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Review on Modeling of hyperbolic cooling towers

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Abstract

Natural Draught cooling towers constitute very important and essential component in nuclear, thermal power plants and industrial setups. They also contribute to environmental protection, from the structural point of view they are constructed tall. These RC structures shows doubly curved thin walled shells of complex geometry, analysis and design has attracted the researcher's attention throughout the world.

The paper deals with the study of comprehensive review articles and research papers published on modeling of hyperbolic cooling towers. The latest developments of the natural draught cooling towers in the field of modeling of superstructure and substructure are discussed. The aspects such as finite shell elements, experimental studies, supporting systems, different foundation systems are discussed. The references included in this paper are mostly concentrated and reviewed the papers published after 2005 till date. The present study makes an attempt to gather the possible alternatives in modeling of hyperbolic cooling towers, mainly focused on finite elements with d.o.f used in the analysis, experimental studies, supporting systems (I, V, X etc column supports), different foundation systems (Independent, raft, ring, annular beam, foundation flexibility). The present paper gives complete collection of the studies done on modeling of cooling towers which would help researchers and design engineers to choose a suitable one for their study and design.

Key words: Cooling tower, Draught, Design, Hyperbolic, Modeling, Systems.

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I. INTRODUCTION

Reinforced concrete cooling towers composed of shell structure, supported on columns with ring beam type of foundation or isolated type foundation are prevalent.

Considerable research is done regarding the understanding the structural behavior of shell, column supports and foundation. Since the cooling towers are tall structures, the action of lateral forces such as wind and seismic forces are more critical in comparison to the gravity loads. The soil-foundation-structure interaction is another aspect which needs critical consideration in the overall structural behavior of cooling towers.

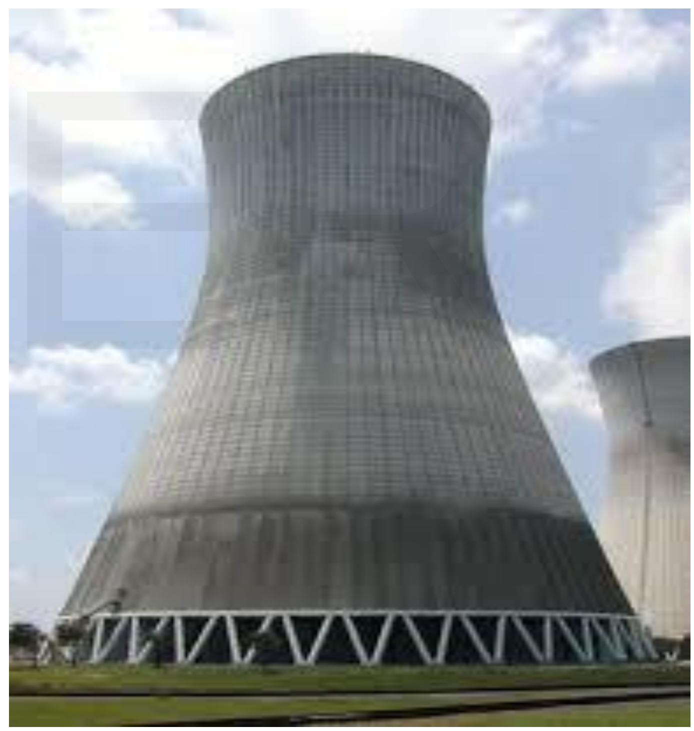

Figure 1: Natural Draught Cooling tower

The present paper concentrates on the research papers published on modeling of hyperbolic cooling towers. The latest developments of the natural draught cooling towers in the field of modeling of superstructure and substructure are discussed. The present paper has more focus on the published research works between 2005 till 2015.

A. Natural Draught Cooling towers (NDCT)

The Natural Draught cooling towers are exceptional structures in view of their shear and complexities. These towers with very small shell thickness are exceptional structures by their shear size and sensitiveness to horizontal loads. They are high rise reinforced concrete structures from structural point of view. The tower consists essentially of an outside hyperbolic shell, the principal function of which is to create a draught of air in a similar way to a chimney. RC hyperboloid cooling towers are generally constructed on column supports, which may have different shapes and configuration. These column shapes are categorized, mainly based on their geometry and length. The shell is supported on RC raker columns resting on pedestals.

Many researchers have contributed towards modeling of superstructure and substructure of hyperbolic cooling towers. The literature papers related to modeling aspects in superstructure and substructure of cooling towers are discussed. The gap between two areas of cooling tower are discussed and tried to find possible gap of work to be researched. The modeling of superstructure includes shell structure and supporting systems. The substructure includes foundation system supporting the tower.

1] Modeling of superstructure includes aspects such as

a) Finite Shell elements.

b) Alternate column supporting systems [V, H, I, X, A].

c) Experimental Studies.

2] Modeling of substructure includes

a) Foundation systems [Independent, raft, ring, annular beam, foundation flexibility].

