impact on wooden poles. Although naturally healthy wood has an appropriate service life, the increased demand for poles and the growth of other utility systems has resulted in a shift to alternative species with sound mechanical properties. The alternative wood species are insufficiently durable and require preservation treatments [63]. Several studies have demonstrated the importance of wood pole evaluation [6,25,26,64–66].

Polyzois and Kell [67], conducted experimental and analytical work on the rehabilitation of wooden poles by adopting fiber-reinforced polymer (FRP). The rehabilitation consists of replacing the present wooden pole with a stub and wrapping the affected area with an FRP jacket. The repair method was developed to improve the strength of the pole while also allowing an easy and environmentally friendly alternative to pole substitute. Twenty-seven wooden poles having a dimension of 3.05 m with an average circumference of 504 mm were examined according to the American Society for Testing Material (ASTM); Standard test method for static test of wood poles (ASTM –D1036-99) [68]. It was reported that the average capacity of the rehabilitated pole was 7% lower than its original capacity and underwent a reasonable deformation of 23% increase than the original pole. Merschman et al. [69] used an FRP sleeve to reinforce decayed and hurricane-prone wood poles, restoring their deteriorated strength and extending their service life. As case studies, specific locations in Miami, Charleston, and New York City were chosen. Climate change's potential impact on the rate of pole decay, as well as the intensity and frequency of hurricanes, was considered. FRP wrap was applied to poles whose strength was reduced to two-thirds of its initial value. Long-term analyses were used. Miami's previously estimated pole service life of 27 years has increased to 35 years with no climate change and approximately 32 years with climate change. With no climate change, FRP added 44 years to the service life in Charleston, while the corresponding additions in New York City were greater than 52 years. The predicted variation in life span of the three locations was due to the fluctuating climates in the regions. Distribution poles in Miami had the highest decay rate because of its tropical monsoon climate. However, no report was found on the treatment of wooden poles to reduce moisture before mounting FRP on them. Moisture migration from the pole to the surface may cause the FRP binder to delaminate from the pole surface, reducing the tensile strength. It has also been reported that adopting FRP sheet on the butt of wooden pole changes its failure modes to the weakest portion [62]. Thus, a holistic check is necessary for strengthening to elongate pole service life. Salman et al. [70], reported a framework optimization maintenance of a network of wooden poles in Florida. Remedial replacement due to hurricane failure and preventative replacement due to excessive decay were both considered to determine the best inspection interval for preventive replacement to reduce long-term maintenance costs. A hurricane simulation approach proposed by Salman and Li [71] was adopted. This involves the selection of historical hurricanes that passed through the study area or simulating a real scenario hurricane. The essential parameters to simulate the hurricane scenario in Florida were taken from Huang et al. [72]. The data were interpolated linearly to get the best fit for the framework by considering 30-minute intervals which had been adjudged to produce accurate results [73]. The incline wind speed at positions of interest was calculated using Holland's radial wind field model [74], which was converted to a surface wind speed and then to a 3-second gust wind speed. They concluded that the current maintenance exercise of utility companies may not be the most cost-effective method. The best inspection/replacement cycle is decided by location, which determines the decay rate and hurricane threat level. The findings have also indicated that climate change has no significant effect on the optimal inspection cycle. Several life cycle assessments of electric wooden poles have also been performed to improve their service [75–77].

Another common method of treating/protecting a timber utility pole from insects and other attacks is by a vacuum pressure technique, which improves preservative penetration from fungal infection and natural decay due to old age. The treatment of a wood pole differs from the restorative treatment of a standard pole in terms of the wood structure, **Fig. 9.** The treatment is mostly applied to the exterior sapwood, which is highly active, contains moisture and minerals, and can shrink or split with time, making it more susceptible to fungus infections [78]. Heartwood is inactive wood that is frequently dried, making it less vulnerable to damage and not suitable for preservative treatment [79]. The most frequent treatment is using creosote, a thick dark brown liquid derived from coal tar, which countries have used for many years to increase the service life of wood. It is normally applied through brushing or full-cell process, giving an additional advantage of waterproofing wood. Mugabi and Thembo [78] tested creosote penetration in eucalyptus with 126 wooden poles of varying sizes. Longer poles have a larger penetration depth than shorter poles. Despite meeting the minimal penetration and retention standards, the penetration depth was less than the sapwood depth. The service period of a wooden pole is one of the factors which can affect the performance of creosote [80].

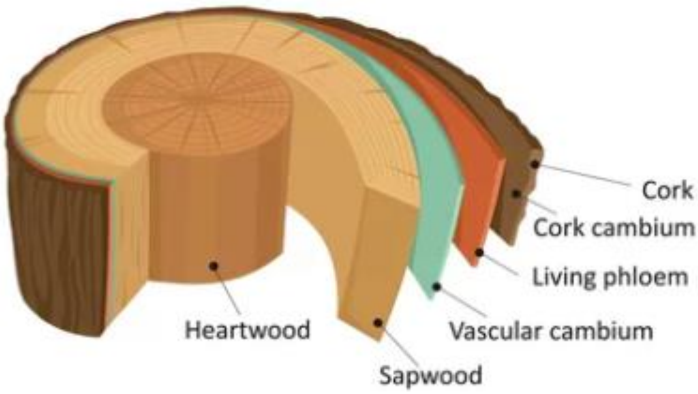


Fig. 9 Anatomy of a tree trunk

The treatment of wooden poles with creosote has only been partially successful because only the sapwood can be penetrated during the procedure, leaving the heartwood impenetrable and deteriorating due to the attack of termites and brown fungi [81,82]. Remedial treatment can be administered to the heartwood and absorbed through reverse osmosis in this case [83]. Chromated copper arsenete (CCA) has also been widely used for treating wooden poles [84–86]. Investigation from different countries has revealed the level of damage done by the biotic and abiotic forces on the wooden poles. Otuko et al. [60] discovered that fungi decay and termite destruction accounted for more than 85% of CCA treated poles and 67% of creosote treated poles in Uganda. Although timber poles in Uganda are supposed to last 10 years, premature damage has been ascribed to location, failure point, and causes of pole failure. Vidor et al. [25] stated that 14% of the over ten thousand timber poles examined in 23 cities of Southern Brazil showed considerable advanced deterioration, with wide variation between localities. Poles treated with CCA demonstrated poorer conservation than poles protected with creosote. An investigation by Gezer et al. [26] in the city of Artin in Turkey revealed that the depth of penetration of CCA in treated wood was shallow resulting in a shorter service life than anticipated. White fungi were reported to be more resistant to CCA preservatives. Knowledge of the environmental conditions of a particular location when selecting appropriate preservatives for wooden poles is also critical to service performance [65]. Sandoz [87] examined the environmental effect on aging wood structures, he opined that wooden poles may experience fatigue under applied load as well as develop cracks due to drying and wetting or under biotic force. In the case of increasing the residual strength of the existing pole for load resistance, high-strength materials that do not affect the overall self-weight may be desired. The use of fiber-reinforced polymer has been suggested for improving the strength of wooden poles [62,67].

Wood preservative materials can negatively impact the environment if they leach out of the wood into soil or water bodies. Boron compounds are effective materials for preserving wood because they possess low toxicity making them suitable for preserving wooden poles for a long time [88]. Log manufacturers commonly employ the dip diffusion technique. Freshly debarked logs for poles have a considerable amount of moisture about 45% which allows the hot borate solution to penetrate the log completely [89]. Logs are immersed in a liquid tank for extended periods before being withdrawn and wrapped for weeks at a time to allow the borate to diffuse into the log. Multiple dip treatments and additional wrapping are not uncommon to ensure complete penetration of the log [90]. Other methods of preservation include copper-based preservation [91,92], coating and sealant [93], thermal modification, chemical treatment, etc.

Machine learning framework systems have also been built for health monitoring of electric wooden poles in service. Yu et al. [94] adopted a multiple process involving data mining and machine learning approach and signal processing to classify different damage conditions of three electric wooden poles of different damage conditions. In the approach, wavelet packet analysis converts multi-channel stress wave data into energy information, which is then compressed using principal component analysis to create a feature vector. The machine learning algorithms were then used to identify the damage condition type. The investigation provided a satisfactory damage condition detection of wooden poles which can be practically adopted for on service wooden poles. Nguyen et al. [95] developed an autonomous vision-based power line inspection system that adopted Unmanned Aerial Vehicle (UAV) inspection with optical image as the primary data source and deep learning algorithm as the pillar of the data analysis, to address the faults in component power systems. Four medium-size data were adopted for data training component detection and classification. The model could quickly detect common fault from power system such as woodpecker damage, rot damage on cross arms.

3.2 Steel protection

Thermodynamic activities in the environment have a significant impact on electric steel poles/towers. Aside from the unsightly physical appearance, the mechanical properties of steel, such as tensile strength, ductility, and density, can be reduced, especially in aggressive environments, affecting the service life and performance of electric steel poles. Because the electrochemical process of steel must occur, much dedication is needed to minimize maintenance costs. Several preventive and corrosion protection measures have been used to reduce or correct corrosion: lowering potential (cathodic protection and lowering oxidant concentration), increasing oxidation potential (anodic protection and oxidizing additives), raising pH, separating metal [96], epoxy coating, galvanizing, anodic hydrogen evolution system [97]. Galvanized steel coating is adopted because of its low cost and attractiveness. Zinc coating of steel is often used; the zinc forms a protective layer preventing corrosion. The most commonly used is hot-dip galvanizing [98]. The surface of the steel is prepared, and molten zinc at about 500 ℃ is applied on the steel, which reacts with iron to form zinc-iron alloy layers [99]. The galvanized steel may be cooled in air or water to solidify the zinc coating [44]. Metal oxide coatings are also widely used for anticorrosion due to their low cost, ease of use, and good anticorrosive properties [100]. Metal oxide coatings provide steel reports with durable wear, abrasion, and corrosion resistance. Fabricating bi and tri-metal oxide composite coatings is a great way to extend the service life of steel [101]. Many studies have reported composite coatings encapsulating various metal oxide nanoparticles such as ZnO, SnO_2, TiO_2, ZrO_2, Al_2O_3, NiO, CeO_2, SiO_2, CrO_3 [102–104].

Pauzai et al. [105] investigated the corrosion behavior of steel poles in various coating environments. Five different coating techniques were used, including epoxy, VEF poly-glass, galvanized, epoxy galvanized, and poly-glass galvanized, with salt spray and water absorption tests used as accelerating aging tests to determine coat degradation and severity of corrosion ingression using American Standard Test Methods. The aging specimens were exposed to ultraviolet light at 60^o for about 8 hours, and then condensation fat at 50^o for 4 hours. Uncoated steel pole specimens experienced a high rate of corrosion, whereas differently coated poles corroded insignificantly. When the corrosion depth in the coating specimens was measured to determine the corrosion rate, epoxy-galvanized and poly-glass-galvanized poles demonstrated a significant corrosion rate. However, after 520 days in a salt solution, the VEF poly-glass coated steel pole lost about 2.4% of its weight, followed by the galvanized VEF poles. Epoxy-coated and galvanized steel poles absorbed more moisture in a water absorption test. Understanding various environmental conditions can aid in the choice of electric steel pole coating techniques. Agnieszka [106], examined the distribution potential and the density of buried traction steel poles made of R35-type steel with a cathodic protection system through a simulation approach. Magnesium alloy of high potential (M1 type, ASTM B843-13 standard) was selected with a service life of 20 years as a reference for the cathodic protection system. The installation of the traction pole structure is depicted in **Fig. 10**. For the electrochemical simulation, an area (in color red, **Fig. 10b**) was selected as the electrolyte domain (soil). These data can aid in the design of a sacrificial electrode supply, which ensures all parts of the protected structure are fully protected. Regrettably, the cost of cathodic protection is difficult to estimate. Diagnostic and design work must be completed before using cathodic protection. Each safety must be prepared individually. In this case, artificial intelligence techniques may be necessary to detect the defects and corrosion emergence in the steel poles. An unmanned area vehicles and thermal camera through deep learning approach has been proposed [107]. This technique is capable of viewing wide angle which addresses the limitation of human viewing angle allowing for more exploration activities. Data relating to the electricity defect is collected using this techniques and analyzed with convolutional neural networks and image processing tools [95].

