Analysis of Stresses in Tapered Rectangular Utility Pole

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Abstract: Power transmission is generally carried out through electric cables supported by transmission pole (Utility pole) of various materials and cross sections. However, their utilization depends on climatic conditions and external loads acting on them. The forces comprise of wind pressure, tension in conductors and seismic vibrations due to earthquakes. These loads induce various stresses in the pole like bending, shear, crushing etc. There is a necessity for investigation of these stresses in the existing utility pole subjected to the loads acting on them. The objective of the paper is to study the stresses developed in the tapered rectangular utility pole made of Steel Reinforced Concrete material which is 8m in total length. The work includes the calculation of stresses in the existing poles made of three grades of concrete (namely M40, M45, and M50), four different load cases of pre stressing (zero or no pre-stress, with a pre-stress of 50%, 60%, and 75% of maximum allowable strength of steel reinforcement), under the effect of 185 kmph wind velocity. Theoretical and FEA of stresses were carried out and the results were compared. The 3D solid modelling of pole is carried out using SOLIDWORKS and imported into ANSYS 15.0 for calculation of stresses. It is observed that in either cases of RCC and PSCC, the stresses developed in the concrete cause failure of the pole. However, in case of PSCC, the stresses causing failure are less compared to RCC and may have longer life.

Keywords: Concrete, FEA, Pre-stress, Utility poles, Wind pressure

Reference: Kondapalli SivaPrasad and Chinthada Mankanteswar Rao, "Analysis of Stresses in Tapered Rectangular Utility Pole", Int J of Advanced Design and Manufacturing Technology, Vol. 11/No. 1, 2018, pp. 15-25.

Biographical notes: K.S. Prasad obtained PhD from Andhra University, India, in 2014. He is currently working as Associate Professor in Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India. His current research interest includes Manufacturing and product design. He received research funds from UGC, DST, AICTE of Government of India. He had published 84 papers in various journals and guided 60 MTech thesis. He served as Editorial Board member and reviewer for various international journals. **Ch. Mankanteswar Rao** is PG student of the Department of Mechanical Engineering, Anil Neerukonda Institute of Technology & Sciences, India.

1 INTRODUCTION

A utility pole is a structure secured into the ground and used to provide overhead support for public utility equipment like power lines, telephone wires and other types of communication cable, streetlights and traffic related equipment. These are often called as line supports because they are used to support transmission lines. These poles range in height and material namely wood, metal, reinforced concrete, composites based on the type and area of application. The basic requirements of a utility pole are high mechanical strength, light weight, longer life, Cheap in cost, economical to maintain and ease of accessibility. Generally, a pole acts as a cantilevered structure, which can be analyzed as a tapered member with combined axial and transverse loads.

Shoheb Ahemad and A. R. Mundhada [1] produced a comparative study on the design and cost analysis of three types of pre-stressed reinforced concrete poles. R. Ramesh Babu and R. Panneer Selvam [2] carried out comprehensive study involving tri-axial shake table testing and finite element analysis of low voltage distribution pole using NASTRAN. Sarah Zakaib and Amir Fam [3] proposed a hybrid system of concrete-filled fiber-reinforced polymer (FRP) tube (CFFT)-encased steel I-section which enhances flexural strength and stiffness, and provides a pseudo-ductile behaviour. Frank Dittmar and Habib Bahous [4] analyzed the advantages of spun pre-stressed concrete poles and realized that the key benefits include greater life expectancy, minimized maintenance costs, greater stability, major environmental benefits, and protection from vandalism, health and safety advantages, and lower costs over the entire life cycle of the product. When comparing all the previous works on the utility poles only few works presented above are available on poles made of concrete material.

The objective the paper is to study the stresses developed in the tapered rectangular utility pole made of Steel Reinforced Concrete material which is 8m in total length and calculation of stresses in the existing poles made of three grades of concrete (namely M40, M45, and M50), four different load cases of pre stressing (zero or no pre-stress, with a pre-stress of 50%, 60%, and 75% of maximum allowable strength of steel reinforcement), under the effect of 185 kmph wind velocity.

2 THEORITICAL ANALYSIS

2.1 Formulation of problem:

A Utility pole consists of a conductor carrying arm at 0.6m from tip. Conductors are supported by these arms which have considerable length and cross section depending upon the supply voltage through them. The pole is grounded to one sixth of its total length and act as cantilever beam in which one end is grounded and other end is subjected to load of conductors. The forces acting on a pole are, the vertical loading (comprising of dead weight of conductors, cross arms, insulators) and the Horizontal loading (due to wind pressure on conductors and pole)

2.2 Loads acting on the pole:

The pole is basically subjected to two types of loadings

2. 2. 1 Direct loading

The direct loads include

a. Wind load

b. Pre-stressing load

2. 2. 2 Indirect loading

The indirect loads include

a. Weight of the conductor

b. Wind load on conductor

c. Vortex shedding force

2. 3 Assumptions made in the formulation:

1. At limiting state, the maximum strain in concrete, which occurs at outermost compression fibre is 0.0035

2. The maximum strain in the tensile reinforcement at failure shall not be less than, $0.87\frac{f_y}{E_s} + 0.002$

3. Wind load on conductor and pole are considered according to the specifications mentioned in Indian Standards IS 875 (part 3):1987[5]

4. The modulus of elasticity for steel and concrete are constant and their properties are obtained from IS 456:2000[6] for concrete and IS 1785.2.1983[7] for steel reinforcement.