II. Modelling of superstructure

A Finite shell Elements

The cooling tower shell is analyzed using the finite elements. Following are the finite elements adopted in modeling the cooling tower structure. i. Four noded rectangular plate element with six degrees of freedom (dof) per node [1, 2] ii. Four noded rectangular plate element with six degrees of freedom (dof) per node with three noded triangular element at the junction of shell and supporting columns. [3, 4] iii. Eight noded shell element with five dof per node accounting for both membrane and bending action (SHELL-93 of ANSYS) [19,20,21,36] iv. Second order Mindlin plate elements [5] v. Thirteen noded subparametric triangular shell element with six dof per node [6] vi. Four noded quadrilateral layered shell element with six degrees of freedom (dof) per node having separate reinforcement layer and concrete layer of SAP-2000 [7]. vii Three or Four noded Timoshenko beam element (includes shear deformation) with spring supports [8] viii. Cooling tower shell using SOLID-65, SOLID-45, SOLID-63 solid shell elements, columns using SOLID-65 and Foundation using SOLID-45 and Soil is modeled using COMBIN-40. All these elements are from the ANSYS-8 element library [9]. ix. Four noded rectangular shell element with six degrees of freedom (dof) per node while the soil was simulated using spring elements [9, 10]. The column supports for the shell are modeled with two noded beam elements with six dof per node with a few exceptions [8,9]. The column supports are mostly considered to be fixed except where the soil-foundation interaction is considered [8, 9, 10] in the analysis. x. 48 dof quadrilateral shell elements is used to model a quarter of the shell for fixed base case, the elements are divided into five layers [11]. xi 8-noded hexahedrons elements are used to model the footings and soil in 3D and 4-noded quadrilateral flat shell element is used for modeling, based on discrete the Kirchhoff's quadrilateral plate bending element, was also added to the software to model the elastic behavior of the cooling tower shell [12]. xii 9-noded harmonic solid ring finite element is used in the numerical model of the cooling tower. Physically a three-dimensional cooling tower problem is reduced to a two dimensional one by expressing earthquake loading in the form of Fourier series for a single harmonic with the help of harmonic elements [13]. xiii The outer shell of cooling tower and pond wall are meshed with Quad8/Quad4 elements, raker columns and foundation with bar elements of MSC/NASTRAN. Analysis has been carried out for different cases by varying the mesh size and aspect ratio of Quad8/Quad4 elements and results are compared [14]. xiv In the analysis, the isoparametric hexahedral element with 20 nodes is adopted. Each node has three translation degrees of freedom [15]. xv iso-parametric solid element has been used for the finite element modeling, and time-integration dynamic analyses have been performed [16]. xvi Physical modeling has been carried out using solid twenty nodded isoparametric element to model the cooling tower, annular raft foundation and soil media [17,18]. xvii four noded shell elements, eight noded shell elements and plastic, hyper noded shell elements available in ANSYS software are compared by modeling cooling tower [37].

B. Alternate column supporting systems

Parametric studies are also done regarding the structural behavior of cooling towers with alternate column support systems namely, I, V, H, X and A frame types [5, 15, 22]. In comparison to I type of supporting columns, V type of supporting columns offer greater rigidity to the cooling tower structure. Even though the displacements are large at the base of tower for I supports, the difference is negligible at throat of the tower [5]. V supports create relatively more flexible structure compared to the one having I supports, when the influence of the wind load is considered. V supports give 73.6% more sway than I support [1, 2]. Two sets of tower is being modeled one with X supporting structure and the other with Y supporting structure under the influence of self-weight, wind load and soil load, the tower with Y shaped raker column is much stiffened when compare to tower with X shaped raker columns. X type of columns governs more steel when compare to tower with Y type of columns [23]. The V, A and X-truss columns are able to carry high horizontal forces with corresponding low deformation, I-beam supporting systems behave much more flexible than other supporting systems [24].

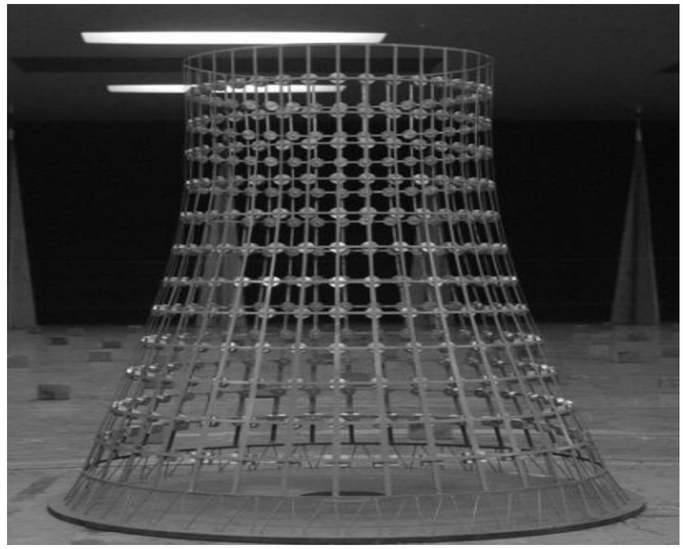

Fig 2: Model of cooling tower for wind tunnel test[45]

C. Experimental studies on cooling tower

The hyperbolic cooling towers are subjected to static and dynamic loads. Dynamic loads are dominant loads among all other loads. Wind loads comprises critical and dominant load. These loads acting on tower deforms the shell tower and induces flow interference effects. Symmetrical and unsymmetrical wind load are made to act upon tower modeled and evaluated experimentally. Many researchers have investigated and performed wind tunnel test to know the variation of pressure distribution and deformation pattern of cooling tower.

