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Effect of Wind Loading on Analysis of Natural Draught Hyperbolic Cooling Tower

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Abstract-_Natural draught cooling towers are very common in modern days thermal and nuclear power stations. These towers with very small shell thickness are exceptional structures by their sheer size and sensitivity to horizontal loads. These are the hyperbolic shells of revolution in form and are supported on closely spaced inclined columns. Wind loading on NDCT governs critical cases and requires research. This paper emphasize on effect of wind on Natural draught hyperbolic cooling tower. The slenderness of the columns and the large dimensions of the shell make these structures vulnerable to earthquake and wind disturbances. In this work efficient Analysis & design of cooling tower is presented with V- shape configuration of Raker column. Finite element modeling of cooling tower shell is done which divide shell into number of plates to apply wind loading on each plate. Gust method and Peak wind Methods are adopted to apply wind load. For this purpose models are workout on Staad Pro V8i to give comparative results of analysis, design and constructability. Effective wind analysis can be done with the help of this methodology.

Keywords – hyperbolic cooling tower, nonlinear inelastic behavior, principal stresses on shell, dynamic Stresses, finite element analysis

I. INTRODUCTION

A. Natural Draught Hyperbolic Tower:

A cooling tower is an enclosed device, designed for the evaporative cooling of water where hot water gets cooled by direct contact with air. Towers are divided into two main types, the first being named natural draught cooling towers and the second mechanical draught cooling towers. In natural draught tower, the circulation of air is induced by enclosing the heated air in a chimney which then contains a column of air which is lighter than the surrounding atmosphere. This difference in weight produces a continuous flow of air through the cooling tower as long as water at a temperature above the wet bulb temperature is circulated through the cooling tower. NDCT makes use of the stack effect of a chimney above the packing to induce air flow up through the packing in counter-flow to the water.

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Silent features & advantages of natural draught cooling tower are given below:

- Low maintenance costs, much better performance than cooling frames but not suitable for high dry bulb air temperatures since.
- Water inlet temperature must be higher than air dry bulb.
- Seldom applicable to air conditioning. Close approach cooling not possible.
- Capital cost may be high owing to great height necessary to produce the draught.
- Exact outlet water temperature control is difficult.
- Used mainly for large cooling duties, e.g. Power stations.

The wind forces acting on the structure are random in nature. The main loading case for natural draught cooling tower of reinforced concrete is produced by wind forces apart from some cases where earthquake forces have to be considered. Such loads are commonly treated as quasi-static in conventional design practice. The Quasi-static wind loading may be defined as,

$$Qz = Kz\ G\ q_{30} H_{\theta}$$

Where,
Qz= effective velocity pressure at height z above ground level
Kz = an exposure factor that establishes the vertical profile of the wind speed
H_θ = coefficient of circumferential distribution of wind pressure which is determined on the basis of test results.

Wind effects on cooling towers like axisymmetric shell structures are characterized by presence of large steady-state components and a significant random component due to air turbulence. The structural response is static and dynamic. The calculation of static response is straight forward. The dynamic response is random process, and its calculations have to be based on rather complicated multiple random excitation by the fluctuating pressure. Therefore it is desirable for practical design purpose, to use an equivalent static design loads.

B. Influence of Wind Shear

The code of practice proved insufficient in many respects for the design of cooling towers. The static wind load is defined as long term average of the fluctuating pressure on the cooling tower surface. The distribution of the mean pressure, especially along the circumference, is influenced by the Reynolds number, surface roughness and wind profile. For design wind speeds, the Reynolds number, R of cooling tower is trans-critical (R > 10^8, based on the diameter). Surface roughness reduces the maximum suction in the sides of the tower.

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This leads to the magnification of the total resistance but nevertheless to the reduction of the maximum meridional stress resultant. Therefore, additional surface roughness such as meridional ribs is beneficial and used frequently. The mean pressure varies with height 'z' and angular coordinate θ.