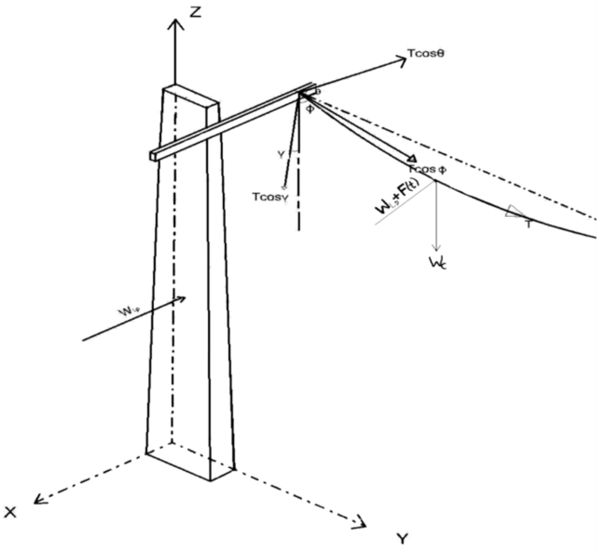

Fig. 1 Loads acting on the pole from all directions

2. 4 Calculations involved in stress analysis

2.4.1 Wind pressure P_z:

Considered wind velocity:

V_b = 185 kmph
= 51.388 m/s

The design wind speed:

$V_z = k_1\, k_2\, k_3\, V_b$

The factors $k_1\, k_2\, k_3$ are obtained from the IS 875:

As, Risk factor, $k_1 = 1.0$

Terrain factor, $k_2 = 0.868$
Topography factor, $k_3 = 1.0$
The design speed V_z $= k_1\, k_2\, k_3\, V_b$
= 1*0.868*1*51.388
= 44.6 m/s

The wind pressure P_z $= 0.6 * (V_z)^2$
$= 0.6 * (44.60)^2$
= 1193.79 N/m^2

2.4.2 Tension due to the weight in the conductor

The weight of the conductor:

W_C = (wt/km) * (conductor length)
= 2140 * 0.067
= 143.383 N

Inclination angle for the conductor during sag is:

$\alpha = cos^{-1}(\frac{67}{67.68})$ = 8.128 deg

Tension in the conductor due to self-weight:

$P = W_C * \frac{sin\alpha}{sin(180-2\alpha)}$
= 72.4189 N

2.4.3 Wind load on conductor W_{LC}

According to IS 875:

$W_{LC} = P_z * C_f * A_C$

Wind effective area of conductor span:

$A_c = D_c * L_c$
= 0.680184 m^2

The force coefficient C_f is obtained from the table 27 of IS 875 as:

$D*V_d = 0.4482 < 0.6$ m^2/s
$C_f = 1.2$

The wind load on conductor:

W_{LC} = 974.396 N

2.4.4 Vortex shedding force

$F(t) = \frac{1}{2} C\rho A_c\, V^2$
$C = (\frac{P}{\rho})^{\frac{1}{2}} = 0.163864$

Area of conductor:

A_c = 0.680184 m^2

Vortex shedding force:

$F(t) = \frac{1}{2} C\rho A_c\, V^2$
= 129.149 N

2.4.5 Total transverse force in z

$F_z = W_{LC} + F(t)$
= 974.396+129.149
= 1103.54 N

2.4.6 Tension in the conductor

Here the tension in the conductor can be obtained by equating its component in x- direction with the total force acting on conductor in that direction:

i.e., $\frac{2T\, z}{\sqrt{x^2+y^2+z^2}} = F_z$

Where:
The relation between the forces:

$\frac{z}{y} = \frac{\boldsymbol{F_z}}{\boldsymbol{F_y}} = \frac{1103.54}{143.383}$
= 7.696

$\sqrt{z^2 + y^2} = 4.261$

Solving the above:

(x, y, z) = (33.5, 0.595, 4. 5824)

Therefore:

T = 4072 N

Tension component along x-axis:

$\cos\theta = \frac{x}{\sqrt{x^2+y^2+z^2}}$ = 0.9906 degrees

$T_x = T\cos\theta = 4033.8$ N
$\cos\varphi = \frac{y}{\sqrt{x^2+y^2+z^2}} = 0.01759$
$T_y = T\cos\varphi = 79.6915$ N
$\cos\gamma = \frac{z}{\sqrt{x^2+y^2+z^2}} = 0.1355$
$T_z = T\cos\gamma = 551.7872$ N

2.4.7 Wind load on pole surface

The wind load on the pole surface above the ground level is given by:

$W_{LP} = (C_{pe} – C_{pi}) * A_p * p_z$
$= (0.85 – 0) * 1.4173 * 1193.79$
$= 1438.244$ N

This load will act the pressure centre of the pole:

C.G. = 3.008 m from ground

2.4.8 Load due to Pre-stressing

According to the IS 1785 part 2 the minimum ultimate tensile strength f_u of 4mm diameter steel wire is 1715 MPa:

Yield strength $f_y = 0.88\ f_u$
$= 0.88*1715$
$= 1509.2$ MPa

According to IS 1343:
Maximum allowable stress in steel reinforcement for pre stressing is:

$f_{max} = 0.87* f_y$
$= 0.87*1509.2$
$= 1313$ MPa

Three different pre stressing cases are considered in this work":

Case 1: 50% of f_{max}
$\sigma_{pre} = 0.5* f_{max}$
$= 0.5*1313$
$= 656.5$ MPa

$A_{st} = n * \frac{\pi}{4} * {d_c}^2$
$= 12 * \frac{\pi}{4} * 4^2$
$= 150.796\ mm^2$

Pre stressing load on wires:

$P_{st} = \sigma_{pre} * A_{st}$
$= 656.5 * 150.796$
$= 98997.574$ N

Compression load on concrete due to pre stress:

$P_c = P_{st}* \cos\beta$
$= 98997.574* \cos(1.0741)$
$= 98997.574* 0.999$
$= 98947.68$ N

Case 2: 60% of f_{max}

$\sigma_{pre} = 0.6* f_{max}$
$= 0.6*1313$
$= 787.8$ MPa

$A_{st} = n * \frac{\pi}{4} * {d_c}^2$
$= 12 * \frac{\pi}{4} * 4^2$
$= 150.796\ mm^2$

Pre stressing load on wires:

$P_{st} = \sigma_{pre} * A_{st}$
$= 787.8 * 150.796$
$= 118797.088$ N

Compression load on concrete due to pre stress:

$P_c = P_{st}* \cos\beta$
$= 118797.088* \cos(1.0741)$
$= 118797.088* 0.999$
$= 118737.26$ N

Case 3: 75% of f_{max}

$\sigma_{pre} = 0.75* f_{max}$
$= 0.75*1313$
$= 984.75$MPa

$A_{st} = n * \frac{\pi}{4} * {d_c}^2$
$= 12 * \frac{\pi}{4} * 4^2$
$= 150.796\ mm^2$

Pre stressing load on wires:

$P_{st} = \sigma_{pre} * A_{st}$
$= 984.75 * 150.796$
$= 148496.361$ N

Compression load on concrete due to pre stress:

$P_c = P_{st}* \cos\beta$
$= 148496.361* \cos(1.0741)$
$= 148496.361* 0.999$
$= 148421.52$ N

2.4.9 Total bending moment which causes the pole bend about x- axis

$M_x = W_{LP} * C_g + T_z * (H_g-0.6) + T_y * L_a$
$= (1438.24*3.008) + (551.7872)(6.07) + (79.6915)(0.3)$
$= 7696.952$ N-m

The moment of inertia of the pole at the ground (y=0) is given by as follows.

For tapered rectangular pole:

$$I_x = \frac{L_{bottom}\times t^3}{12}$$
$$= \frac{0.275\times 0.1^3}{12}$$
$$= 2.29167\text{E-05} \ldots\ldots \text{m}^4;\ y = \frac{t}{2} = \frac{0.1}{2}$$

The bending stress in y-direction is given by:

$$\sigma_b = \frac{M_x * y}{I} = \sigma_b$$
$$= \frac{7696.952*0.05}{2.29167E-05}$$
$$= 16793351.47 \ldots\ldots \text{N/m}^2$$

2.4.10 Compression stress developed in the pole in y direction

a. When there is no pre stress acting on the pole

Both Compression stress and bending stress develops in the pole as component of tension T_y acts eccentrically to the axis of pole (as conductor passes through arm at a distance of 0.3m)

Bending moment about x axis:

$= T_y * L_a$……N-m

Compression stress

For tapered rectangular pole:

$$\sigma_y = \frac{T_y}{L_{bottom} * t} = \frac{79.6915}{0.275*0.1}$$
$$= -3373.71764 \ldots\ldots \text{N/m}^2$$

(-ve, acts down ward direction)

b. When a certain amount of pre stress is acting on the pole

In addition to the load T_Z, the pre stressing load P_C will also act in the direction of pole axis and results in the stress given by

Compression stress:

i. *For 50% f_{max}*

$$\sigma_y = -\frac{T_y + P_C}{L_{bottom} * t}$$
$$= -4659735.129 \ldots \text{N/mm}^2$$

ii. *For 60% f_{max},*

$$\sigma_y = -\frac{T_y + P_C}{L_{bottom} * t}$$
$$= -5591007.412 \ldots \text{N/mm}^2$$

iii. *For 75% f_{max},*

$$\sigma_y = -\frac{T_y + P_C}{L_{bottom} * t}$$
$$= -6987915.835 \ldots \text{N/mm}^2$$

2.4.11 Combined stresses developed in the pole in y- direction

Total stress in the pole $\sigma = \sigma_y \pm \sigma_b$

Stress in the compression side of pole:

$$\sigma = \sigma_y + \sigma_b$$

For No Pre-stress:

σ = -3373.71764+16793351.47
= 16789977.75 N/mm^2

For Pre-stress of 50% f_{max}:

σ = -4659735.129 +16793351.47
= 12133616.338 N/mm^2

For Pre-stress of 60% f_{max}:

σ = -5591007.412+16793351.47
= 11202344.056 N/mm^2

For Pre-stress of 75% f_{max}:

σ = -6987915.835 +16793351.47
= 9805435.632 N/mm^2

Stress in the tension side of pole:

$$\sigma = \sigma_y - \sigma_b$$

For No Pre-stress:

σ = -3373.71764-16793351.47
= -16796725.185 N/mm^2

For Pre-stress of 50% f_{max}:

σ = -4659735.129 -16793351.47
= -214530.86.597 N/mm^2

For Pre-stress of 60% f_{max}:

σ = -5591007.412-16793351.47
= -22384358.879 N/mm^2

For Pre-stress of 75% f_{max}:

σ = -6987915.835 -16793351.47
= -23781267.303 N/mm^2

2.4.12 Shear stress acting on pole about xy – plane

Twisting Moment = T_x*0.3
= 1210.143 …. N-m

Polar moment of inertia:

$$J = I_x + I_y = \frac{{L_{bottom}}^3 * t}{12} + \frac{L_{bottom} * t^3}{12}$$

$$= 196.2166*10^{-6} \ \ldots\ldots\ m^4$$

Radius of curvature $R = \frac{0.1}{2} = 0.05$

Shear stress $\frac{T}{J} = \frac{\tau}{R}$

$$\tau_{xz} = \frac{T*R}{J}$$

$$\tau_{xz} = \frac{1210.143*0.05}{196.2166*10^{-6}}$$

$= 308369.1696$ …. N/m^2

3 MODELLING AND FEA

Utility pole's 3-D model was created using SOLIDWORKS 2013. A concrete body part and reinforcement pat consisting of 12 wires is created and assembled to generate the complete pole structure. This assembly model is used to create an IGES file and imported to ANSYS 15.0 to perform FEA. Concrete material is assigned to the body and high strength steel is assigned to the reinforcement. The boundary conditions and loads are given as a fixed support at the bottom, wind pressure on the pole, conductor loading and pre-stressing load at specified locations. The bending stress, shear stress and deflection developed in the pole for different pre-stress load conditions are solved and are shown below.