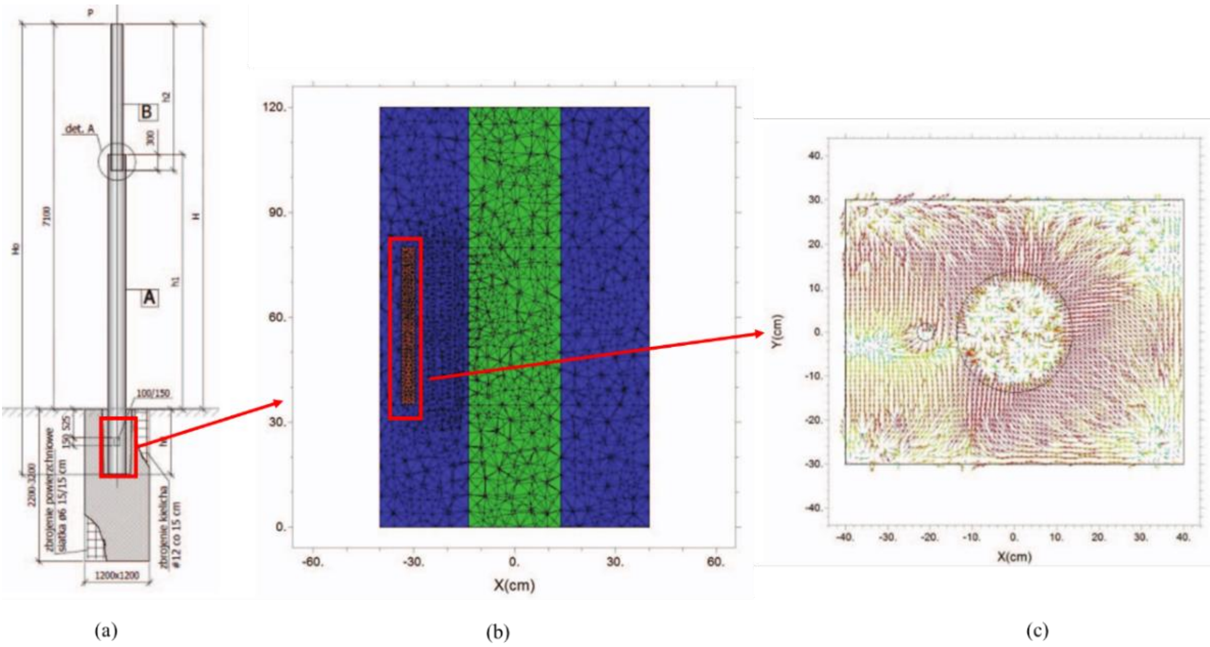


Fig. 10 (a) Traction pole showing the investigated underground section (b) Galvanic anode simulation of selected section (c) vector of current density in the electrolyte [106].

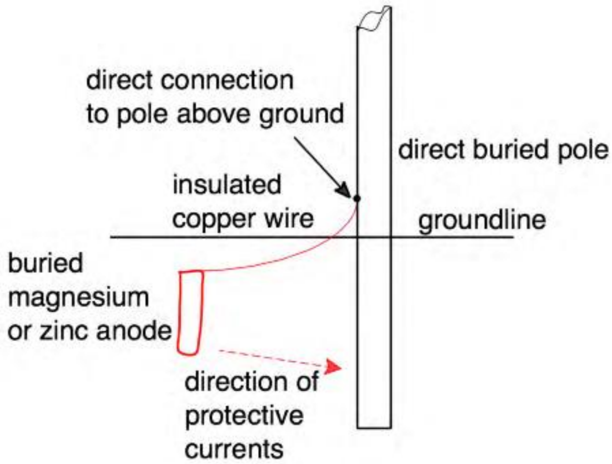


Fig. 11 Cathodic protection system for embedded distribution steel poles [45]

Byrd [45], proposed a low-cost cathodic protection scheme for preventing below-grade steel pole corrosion. He identified the potential cell separating the copper system and the galvanized steel as one of the problems of steel-grade corrosion because the steel pole is grounded with non-sacrificial materials, causing the steel to act as an anode for ground copper, triggering the rust (see **Fig. 7** right side). He opined that cathodic protection, whether coated or uncoated, will be adequate for protecting buried steel corrosion because it has been tested on buried pipelines for decades by pipeline industries [108]. He described a simple cathodic protection system suitable for protecting buried steel as shown in **Fig. 11**. The reference pole is attached to a zinc or magnesium anode container for protection, which is not far from the pole. The anode interlinks are made of an insulated copper wire connected to the pole and the anode. All connections are made above the ground with magnetic, or CAD welds protected against moisture. The anode is the material that gives out electrons to the copper ground system, or oxygen cell, which produces electrical currents to the steel.

3.3 Strengthening and protection of concrete poles

Reinforcing bars within reinforced concrete poles are critical in controlling tensile behavior caused by external forces such as high winds, hurricanes, heavy snow, typhoons, earthquakes, etc. Over/under-reinforcing the concrete poles may result in concrete cracking under the tension load. Furthermore, plastic shrinkage during the early concrete casting stage, as well as long-term environmental thermodynamics issues, can reduce the durability performance of concrete due to the migration of moisture through the cracked/deteriorated parts, causing corrosion concern [109]. It has been discovered that the primary cause of steel corrosion in concrete poles is the carbonation process and the capillary flow of groundwater, which results in high humidity [110–112]. Carbonation is a chemical reaction in concrete in which atmospheric carbon IV oxide reacts with calcium hydroxide and hydrated silicate, resulting in calcium carbonate and lowering the pH. These phenomena neutralize the concrete cover, causing corrosion of steel. Corrosion fumes can occupy a significant volume of capillary pores in concrete [113], causing high stresses to dislodge the concrete layer and resulting in cracks.

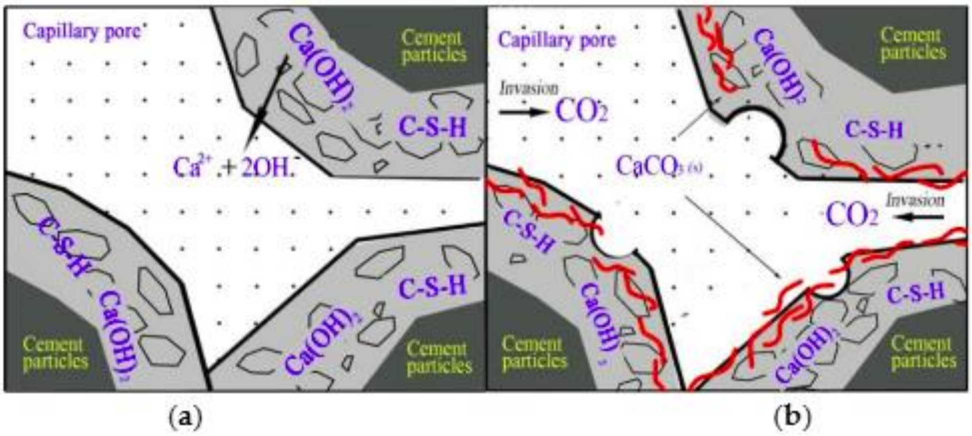


Fig. 12 Carbonation mechanism of ordinary concrete: (a) Non-carbonized; (b) After carbonization [114]

Figure 12a depicts the internal mechanism before concrete carbonation [114]. After cement particles react with water, producing C-S-H gel and solid-phase crystals $Ca(OH)_2$ by hydration [115,116]. **Figure 12b** depicts the internal process following concrete carbonation. CO_2 in the air combines with $Ca(OH)_2$ in the cement gel after penetrating the concrete's pores and capillaries, creating $CaCO_3$, which may precipitate due to its low solubility. To ensure constant Ca^{2}+ and OH- concentrations in the pore solution, $Ca(OH)_2$ is dissolved in the initial solid phase to maintain a balanced Ca^{2}+ content.

Several approaches are available to cure carbonation, the depth of penetration of carbon must first be assessed using phenolphthalein. The application remains colorless in the carbonated area [114]. Shallow depths of carbonation penetration are often surface-coated to prevent more penetration, however, if there is significant penetration, mechanical removal may be required [117]. Alkalinity restoration in concrete can also be done using pozzolanic cement such as fly ash to remediate the affected part [118,119].

Several strategies have been used to increase the tensile strength of concrete poles [120–122]. Since reinforcement inside the concrete are vital for weight support under tension, stress concentration under tension especially when there are defects in the concrete poles can cause the poles to collapse. Thus, non-destructive techniques that can detect the structural defect under services is important. Park et al. [123] adopted a magnetic sensor-based diagnostic approach with deep learning to detect flaws and breakage in the steel in concrete poles. The proposed method enhanced the accuracy of using sensors for breakage detection and are essential for onsite investigation. Ullah et al. [124] used a nondestructive approach to inspect the reinforcement in concrete poles. An application was used to classify field signals from multiple channels based on magnetic variation. Concrete sensors were inserted into the poles, and collected signal data were used to understand the forms of safe and damaged pole structures as shown in **Fig. 13**. The isometric mapping (ISOMAP) algorithm was also applied to these features. Following that, the reduced data was subjected to a random forest classification algorithm. According to actual sensor data, the proposed approach can determine whether the reinforcement in the concrete poles is broken or not.

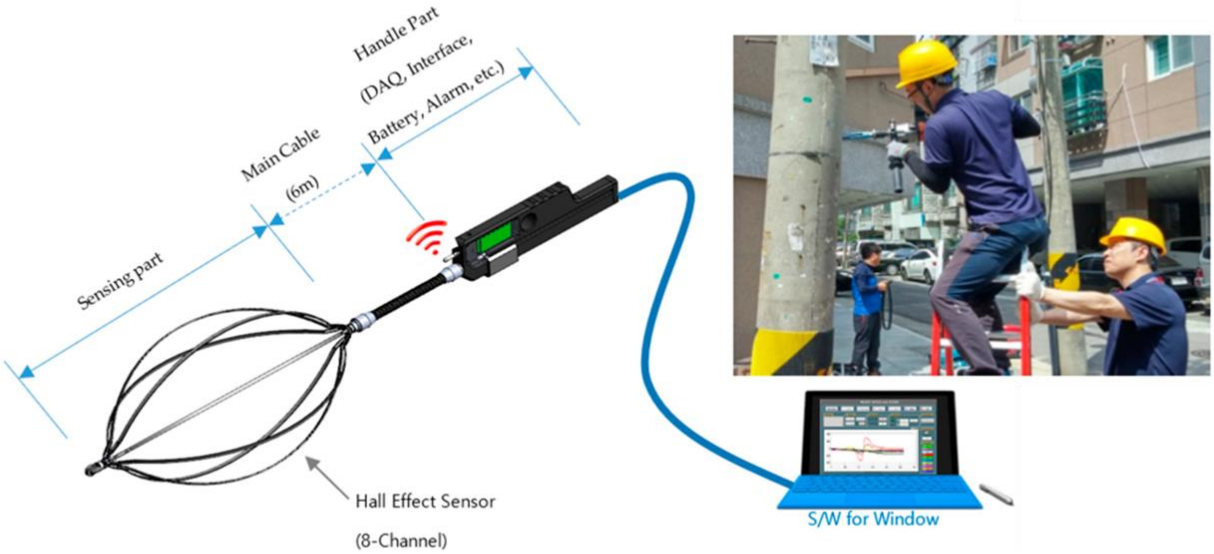


Fig. 13 Magnetic sensing devices and the field testing [124].