C. Wind Stresses

The dynamic nature of wind loading is now well recognized. The structural response to wind is a function of the wind (e.g., velocity and turbulence), the structure, (e.g. stiffness, mass, damping) and the wind structure-interaction. Significant progress has been made to understand this complex phenomenon. Cooling tower response is governed by both vertical and circumferential wind distribution. Experimental result on cooling tower models has shown that dynamic stresses are of same order as static stresses. Current design practice for cooling tower doesn't allow for dynamic stresses. The vertical reinforcement in cooling tower is usually governed by the difference in tensile wind stresses and compressive dead load stresses. This difference is very sensitive to small changes in wind stresses. With the cooling tower becoming taller and relatively thinner than before, the need for a rational dynamic wind analysis becomes evident.

D. Static and Dynamic Stresses

A convenient way of dealing with wind stresses is to divide them into static stresses based on the reference value of hourly mean wind speed (which is stable measure) and dynamic stresses which is take into fluctuating wind components and towers structural properties and configurations. The static wind pressure distribution is largely depends on Reynolds number and surface roughness. The effect of these factors on cooling tower has been studied experimentally in wind tunnel. With respect to measurement of forces that might be expected to act on the tower during a windstorm, two general approaches have been followed:

1. Wind tunnel studies
2. Full scale measurements.

Full scale result indicates significantly smaller suction than wind tunnel models due to considerable difference in Reynolds number. While wind tunnel models indicate significant influence of surface roughness on pressure values at low Reynolds number.

II. GEOMETRY AND METHODS OF ANALYSIS

A. Introduction:

The structural analysis of large cooling lowers exist different computation techniques developed to obtain the shell stresses with sufficient accuracy. Natural draft cooling towers are mostly designed as thin shells supported along the circumference by a system of columns. Hyperbolic, natural-draught cooling towers to be erected in seismically active zones are routinely analysed for earthquake excitation. Thus the earthquake safety of natural-draught cooling towers grows more important. The response of cooling towers assuming rigid-base translation excitation can be approximated by beam elements with shear distortion and rotary inertia. Shell structures have many applications including cooling towers, liquid-retaining structures and roofs where large uninterrupted space is required. These structures are aesthetically pleasing, make efficient use of construction materials and can economically meet design criteria. A number of serious failures of shell structures during the last century has led to significant research into their behaviour, analysis, design and construction. Despite this, further research is still required to improve design, especially with respect to shell dynamics. While some research on free vibration has been carried out, very little or none has been documented to date on the response to earthquake loading. In earlier research carried out by the authors, it has been shown that the hyperbolic shape is very efficient for use as an axisymmetric shell. In view of this and other existing information, this paper treats the free vibration and seismic response of hyperbolic shells, and examines the influence of thickness, height and curvature on this response. It is found that the period of vibration decreases approximately linearly with increasing curvature, but at high curvatures this trend reverses. The early periods of the circumferential mode of vibration are also found to vary linearly with changes of height and thickness, with increasing thickness reducing the period and increasing height increasing the period. The response of the first lateral mode is also significantly affected by a change in the parameters. Transient earthquake analysis shows that height is the most important factor governing the dynamic response. However, significant changes in hoop and Meridional stresses are also observed for structures with different shell thickness and curvature. Analysis has been undertaken using the finite element method, and results are presented in tabular and graphical format.

