Reliability Assessment of Axial Load Effect on Electric Power Distribution Concrete Poles in Southwest Nigeria

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Abstract— Electric power is distributed by overhead distribution line fixed on wooden or concrete poles. Often times these poles are susceptible to extreme damage from hazard under excessive loads occasioned by storm and accident impact by vehicles. In this research, numerical study was accomplished to assess the vulnerability of typical tapered electric power distribution concrete poles of height 9 m under ambivalent loading conditions. The reaction of the poles to the environmental loading was determined with the help of SAP2000 Advanced 14.0.0 finite element analysis software program. The British Standard Code (BS 8110-1:1997) was adopted to generate the limit states equation with the load combination being at adverse effect. The reliability level of the concrete poles was extrapolated using the First-Order reliability Method (FORM) encoded in CalREL, a multipurpose structural reliability analysis software. Since every natural event is unpredictable, the interaction between the capacity of a pole and the demand (axial forces) on it must also be uncertain. The study shows that the reliability level of the poles increase as the reinforcement ratio increases but decrease as the cross-sections of the concrete poles decrease or as the heights increase, above 4.5m height, the probability of failure of the Nigerian concrete poles is high. Critical positions/areas of the concrete poles that require amendment have been identified based on the implied levels of reliability and when factors affecting material properties, geometry and loading are considered random in nature.

Index Terms— *Concrete poles, Reliability analysis, CalREL SAP 2000, Axial forces.*

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1 Introduction

In recent times, efforts have been geared towards the production of Electric Power Distribution Concrete poles (EPDC) that meet the international quality standards. With the level of development in Nigeria, the use of EPDC poles has been on the increase as a result of the rural electrification programme. In effect, efforts have been made to provide quality facilities and amenities for the production of poles in the rural and urban areas. Reinforced concrete is a viable and durable material for building and construction that can be formed into various forms and sizes. Its utility and versatility are achieved by combining the best features of concrete and other materials. In Nigeria, electricity is transmitted by conductors carried overhead by concrete and wooden poles. Concrete pole design is dependent on the power and voltage that is to be transmitted. In Nigeria, 33/11/0.415KV is usually transmitted generally by overhead conductors; hence the wooden and concrete pole types are suitable for use [8]. The design of poles are mainly based on the principle of loading. However, sag-tension calculation is quite involved due to the varying loading effect on conductors and the nature of conductor materials.

The technology advancements in recent years have propelled the use of concrete poles into an ever increasing, and significant role in the design and construction of high voltage electrical transmission lines. These technologies significantly have occurred in three key aspects namely; the types and quality of the raw materials utilized in the production of high performance concrete have dramatically improved, and in some instances have just recently been developed. Also, scaled up manufacturing methods and equipment to produce high quality, stronger, longer length poles are being realized. [11]

Due to shear forces been small compared to bending moments, concrete poles are very resilient. Axial loads are also significant, and should not be ignored most especially when the structure is guyed. Stresses induced by handling, transportation and erection should always be considered in the design of electric transmission. Besides, weight of cross arms and other attachments should be put into proper consideration in calculating the center of gravity of the electric transmission pole [15].

Generally, concrete is poor in tension, the tensile strength only accounted for about 10% of the compressive strength. Due to this, nearly all reinforced concretes are designed on the assumption that concrete does not resist any tensile force. Reinforcement is designed to carry these tensile forces, which are transferred by bonds between the interface of the two materials. If this bond is not adequate, the reinforcing bars will slip within the concrete and there will not be a composite action. [5].

2 Power Distribution Systems

The electric power system can be broadly divided into three subsystems: generation, transmission, and distribution. The generation plants produce electricity by using fossil fuels, nuclear energy, or renewable sources of energy. The power is then transported in bulk using the transmission system that uses wires supported by steel towers that are about 45 metres high and spaced about 240 metres apart [16]. The voltage levels for the transmission system ranges from 34.5 KV to as high as 1100 KV in the US [5]. The distribution system transports and delivers power to the consumers after the voltage has been stepped down to the appropriate level. The distribution system uses wires that are carried by timber, steel or concrete poles that are 9 to 12 metres high and spaced 30 metres to 45metres. in the suburbs and 90metres to 120metres in rural areas [14]. The voltage is usually between 4.16 KV to 34.5 KV in the primary distribution system [5]. Considering failure due to natural hazards, the distribution system is the most vulnerable [6]. This is because the generation stations are few and are usually designed to withstand high wind, floods, and earthquakes. The transmission system (towers and lines) is also designed to withstand natural hazards better than the distribution system. Another reason is that unlike the distribution system, there is always redundancy in the transmission system, i.e. there is always more than one way to transport the electricity from the generation plants.

