

DESIGN AND ANALYSIS OF COOLING TOWER IS 456

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ABSTRACT

Natural draught cooling towers are large thin shell structures used in thermal and nuclear power plants to reject waste heat from the condenser cooling water to the atmosphere. The tower shell is usually a hyperboloid of revolution made of reinforced concrete, supported on a ring of inclined columns at the base and stiffened by a ring beam at the top. Because of its large height, small wall thickness, and exposure to wind, the tower is sensitive to wind loading, and its design requires careful assessment of membrane forces, bending moments, and buckling. The present study deals with the analysis and design of a reinforced concrete hyperbolic cooling tower following the provisions of IS 456:2000 together with the loading guidance of IS 875 and IS 11504.

A hyperbolic cooling tower of 120 m height with a base diameter of 90 m, throat diameter of 56 m, and top diameter of 60 m is considered. The shell thickness varies from 600 mm at the lintel level to 200 mm in the middle portion and increases to 300 mm near the top ring beam. The shell is supported on 40 pairs of raker columns resting on a ring foundation. The structure is modelled in STAAD.Pro using plate elements for the shell and beam elements for the columns and ring beams, and the geometry is generated from the equation of the hyperbola.

Dead load, wind load, and seismic load are considered. Wind pressure is calculated from the basic wind speed and height factors of IS 875 (Part 3):2015, and its circumferential variation around the shell is represented by the Fourier cosine series given in IS 11504. Seismic load is applied using the response spectrum of IS 1893 (Part 1):2016, and temperature effects are discussed. Load combinations are formed for the limit state of collapse and serviceability as specified in IS 456:2000.

The analysis gives meridional and hoop membrane forces, meridional and circumferential bending moments, and column forces for each load case. Wind is found to govern the design of most of the shell, producing tension on the windward meridian and compression on the flanks. Reinforcement in both directions is designed according to IS 456:2000 for combined axial force and bending, with minimum steel and crack-width limits applied, and the raker columns and ring foundation are designed for the governing forces.

The study shows that software-based finite element analysis provides a detailed picture of force distribution in the shell that is difficult to obtain by classical membrane theory alone, especially near the lintel and top ring beam where bending is significant. The design procedure followed in the study can serve as a reference for students seeking to understand how IS 456:2000 is applied to shell structures and how wind governs the behaviour of tall cooling towers.

I. INTRODUCTION

Thermal power stations require very large quantities of water to condense the steam leaving the turbines. Once-through cooling from rivers or the sea is no longer permitted in many locations because of the thermal pollution it causes, and closed-

cycle cooling with cooling towers has become standard practice. In a natural draught cooling tower, hot water is sprayed over fill material near the base, and air entering through the openings between the supporting columns rises through the tower by the chimney effect, carrying away heat by evaporation. No fans are required, which makes this type of tower economical in operation for large plants.

The hyperbolic shape is chosen because it offers several structural and functional advantages. The doubly curved surface has high stiffness against buckling for a small wall thickness, the narrowing throat accelerates the upward flow of air, and the form can be built using straight generating lines, which simplifies formwork. However, the shell must resist its self-weight, wind pressure that varies both with height and around the circumference, seismic forces, and temperature gradients. Collapses of cooling towers in the past, such as the failure of the Ferrybridge towers in the United Kingdom under high wind, showed that inadequate assessment of wind loading and group effects can lead to catastrophic failure.

In India, the design of reinforced concrete cooling towers is guided by IS 11504, which deals with the structural design of hyperbolic cooling towers, together with IS 875 (Part 3) for wind load, IS 1893 for seismic load, and IS 456:2000 for the design of reinforced concrete sections. The design requires the calculation of membrane forces and bending moments at many points on the shell, which is laborious by hand. Finite element programs have made it possible to model the full shell, the column supports, and the ring beams together and obtain these forces with reasonable accuracy.

The objective of the present work is to model, analyse, and design a hyperbolic cooling tower shell and its supporting system using STAAD.Pro, to study the distribution of forces under dead, wind, and seismic loading, and to design the reinforcement according to IS 456:2000. The study also compares the finite element results with values from membrane theory at selected levels in order to understand where bending effects become important.

II. LITERATURE SURVEY

The structural behaviour of hyperbolic cooling tower shells has been studied since the middle of the twentieth century, when the size of towers began to increase rapidly with the capacity of power plants. Early analyses were based on membrane theory, in which the shell is assumed to carry loads only through in-plane meridional, hoop, and shear forces. Membrane theory gives satisfactory results over most of the shell for axisymmetric loads such as self-weight, but researchers soon recognised its limitations near the supports and the top ring, where compatibility of deformation produces local bending. Bending theory solutions for shells of revolution were developed to account for these edge effects, and later work introduced numerical methods based on finite differences and then finite elements. Authors examining these methods agreed that the membrane solution is a useful first estimate but that a complete design requires analysis that captures bending, especially near the lintel region where the shell is supported on discrete columns rather than continuously.