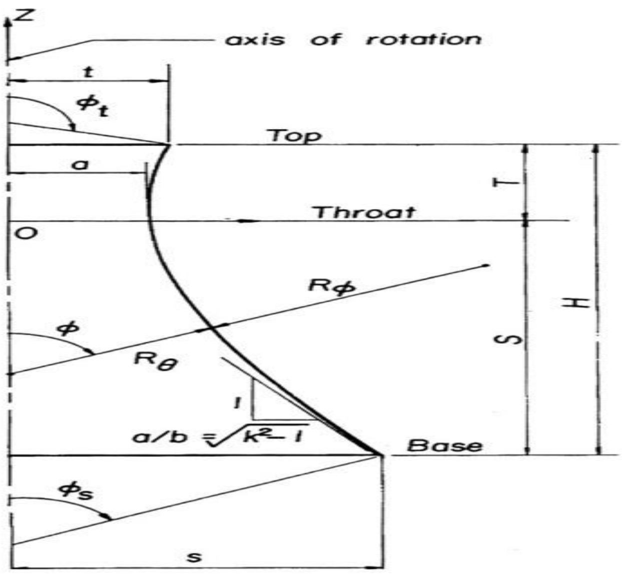

Fig. 2.2 Hyperbolic Curve Generator and Typical Nomenclature

Axisymmetric shell structures, generated by rotating a plane curve generator around an axis of rotation to form a circumferentially closed surface, have many applications such as hyperbolic cooling towers, cylindrical or conical liquid-retaining structures and spherical dome roofs. These structures are thin, and due to their curvature, are not only aesthetically pleasing but also have adequate strength. Though hyperbolic shells have been extensively used as cooling towers, they can also be used efficiently for other purposes.

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Previous studies have shown that the hyperbolic shape is the most economical solution for axisymmetric shells, and more attractive than a polynomial shape. Much research into the behavior of hyperbolic axisymmetric shell structures has been carried out since the development of the finite-element method. Areas of interest during the last few decades have included static and pseudo-static effects of wind and earthquake loading, thermal effects, structural stability, non-linear analysis, durability, limit-state loading, construction material and techniques, foundation settlement and idealization of the supporting members at the base. This previous research has concentrated on shell behavior under static loading, with dynamic loads being modeled as equivalent static loads, and hence providing limited knowledge on the dynamic behaviour. It has already been established that the hyperbolic shape is the most economical solution of axisymmetric shells under various combinations of static loading, namely

(i) Self-weight and static wind loading, and

(ii) Self-weight, static wind loading plus liquid pressure.

Curvature, height and shell-wall thickness are important parameters for such structures. The effect of these parameters on free vibration response has been studied, and dimensional analysis carried out to develop empirical relationships for calculating fundamental frequencies of hyperbolic axisymmetric shell structures within a height range of 100 to 200 m, Seismic response of axisymmetric shells has also been briefly investigated [38] under two earthquakes. This paper discusses the response of hyperbolic axisymmetric shell structures to free and forced vibrations, with variations in shell thickness, height and curvature. Dynamic response under Tenant-Creek and El-Centro earthquakes, and under simulated sinusoidal early excitations with different time periods, has been investigated. Results have been presented in tabular and graphical format.

B. *Finite-Element Analysis and Model Verification:*

The hyperbolic shell structure examined as a starting point was based upon an existing cooling tower at Stanwell Power Station, located west of Rockhampton in Queensland (Australia), and shown in Fig. 1. This is a 121.5 m-high cooling tower with base, throat and top radii of 45.30 m, 27.89 m and 29.02 m respectively, with the throat located 95.6 m above the base of the shell. A constant shell-wall thickness of 240 mm, and reinforced concrete with a unit weight of 25 kN/m3, Poisson's ratio of 0.2 and elastic modulus of 39 GPa were considered for the finite-element numerical model. A hyperbolic shell is a surface with negative Gaussian curvature, as shown in Fig.2. The equation of the generating curve of a hyperbolic shell of revolution is expressed as,

$$\frac{r^2}{a^2} - \frac{H^2}{b^2} = 1$$

in which r is the radius of a parallel circle, a is the throat radius, H is the total height of the structure, and b is the characteristic dimension of the shell study has considered seismic response. Seismic loads are modeled in the finite-element time-history analysis as ground accelerations applied at the base of the structure, and the response is analysed by direct integration using time-history records. The time step in numerical integration is set to be at most 0.1 times the period of the highest mode being considered, in order to include the contribution of all modes up to that. However, it must be realized that the seismic effects are highly random, and that any two earthquakes can have different dominant component frequencies.

A. *Description of the Structure*

Minimum thickness of shell (t) = 0.27 m
Thickness of shell at top (t) = 1.00 m
Thickness of shell at ring beam bottom (t) = 1.4 m
Height of cooling tower (H) = 172 m
Height of cooling tower up to through level (H_T) =129m
Height of cooling tower up to air gap (H_A) =8.5 m

Design Parameters

Diameter of cooling tower mentioned here are inside diameter at respective levels

Item	Level(m)	Inside Diameter (m)
Sill	0	130
Throat	129	78
Top	172	79.8

Wind Loading

Basic wind speed (V_b) = 47 m/s
Pressure Coefficient =1.25
Pressure Coefficient including 10 % for shell imperfection =1.375