Long-term constant inspection of concrete poles can also reduce early replacement and durability issues. Health monitoring designed checklist can be done and concrete health index can be calculated from score obtained from the checking sheet comprised of issues such as physical condition, aging and deterioration of concrete poles, etc. The health index can then be used as an indicator to provide or determine the maintenance system for concrete poles [125].

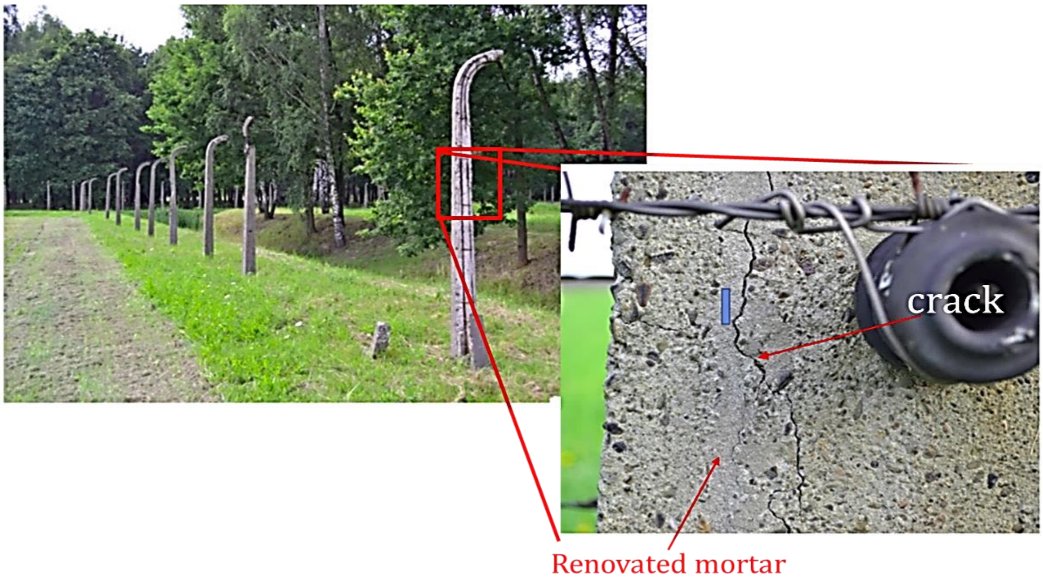


Fig. 14 Pole fence at Auschwitz city showing cracks after 10 years of renovation [126]

Miszczyk et al. [126] described an organic coating used to protect the rebar in degraded concrete poles in the former Auschwitz city. The concrete was repaired using high-strength mortar. It was reported that after ten years, the restored poles cracked. The cracks run at the contact between the concrete and the mortar used for repair, as shown in **Fig. 14**. One probable reason for deterioration is an unsatisfactory bond between the mortar and the old part of the concrete as a result of fresh mortar shrinkage. The mortar's carbonation effect is a significant occurrence caused by periodic exposure to the atmosphere. The anti-corrosive chemical employed became ineffective, resulting in cracking. To rescue the deterioration, cathodic protection involving sacrificial anode which exhibits lower electrochemical potential compared to the protected materials was adopted by Miszczyk. The protecting material (Zinc) was grounded at the vicinity of the concrete poles and electrical connection was established between the protector and the reinforcement for corrosion protection process. Hydrophobic treatment was also applied to enhance the performance of the setup, this will allow water repellant agent to deposit on the concrete surface which will elongate the period of water ingress into the neighborhood of the reinforcement. Anti-weathering coating against thermal fatigue has also been proposed using epoxy resing curing agent, phthalate, alkyed resin [127]. These are ideal for sealing pole cracks and preventing weathering on reinforced concrete transmission poles, making maintenance easier and more effective.

Fiber-reinforced polymers (FRP) have also been used to upgrade the weakness of concrete, increasing its flexural properties and overall strength against variable loadings [128]. FRP is a composite material composed of high-tensile continuous fibers arranged in a specified pattern within a proprietary resin matrix. Continuous fibers are mounted on the member's external surface, strengthening it in the direction of tensile force or serving as confining reinforcement normal to the axis. FRP can improve a deficient member's shear, flexural, compression, and ductility. Various FRPs adopted for strengthening reinforced concrete in services include; aramid, carbon, steel, polyacetal, and glass fiber [129]. Structural members such as beams, columns, slabs, bridge girders have been strengthened with FRP [128,130–134]. Increase in selfweight during strengthening can affect the overall service period of concrete structures, however, by using FRP, insignificant increase in selfweight is experienced by the structures. Currently, the advantage of mechanical properties provided by these innovative materials is yet to be used to strengthen electrical reinforced concrete poles in service. In contrast, ambient thermodynamic activities have been shown to alter FRP performance [135]. Atmospheric conditions can limit the efficiency of bonding materials used between the fiber and the concrete surface. Furthermore, under high tension due to overloading, FRP may peel/tear because its tensile qualities may not be properly utilized [130]. These issues may impair the performance of FRP when adopted for concrete pole strengthening. Thus, putting FRP on concrete should be done by a professional.

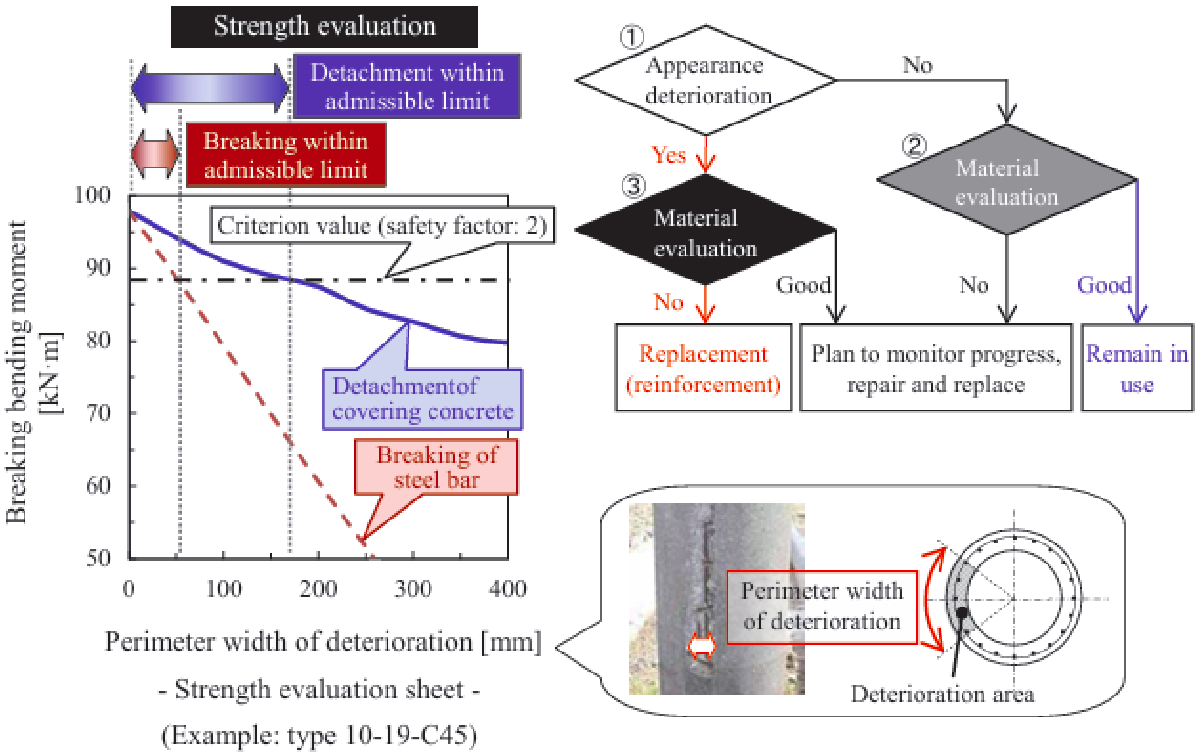


Fig.15 Procedure for determining the replacement of the concrete catenary pole [136]

Tsunemoto et al. [136] proposed a standard procedure for evaluating the period of service of concrete catenary poles under tension load. Firstly, a physical inspection is done to detect any crack in the concrete pole, carbonation testing is also carried out in case of the absence of crack. If deterioration is detected, then the strength of the concrete pole is evaluated using the procedure highlighted in **Fig. 15**. The procedure is however limited to 10-19-C45 concrete catenary pole types.

4. Design and erection of electric poles

The distribution system is the most susceptible component of the power system (generating station, transmission system, and distribution system) to failure due to natural disasters. The generating depots are limited and are often designed to endure high winds up to 70 mph, floods, vibration, and seismic actions. Besides, the transmission systems (towers and lines) are more resistant to natural disasters than the distribution system. The transmission system always has redundancy, which means that there are several ways to transport electricity from the generation point [137]. Many existing electricity distribution pole standards do not take into account the design vibration of poles, which can be caused by steady relatively low wind speeds (10-30 mph) or the terrain of the area where the pole is erected, which can have a serious impact on electric pole performance because they are designed as cantilever structures. According to studies, the natural turbulence of the airstream at higher wind speeds above 30 mph inhibits vibration, which can affect the concrete electric poles [138].

Electric poles are designed or selected using AASHTO, ANSI, and some local annex standards based on 50 years or more of experience. Overturning moments from soil problems, and tension problems from electric pole accessories constituting the loading all play important roles in the design of formidable poles. Rodgers [139] proposed a wind pressure for prestressed concrete design based on a 50-year mean recurrent wind. The design procedure outlined in ACI 318-63 [140] (the building code requirement for reinforced concrete) was used, with modifications to include the effect of prestressing. Eq. (1) expresses the ultimate design pressure.

$$P = \frac{KC_D\rho(1.3V_Z)^2}{2} \tag{1}$$

where K is the overload factor that ensures safety and reliability. For distribution and transmission structures, K is taken as 1.1, while 1.3 is adopted for major line crossings and sub-station structures. V_Z is the adjusted wind velocity based on the U.S. Weather Bureau's record at 30ft. C_D is the coefficient of drag, and ρ is the density of air.

Furthermore, the initial flexural moment causing initial cracking at the tension face of the pole was expressed as $6\sqrt{f_c'}$ in relation to the 28 days compressive strength of concrete, f_c',. The pole was allowed to exceed the flexural moment but not fail in high winds. However, if the 50-year storm is exceeded, the overloading factor may be insufficient, resulting in structural failure.