3.1 Bending stress plots at 185 kmph for concrete M40

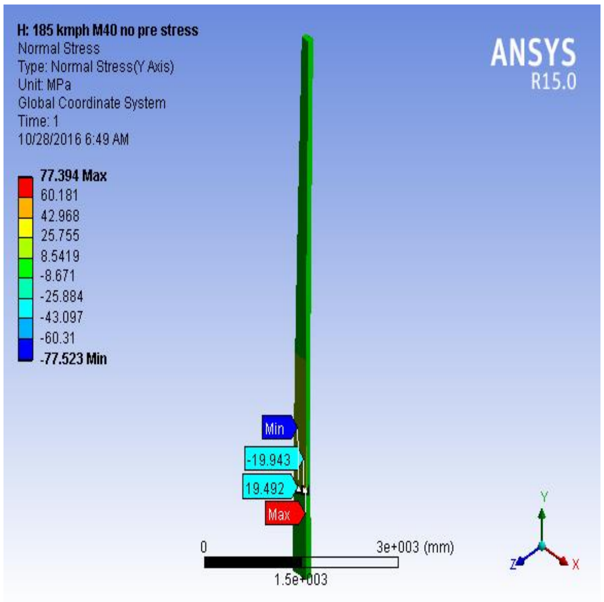

Fig. 2 σb for M40 no pre stress

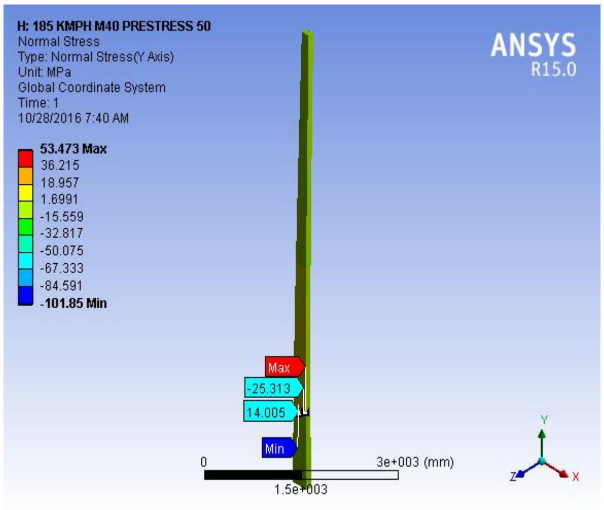

Fig. 3 σb for M40 50% pre stress

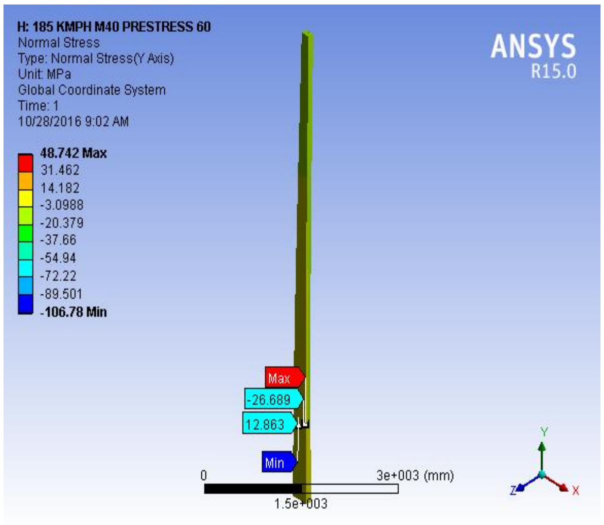

Fig. 4 σb for M40 60% pre stress

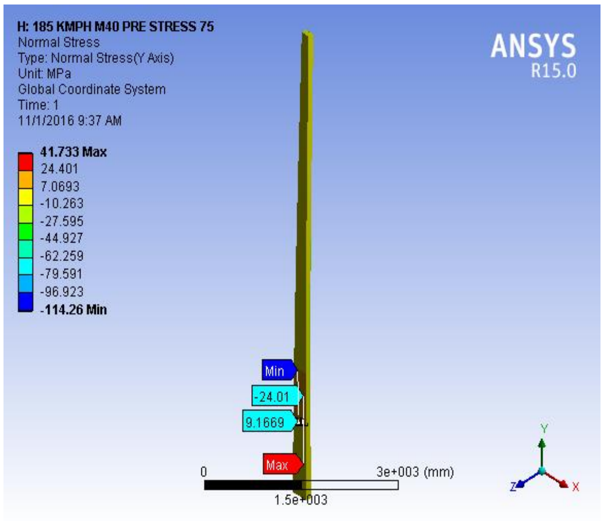

Fig. 5 σb for M40 75% pre stress

3.2 Shear stress plots at 185 kmph for concrete M40

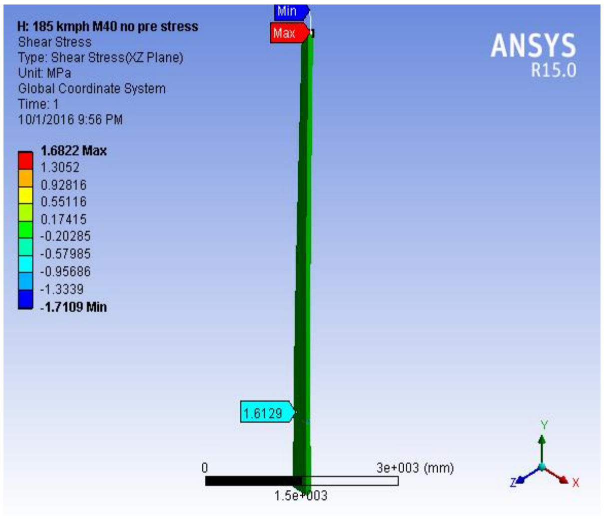

Fig. 6 τ_{xy} for M40 no pre stress

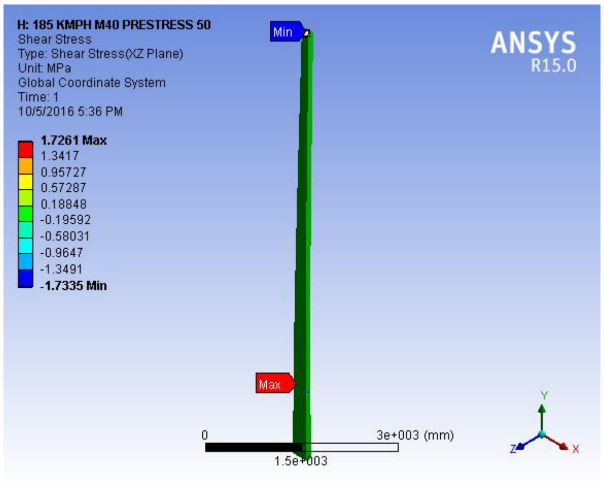

Fig. 7 τ_{xy} for M40 50% pre stress

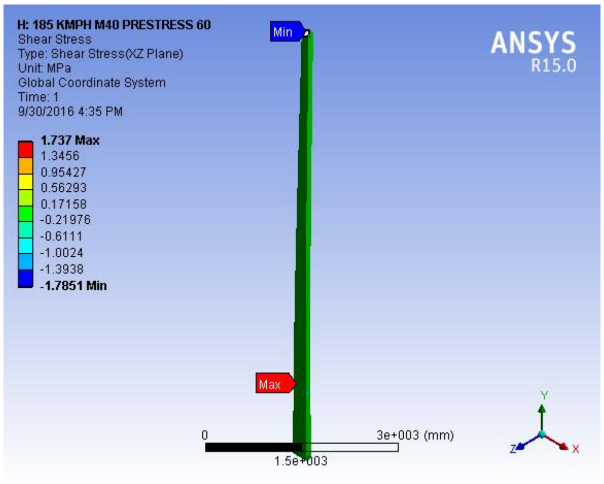

Fig. 8 τ_{xy} for M40 60% pre stress

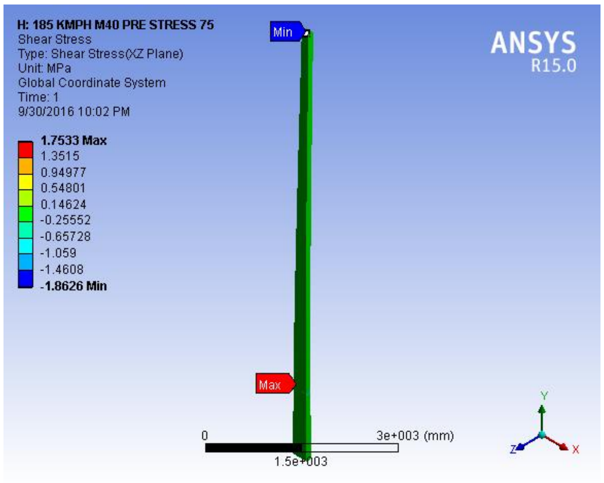

Fig. 9 τ_{xy} for M40 75% pre stress

3.3 Maximum principal stress plots at 185 kmph for concrete M40