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2.2 Structural Reliability

Reliability is the ability of the structure to meet the construction requirements set out under specific conditions during the service life, according to which it is designed. It refers to the carrying capacity, serviceability and durability of construction and according to them different degrees of reliability can be defined. One of the best ways of presenting the size of the uncertainty in the theory of reliability is the reliability index, because it is a measure of security that can be used in the comparison between the different elements or entire system [17]. The concept of structural reliability was incorporated into design methods in the seventies in the form of Load and Resistance Factor Design (LRFD). The objective of structural design based on reliability theory is to reduce the probability of failure to a tolerable level. [13] on Probabilistic assessment of electric power distribution concrete poles, examined the overturning moment on

2.2.1 Limit State

The limit state is the state of the structure at which the object performance transforms from acceptable to unacceptable. There are several types of limit states: design limit state, serviceability limit states, serviceability limit state of fatigue. Any of these conditions can be defined by limit state function:

$$g = S - Q \tag{1}$$

where S is the resistance, i.e. the capacity of the construction and Q is a load, or the load on the construction [10]. If $g < 0$, it leads to unauthorized breakage of constructions and its performance, and if $g \geq 0$, structures performance are satisfied. In the case of design limit states or bending capacity, S represents structure bending capacity, while Q represents the load bending moment. In the case of serviceability limit states, S may represent a maximum allowable deflection of the structure, while Q can represent deflection under load. However, the limit state function may be more complex (eg. nonlinear) and its parameters can be variable in time.

2.2.2 Application of Reliability Concept

Probability of achieving the ultimate limit state can be explained by the equation:

$$P_f = P((S - Q) < 0 = P(g < 0) \tag{2}$$

Probability P_f is equal to the cumulative distribution function of the random variable g. The reliability index is defined as a function of the probability P_f:

$$\beta = -\phi^{-1}(P_f), \tag{3}$$

$$P_f = (-\beta) \tag{4}$$

Where ф and ф-1 are the function of the standard normal cumulative distribution. The reliability index β is a measure of security that can be used in the comparison between the different elements or entire system [12].

3. Collection of Data for Concrete Pole Modelling

The design data of a typical tapered electric power distribution concrete pole of 9 m high in Plate 1, were collected from Benin Electricity Distribution Companies.. The tapered height of the concrete pole was divided into eight sections as shown in Table 1. The concrete pole carries electric cables made of aluminum spanning 45 m. The loads on the concrete pole include: the cross arms, the insulators, the street lamp, the self weight of the concrete and the effect of wind load.

Plate 1: Electric Power Distribution Concrete

ISSN 2229-5518

Table 1: Section Properties of the Concrete Pole

Pole Sections	Height (mm)	Width (mm)	Depth (mm)
1	0	350	300
2	0-1500	320	260
3	1500-3000	300	240
4	3000-4500	270	220
5	4500-6000	220	210
6	6000-7000	200	185
7	7000-8000	160	157
8	8000-9000	140	140

3.1 Load Data

(i) Dead Load

(a) Weight of Concrete

Total volume of concrete = $3.98m^3$

Unit Weight of Concrete = $24kN/m^3$

Weight of Concrete = 3.98x24 = 95.5 kN

(b) Cross arms and Insulator = $0.15\ kN/m^2$

(c) Street Lamp = $0.005\ kN/m^2$

(d) The self-weight of aluminum = $0.86kN/m^2$

(ii) Wind Load

BS 6399-2:1997 (Code of Practiced for wind loading), was used for the analysis of wind load

The dynamic pressure q_s is given as

$$q_s = kV_s^2 \quad (5)$$

where;

$k = 0.613$

and

$$v_s = v_s \times k_1 \times k_2 \quad (6)$$

In which v_s is the wind speed taken as 3.6m/s according to local wind condition in Akure, Ondo State (Adaramola and Oyewola, 2011).