In a similar vein, the American Society of Civil Engineers (ASCE) [141] has expressed the force from the velocity wind field as expressed in Eq. (2)

$$F_{wi} = \frac{1}{2}\rho G C_D A(Z_v V_i)^2 \tag{2}$$

where F_{wi} is the force in i-direction, ρ is given as 1.225 kg/m^3, G is the gush factor, A is the nodal projected area normal to i-direction, Z_v is the terrain factor [142]. V_i is the downburst/ tornado velocity in the i-direction (m/s). For a circular pole, the drag coefficient is taken as 1.0 [141].

The tornado's action around poles behaves differently and its speed concentrates on a part of the pole. It is also difficult to measure its intensity using traditional means in the field. Thus, the simulation approach is often adopted to quantify the intensity [142].

Concrete poles may be designed using the reinforced concrete analysis theory; however, it should be noted that beyond the cracking moment, concrete poles always have nonlinear characteristics because of the changes in response due to the cracks. In this case, greater deflection occurs than in the uncracked pole when the applied load increases. Quadri and Afolayan [143] adopted the design resistance capacity proposed by Eurocode (EC-2) 2004 [144] from the stress block as shown in

Fig. 16. The moment of resistance can be related to the forces from the compression and tension zones in relation to the neutral axis of the structure. EC-2 limits the depth of the neutral axis (×) to 45% of the effective depth for concrete strength classes less than or equal to C50/60 and 35% for concrete strength classes C55/67 and greater, this is to ensure adequate ductility under service.

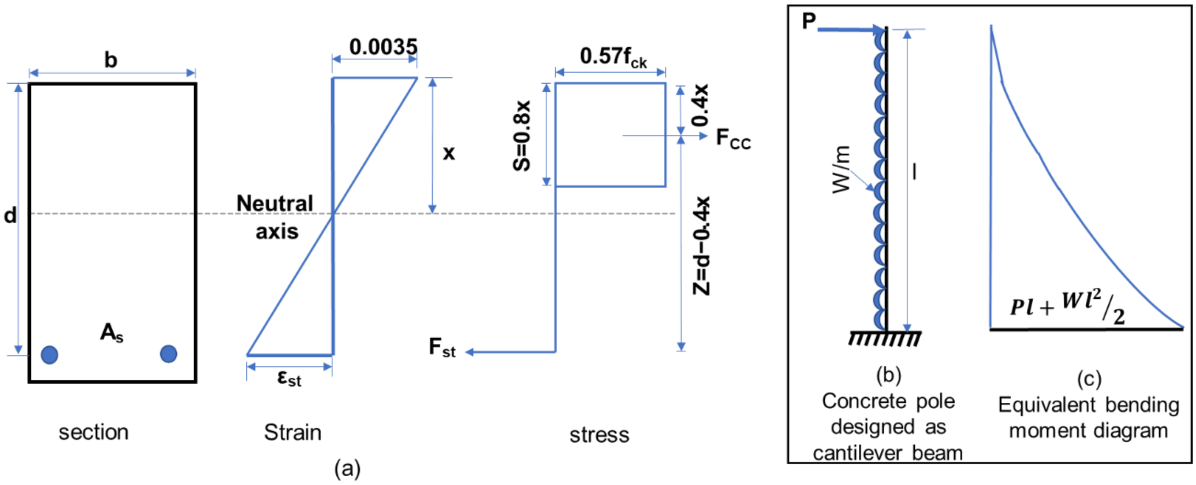


Fig. 16 Analysis of capacity and demand; (a) Stress block used for the analysis of concrete pole sections (b) Loads on concrete poles (c) demand moment [143]

ACI 318-95 [145] proposed that the shear design of the concrete pole cross-section be based on the nominal shear strength as given in Eq. (3)

$$v_u = \emptyset v_n \quad (3)$$

where $\emptyset$ is the nominal shear strength reduction factor, taken as 0.85, v_u is the factored shear force and $v_n$is the nominal shear strength given as;

$$v_n = v_c + v_s \quad (4)$$

The nominal strength provided by a prestressed concrete pole, v_c. In the design of rectangular or square members with effective force of prestress not less than 40% of the tensile strength is given as;

$$v_c = \left[\sqrt{0.36 f_c'} + 700\left(\frac{V_u d}{M_u}\right)\right] b_w d \quad (5)$$

The factored moment, M_u, occurring together with V_u at a distance d from extreme compressive fiber to the centroid of the restressing reinforcement, in which the quantity $\frac{V_u d}{M_u}$ shall not be more than 1. b_w is the width of the web.

The circular prestressed concrete strength can be expressed as;

$$v_c = \frac{\sqrt{F_t^2 + F_t f_{pc}}}{\frac{Q}{2It}} \quad (6)$$

where F_t is the concrete tensile strength equivalent to $4\sqrt{f_c'}$, Q, is the moment area above the centroid, and t is the thickness. I is the moment of inertia, f_{pc} is the effective concrete compressive stress of prestress.

The contribution of the shear reinforcement in the concrete pole is given as;

$$v_s = \frac{A_v f_y d}{s_v} \quad (7)$$

A_v, f_y are the area and yield strength of reinforcement, respectively, and s_v is the shear spacing of reinforcement.

Buckling of the concrete pole may not occur; however, in some scenarios, guyed pole structures may be critical. In this case, numerical analysis or simplified techniques may be adopted [146]. The critical buckling load may also be sufficient [147,148].

The design of concrete poles strengthened with fiber-reinforced polymer (FRP) has been carried out by Taranu et al. [149] who opined that the concrete area resists the self-weight and the weight of fittings on the concrete poles, and the FRP reinforcement can only resist flexural load under design rules. Thus, the bending moment analysis relies on the location of the neutral axis, whose position depends on the equilibrium equation between concrete in compression and FRP in tension. It was noted that the design of the composite element is controlled by stiffness under the serviceability design state regarding allowable deflection. The crushing of concrete and rupture of the FRP define the ultimate state of the system. The total bending stiffness, $K,$ of the system is given as;

$$K=K_C+K_f \quad (8)$$

K_C is the concrete gross section stiffness, and K_f is the bending stiffness of the FRP bars derived experimentally as $5.917\times\ 10^{11}$. K_C is given as;

$$K_C=0.4EI_o \quad (9)$$

while EI_o is the flexural rigidity of the column.

Steel poles are usually designed as unguyed cantilevers; the main load arises during installation, in the catenary lines, and external loads such as wind and ice. Load factors are considered in case of overloading and the pole is designed on a yield-stress basis for various overloading combinations [150]. The pole could be tapered to reduce the effect of self-weight under bending action, hence, resistance to bending requires a pole with a large diameter and thin wall so that local buckling is essentially considered. A numerical expression developed by Gere and Carter [151] and modified by Ibrahim [152] is expressed as;

$$P_{cr}=\frac{\pi^2 EI_o}{(gL)^2} \quad (10)$$

$$g=1\text{-}0.375\varphi+0.08\varphi^2+0.0062\varphi^3 \quad (11)$$

$$\varphi=\frac{d_2\text{-}d_1}{d_1} \quad (12)$$

d_1 and d_2 are the areas of the largest and smallest tapered section, g, is the length factor that enables the analysis of the critical load, P_{cr}, throughout the length, L, (gL) expresses the buckling length. In the case of steel transmission pole frames, the recommended design chart for the buckling length factor of tapered poles has been developed by Lee and Morrel [153]. Their design was based on the tapered members provided by AISC [154]. It was revealed that the effective buckling length of steel frame structures with a tapered section can be adequately analyzed utilizing AISC no. 3. Hirt and Crisinel [155] suggested an elastic critical load estimate for prismatic symmetrical web poles pin-ended about their major axis because of the nonconservative curve's overfitting.

Clause 2.4 of Eurocode 5 (design of timber) [156] recommends the strength of timber be calculated as;

$$\chi_d=k_{mod}\frac{\chi_k}{\gamma_m} \quad (13)$$

where χ_d is the design strength, χ_k is the characteristic value of strength properties, γ_m is the factor of safety for a material property k_{mod} is the modification factor that accounts for the effect of the duration of load and moisture content, its value for various kinds of timber has been highlighted in Clause 3.1.3 of Eurocode 5.

Wood is vulnerable to decay due to exposure to environmental phenomena. The rate of deterioration relies on factors such as species of wood, climate condition of an area, soil properties, and nature of fungi attack [157]. Thus, the design of wood decay is based on in-field or laboratory investigation. Leicester et al. [158] proposed a decay model developed for above-ground conditions.

The empirical model was based on 20 years exposure of 4000 pieces of Australian timbers at 11 sites in Australia. The proposed equation for the progress of decay, δ_{mean}, is expressed as;

$$\delta_{mean}=\begin{cases} 0 & \text{if } t\leq t_{lag} \\ (t\text{-}t_{lag})r & \text{if } t> t_{lag} \end{cases} \quad (14)$$

The lag and rate are assumed to be related by:

$$t_{lag} = 8.5r^{-0.85} \quad (15)$$

r is the rate that relies on wood, climate, and construction parameters. The proposed model has been widely adopted to examine the decay of wood above the ground [159,160].

4.1 Finite Element Model response of electric Poles

Finite element modeling (FEM) has also been adopted to design the behavior of electric poles under varying loading conditions. FEM aids as an alternative to rigorous and expensive experimental testing and can be used for large-scale modeling which will take time to execute [161]. However, FEM requires expertise and caution in handling. Several researchers have investigated the response of different shapes of electric poles in services with the FEM approach. Yu et al. [162] investigated the response of electrically conducting round poles using ABAQUS software . The model adopted separate modeling of concrete behavior and steel response hexagonal elements combined with eight nodes and incorporating tendons to gain more ductility. It was reported that the slip effect of the composite was neglected in the investigation because it offers negligible effect. The concrete element was 50 mm while the steel element was 30 mm. The moment capacity and deflection were enhanced under prestressing. It was also noted that increasing the thickness of concrete only improved the concrete compression capacity but had no significant effect on the ultimate loading capacity. Aliu and Abejide [163] adopted ABAQUS software to model the stress and displacement development in 12 m circular electric poles. Wind load distributed along the height of the pole, the load from catenary wires, the weight of the fittings, and the self-weight of the steel pole were considered in the analysis. It was reported that although the stress generated was below the yield stress, the pole was more vulnerable above 9 m height. Lian et al. [164] also adopted ABAQUS to model the deterioration of a 12 m circular pole. The effect of internal reinforcement on concrete was considered with the whole model behaving like a truss structure. A friction coefficient of 0.3 for slip movement was considered together with the soil effect at 2 m below. Under different loading conditions, the vulnerability position of the pole increased up to 3 m. The ultimate capacity was affected due to a serious crack depth increase. Increasing the concrete strength improved the anti-fracture ability and stability of the pole.

5 Recycle materials used for electricity distribution

There are existing guides for handling and maintaining electricity distribution pole [136,165,166]. The service life of materials used as electric distribution poles (steel, wood, and concrete) differs greatly. Several factors that can affect the performance of these materials have been discussed. It is essential to constantly maintain or replace electricity distribution poles for continued services to the end users. The materials may pose a great environmental impact after removal from service if not properly disposed of. Iwaki et al. [167] reported that the electricity distribution company in Japan disposes of about ten thousand concrete poles as waste on dumpsites each year. According to Quadri and Afolayan [2], about half of the distribution concrete poles in the Southwest of Nigeria have failed and have not been replaced due to a lack of maintenance. Over 140,000 utility wood poles were reported to have been disposed of each year in Oklahoma after an average service life of 30 years. A considerable percentage of these woods are in good condition for other uses but are dumped in landfills [168]. Additionally, approximately 6×10^6 m^3 of treated wood are disposed of annually in landfills and through combustion in some parts of the US [169]. This disposal contributes significantly to greenhouse gas emissions into the atmosphere [170].