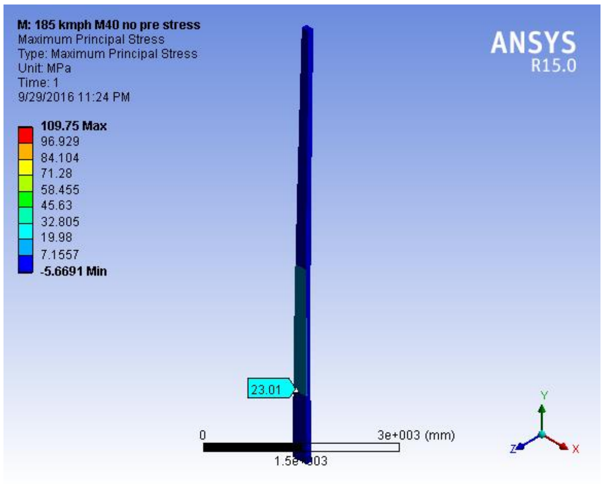

Fig. 10 σ_{max} for M40 no pre stress

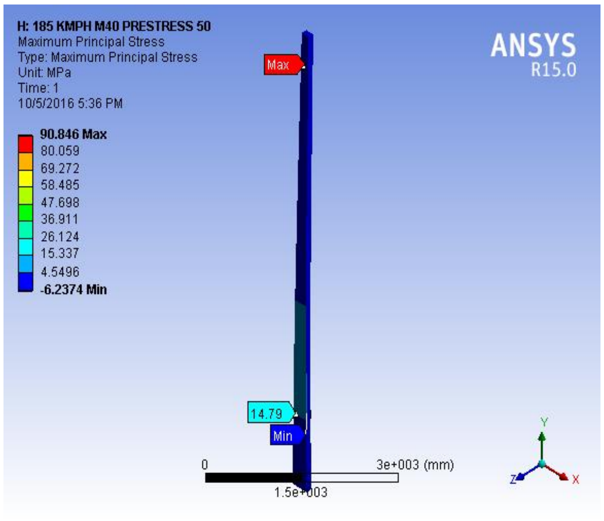

Fig. 11 σ_{max} for M40 50% pre stress

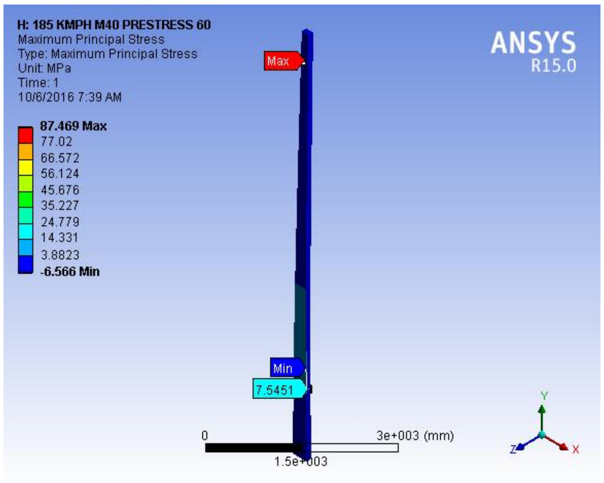

Fig. 12 σ_{max} for M40 60% pre stress

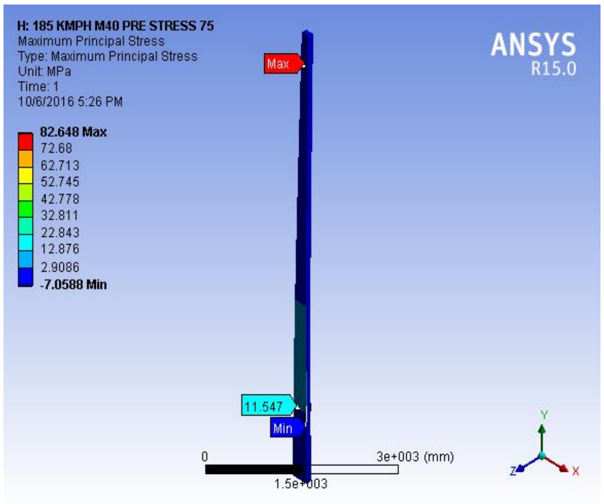

Fig. 13 σ_{max} for M40 75% pre stress

3.4 Equivalent Von-Mises stress plots at 185 kmph for concrete M40

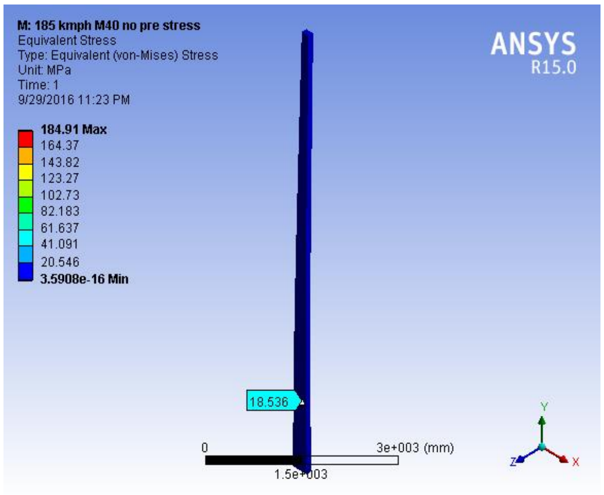

Fig. 14 σ_e for M40 no pre stress

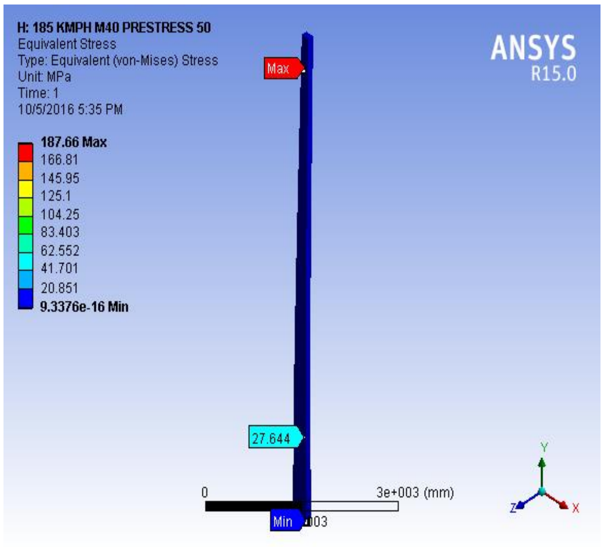

Fig. 15 σ_e for M40 50% pre stress

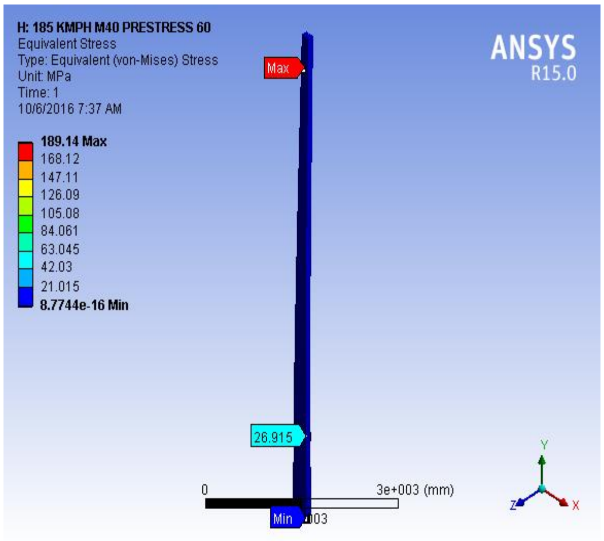

Fig. 16 σ_e for M40 60% pre stress

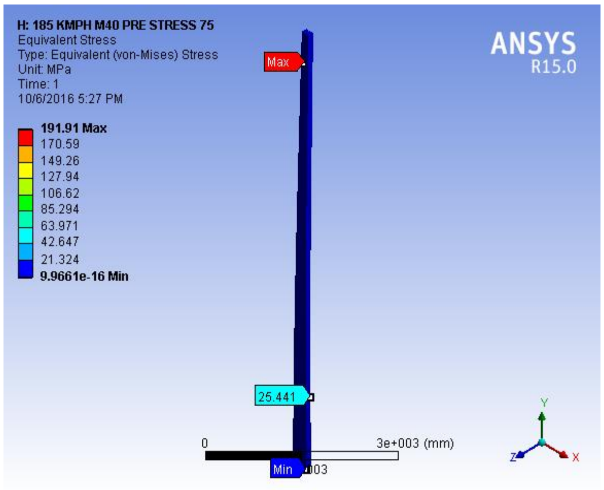

Fig. 17 σ_e for M40 75% pre stress

3.5 Total deformation plots at 185 kmph for concrete M40

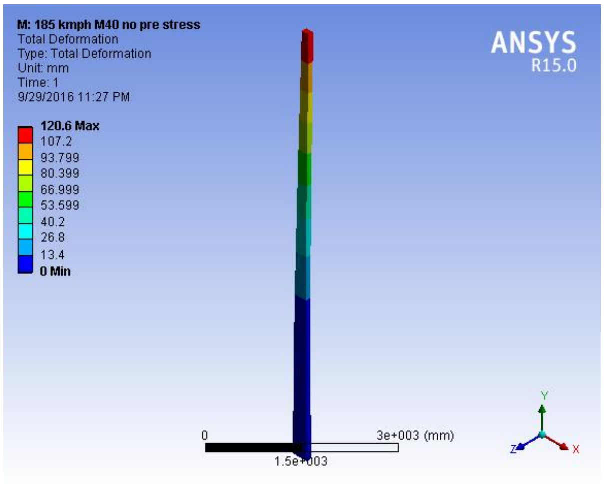