k_1 is the risk coefficient taken as 1.0

k_2 is the terrain factor taken as 1.0 for flat terrain. Therefore,

$$q_s = 0.613 \times (3.6^2) = 7.94\ N/m^2 = 0.00794\ kN/m^2$$

3.2 SAP2000 Build-Up Analysis

The SAP2000 (ref) Application Programming Interface (API) allows users to automatic operate many of the processes required to build, analyze and design models and to obtain customized analysis and design results. It also aids users to link SAP2000 with athird-party software providing a path for two-way exchange of framework information with other programs. A typical electric power distribution concrete pole under consideration was first modeled on AutoCAD and then exported to SAP2000 software interface as presented in Fig. 1, for analysis to obtain the axial forces effect at each section of the concrete pole due to the applied design dead and wind loads at uncertain loading conditions (1.4 Wind load + 1.4 Dead load) as specified by BS 8110-1:1997.

3.3 Probabilistic Testing Using CalREL

CalREL is a general-purpose structural reliability analysis program. The aim is to estimate how reliable or otherwise the probability of failure in the uncertainty of a structure,

CalREL adopts four major techniques for analyzing probability of failure. The First-order reliability method (FORM),which is applicable to series system reliability, the Second-order reliability method (SORM), which is applicable to component reliability analysis, Directional simulation with exact or approximate surfaces, which is applicable to component or system reliability analysis, and Monte Carlo simulation which can be applied to all classes of problems.

In this investigation, reliability analyses were performed using FORM.

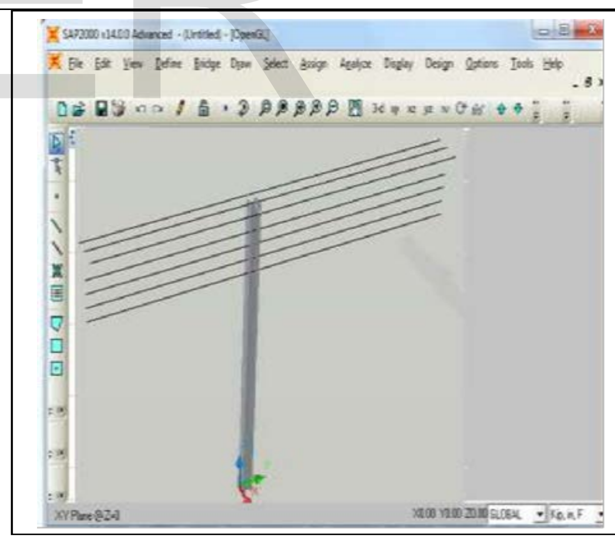

Fig. 1: Typical electric power distribution concrete pole modeled on SAP2000

Table 2: The Limit State Function

Parameter	Assumed Distribution	Coefficient of Variation (%)
Breadth	Normal	10
Depth	Normal	10
Characteristic concrete strength (fcu)	Log Normal	30
Characteristic steel strength (fy)	Log Normal	30
Reinforcement ratio (ρ)	Normal	10
Axial Force (F)	Log Normal	30

The difference between the resistance of the concrete pole and the applied load effect is the limit state function as given in equation (1)

The load combination for the ultimate limit state at adverse level from BS 8110-1: 1997 is given as;

$$W=1.4G_k + 1.4W_k \quad (9)$$

The Axial force capacity for the compressive section is given as;

$$F_{cc} = 0.45 f_{cu} bs \quad (10)$$

In which

$$s = 0.9x$$

At the ultimate limit state, $x = 0.636d$. Thus,

$$F_{cc} = 0.2576 f_{cu} bd \quad (11)$$

The Axial force capacity for the tension section is given as;

$$F_{st} = 0.87 f_y A_s \quad (12)$$

Hence,

$$F_{st} = 0.87 f_y \rho bd \quad (13)$$

The percentage reinforcement ratio (ρ) was varied from the minimum of 0.55% to maximum of 3.00% with an interval of 0.55. From equation (11) and (13), the axial forces capacity is a function of the breath, effective depth, characteristics strength of concrete and steel, lever arm and the area of steel provided. The statistical data adopted for the analyses are as presented in Table 2.