The cooling tower is analyzed for wind loads and structural deformation of tower is analyzed by performing wind tunnel test method. Pressure patterns on rigid model of cooling tower are measured experimentally, where as structural deformation at throat level is also investigated simultaneously. Further these experimental values of pressures were used for numerical linear analysis to find the deformation of cooling tower. It is found that the maximum nodal displacement in the tower due to mean wind loads occurred at throat level for isolated tower [25]. Hyperbolic cooling towers subjected to static wind loads including flow-interference were investigated by performing wind-tunnel test. Different static wind pressure measured in wind tunnel tests are applied in structural analysis to compare with other standard methodologies. Variation of wind pressure with flow-interference is evaluated. In general, traditional concept using single amplification coefficient prove to be conservative to some extent, while proposed methods has better precision and efficiency [26]. Shake Table Test for Large Indirect-Air-Cooling Tower Structure of Fire Power Plant—Part I were investigated for dynamic non-linear finite element analysis. New model material simulation method is developed. Analytical and shake table test (prototype) of cooling tower is compared and evaluated. The earthquake resistant capacity of the tower as well as its critical element, the support X-type columns were verified and studied carefully [27]. Wind-Induced Static Performance of Cooling Tower Considering Multiple Loading Effects is investigated using FEM and wind tunnel test. With the help of the finite element method (FEM) numerical simulation, the performance of cooling towers due to the static wind loads, including stress, displacement and local elastic stability is carried out, considering material and geometrical non-linearities of reinforced concrete, the ultimate bearing capacity of the structures under static wind action is discussed. Analysis process focuses on considerations of some key effects concerning structural design works, i.e., the internal pressure effect, the distribution mode of external surface pressure, the boundary effect, the wind profile index and the group tower interference effect [28]. Wind induced responses of super large cooling towers is investigated by performing wind tunnel test. With Combination of wind tunnel test and CCM, the wind induced response and self excited force on the surface pressures effect are discussed. It can be concluded that the understanding of mechanism of wind induced response must be made to direct the wind resistant design for super large cooling towers. The influence of self excited force breaks the symmetrical characteristic of fluctuant wind pressure distribution, and makes the values greater than the results without self excited effect. With the increase in height, wind vibration coefficients variations are studied [29]. Effect of Wind Break Walls on Performance of a Cooling Tower Model was investigated, modeled including design of curvature devices. The cooling efficiency of dry cooling tower can be less than the cooling efficiency with a wet cooling tower [30]. Experimental Study on the design of a Cooling tower for a Central Air-conditioning Plant emphasizes a case study of large cooling tower and reconditioning a small cooling tower of an air conditioning plant. Design of cooling tower mainly depend upon Characteristic and different types of losses generated in a cooling tower. Cooling tower performance increases with an increase in air flow rate and characteristic decreases with increase in water to air mass ratio. Based upon investigation, it is observed that the test result between wet and dry type cooling towers shows that for a given flow rate of water and inlet temperature, the cooling range of the wet type is more than the dry type [31]. Experimental Research on the Models of Cooling Tower subjected to seismic responses is studied, which includes vibration experiment and FEM calculations to investigate seismic-resistance of organic model and steel model. Two cooling towers are modeled and analyzed for dynamic responses, natural frequencies and damping are measured by hammering experiments, comparison with the results of ANSYS calculations are made [32].

III. Modelling of substructure

A. Foundation systems (Independent, raft, ring beam, annular beam, foundation flexibility)

The hyperbolic cooling towers are very important and essential component in the thermal, nuclear power stations and industrial power plants. They are rested on different types of foundation systems (supporting systems). Apart from columns of cooling towers they are rested on independent, raft, annular etc types of foundation systems. Following are the contributions of cooling towers rested on different foundation systems, cooling towers with different foundation systems considering soil-property gives overall picture of the analysis.