Design Coefficients

Risk Coefficients (K1) =1.08
Terrain Coefficient (K2) = 0.9776 (Terrain category – Type 1, Class C)
Topography Factor (K3) = 1

Wind pressure distribution coefficients

(As per Appendix A, pg-13, IS:11504-1985)

a_0 = -0.00071
a_1 = 0.24611
a_2 = 0.62296
a_3 = 0.48833
a_4 = 0.10756
a_5 = -0.09579
a_6 = -0.01142
a_7 = 0.04551

Seismic Loading

Damping Factor = 5%
Zone factor for zone III = 0.16
Response reduction factor (R) = 3
Importance Factor (I) = 1.5
Average response acceleration coefficient for 5 percent damping depending upon fundamental period of vibration T (Sa/g)

For Shell
Minimum Lap length =1.3 x Ld
Minimum anchorage length = 2x Ld

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B. Input for Geometry

- Slope of the shell at ring beam(S) =0.3
- Basin wall depth up to top of pond floor (P_h) =2.1m
- Pitch of diagonal columns at their top (C_{top})=2m
- Pitch of diagonal columns at sill level (C_{bot})=1.10m
- Total no of diagonal column pairs (N_{rc}) =52
- No of lifts in the top console (N_c) = 2m

Hyperbola constants for shell below throat:

a = 30.55
b = 82.63
d = 8.45

Hyperbola constants for Shell above throat:

D_{ti} = Diameter at top of console =79.8m
R_{ti} = Radius at top = 39.9 m
d_1= 38.875
b_1= 0.125
d_1= 5.289

C. Hyperbolical Profile of Cooling Tower

Cooling tower profile is divided into two parts: 1. Upper Hyperbola 2. Lower Hyperbola. The separation of the profile is at throat level; according to the upper and lower part of throat level. Coordinates of hyperbolic profile depends upon the lift height of the shell which is generally taken 1.5 m. Shell is divided into 52 parts horizontally & 112 parts vertically Diameter has to be determine according to equation of hyperbola. Coordinates of hyperbolic profile is determined with help of excel sheet.

Equation of hyperbola is as follows:

$$\frac{(x-d)^2}{a^2}-\frac{y^2}{b^2}=1$$

D. Finite Element Model of Hyperbolic Cooling Tower

Finite element model was prepared with the help of a coordinates mentioned in previous module. Configuration of Raker column is in V shape generated with the help of Staad Pro V8i Software. 3D and render view of a finite element module of cooling tower is shown below.

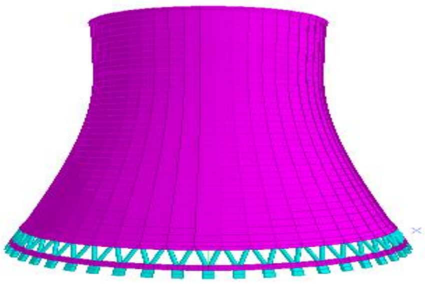

Fig. 4.1 Finie Element Model of a Hyperboli Cooling Tower

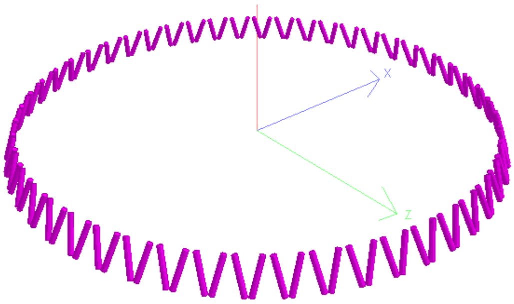

Fig. 4.3 V Shape Configuration of Racker Column of Cooling Tower

Loading on NDCT:

Four types of loading considered as follows:

a. Dead Loading
b. Wind Loading
c. Seismic Loading
d. Thermal Loading

III. WIND LOAD CALCULATIONS ON NDCT

Wind Pressure for the design of a structure above foundation is calculated with the help of Peak Wind Method and Gust Factor Method.