3.4 Discussion of Modes of failure

The safety of a structure can be menstruated in terms of reliability index, β, or otherwise, its failure can by assessed by probability of failure, P_f. Probabilistic assessments were executed for electric power distribution concrete poles based on the extrapolated limit state equations. The results derived from reliability evaluation are discussed.

Figs.2 to 7 have been plotted to show the variation of reliability indices against height of the electric power concrete pole of 9 m high at different ρ under axial loading. It can be seen that the plots exercise similar tendency; the reliability indices increase with increase in height of the concrete pole from the base to about a height of 4.5m, it then drops drastically. This implies that the probability of failure of electric concrete poles at uncertain loading conditions is high at sections beyond 4.5m from the base. In fact, the failure can be catastrophic.

Fig. 8, presents the reliability indices comparison for the electric concrete pole at varying reinforcement ratio (ρ) from 0.55 to 3.00 as the height increases from base to the top. As ρ increases, there is a general increase in β to a height of about 4.5m beyond which β drastically drops for all ρ. This implies that the critical region of electric concrete pole is just beyond 4.5m because the section provided at this region is usually not enough.

In Fig. 9 the reliability indices at different reinforcement ratio for the tapered concrete pole against the various cross-sections are compared. At the ground level the cross-section is rectangular while the next five sections are I-section, and the last two sections are also rectangular. As the cross-section of a tapered electric concrete pole decreases with increasing height so does the reliability decreases. Therefore, on the basis of an assumed target reliability index, β_T, of 3.0 proposed by the Joint Committee on structural Safety [9], it implies that the cross-sections provided beyond 0.03m² are not enough to carry the axial load on an electric concrete pole. At any given reinforcement ratio, the reliability index increases with the cross-section before a gradual fall as the cross-section increases towards the base of the pole. At lower cross-sections, a reinforcement ratio less than 1.1 will lead to a reliability level lower than the assumed target level. Under axial loading condition, the tapered ends of electric concrete poles are extremely pruned to failure.

In order to examine the dependence of the reliability of an electric concrete pole on its geometry and resistance property, Fig. 10 was plotted. It can be seen that as the height of the concrete pole increases at any given reinforcement ratio, reliability indices decrease. Similarly, an increase in the reinforcement ratio at any height of the pole leads to an increased reliability index. It is obvious that geometry plays a significant role in the performance of electric concrete poles.