The cooling tower foundation is analyzed using finite element method under the action of wind loading, physical and material modeling of cooling tower foundation-soil system is carried out. The effect of interactive and non-interactive analysis is carried out to study the effect. Cooling tower, foundation-soil system was analyzed under vertical and lateral load generated from wind loads, considering soil non-linearity. The interactive analysis of the cooling tower-foundation-soil media plays a major role in releasing the stresses in the cooling tower, particular at the bottom ring beam [17]. Optimum shape and design of hyperbolic cooling towers based on coupling a non-linear finite element model developed in-house and a genetic algorithm optimization technique was investigated. Objective function is set to obtain minimum weight of the tower. The geometric modeling of the tower is carried out using B-spline curves; shape optimization of the tower with shell rings radii taken as design variables is formulated. The optimality study for shape and shell thickness is carried out [6]. Static soil–structure interaction response of hyperbolic cooling towers to symmetrical wind loads is investigated considering column supported tower and annular raft-soil system. Soil–structure interaction response of the tower has been compared with that of a tower whose supporting columns are treated as fixed at the base. Radial displacements, design forces and moments occurring in the tower shell and supporting columns are obtained from the analysis [33]. Nonlinear interactive analysis of cooling tower–foundation–soil interaction under unsymmetrical wind load considering physical and material modeling is investigated. The cooling tower–foundation–soil system (annular raft foundation) was analyzed under vertical and lateral load generated due to self-weight and wind loads considering soil non-linearity. The displacement and stresses are evaluated for response of the structure [18]. Effect of Stiffening Rings on Buckling Stability of RCC Hyperbolic Cooling Towers is studied using finite element method. The buckling modes are obtained from FEA analysis, resistance of tower due to wind loading for different number of stiffening rings is also carried out. Maximum deformation due to buckling is analyzed; added stiffening ring increases the buckling resistance of the concrete shell, Dependent to the dimensions of the stiffening rings the ring will behave flexible or rigid [10]. Shake Table Test for Large Indirect-Air-Cooling Tower Structure of Fire Power Plant—Part I investigated linear and non linear static and dynamic analysis. X shaped column and supporting piers, ring foundation were modeled with solid elements. Results of the nonlinear dynamic analysis (numerical analysis) and the shaking table test are compared [27]. Wind-Induced Static Performance of Cooling Tower Considering Multiple Loading Effects is studied. Considering modeling of main body of the FEM model is comprised of discrete spatial shell elements, and the top stiffening ring and 48 pairs of herringbone columns connected to a ring foundation with fixed bottom ends are modeled using space beam elements. Finite element method (FEM) numerical simulation, the performance of cooling towers due to the static wind loads, including stress, displacement and local elastic stability are presented [28]. Seismic analysis of hyperbolic cooling tower in time domain is carried out. Fourier expansion in circumferential direction and higher order finite element frusta with isoparametric expansion in meridional direction is formulated. The stiffening ring beam, foundation ring beam, and supporting columns were synthesized into dynamic stiffness matrix with axisymmetric shell element. Soil was modeled and represented as spring and damper [4]. RC Column Supported hyperboloid cooling tower stability assessment for seismic loads is investigated, the tower stability and the modeling are carried out with finite element method, and shell elements were applied for the ring strip foundation. The columns were modeled with solid elements. Seismic behavior of RC hyperboloid cooling towers with relatively long X shape supporting columns is carried out [34]. The 2D and 3D behavior of soil-cooling tower-interaction is modeled. Idealization of the structure and soil on the resulting parameters, have been investigated. A 3D finite element model was created, comprising the cooling tower, columns support, foundation, and elasto-plastic soil behavior. Two-dimensional Geotechnical Finite Element Analysis Program (GeoFEAP) is used to create a 3D finite element model [12]. Stress resultants in hyperboloid cooling tower shells subjected to foundation settlement is carried out using finite element method. Considering two different base conditions, the effect of column flexibility on the stress resultants due to differential settlement is studied. First is a rigid base condition where all columns are assumed rigid, second base condition using a two-noded discrete column elements having six d.o.f. per node to idealize the columns. The axial, flexural and torsional rigidities are given as input in the analysis. The results of the fixed base condition and flexible base condition are compared to evaluate the stresses developed in the shell due to differential settlement; the effect of column flexibility is also found [35]. Natural draught cooling towers using MSC/NASTRAN studied the analysis of cooling tower, outer shell, raker columns, pond wall and ring foundation. The shell is supported on 44 pairs of diagonal columns which are racked in the vertical plane; these columns are rested on pedestals with same inclinations as that of vertical plane. A ring spread footing is provided at bottom below pond wall [14].

IV. CONVERGENCE AND SUITABILITY STUDY OF FINITE SHELL ELEMENTS

Suitability

In present paper, a convergence study of finite shell elements available in ANSYS software is carried out, in order to compare the performance of different shell elements and the element size. The linear static analysis of hyperbolic cooling tower is carried out using different shell elements. The 1st principal stress at top, deflection in Y-direction etc are obtained from the analysis, the optimum mesh size for a given finite shell element was obtained from convergence study for static load [Self weight or dead load].

Following shell elements are adopted in the convergence study. The properties of the finite SHELL elements are presented in Appendix-1.

1)	4 node SHELL 63
2)	4 node SHELL 181
3)	4 node SHELL 41
4)	Elastic 4 node SHELL 63
5)	8 node SHELL 93
6)	8 node SHELL 91
7)	Plastic 4 node SHELL 143
8)	Hyper 4 node SHELL 181
9)	Plastic 4 node SHELL 43

A. Material Properties

1] Material Properties = Structural- Linear- Elastic- Isotropic.