A. Gust Factor Calculations:

Gust Factor

(Refer Cl. 8, Pg. 49, IS: 875 (Part3) - 1987)

Gust factor is calculated using following formula:

$G = 1 + gf \times r \times [B(1+f)^2 + (S \times E)/b]^{1/2}$

Damping coefficient (β)

(Refer Table 34, Pg. 52, IS: 875(Part3)-1987)

Damping coefficient (As a fraction of critical damping) of the structure:

$$\beta = 0.016$$

Gust Factor calculated from the above parameters:

G = 1 + gf x r x [B(1+f)2 + (S x E)/b]1/2
=1.601

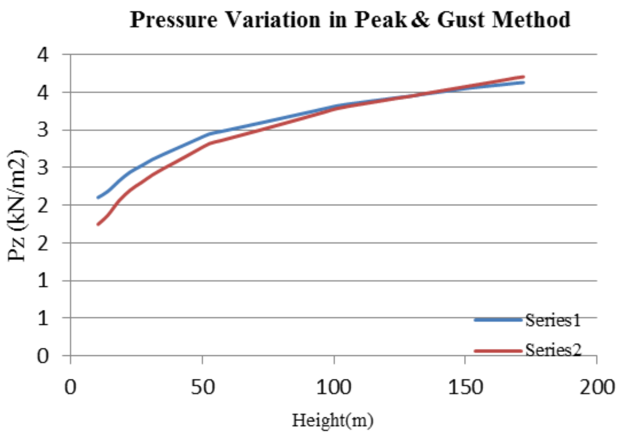

Fig. 4.4 Comparison between Pressure Intensity from Peak Wind Method and Gust Factor Method

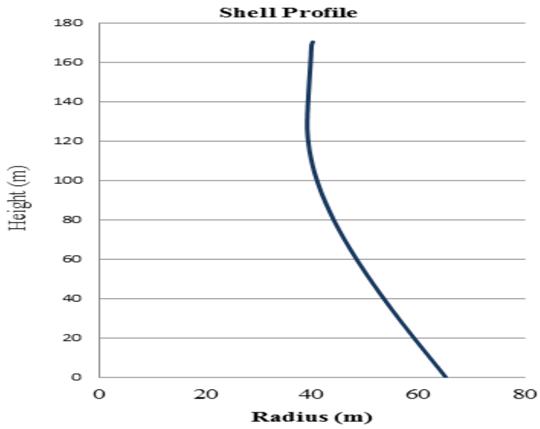

Fig. 4.5 Hyperbolic Profile of Cooling Tower

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B. Circumferential Net Wind Pressure Distribution

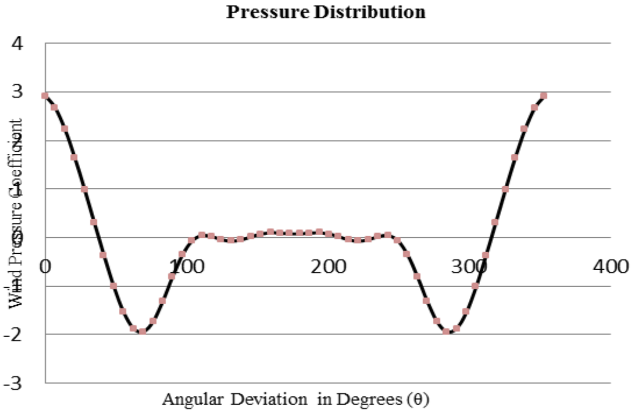

Fig. 4.7 Circumferential Net Wind Pressure Distribution

C. Maximum Forces Developed At Throat Levels:

Variation of S_x in kN/m^2 along Height :

The graph below represent the variation of Shear stress along Circumferential direction. Comparison between Maximum and minimum Shear stress variation in X direction gives that Stresses at top console and raker column have maximum impact to provide more steel .