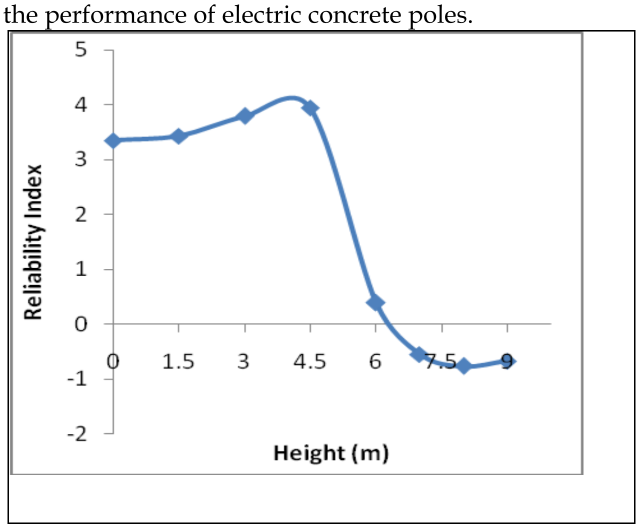

Fig. 2: Reliability Index at varying height for ρ=0.55

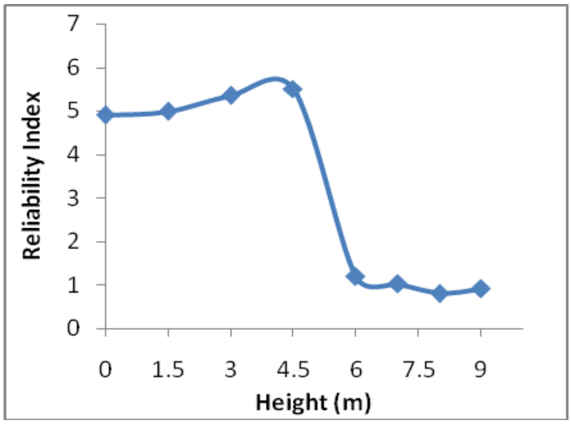

Fig. 3: Reliability Index at varying height for ρ=1.10

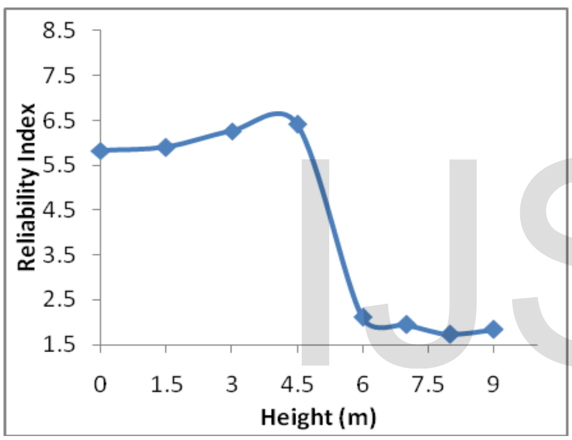

Fig. 4: Reliability Index at varying height for ρ=1.65

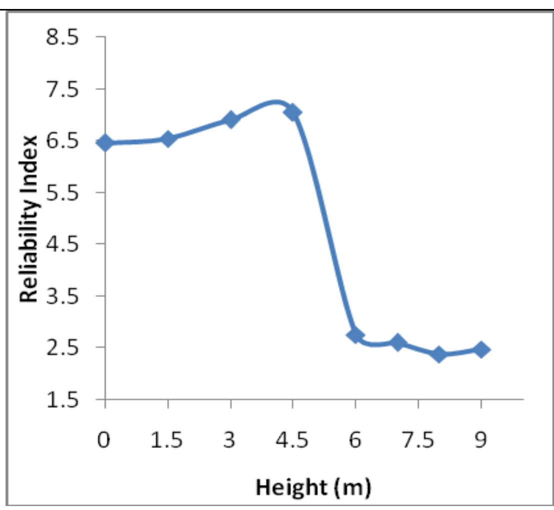

Fig. 5: Reliability Index at varying height for ρ=2.20

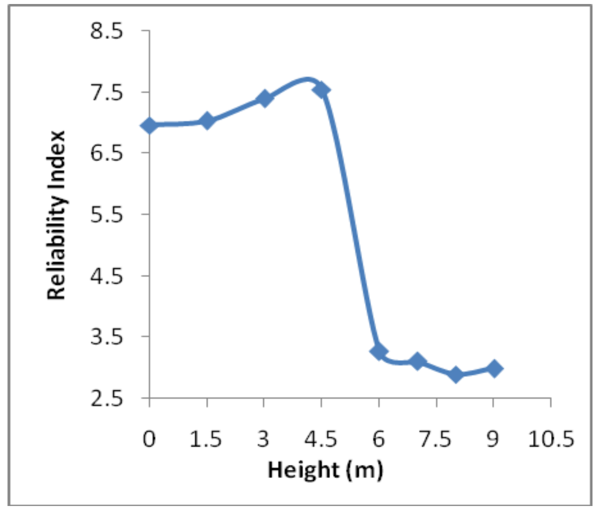

Fig.6: Reliability Index at varying height for ρ=2.75

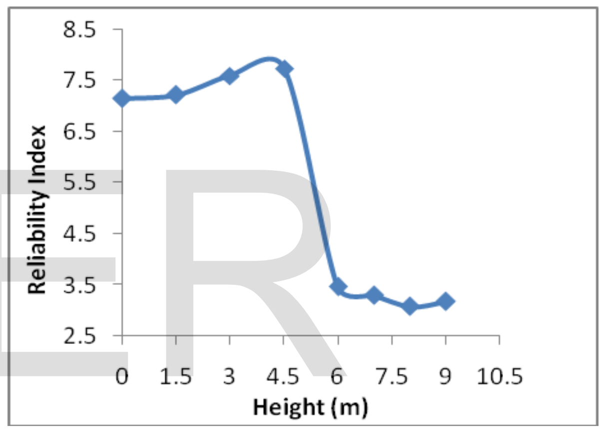

Fig.7: Reliability Index at varying height for ρ= 3.00

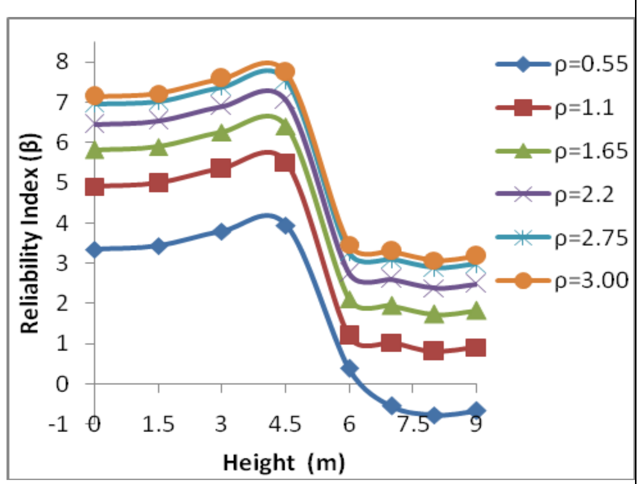

Fig. 8: Reliability Indices for the Concrete Pole at varying height under Axial load.

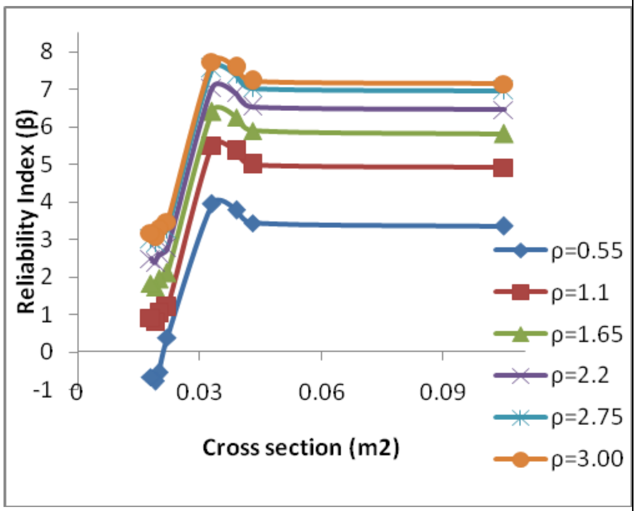

Fig. 9: Reliability Indices for the Concrete Pole at varying Cross-section under axial load.

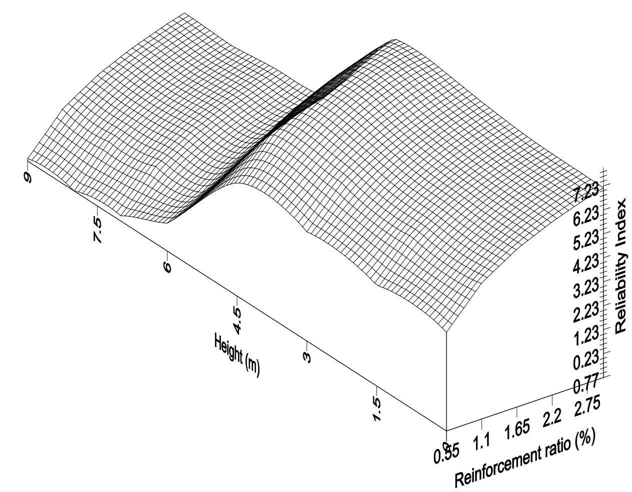

Fig. 10: 3-dimensional plot of Reliability Index, Reinforcement Ratio and the Height of Concrete pole for Axial Forces

4 Conclusion

The intrinsic reliability levels of tapered electric power distribution concrete poles have been found to be non-uniform over their height. The level of reliability increases as the reinforcement ratio increases but decreases as the height of the concrete pole increases. Due to the axial loads acting on the concrete pole, the probability of failure is significantly high at cross-section lower than 0.033m2 or at height greater than 4.5m. From the findings of this study, the use of First Order Reliability Method (FORM) in estimating the reliability of the concrete poles has shown area of weakness in their performance. Thus, adequate reinforcement should be provided where necessary most especially the weak areas to enhance the performance of the concrete poles, in addition, reliability assessment is advocated for newly designed facilities before construction is carried out.

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