2] Young's modulus E= 31Gpa.

3] Poisson's ratio μ= 0.15.

4] Density of RCC= 25kN/m^3.

5] Cooling tower height- 143.50m.

6] SHELL thickness-500mm.

7] Boundary condition- Fixed at bottom and free at top.

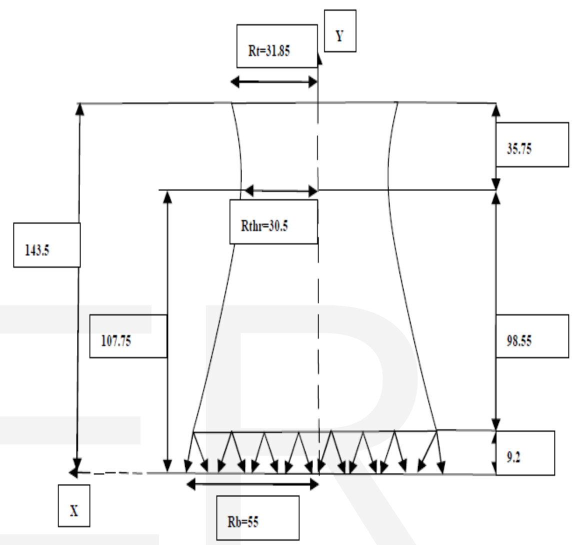

Fig-3. Geometry of cooling tower (143.50m)

The Total height of the tower is 143.50 m. The tower has a base, throat and top radii of 55 m, 30.5 m and 31.85 m respectively, with the throat located 107.75 m above the base. Fig 3 shows geometry of cooling tower.

The element size (edge length) was varied from **40000 to 1000 (coarse to fine)** for the convergence study. **The convergence study is presented in the Fig.6.**

From the convergence study it is noticed that most of the 4-noded shell elements with element size 15000, except for node shell-41 of ANSYS converge to the same value of 7.33mm deflection at the top of the cooling tower shell under consideration. However, the 8-noded shell elements 91 and 93 with element size 35000 converge to the same value of 7.33mm deflection at the top of the cooling tower shell under consideration. Therefore the coarser mesh with element size of 35000 would be sufficient if 8-noded shell elements 91 and 93 of ANSYS are used for the analysis.

Table 1- Converged response for different shell elements

Sl no	SHELL Elements	Element size	Deflection in Y direction (mm)	1st Principal Stress at TOP (Mpa)
1	4 node SHELL 63	15000	7.330	0.0916
2	**4 node SHELL 181**	**20000**	**7.374**	**0.0655**
3	4 node SHELL 41	15000	7.562	0.0584
4	4 node SHELL Elastic 63	15000	7.330	0.0916
5	8 node SHELL 93	15000	7.329	0.0534
6	8 node SHELL 91	15000	7.329	0.0534
`7	**Plastic 4 node SHELL 143**	**20000**	**7.337**	**0.0646**
8	Hyper 4 node SHELL 181	20000	7.374	0.0655
9	Plastic 4 node SHELL 43	15000	7.333	0.0657