Fig. 18 δ for M40 no pre stress

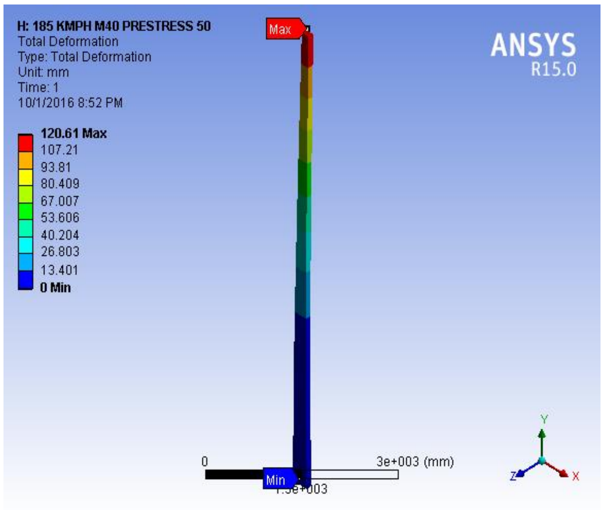

Fig. 19 δ for M40 50% pre stress

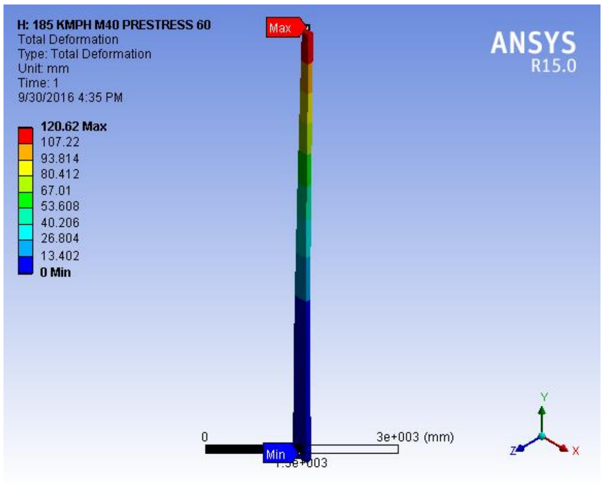

Fig. 20 δ for M40 60% pre stress

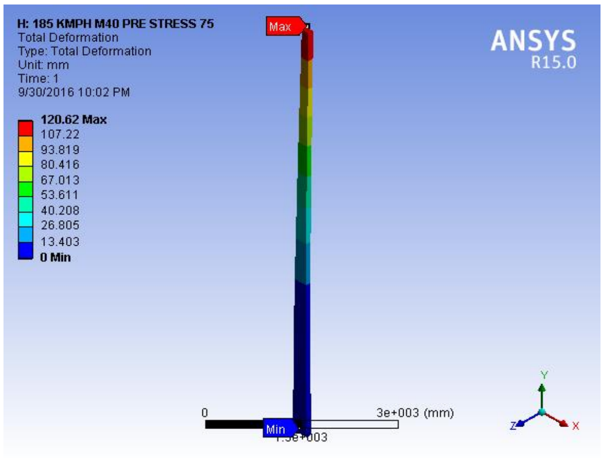

Fig. 21 δ for M40 75% pre stress

4 RESULTS & DICUSSIONS

The theoretical analysis carried out on the pole bending stresses developed for different load cases at wind velocity of 185 kmph are given in Table 1 as below:

Table 1 Theoretical stresses developed in pole for all Pre-stress cases

Load case % f_{max} of pre-stress	Stress due to Pure bending	Pre-compressive stress	Combined bending stresses	
	σ_b (MPa)	σ_y (MPa)	$\sigma_{tensile}$ (MPa)	$\sigma_{compressive}$ (MPa)
0% f_{max}	16.7934	-0.0034	16.7900	-16.7967
50% f_{max}	16.7934	-4.6597	12.1336	-21.4531
60% f_{max}	16.7934	-5.5910	11.2023	-22.3844
75% f_{max}	16.7934	-6.9879	9.8054	-23.7813

The values of bending stress obtained theoretically are compared with the values of bending stress obtained from the FEA conducted using ANSYS. The bending stress values obtained from FEA for three different poles at all four load cases are given in Table 2 as below:

Table 2 Bending stresses obtained in FEA for all Pre-stresses

Load case % f_{max} of pre-stress	Pole 1 Concrete M40		Pole 2 Concrete M45		Pole 3 Concrete M50	
	σ_t (MPa)	σ_c (MPa)	σ_t (MPa)	σ_c (MPa)	σ_t (MPa)	σ_c (MPa)
0% f_{max}	19.942	-19.943	18.184	-18.325	20.474	-20.437
50% f_{max}	14.005	-25.005	13.171	-27.116	14.141	-24.79
60% f_{max}	12.863	-26.689	11.877	-21.587	13.429	-27.295
75% f_{max}	9.1669	-24.01	10.003	-23.662	10.176	-23.419