Meanwhile, due to the paucity of construction materials, the construction industry has been capturing and repurposing waste resources to create a more sustainable green environment. Furthermore, concrete's ingredients, sand and gravel, are irreplaceable elements that are constantly depleted from their natural position, resulting in a lack of construction materials [171,172]. Moreover, indiscriminate deforestation for sustainable housing without proper planning to replant for a green environment is rampant in developing countries. This trend is accelerating as the demand for shelter and energy grows. Recycling out-of-service electricity distribution materials could improve the prospects of the construction industry, create more job opportunities, and, in turn, increase revenue generation [173].

6 Concluding remarks

This investigation has dwelled on the challenges associated with the use, protection, and design of the three essential materials used for the distribution of electricity to the end users. The following conclusions are therefore drawn;

i. The use of a typical material for electricity distribution relies on the condition of an area. The use of steel may not be effective in areas susceptible to corrosion and may be expensive to maintain over the service life. Besides, wood may not be effective in areas under insect attack. The use of concrete poles must also be examined before erection. Thus, the selection of appropriate material for an area is important.
ii. It is crucial to consider the wind conditions in the area before installing an electric pole. The wind velocity characteristic specified for a certain area should be followed when choosing the optimum material for electric distribution since excessive wind might increase the tensile load on a pole. As a result, installing and maintaining distribution poles in a community may become less expensive and safer.
iii. Appropriate right of way should be understood in erecting electric distribution poles to avoid cost overrun in changing pole alignment. Additionally, maintenance of electric poles should be regular to increase their performance towards the service life.

7 Future Direction

It is crucial to distribute electricity from the generating plant to the final consumers. Transmission of power to each dwelling requires the use of electric distribution poles. Due to subterranean thermal fatigue, economy, power outages or possible losses at the overhead connection junction, difficulty locating faults, susceptibility to shock during flooding, and other factors, adopting materials for overhead distribution may be preferable to underground electricity distribution [174,175]. Many environmental factors are not fully understood under variable applied loadings, including ice load in winter-prone areas, fatigue under dynamic wind gusts, vehicle collisions, corrosion of steel poles and reinforcement, and corrosion of prestress tendon resulting in loss of prestress. While every region faces unique challenges, the deterioration of materials used for power distribution owing to fatigue may be a typical occurrence. Understanding the fatigue issues distribution poles face under varying loads is therefore essential. Furthermore, the use of artificial intelligence (AI) in power distribution has not been thoroughly investigated. AI can help detect and control electrical pole faults while also improving efficiency, safety, and maintenance. Drone or pole-mounted cameras can detect cracks, rust, and unstable poles in service. Overheating caused by electrical issues can be diagnosed. Machine learning (ML) can identify and categorize potential hazards connected with these issues [176]. Research efforts have been focused on automating the power line inspection process by investigating different necessities for inspection [177].

CRediT authorship contribution statement

Ajibola Ibrahim Quadri: Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **Williams Kehinde Kupolati**: Administration, Methodology, Investigation. Writing – review & editing, Supervision, Investigation, Conceptualization. **Chris Ackerman**: Writing original draft, Visualization. **Chibueze Godwin Achi:** Writing original draft, Visualization **Jacque Snyman**: Validation, Conceptualization. **Julius Musyoka Ndambuki**: Writing review & editing, Resources, Investigation,

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

References

[1] Zohuri B. Electricity, an Essential Necessity in Our Life. Application of Compact Heat Exchangers For Combined Cycle Driven Efficiency In Next Generation Nuclear Power Plants: A Novel Approach, Cham: Springer International Publishing; 2016, p. 17–35. https://doi.org/10.1007/978-3-319-23537-0_2.

[2] Quadri AI, Afolayan JO. Reliability assessment of H-section tapered electric power distribution concrete poles. International Journal of Reliability and Safety 2022;16:189–217. https://doi.org/10.1504/IJRS. 2022. 131470.

[3] Ashraf M, Ahmad HM, Siddiqi ZA. A Study oF Power Transmission Poles. Asian Journal of Civil Engineering (Building and Housing) 2005;6(6):pp 511-532.

[4] Torres A. General characteristics of steel poles used to support transmission and distribution lines. 2015 IEEE Thirty Fifth Central American and Panama Convention (CONCAPAN XXXV), Tegucigalpa, Honduras: IEEE; 2015, p. 1–6. https://doi.org/10.1109/CONCAPAN.2015.7428491.

[5] He J, Wang X, Yu Z, Zeng R. Statistical Analysis on Lightning Performance of Transmission Lines in Several Regions of China. IEEE Trans Power Delivery 2015;30:1543–51. https://doi.org/10.1109/TPWRD. 2014.23 63122.

[6] Kalaga S. Equivalent Pole Concept for Tapered Power Poles. Journal of Structural Engineering 2012;38 (6):pp 507-518.

[7] Food, Branch AO of the UNMWP. Wood Preservation Manual. Food and Agriculture Organization of the United Nations; 1986.

[8] Vidor FLR, Pires M, Dedavid BA, Montani PDB, Gabiatti A. Inspection of Wooden Poles in Electrical Power Distribution Networks in Southern Brazil. IEEE Transactions on Power Delivery 2010;25:479–84. https://doi. org/10.1109/TPWRD.2009.2034913.

[9] Muthike G, Ali G. EFFECTS OF THE SHIFT TO CONCRETE POLES ON TREE GROWERS. Feature Miti 2021:1–4.

[10] Sakah M, Diawuo FA, Katzenbach R, Gyamfi S. Towards a sustainable electrification in Ghana: A review of renewable energy deployment policies. Renewable and Sustainable Energy Reviews 2017;79:544–57. https: //doi.org/10.1016/j.rser.2017.05.090.

[11] Adaam I. Establishing a wood pole treatment Plant in Ghana, Ghana: Degree thesis, Karelia University of Applied Science, Ghana; 2014, p. 1–59.

[12] Quadri AI. Strut and Tie Modelling of Reinforced Concrete Deep Beams Under Static and Fixed Pulsating Loading. NJES 2020;23:306–12. https://doi.org/10.29194/NJES.23030306.

[13] Rodgers TE. Prestressed Concrete Poles: State-of-the-Art. Pcij 1984;29:52–103. https://doi.org/10.15554/pc ij.09011984.52.103.

[14] Dilger WH, Ghali A. Response of Spun Cast Concrete Poles to Vehicle Impact. Pcij 1986;31:62–82. https:// doi.org/10.15554/pcij.01011986.62.82.

[15] McGuire JM, Lynch OJ, Schneider V, Reay JT, Wachholz TP, Bingel NG. Design of Wood Pole Structures. Wood Pole Structures for Electrical Transmission Lines, 2019, p. 31–41. https://doi.org/10.1061/978078441 5245.ch04.

[16] Zeynalian M, Khorasgani MZ. Structural performance of concrete poles used in electric power distribution network. Archives of Civil and Mechanical Engineering 2018;18:863–76. https://doi.org/10.1016/j.ac me.20 18.01.005.

[17] Kliukas R, Jaras A, Lukoševičienė O. Reinforced Spun Concrete Poles—Case Study of Using Chemical Admixtures. Materials 2020;13:302. https://doi.org/10.3390/ma13020302.

[18] Food, Branch AO of the UNMWP. Wood Preservation Manual. Food and Agriculture Organization of the United Nations; 1986.

[19] Nguyen M, Foliente G, Wang XM. State-of-the-Practice & Challenges in Non-Destructive Evaluation of Utility Poles in Service. Advances in Nondestructive Evaluation, vol. 270, Trans Tech Publications Ltd; 2004, p. 1521–8. https://doi.org/10.4028/www.scientific.net/KEM.270-273.1521.

[20] Yu Y, Li J, Yan N, Dackermann U, Samali B. Load capacity prediction of in-service timber utility poles considering wind load. J Civil Struct Health Monit 2016;6:385–94. https://doi.org/10.1007/s13349-016-0156-9.

[21] Wong KL, Pathak S, Yu X. Aging effect on leakage current flow in wooden poles. IEEE Transactions on Dielectrics and Electrical Insulation 2009;16:133–8. https://doi.org/10.1109/TDEI.2009.4784560.

[22] Wong KL, Pathak S, Yu XH. Leakage current flow through wooden pole structures of varying age on overhead distribution system. 2007 Australasian Universities Power Engineering Conference, 2007, p. 1–6. https://doi.org/10.1109/AUPEC.2007.4548085.