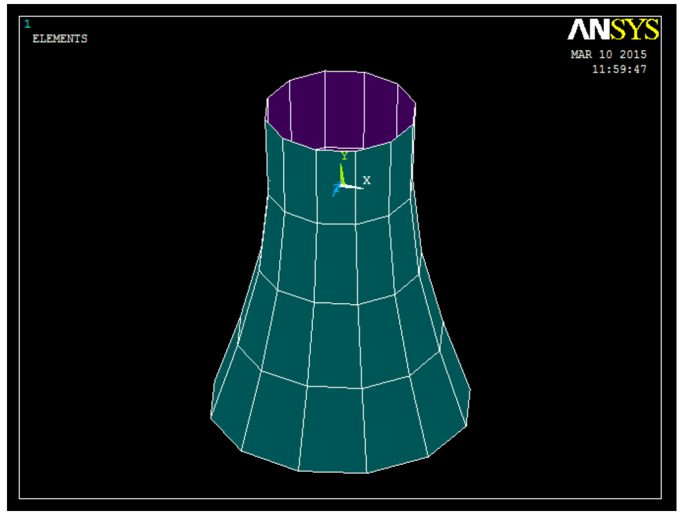

Fig 5- Model of cooling tower with Element size-40000

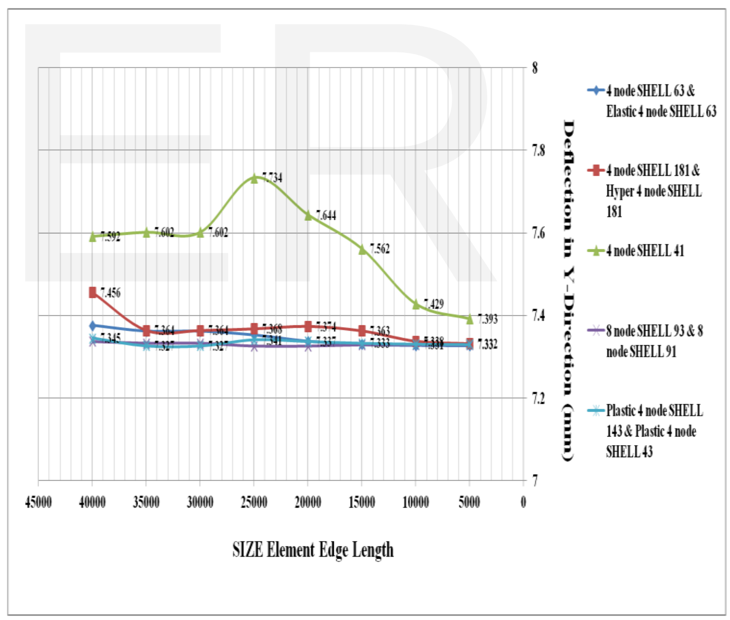

Fig 6: Convergence of results

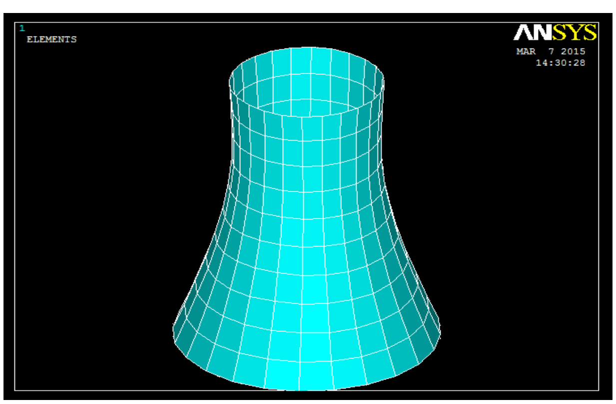

Fig 4- Model of cooling tower with Element size-15000

V. VALIDATION OF CONVERGED SHELL ELEMENTS

In present paper convergence study of different shell elements is carried out. The performance of shell elements are obtained by carrying out static analysis. The converged response of shell elements is obtained. The graphical representation in fig 6 shows the convergence of shell elements for optimum element size.

The cooling tower (143.50m) shown in fig-3 is analyzed theoretically and compared with ANSYS software results for converged shell elements for their element sizes. The values of membrane stress resultants obtained from ANSYS software for converged shell elements are nearly same as that of theoretical values (Table 2).

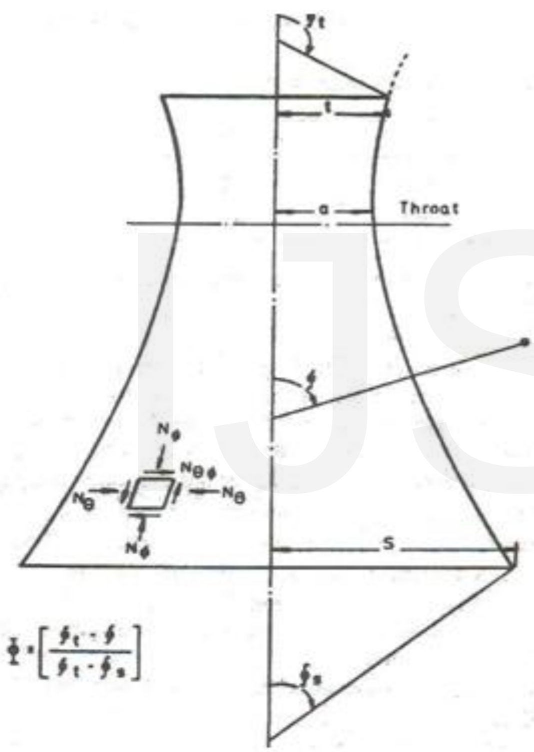

Fig 7- Cooling tower parameters

Table 2- Membrane Stress resultants (in KN/m) at the bottom of the shell of cooling tower.

Stress resultants	Theoretical values	ANSYS results for 4 node SHELL 181 element	ANSYS results for Plastic 4 node SHELL 143 element
N_θ	-234.068	-299.62	-287.028
N_ϕ	-2045.54	-2084	-2078

Membrane forces= -ve values indicates compression

VI. CONCLUSIONS

The current review article discusses on the modeling of superstructure and substructure of hyperbolic cooling tower using the finite shell elements, experimental investigations. Following are the conclusions drawn from present study.

1] Modeling of cooling tower shell, column, footing, soil-foundation and other components of cooling towers greatly influences on static and dynamic analysis. The tower shell is analyzed using different finite elements in the literature; the proper selection of finite shell element in modeling and the element size is the prime factor for the analysis. This can be achieved through **proper convergence study**, which includes element size and finite shell element. Based on the convergence study of nine finite shell elements, with element size varying from **40000 to 1000 (coarse to fine)**, it is observed that the coarser mesh with element size of 35000 would be sufficient if 8-noded shell elements 91 and 93 of ANSYS are used for the analysis. Otherwise a finer mesh size of 15000 is to be adopted if the 4-noded shell elements are used for the analysis.