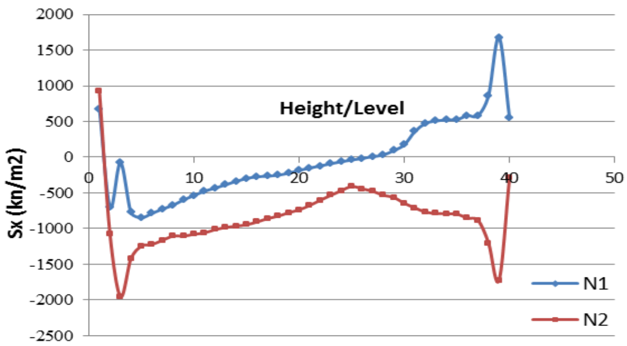

Fig. 4.8 Max. and Min. Membrane Stresses along Height in X Direction

Variation of S_y in kN/m^2 along height:

The graph below represents the variation of Shear stress along Height direction. Comparison between Maximum and minimum Shear stress variation in Y direction is compared. Maximum stress will occur at throat due to impact of wind loading.

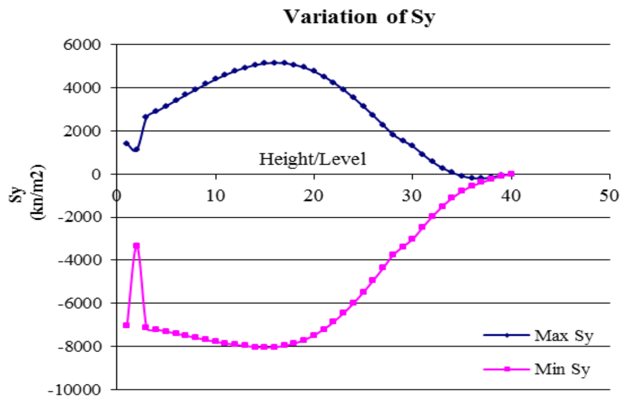

Fig. 4.9 Variation of Max. Sy and Min. Sy (Membrane Stresses) in Y Direction

D. Variation of Analysis results

a) Variation in inplane Shear
b) Variation in twisting moment along height
c) Variation in maximum and minimum principle stress along height.