[23] Pathak S, Sokolowski P, Dwivedi A, Buratto F, Yu X, Wong KL. Investigation of pole fire on a 22kV wooden power pole structure. Symposium on Electrical Energy Evolution in China and Australia, Australia: Electrical Energy Evolution; 2008, p. 6.
[24] Langat DK, Cheboiwo JK, Muchiri MN. Financial analysis of growing Eucalyptus grandis for production of medium size power transmission poles and firewood in Kenya n.d.:9.
[25] Vidor FLR, Pires M, Dedavid BA, Montani PDB, Gabiatti A. Inspection of Wooden Poles in Electrical Power Distribution Networks in Southern Brazil. IEEE Trans Power Delivery 2010;25:479–84. https://doi.org/10.1109/TPWRD.2009.2034913.
[26] Gezer ED, Temiz A, Yüksek T. Inspection of Wooden Poles in Electrical Power Distribution Networks in Artvin, Turkey. Advances in Materials Science and Engineering 2015;2015:659818. https://doi.org/10.1155/2015/659818.
[27] Morrell JJ. Estimated Service Life of Wood Poles. North American Wood Pole Council Technical Bulletin 2016;101 (6):1–8.
[28] Alam MdM, Eren Tokgoz B, Hwang S. Framework for Measuring the Resilience of Utility Poles of an Electric Power Distribution Network. International Journal of Disaster Risk Science 2019;10:270–81. https://doi.org/10.1007/s13753-019-0219-8.
[29] Sokolowski PJ, Dwivedi A, Pathak S, Buratto F, Yu X. Investigating the Impedance of a Wooden Power Pole after a Pole Fire. Australasian Universities Power Engineering Conference 2008:1–6.
[30] Yassine R, Mustapha S. The effect of moisture content and temperature on the propagation characteristics of guided waves in timber utility poles-numerical and experimental validation. Wood Sci Technol 2024;58:533–73. https://doi.org/10.1007/s00226-023-01528-9.
[31] Bastidas-Arteaga E, Aoues Y, Chateauneuf A. Optimal design of deteriorating timber components under climate variations 2015:1–8. https://doi.org/10.14288/1.0076280.
[32] Viitanen, Hannu, Ritschkoff, Anne-Christine. Brown rot decay in wooden construction : effect of temperature, humidity and moisture. Uppsala Institutionen För Virkeslära 1991;22:57.
[33] Lacoursiere B. Steel utility poles: advantages and applications. 1999 Rural Electric Power Conference (Cat. No. 99CH36302), Indianapolis, IN, USA: IEEE; 1999, p. B2/1-B212. https://doi.org/10.1109/R EPCON.1999.768681.
[34] Bantupalli R, Potireddy S, K.V.G.D B, B SK. ADVANTAGES OF MONOPOLE TRANSMISSION TOWER WITH NEW GENERATION CONDUCTORS. engrXiv; 2020. https://doi.org/10.31224/osf.io/mcr6s.
[35] Tucker KB, Haldar AK. Numerical Model Validation and Sensitivity Study of a Transmission-Line Insulator Failure Using Full-Scale Test Data. IEEE Transactions on Power Delivery 2007;22:2439–44.
[36] Li J, Wang B, Sun J, Wang S, Zhang X, Fu X. Collapse Analysis of a Transmission Tower-Line System Induced by Ice Shedding. Frontiers in Physics 2021;9. https://doi.org/10.3389/fphy.2021.712161.
[37] Salman AM, Li Y. Age-dependent fragility and life-cycle cost analysis of wood and steel power distribution poles subjected to hurricanes. Structure and Infrastructure Engineering 2016;12:890–903. https://doi.org/10.1080/15732479.2015.1053949.
[38] Siddam A. Cascade failure analysis of electrical transmission lines using ADINA. Master thesis, Canada: Memorial University of Newfoundland; 2014, p. 1–114.
[39] Aghaei M, Fairbrother A, Gok A, Ahmad S, Kazim S, Lobato K, et al. Review of degradation and failure phenomena in photovoltaic modules. Renewable and Sustainable Energy Reviews 2022;159:112160. https://doi.org/10.1016/j.rser.2022.112160.
[40] Okenyi V, Bodaghi M, Mansfield N, Afazov S, Siegkas P. A review of challenges and framework development for corrosion fatigue life assessment of monopile-supported horizontal-axis offshore wind turbines. Ships and Offshore Structures 2024;19:1–15. https://doi.org/10.1080/17445302.2022.2140531.
[41] Quadri AI, Ali K. Numerical Appraisal of Reinforced Concrete Dapped-End Girder Under High-Fatigue Fixed Pulsating and Moving Loads. Transportation Research Record: Journal of the Transportation Research Board 2024;2678:257–78. https://doi.org/10.1177/03611981231184176.
[42] Komai K. Corrosion Fatigue. Comprehensive Structural Integrity, Elsevier; 2003, p. 345–58. https://doi.org/10.1016/B0-08-043749-4/04091-X.
[43] Quadri AI, Chikako F. Cyclic Shear Response of Reinforced Concrete Dapped- End Beams (RCDEBs) Under Bond Deterioration. Proceeding of the 2021 session of the 13th fib International PhD Symposium in Civil Engineering, vol. 2, France: fib; 2021, p. 227–34.
[44] Zamanzadeh M, Kernpkes C, Riley D, Gilpin-Jackson A. Galvanized Steel Pole and Lattice Tower Corrosion Assessment and Corrosion Mitigation. vol. All Days. 2016.
[45] Byrd WA. Below Grade Coated Direct Imbedded Steel Pole Corrosion Failures With Solutions. IEEE Power Energy Technol Syst J 2019;6:41–6. https://doi.org/10.1109/JPETS.2018.2884974.
[46] NACE International. Standard test method: measurement techniques related to criteria for cathodic protection on underground or submerged metallic piping systems. Houston, TX: NACE International; 2002.
[47] Liu W, Cao X, Hu Y, Li D, Xie Y. Failure Analysis of the Strain Clamp Steel Anchor Corrosion of a 500 kV

Transmission Line. E3S Web Conf 2021;252:02032. https://doi.org/10.1051/e3sconf/202125202032.
[48] Zamanzadeh M, Kempkes CD, Aichinger D, Riley D. Laboratory and Field Corrosion Investigation of Galvanized Utility Poles. Electrical Transmission Line and Substation Structures, 2006, p. 235–49. https://doi.org/10.1061/40790(218)22.
[49] Alkam F, Lahmer T. Quantifying the Uncertainty of Identified Parameters of Prestressed Concrete Poles Using the Experimental Measurements and Different Optimization Methods. EAS 2019;4:84. https://doi.org/10.11648/j.eas.20190404.13.
[50] Gong J, Ren DX, Zhou C, Ma GQ. Mechanical Properties Contrast Between Fiber Reinforced Composite Poles and Traditional Poles. Progress in Industrial and Civil Engineering II, vol. 405, Trans Tech Publications Ltd; 2013, p. 2690–3. https://doi.org/10.4028/www.scientific.net/AMM.405-408.2690.
[51] Kudzys A. Safety of power transmission line structures under wind and ice storms. Engineering Structures 2006;28:682–9. https://doi.org/10.1016/j.engstruct.2005.09.026.
[52] Kliukas R, Daniunas A, Gribniak V, Lukoseviciene O, Vanagas E, Patapavicius A. Half a century of reinforced concrete electric poles maintenance: inspection, field-testing, and performance assessment. Structure and Infrastructure Engineering 2018;14:1221–32. https://doi.org/10.1080/15732479.2017. 1402068.
[53] Kuebler M, Polak MA. Torsion tests on spun-cast prestressed concrete poles. Pcij 2012;57:120–41. https://doi.org/10.15554/pcij.03012012.120.141.
[54] Ibrahim AM. Behaviour of Pre-stressed Concrete Transmission Poles under High Intensity Wind. ElectronicThesis and Dissertation Repository 5029 2017:1–188.
[55] Ibrahim QA, Olasehinde AJ. Probability-Based Assessment of Electric Power Distribution Concrete Poles in Southwest of Nigeria. IJASRM 2016;1:102–10.
[56] Dilger WH, Ghali A, Rao SK. Improving the Durability and Performance of Spun-Cast Concrete Poles. Pci Journal 1996;41:68–90.
[57] Suvimolwan S, Sujaritpong A. The stress analysis in electric poles with CFRP to prevent the consecutive demolishing from car accidents. MATEC Web Conf 2018;192:02065. https://doi.org/10.1051/mat ecconf/201819202065.
[58] Kai X, Qingchun H, Wenping X, Jiaqi W, Xiaoyu L, Zhisheng L. The Stress Analysis and Calculation Method of the Poles of Different Arrangement Styles in the Distribution Network Lines and the Research of “Abandoning Wires to Protect Electric Poles” Project. 3rd International Conference on Mechatronics and Information Technology, 2016.
[59] Thomas P, Dwarakanath K, Sampathkumaran P, Seetharamu S, Kishore. Influence of moisture absorption on electrical characteristics of glass-epoxy polymer composite system. Proceedings of 2005 International Symposium on Electrical Insulating Materials, 2005. (ISEIM 2005)., Kitakyushu, Japan: IEEE; 2005, p. 612-615 Vol. 3. https://doi.org/10.1109/ISEIM.2005.193443.
[60] Otuko E, Mugabi P, Nabatanzi T, Kityo P, Kakeeto P, Kinhonhi I, et al. Performance of treated wooden electricity distribution poles in service in Uganda 2024. https://doi.org/10.21203/rs.3.rs-3966267/v1.
[61] Scott MH. The Use Of Chemically Treated Wooden Poles For Telephone And Power Transmission Lines In South Africa. Journal of the South African Forestry Association 1946;13:21–34. https://doi.org/10.1080/03759873.1946.9631037.
[62] Saafi M, Asa E. Extending the Service Life of Electric Distribution and Transmission Wooden Poles Using a Wet Layup FRP Composite Strengthening System. J Perform Constr Facil 2010;24:409–16. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000117.
[63] Morrell JJ. Wood Pole Maintenance Manual: 2012 Edition, 2012.
[64] Zhang X, Yang J, Zhu W, Li G. A Non-Destructive Health Evaluation Method for Wooden Utility Poles with Frequency-Modulated Empirical Mode Decomposition and Laplace Wavelet Correlation Filtering. Sensors 2022;22:4007. https://doi.org/10.3390/s22114007.
[65] Goodman JR, Stewart AH. Wood pole management-utility case studies. IEEE Trans Power Delivery 1990;5:422–6. https://doi.org/10.1109/61.107307.
[66] Gustavsen B, Rolfseng L. Asset management of wood pole utility structures. International Journal of Electrical Power & Energy Systems 2005;27:641–6. https://doi.org/10.1016/j.ijepes.2005.08.005.
[67] Polyzois D, Kell JA. Repair and rehabilitation of wood utility poles with fibre-reinforced polymers. Canadian Journal of Civil Engineering 2007;34:116–9. https://doi.org/10.1139/l06-105.
[68] ASTM. Standard Test Methods of Static Tests of Wood Poles, ASTM D-1036, American Society for Testing and Materials 1999. West Conshohocken, Pa n.d.
[69] Merschman E, Salman AM, Bastidas-Arteaga E, Li Y. Assessment of the effectiveness of wood pole repair using FRP considering the impact of climate change on decay and hurricane risk. Advances in Climate Change Research 2020;11:332–48. https://doi.org/10.1016/j.accre.2020.10.001.
[70] Salman AM, Salarieh B, Bastidas-Arteaga E, Li Y. Optimization of Condition-Based Maintenance of Wood Utility Pole Network Subjected to Hurricane Hazard and Climate Change. Frontiers in Built Environment