2] The Structural behavior of cooling tower is greatly influenced by the alternate supporting systems as well as different foundation systems, such as independent footing, raft footing, ring footing and annular beam footing. The alternate supporting systems (X, V, I, H, A etc), its choice in terms of flexibility, displacement and deformation offers great variability in the rigidity and strength of cooling tower. The proper selection of column supporting systems and footing in compatible with soil property beneath the footing is required.

3] It is preferable and appropriate to consider the soil structure interaction for comparing the performance of cooling towers with different column and foundation supporting systems. The authors notice deficiency of such studies in the literature.

4] The cooling tower subjected to dynamic loading (wind and seismic loads) being studied experimentally using wind tunnel and shake table, such tests can be conducted with different column supporting systems.

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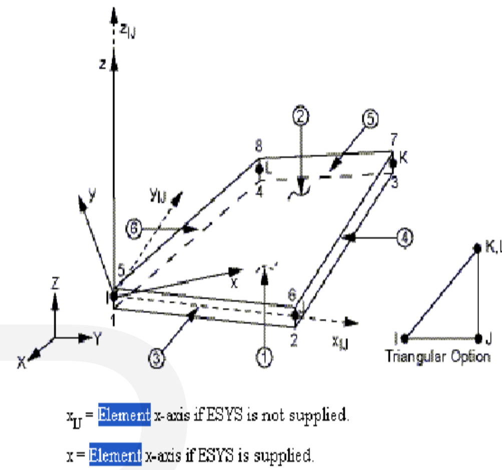
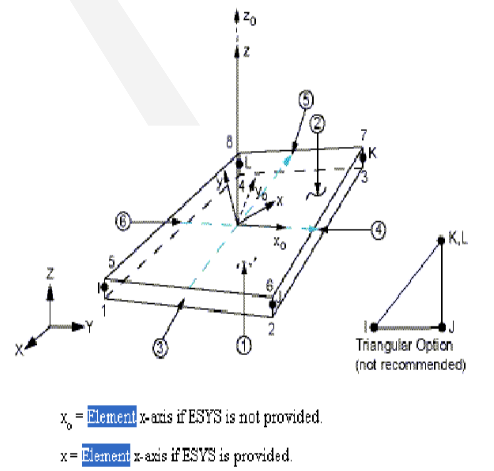
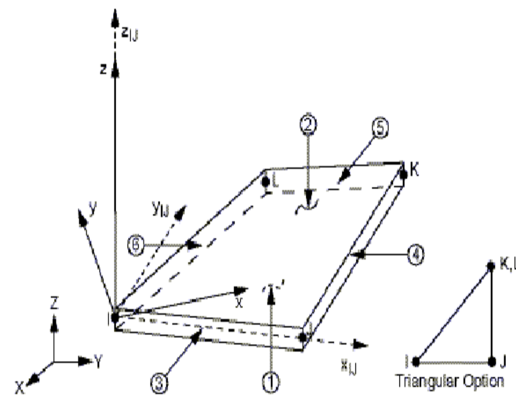
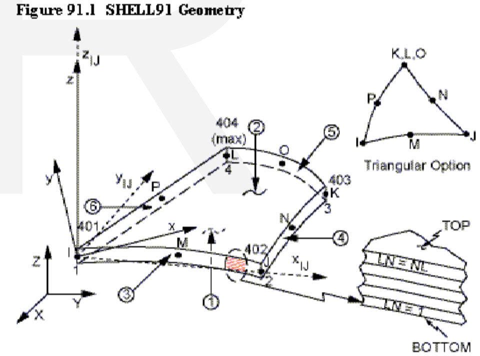
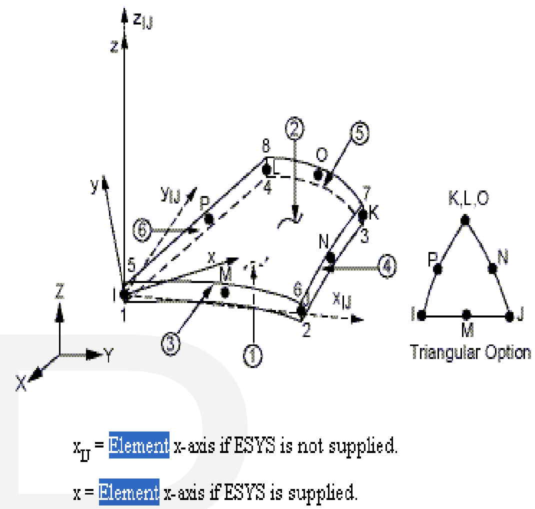
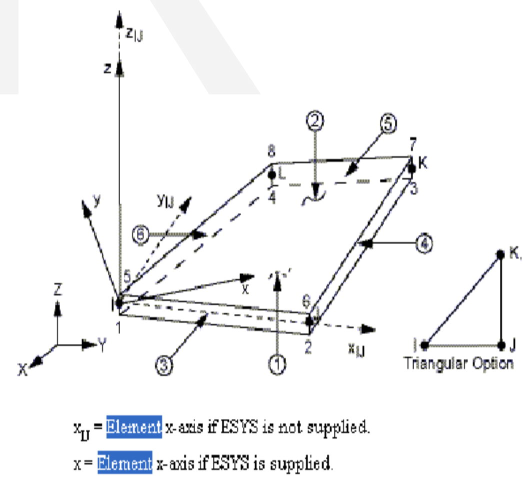
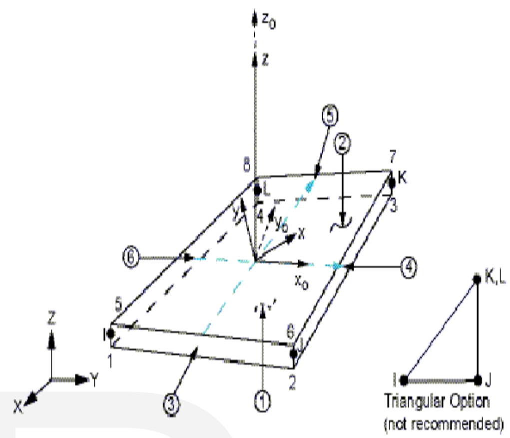
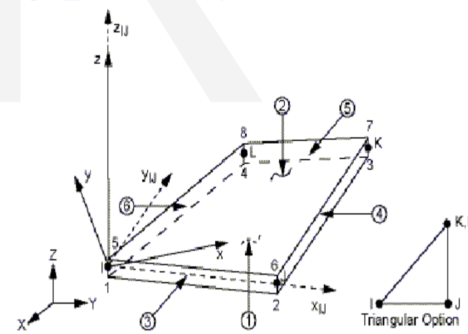
Element Table (Appendix-1)