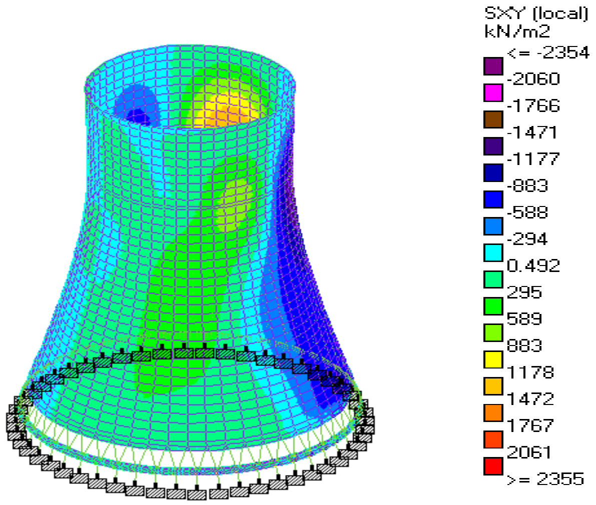

Fig. 4.9 Variation of Inplane Shear Stress Sxy along Height of Cooling Tower

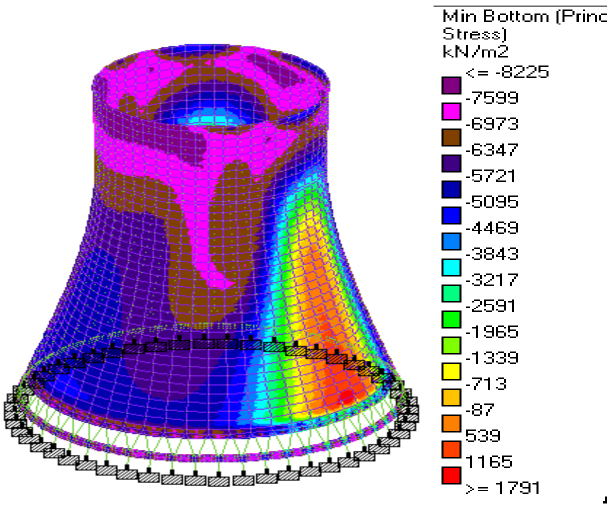

Fig. 4.11 Variation of Min. Principal Stresses along

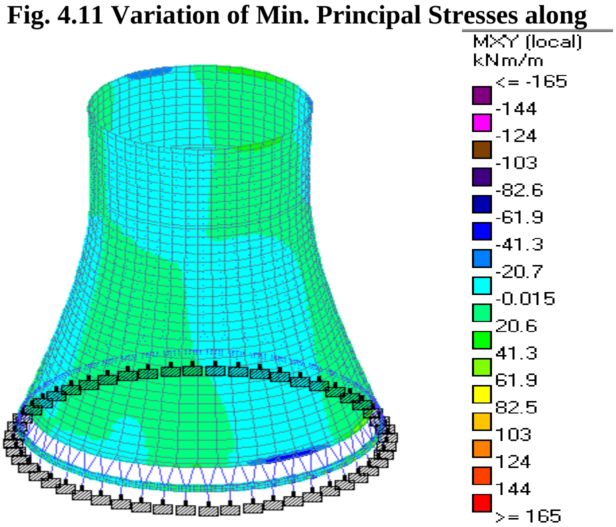

Fig. 4.10 Variation of Twisting Moment Mxy along Height of Cooling Tower

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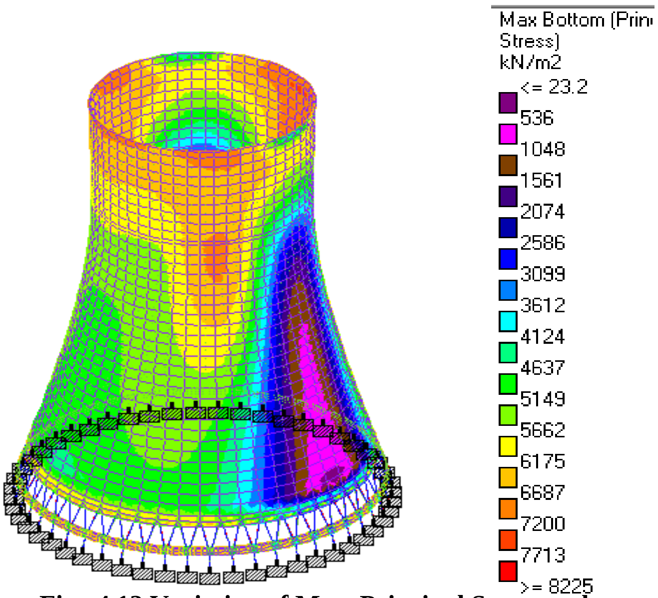

Fig. 4.12 Variation of Max. Principal Stresses along

IV. CONCLUSION

The following conclusions are drawn based on present work which are very use full in future study.

- Cooling tower response is governed by both vertical and circumferential wind distribution.
- The cooling is achieved due to heat transfer between air and water. In ideal condition, the heat loss by water must be equal to heat gain by air. But in actual practice it is not possible because of some type of losses. .
- Modeling the cooling towers by using bar type finite elements having three or four inner nodes offers an efficient vibration analysis which emphasizes simplicity and an acceptable accuracy for the practical engineering needs.
- Free vibration analysis technique maybe used in a seismic analysis using the enforced seismic design needs of NDCT.
- The ultimate load bearing capacity of the cooling tower shell under consideration is obtained as 1.925 times that of the design wind pressure that corresponds to the wind velocity of 40.2 m/s (90 mph).
- The nonlinear behavior is commenced by the formation of horizontal tension cracks in the windward meridian at the 43% height of the cooling tower shell.
- Hyperbolic shell structures have in previous studies been observed to be the most economical of axisymmetric shell structures, for different uses.
- Hoop stresses are greatly affected by changes in shell curvature in NDCT.
- Height (of the shell structure) is seen to have the greatest influence on the free vibration response, with increase of height significantly increasing the period of vibration.
- Modeling and meshing of cooling tower can be done quickly by using MSC/XL.
- Due to environmental factors, the actual effective values of concrete tensile characteristics such as effective tension stiffening (after cracking) may vary significantly during the life of a tower, thus making the prediction of the realistic buckling load difficult.
- The stress state in the cooling tower takes the full range from the tension to the compression domain.
- The tall shells for natural draft cooling towers show the necessity for continuous scientific research.

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