2020;6. https://doi.org/10.3389/fbuil.2020.00073.
[71] Salman AM, Li Y. A framework to investigate the effectiveness of interconnection of power distribution systems subjected to hurricanes. Structure and Infrastructure Engineering 2018;14:203–17. https://doi.org/10.1080/15732479.2017.1345954.
[72] Huang Z, Rosowsky DV, Sparks PR. Hurricane simulation techniques for the evaluation of wind-speeds and expected insurance losses. Journal of Wind Engineering and Industrial Aerodynamics 2001;89:605–17. https://doi.org/10.1016/S0167-6105(01)00061-7.
[73] Jayaram N, Baker JW. Efficient sampling and data reduction techniques for probabilistic seismic lifeline risk assessment. Earthquake Engng Struct Dyn 2010:n/a-n/a. https://doi.org/10.1002/eqe.988.
[74] Holland GJ. An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Monthly Weather Review 1980;108:1212. https://doi.org/10.1175/1520-0493(1980)108\textless1212:AAMOTW\textgreater2.0.CO;2.
[75] Bolin CA, Smith ST. Life Cycle Assessment of CCA-Treated Wood Highway Guard Rail Posts in the US with Comparisons to Galvanized Steel Guard Rail Posts. JTTs 2013;03:58–67. https://doi.org/10.4236/jt ts.2013.31007.
[76] Shafieezadeh A, Onyewuchi UP, Begovic MM, DesRoches R. Age-Dependent Fragility Models of Utility Wood Poles in Power Distribution Networks Against Extreme Wind Hazards. IEEE Transactions on Power Delivery 2014;29:131–9. https://doi.org/10.1109/TPWRD.2013.2281265.
[77] Tari AN, Sepasian MS, Kenari MT. Resilience assessment and improvement of distribution networks against extreme weather events. International Journal of Electrical Power & Energy Systems 2021;125:106414. https://doi.org/10.1016/j.ijepes.2020.106414.
[78] Mugabi P, Thembo J. Effect of pole size on preservative penetration and retention in air-dried ugandan grown eucalypt utility poles. Maderas, Cienc Tecnol 2018:0–0. https://doi.org/10.4067/S0718-221X2018005001701.
[79] Cookson LJ. The preservation of eucalypts. The future of eucalypts for wood products. Proceedings IUFRO conference, 2000, p. 19–24.
[80] Roliadi H, Hse CY, Choong ET, Shupe TF. Decay resistance of out-of-service utility poles as related to the distribution of residual creosote content. Forest Products Journal 2000;50:64–8.
[81] Giron MY, San Pablo MR, Morrel JJ. Controlling internal decay of preservative-treated utility poles. 1996.
[82] Bouzon J, Haloui A, Vergnaud JM. Study of the release in water of a chemical used for preservation of wood. Effect of the dimensions of the wood. Wood SciTechnol 1996;30. https://doi.org/10.1007/BF00244439.
[83] Lloyd JD, Taylor AM, Brischke C, Irby N. Protecting the heartwood of wood infrastructure–improving performance with borate dual treatments. Wood Material Science & Engineering 2020;15:361–7.
[84] Solo-Gabriele H. Characteristics of chromated copper arsenate-treated wood ash. Journal of Hazardous Materials 2002;89:213–32. https://doi.org/10.1016/S0304-3894(01)00311-9.
[85] Hingston JA, Collins CD, Murphy RJ, Lester JN. Leaching of chromated copper arsenate wood preservatives: a review. Environmental Pollution 2001;111:53–66. https://doi.org/10.1016/S0269-7491(00)00030-0.
[86] Rahman FA, Allan DL, Rosen CJ, Sadowsky MJ. Arsenic Availability from Chromated Copper Arsenate (CCA)–Treated Wood. J of Env Quality 2004;33:173–80. https://doi.org/10.2134/jeq2004.1730.
[87] Sandoz JL. Wood poles ageing and non destructive testing tool. 14th International Conference and Exhibition on Electricity Distribution (CIRED 1997 - Distributing Power for the Millennium), vol. 1997, Birmingham, UK: IEE; 1997, p. v3-26-v3-26. https://doi.org/10.1049/cp:19970532.
[88] Kartal SN, Morrell JJ. Borates in remedial treatments for timber in service. Journal of Boron 2023. https://doi.org/10.30728/boron.1208619.
[89] Obanda DN, Shupe TF, Barnes HM. Reducing leaching of boron-based wood preservatives – A review of research. Bioresource Technology 2008;99:7312–22. https://doi.org/10.1016/j.biortech.2007.12.077.
[90] Lloyd JD, Taylor AM, Brischke C, Irby N. Protecting the heartwood of wood infrastructure – improving performance with borate dual treatments. Wood Material Science & Engineering 2020;15:361–7. https://doi.org/10.1080/17480272.2020.1749881.
[91] Cao Y, Fang J, Chen S, Zhu L, Xie X, Xing H, et al. Preservation of wood-based products against biotic and chemical degradation: past, present and future. Wood Material Science & Engineering 2025:1–22. https://doi.org/10.1080/17480272.2025.2459898.
[92] Humar M, Thaler N. Performance of copper treated utility poles and posts used in service for several years. International Biodeterioration & Biodegradation 2017;116:219–26. https://doi.org/10.1016/j.ibiod. 2016.11.004.
[93] Baldwin EA, Nisperos-Carriedo MO, Baker RA. Use of edible coatings to preserve quality of lightly (and slightly) processed products. Critical Reviews in Food Science and Nutrition 1995;35:509–24. https://doi.org/10.1080/10408399509527713.
[94] Yu Y, Dackermann U, Li J, Niederleithinger E. Wavelet packet energy–based damage identification of wood utility poles using support vector machine multi-classifier and evidence theory. Structural Health Monitoring 2019;18:123–42. https://doi.org/10.1177/1475921718798622.

[95] Nguyen VN, Jenssen R, Roverso D. Intelligent Monitoring and Inspection of Power Line Components Powered by UAVs and Deep Learning. IEEE Power Energy Technol Syst J 2019;6:11–21. https://doi.org/10.1109/JPETS.2018.2881429.
[96] Chantler RA. Corrosion and the Protection of Metals. HYDRAULIC STRUCTURES 2001;4:1–9.
[97] Song G. Recent Progress in Corrosion and Protection of Magnesium Alloys. Adv Eng Mater 2005;7:563–86. https://doi.org/10.1002/adem.200500013.
[98] Pedeferri P. Cathodic protection and cathodic prevention. Construction and Building Materials 1996;10:391–402. https://doi.org/10.1016/0950-0618(95)00017-8.
[99] Wijaya H, Bandara S, Rajeev P, Gad E, Shan J. Failure assessment of deteriorated steel light poles. Results in Engineering 2024;23:102621. https://doi.org/10.1016/j.rineng.2024.102621.
[100] Shen L, Li Y, Zhao W, Wang K, Ci X, Wu Y, et al. Tuning F-doped degree of rGO: Restraining corrosion-promotion activity of EP/rGO nanocomposite coating. Journal of Materials Science & Technology 2020;44:121–32. https://doi.org/10.1016/j.jmst.2019.09.043.
[101] Mandal S, Das VV, Debata M, Panigrahi A, Sengupta P, Rajendran A, et al. Study of pore morphology, microstructure, and cell adhesion behaviour in porous Ti-6Al-4V scaffolds. Emergent Mater 2019;2:453–62. https://doi.org/10.1007/s42247-019-00055-3.
[102] Ibrahim M, Kannan K, Parangusan H, Eldeib S, Shehata O, Ismail M, et al. Enhanced Corrosion Protection of Epoxy/ZnO-NiO Nanocomposite Coatings on Steel. Coatings 2020;10:783. https://doi.org/10.3390/coatings10080783.
[103] Cooke KO, Khan TI. Effect of thermal processing on the tribology of nanocrystalline Ni/TiO2 coatings. Emergent Mater 2018;1:165–73. https://doi.org/10.1007/s42247-018-0015-z.
[104] Fayyad EM, Abdullah AM, Hassan MK, Mohamed AM, Jarjoura G, Farhat Z. Recent advances in electroless-plated Ni-P and its composites for erosion and corrosion applications: a review. Emergent Mater 2018;1:3–24. https://doi.org/10.1007/s42247-018-0010-4.
[105] Shuhada Pauzai N, Ruszaini Mohd Zin ND, Abdullah K, Bala Sundaram MS. Corrosion Behavior Study of Steel Pole In Different Coating Technology. IJEAST 2021;5. https://doi.org/10.33564/IJEAS T.2021.v05i09.008.
[106] Agnieszka W. Numerical analysis of cathodic protection for traction poles. 2018 Applications of Electromagnetics in Modern Techniques and Medicine (PTZE), Racławice: IEEE; 2018, p. 272–5. https://doi.org/10.1109/PTZE.2018.8503251.
[107] Ertunç K, Oğuz Y. Detection of Potential Faults in the Electricity Distribution Network Using Unmanned Aerial Vehicles and Thermal Cameras Through Deep Learning Methods. Electric Power Components and Systems 2024;52:1671–91. https://doi.org/10.1080/15325008.2024.2319325.
[108] Pedeferri (Deceased) P. Cathodic and Anodic Protection. Corrosion Science and Engineering, Cham: Springer International Publishing; 2018, p. 383–422. https://doi.org/10.1007/978-3-319-97625-9_19.
[109] Quadri AI, Fujiyama C. Response of Reinforced Concrete Dapped-End Beams Exhibiting Bond Deterioration Subjected to Static and Cyclic Loading. ACT 2021;19:536–54. https://doi.org/10.3151/jact.19.536.
[110] Crevello G, Hudson N, Noyce P. Corrosion condition evaluations of historic concrete icons. Case Studies in Construction Materials 2015;2:2–10. https://doi.org/10.1016/j.cscm.2014.12.005.
[111] Ann KY, Pack S-W, Hwang J-P, Song H-W, Kim S-H. Service life prediction of a concrete bridge structure subjected to carbonation. Construction and Building Materials 2010;24:1494–501. https://doi.org/10. 1016/j.conbuildmat.2010.01.023.
[112] Nguyen TTH, Bary B, De Larrard T. Coupled carbonation-rust formation-damage modeling and simulation of steel corrosion in 3D mesoscale reinforced concrete. Cement and Concrete Research 2015;74:95–107. https://doi.org/10.1016/j.cemconres.2015.04.008.
[113] Jaffer SJ, Hansson CM. Chloride-induced corrosion products of steel in cracked-concrete subjected to different loading conditions. Cement and Concrete Research 2009;39:116–25. https://doi.org/10.1016/j. cemconres.2008.11.001.
[114] Liu L, Ji Y, Gao F, Xu Z. Research on Influences of Ultrasonic Vibration Agitation Stirring on Carbonation Resistance of Cement-Based Materials after Absorption of CO2. Applied Sciences 2023;13:4256. https://doi.org/10.3390/app13074256.
[115] Fernández-Carrasco L, Rius J, Miravitlles C. Supercritical carbonation of calcium aluminate cement. Cement and Concrete Research 2008;38:1033–7. https://doi.org/10.1016/j.cemconres.2008.02.013.
[116] Liu Z, Meng W. Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites: A review. Journal of CO2 Utilization 2021;44:101428. https://doi.org/10. 1016/j.jcou.2020.101428.
[117] Liu Z, Van Den Heede P, De Belie N. Effect of the Mechanical Load on the Carbonation of Concrete: A Review of the Underlying Mechanisms, Test Methods, and Results. Materials 2021;14:4407. https://doi.org/10.3390/ma14164407.