Sl no	SHELL Element	Element Description	Nodes	Degree of freedom	Thickness	Output data	SHELL Element Geometry
1	SHELL 63	Shell 63 has both bending and membrane capabilities. Both in-plane and normal loads are permitted	4 I, J, K, L	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 63.1 SHELL63 Geometry 
2	SHELL 181	SHELL 181 is suitable for analyzing thin to moderately thick shell structure. SHELL 181 is well suited for linear large rotation and or large strain non-linear applications. SHELL 181 may be used for layered application for modeling laminated composites shells or sandwich construction.	4 I, J, K, L	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 181.1 SHELL181 Geometry 

Sl no	SHELL Element	Element Description	Nodes	Degree of freedom	Thickness	Output data	SHELL Element Geometry
3	SHELL 41	SHELL 41 is a 3-D element having membrane (in-plane) stiffness but no bending (out of plane) stiffness. It is intended for shell structure where bending of the elements is of secondary importance. The element has variable thickness. Stress stiffening large deflection.	4 I, J, K, L	3 at each node Translations in the nodal x, y and z	4	Nodal degree of freedom results included in the overall nodal solution	**Figure 41.1 SHELL41 Geometry**  x_{IJ} = Element x-axis if ESYS is not supplied. x = Element x-axis if ESYS is supplied.
4	SHELL 91	SHELL 91 may be used for layered application of a structural shell model or for modeling thick sandwich structures.	8 I, J, K, L M, N, O, P	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	Layered thickness	Nodal Displacements included in the overall nodal solution Nodal	**Figure 91.1 SHELL91 Geometry**  x_{IJ} = Element x-axis if ESYS is not supplied. x = Element x-axis if ESYS is supplied. LN = Layer Number NL = Total Number of Layers

Sl no	SHELL Element	Element Description	Nodes	Degree of freedom	Thickness	Output data	SELL Element Geometry
5	SHELL 93	SHELL 93 is particularly well suited to model curved shells. The deformation shapes are quadratic in both in-plane directions. The element has plasticity stress stiffening, large deflection and large strain capabilities.	8 I, J, K, L M, N, O, P	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 93.1 SHELL93 Geometry 
6	Plastic SHELL 143	SHELL 143 is well suited to model non-linear, flat or warped, thin to moderately thick shell structures. The deformation shapes are linear in both in-plane directions. For out of plane motion, it uses a mixed interpolation of tensorial components.	4 I, J, K, L	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 143.1 SHELL143 Geometry 

Sl no	SHELL Element	Element Description	Nodes	Degree of freedom	Thickness	Output data	SHELL Element Geometry
7	Hyper SHELL 181	SHELL 181 is suitable for analyzing thin to moderately thick shell structures.	4	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 181.1 SHELL181 Geometry  x_o = Element x-axis if ESYS is not provided. x = Element x-axis if ESYS is provided.
8	Plastic SHELL 43	SHELL 43 is well suited to model linear warped, moderately thick-shell structures.	4	6 at each node Translations in the nodal x, y and z Rotation in the nodal x, y and z axis	4	Nodal Displacements included in the overall nodal solution	Figure 43.1 SHELL43 Geometry  x_{IJ} = Element x-axis if ESYS is not supplied. x = Element x-axis if ESYS is supplied.