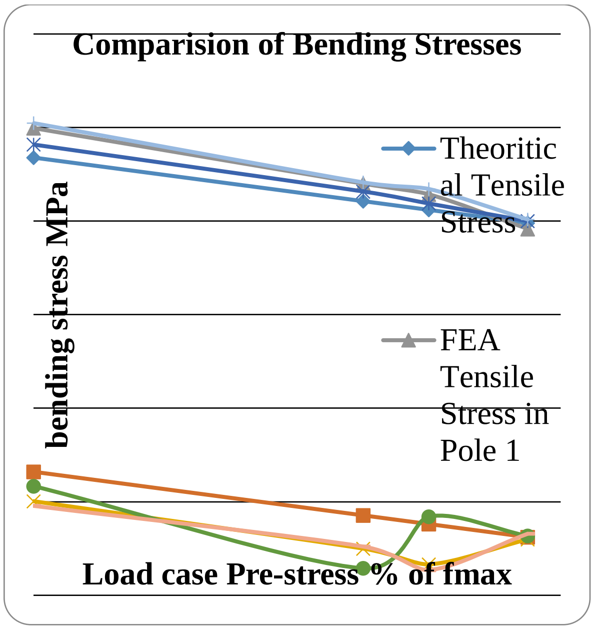

Fig. 22 bending stress developed in the pole by theoretical analysis and FEA

From the above graph, it is observed that the bending stress calculated theoretically and evaluated by using FEA shows a very close matching and the slight deviations observed are less considered.

While comparing these results with the limiting stress values of concrete both, in tension f_{cr} (4.427 MPa for M40, 4.695 MPa for M45, and 4.949 MPa for M50) and in compression $0.44f_{ck}$ (17.6 MPa for M40, 19.8 MPa for M45, and 22 MPa for M50), it is observed that as the wind velocity approaches 185 kmph, both tensile and compressive stresses exceed the limiting stress values of concrete and eventually lead to the failure in tension fibers and then crushing in the compression fibers.

From the calculations, it is observed that the pre-stressing has a considerable effect in reducing the stress in tension fibers of pole under loading. The pre-tensioning load given to the reinforcement tendons develops an initial compression stress in the concrete and lead to the reduction in tensile stress developed due to external loading.

It is evident that the developed FEA model of 8m utility pole by ANSYS Workbench can be used for the evaluation of other stresses developed and the deflection can be obtained.

FEA is used to evaluate the equivalent stress, maximum principle stress shear stress and the deformation developed in the pole for all four pre-stress cases (0, 50%, 60%, 75% of f_{max}), using three different materials (M40, M45, M50) are evaluated. The values obtained are tabulated below.

Table 3 Stresses and deflection obtained in the poles 1, 2, and 3 using FEA

Pole type	Load case	Equivalent stress σ_e (MPa)	Principal stress σ_{max} (MPa)	Shear stress Τ (MPa)	Deflection δ (mm)
Pole 1 (Concrete M40)	0% f_{max}	184.91	23.01	1.6822	120.6
	50% f_{max}	187.66	14.79	1.7261	120.61
	60% f_{max}	189.14	13.545	1.737	120.62
	75% f_{max}	191.91	11.547	1.7533	120.62
Pole 1 (Concrete M40)	0% f_{max}	183.94	21.606	1.6763	114.07
	50% f_{max}	187.69	13.369	1.7415	114.09
	60% f_{max}	187.69	13.353	1.7415	114.09
	75% f_{max}	190.18	11.525	1.7578	114.1
Pole 1 (Concrete M40)	0% f_{max}	182.99	22.929	1.6803	108.35
	50% f_{max}	185.16	13.73	1.7345	108.54
	60% f_{max}	186.35	13.46	1.7454	108.54
	75% f_{max}	188.61	11.76	1.7616	108.55
	0% f_{max}	182.99	22.929	1.6803	108.35

From the above table it is observed that the amount of pre stress applied has a considerable effect on the stresses developed in the concrete. The maximum principle stress in the concrete and the deformation are reducing with increase in pre stress. The equivalent stress developed in the steel is far less than maximum permissible stress.

5 CONCLUSIONS

The work conducted so far gives the following conclusions

1- The bending stresses developed in the pole for all different wind velocities in both theoretical and FEA have a close match where the difference in the values is due to inaccuracy of the procedure followed.

2- Therefore, the analytical model developed can be used for the purpose of design modification and evaluation of other factors.

3- The deflection of the pole decreases with increase in the grade of concrete used for the RCC pole construction.

4- The stresses causing failure of the pole can be reduced by introducing Pre-stressing of the RCC pole by using pre tensioning of high strength steel reinforcement. This structure is termed as Pre stressed Cement Concrete (PSCC).

5- Pre stressing of the concrete for the construction of pole have the following advantages:
Reduction of the tensile stress developed due to bending.
Increase in the flexural strength
Increase in the shear strength
Durability of the pole may be achieved.

6- It is observed that in either cases of RCC and PSCC, the stresses developed in the concrete cause failure of the pole. However, in case of PSCC, the stresses causing failure are less compared to RCC and may have longer life.

REFERENCES

[1] Shoheb A., Mundhada, A. R., “Comparative Study of Pre-Tensioned Pre-Stressed Concrete Electric Poles of Type I, II & III”, International Journal of Emerging Technology and Advanced Engineering. 2013, Vol. 3, No. 12, pp. 594-598.

[2] Ramesh Babu, R., Panneer Selvam, R., “Earthquake Resistance Capability of Distribution Pole”, 2012, 15 WCEE, Lisboa, pp. 1-7.

[3] Zakaib, S., Fam, A., “Flexural Performance and Moment Connection of Concrete-Filled GFRP Tube–Encased Steel I-Sections”, Journal of Composites for Construction, ASCE.2012, Vol. 16, No. 5, pp. 604-613.

[4] Dittmar, F., Bahous, H., “Spun Pre-Stressed Concrete Poles: Alternative to Wooden and Steel Poles for Low”, Medium, and High Voltage, C I R E D, 21st International Conference on Electricity Distribution Frankfurt, 2001, Paper 0392, pp. 6-9.

[5] IS 875.3.1987: Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures, Part 3: Wind Loads [CED 37: Structural Safety.

[6] IS 456.2000: Plain and Reinforced Concrete - Code of Practice.

[7] IS 1785.1.1983: Plain hard-drawn steel wire for prestressed concrete, Part 2 as drawn stress- wire.