[118] Hussain S, Bhunia D, Singh SB. Comparative study of accelerated carbonation of plain cement and fly-ash concrete. Journal of Building Engineering 2017;10:26–31. https://doi.org/10.1016/j.jobe.2017.02.001.
[119] Beltrame NApM, Dias RL, Witzke FB, Medeiros-Junior RA. Effect of carbonation curing on the physical, mechanical, and microstructural properties of metakaolin-based geopolymer concrete. Construction and Building Materials 2023;406:133403. https://doi.org/10.1016/j.conbuildmat.2023.133403.
[120] Efanov D, Sedykh D, Osadchy G, Barch D. Permanent monitoring of railway overhead catenary poles inclination. 2017 IEEE East-West Design & Test Symposium (EWDTS), Novi Sad: IEEE; 2017, p. 1–5. https://doi.org/10.1109/EWDTS.2017.8110142.
[121] Nakada K, Yokota T, Yokoyama S, Asakawa A, Nakamura M, Taniguchi H, et al. Energy absorption of surge arresters on power distribution lines due to direct lightning strokes-effects of an overhead ground wire and installation position of surge arresters. IEEE Trans Power Delivery 1997;12:1779–85. https://doi.org/10.1109/61.634205.
[122] Najafi Tari A, Sepasian MS, Tourandaz Kenari M. Resilience assessment and improvement of distribution networks against extreme weather events. International Journal of Electrical Power & Energy Systems 2021;125:106414. https://doi.org/10.1016/j.ijepes.2020.106414.
[123] Pak J, Shim Y, Song J, Kim SJ, Lee JH, Jeong S. Deep learning-based automatic detection of defective steel bars in concrete poles. IET Conf Proc 2023;2023:574–8. https://doi.org/10.1049/icp.2023.0419.
[124] Ullah S, Jeong M, Lee W. Nondestructive Inspection of Reinforced Concrete Utility Poles with ISOMAP and Random Forest. Sensors 2018;18:3463. https://doi.org/10.3390/s18103463.
[125] Thongchai P, Pao-La-Or P, Kulworawanichpong T. Condition-based health index for overhead transmission line maintenance. 2013 10th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Krabi, Thailand: IEEE; 2013, p. 1–4. https://doi.org/10.1109/ECTICon.2013.6559646.
[126] Miszczyk A, Szocinski M, Darowicki K. Restoration and preservation of the reinforced concrete poles of fence at the former Auschwitz concentration and extermination camp. Case Studies in Construction Materials 2016;4:42–8. https://doi.org/10.1016/j.cscm.2015.12.002.
[127] Li X, Zhang L, Bu Y, Zhang Z, Suo S, Li W, et al. Research on Anti-Weathering Coating for Reinforced Concrete pole. In: Gao Q, Jiang L, Chen Y, editors. Proceedings of the 2024 7th International Conference on Structural Engineering and Industrial Architecture (ICSEIA 2024), vol. 30, Dordrecht: Atlantis Press International BV; 2024, p. 130–7. https://doi.org/10.2991/978-94-6463-429-7_15.
[128] Mohammed AA, Manalo AC, Ferdous W, Zhuge Y, Vijay PV, Alkinani AQ, et al. State-of-the-art of prefabricated FRP composite jackets for structural repair. Engineering Science and Technology, an International Journal 2020;23:1244–58. https://doi.org/10.1016/j.jestch.2020.02.006.
[129] Quadri AI. Assessment of Reinforced Concrete Dapped End Beams Subjected to Cyclic Loading under Bond Deterioration and Retrofitting Approach. Yokohama National University, Japan Dissertation 2021:1–187.
[130] Quadri AI, Fujiyama C. Assessment of repaired reinforced concrete dapped-end beams exhibiting bond deterioration under static and cyclic loading. Construction and Building Materials 2023;403:133070. https://doi.org/10.1016/j.conbuildmat.2023.133070.
[131] Quadri AI. Behavior of disturbed region of RC precast beams upgraded with near surface mounted CFRP fiber. Asian Journal of Civil Engineering 2023;24:1859–73. https://doi.org/10.1007/s42107-023-00605-5.
[132] Abadel A, Abbas H, Almusallam T, Alshaikh IMH, Khawaji M, Alghamdi H, et al. Experimental study of shear behavior of CFRP strengthened ultra-high-performance fiber-reinforced concrete deep beams. Case Studies in Construction Materials 2022;16:e01103. https://doi.org/10.1016/j.cscm.2022.e01103.
[133] Barros J, Sena-Cruz J. Numerical Assessment of Dapped Beam Ends Retrofitted with FRP Composites n.d.:11.
[134] Gudonis E, Timinskas E, Gribniak V, Kaklauskas G, Arnautov AK, Tamulėnas V. FRP Reinforcement For Concrete Structures: State-Of-The-Art Review Of Application And Design. Engineering Structures and Technologies 2014;5:147–58. https://doi.org/10.3846/2029882X.2014.889274.
[135] Cromwell JR, Harries KA, Shahrooz BM. Environmental durability of externally bonded FRP materials intended for repair of concrete structures. Construction and Building Materials 2011;25:2528–39. https://doi.org/10.1016/j.conbuildmat.2010.11.096.
[136] Tsunemoto M, Shimizu M, Kondo Y, Kudo T, Ueda H, Iijima T. Replacement Criteria for Concrete Catenary Poles. Q Rep RTRI 2017;58:270–6. https://doi.org/10.2219/rtriqr.58.4_270.
[137] Ibrahim QA, Olasehinde AJ. Reliability Assessment of Axial Load Effect on Electric Power Distribution Concrete Poles in Southwest Nigeria. IJSER 2017;8:358–64. https://doi.org/10.14299/ijser.2017.05.021.
[138] Oraegbune OM, Ataguba OC. Failure, Causes and Impacts of Reinforced Electric Concrete Poles in Some Areas of Adamawa State, Nigeria. Nigeria Journal of Engineering Science and Technology Research 2017;3:33–56.

[139] Rodgers TE. A Utility's Development and use of Prestressed Concrete Poles. Pcij 1972;17:8–13. https://doi.org/10.15554/pcij.05011972.8.13.
[140] ACI Committee 318. Building code requirements for reinforced concrete (ACI 318-63). Detroit, Mich.: American Concrete Institute; 1963.
[141] ASCE. Prestressed Concrete Transmission Pole Structures. ASCE manuals and reports on engineering practice 2012.
[142] Ibrahim AM, El Damatty AA, El Ansary AM. Finite element modelling of pre-stressed concrete poles under downbursts and tornadoes. Engineering Structures 2017;153:370–82. https://doi.org/10.1016/j.eng struct.2017.10.047.
[143] Quadri AI, Afolayan JO. Reliability assessment of H-section tapered electric power distribution concrete poles. IJRS 2022;16:189–217. https://doi.org/10.1504/IJRS.2022.131470.
[144] British Standards Institution. Eurocode 2: design of concrete structures : British standard. London: BSi; 2006.
[145] Committee 318 ACI, Institute AC. Building Code Requirements for Structural Concrete: (ACI 318-95) ; and Commentary (ACI 318R-95). American Concrete Institute; 1995.
[146] Lanikova I, Štěpánek P, Simůnek P. Optimized design of concrete structures considering environmental aspects. Advances in Structural Engineering 2014;17:495–511.
[147] Desai N, Yuan R. Investigation of bending/buckling characteristics for FRP composite poles. Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment, 2006, p. 1–18.
[148] Magalhães KMM, Rebello da Fonseca Brasil RML, de Macêdo Wahrhaftig A, Siqueira GH, Bondarenko I, Neduzha L. Influence of atmospheric humidity on the critical buckling load of reinforced concrete columns. International Journal of Structural Stability and Dynamics 2022;22:2250011.
[149] Taranu N, Oprisan G, Budescu M, Gosav I. Hollow Concrete Poles with Polymeric Composite Reinforcement. J of Applied Sciences 2009;9:2584–91. https://doi.org/10.3923/jas.2009.2584.2591.
[150] Gaylord EH. Design Criteria for Steel Transmission Poles. International Specialty Conference on Cold-Formed Steel Structures 1973;2:789–812.
[151] Gere JM, Carter WO. Critical Buckling Loads for Tapered Columns. J Struct Div 1962;88:1–12. https://doi.org/10.1061/JSDEAG.0000737.
[152] Ibrahim SM. Effective buckling length of frames with tapered columns and partially tapered beams. Journal of Constructional Steel Research 2021;187:106993. https://doi.org/10.1016/j.jcsr.2021.106993.
[153] Lee GC, Morrell ML. Application of AISC design provisions for tapered members. Engineering Journal 1975;12:1–13.
[154] Design AS. Specification for structural steel buildings. AISC, December 1999;27.
[155] Hirt MA, Crisinel M. Charpentes métalliques: conception et dimensionnement des halles et bâtiments. PPUR presses polytechniques; 2005.
[156] Eurocode 5: design of timber structures. London: BSI; 2004.
[157] Caspeele R, Taerwe L, Frangopol DM, editors. Life-cycle analysis and assessmanet in civil engineering: towards an integrated vision: proceedings of the sixth International Symposium on Life-Cycle Engineering (IALCCE 2018), 28-31 October 2018, Ghent, Belgium. Boca Raton: CRC Press, Taylor & Francis Group; 2019.
[158] Leicester RH, Wang CH, Nguyen MN, MacKenzie CE. Design of Exposed Timber Structures. Australian Journal of Structural Engineering 2009;9:217–24. https://doi.org/10.1080/13287982.2009.11465024.
[159] Ryan PC, Stewart MG, Spencer N, Li Y. Reliability assessment of power pole infrastructure incorporating deterioration and network maintenance. Reliability Engineering & System Safety 2014;132:261–73. https://doi.org/10.1016/j.ress.2014.07.019.
[160] Sousa HS, Branco JM, Lourenço PB. Characterization of Cross-Sections from Old Chestnut Beams Weakened by Decay. International Journal of Architectural Heritage 2014;8:436–51. https://doi.org/10.1080/15583058.2013.826303.
[161] Quadri AI. Investigation of reinforced concrete members with bond deterioration under tensile load. Materconstrucc 2023;73:e319. https://doi.org/10.3989/mc.2023.297522.
[162] Yu XM, Cai WX, Wang PF. Finite element modeling and analysis of lightning protection poles using electrically conductive concrete. J Phys: Conf Ser 2025;2944:012013. https://doi.org/10.1088/1742-6596/2944/1/012013.
[163] Aliyu M, Abejide OS. Finite element modelling of steel poles for power production and transmissions. Nig J Tech 2019;38:840. https://doi.org/10.4314/njt.v38i4.4.
[164] Lian L-M, Zhang R, Ma H, Shen P. Analysis of failure mechanism of concrete pole based on finite element extended method. Eng Res Express 2024;6:025123. https://doi.org/10.1088/2631-8695/ad58a3.
[165] PCI Committee on Prestressed Concrete Poles, ASCE Task Force on Concrete Poles. Guide for the Design of Prestressed Concrete Poles. PCIJ 1997;42:94–134. https://doi.org/10.15554/pcij42.6-06.
[166] ASCE/SEI 48-19. Design of steel transmission pole structures: ASCE/SEI 48-11. Reston, Va.: American

Society of Civil Engineers; 2012.
[167] Iwaki N. Study for recycling of scrapped concrete poles; Haihin konchu no recycle kenkyu. Kenkyu Kiho (Kyushu Denryoku); Journal 1997:61–76.
[168] Huhnke RL, Zwerneman F, Lewis DK, Harp S, Doeksen GA, Green CB. Recycling wood utility poles 1995.
[169] Felton CC, Groot RCD. The recycling potential of preservative-treated wood. Forest Products Journal 1996;46:37–46.
[170] Sedjo RA. Wood materials used as a means to reduce greenhouse gases (GHGs): An examination of wooden utility poles 2002:191–200.
[171] Quadri AI, Olanitori LM, Sadiq A. Effect of non-biodegradable waste materials on the strength performance of concrete. Res Eng Struct Mater 2023;9:1–13. https://doi.org/10.17515/resm2023.751st0428.
[172] Cao G, Liu Y, Long S, Deng D, Jiang S, Su H, et al. Influence of aggregate shape on the flow properties of fresh concrete. Powder Technology 2023;415:118186. https://doi.org/10.1016/j.powtec.2022.118186.
[173] Buckley M, Zendel A, Biggar J, Frederiksen L, Wells J. Migrant work and employment in the construction sector. 1st ed. Geneva: ILO; 2016.
[174] McNair BJ, Bennett J, Hensher DA, Rose JM. Households' willingness to pay for overhead-to-underground conversion of electricity distribution networks. Energy Policy 2011;39:2560–7. https://doi.org/10.1016/j.en pol.2011.02.023.
[175] Burges K, Bömer J, Nabe C, Papaefthymiou G, Maher M, Mills C, et al. Study on the comparative merits of overhead electricity transmission lines versus underground cables. Ecofys Germany GmbH 2008.
[176] Shakiba FM, Azizi SM, Zhou M, Abusorrah A. Application of machine learning methods in fault detection and classification of power transmission lines: a survey. Artif Intell Rev 2023;56:5799–836. https://doi.o rg/1 0.1007/s10462-022-10296-0.
[177] Sampedro C, Martinez C, Chauhan A, Campoy P. A supervised approach to electric tower detection and classification for power line inspection. 2014 International Joint Conference on Neural Networks (IJCNN), Beijing, China: IEEE; 2014, p. 1970–7. https://doi.org/10.1109/IJCNN.2014.6889836.