Wind loading has been the most extensively studied aspect of cooling tower design because wind governs the reinforcement in most of the shell. Wind tunnel experiments on models of hyperbolic towers established that the external pressure around the circumference varies from positive pressure on the windward meridian to strong suction at about 70 to 80 degrees from the windward direction and a nearly uniform suction on the leeward side. This distribution is commonly represented by a

Fourier cosine series whose coefficients depend on the surface roughness of the shell. IS 11504 provides such a distribution for use in design, while IS 875 (Part 3) provides the basic wind speed and the variation of wind pressure with height and terrain. Investigations have also examined the influence of neighbouring towers, known as group or interference effects, and reported that towers in a group may experience considerably higher loads than an isolated tower, which is why an interference factor is often applied in practice.

Finite element analysis of cooling towers has been reported by many researchers using both general-purpose and structural analysis programs. Studies have modelled the shell with four-noded or eight-noded shell elements and the supporting columns with beam elements, and compared the results with classical solutions. Mesh refinement studies indicate that the circumferential division must be fine enough to represent the cosine variation of wind pressure and the discrete column supports, and that a vertical division that places more elements near the lintel and top ring improves the accuracy of bending moments. Researchers using STAAD.Pro and SAP2000 have reported that programs of this type can reproduce the membrane forces of classical theory to within a few percent while additionally giving the local bending effects, and that they are suitable for design office use when the geometry is generated carefully from the hyperbola equation.

The seismic behaviour of cooling towers has been examined through modal and response spectrum analysis. Because the shell is very stiff in its own plane but flexible in bending, the natural modes include beam-type modes, in which the tower sways as a cantilever, and shell-type modes, in which the circumference deforms into lobes. Studies have shown that the beam-type modes dominate the seismic response and that the supporting columns attract significant shear and axial force during an earthquake. In regions of moderate seismicity, wind usually governs the shell design, while seismic loading may govern the design of the columns and foundation. Researchers have recommended that the column arrangement be checked carefully, because the column region forms a relatively flexible storey beneath a very stiff shell, which is similar in principle to a soft storey in buildings.

The design of reinforcement for cooling tower shells has been discussed in relation to limit state principles. The shell is subjected to combined axial force and bending in both meridional and circumferential directions, and meridional tension may develop on the windward side under high wind. Researchers have emphasised the importance of providing adequate minimum steel in both faces of the shell, controlling crack widths to protect reinforcement from the humid environment inside the tower, and providing sufficient cover. IS 456:2000 provides the basis for sectional design under combined axial force and bending, together with durability requirements based on exposure conditions, while IS 11504 gives additional guidance on minimum thickness and reinforcement. Studies on buckling have shown that the ratio of the critical buckling pressure to the applied wind pressure should be maintained above a safe value, and thickened rings at the top and lintel improve stability. The present work follows these principles in the design of the shell, columns, and foundation.

III. SYSTEM ANALYSIS

The structural problem considered is the analysis and design of a reinforced concrete hyperbolic cooling tower shell with its supporting raker columns and ring foundation. The tower height is 120 m, with the throat at 90 m above the base, a base diameter of 90 m, throat diameter of 56 m, and top diameter of 60 m. The shell thickness varies

from 600 mm at the lintel to 200 mm over the middle height and 300 mm near the top ring. The shell rests on 40 pairs of inclined columns of 700 mm diameter supported on an annular raft foundation. M30 concrete and Fe500 steel are adopted. Loads considered are self-weight, wind load for a basic wind speed of 44 m/s according to IS 875 (Part 3) with the circumferential pressure distribution of IS 11504, seismic load for Zone III according to IS 1893 (Part 1):2016, and a temperature gradient across the shell thickness. The parameters studied are meridional and hoop forces, bending moments, column forces, lateral deflection, and reinforcement.

Existing System

Conventional analysis of cooling tower shells relies mainly on the membrane theory of shells of revolution. The designer computes meridional and hoop forces for self-weight using closed-form expressions and treats wind load by expanding the pressure distribution in a Fourier series and solving for each harmonic separately. The forces are calculated at a limited number of levels and angular positions, and the results are then combined by hand. Bending effects near the lintel and top ring are estimated from simplified edge-disturbance formulas or are covered by providing additional reinforcement based on experience. The supporting columns are analysed by resolving the shell forces at the lintel into the inclined column directions, and the foundation is designed for the resulting reactions. Seismic forces are often estimated by treating the tower as an equivalent cantilever. This method provides useful insight but is very lengthy, gives forces only at selected points, and cannot represent the interaction between the discrete column supports and the shell with sufficient accuracy.

Disadvantages of Existing System

- Membrane theory does not capture bending near the lintel and top ring beam.
- Discrete column supports are replaced by an idealised continuous support.
- Forces are calculated only at a limited number of levels and angular positions.
- Superposition of many Fourier harmonics by hand is lengthy and error-prone.
- Seismic response is approximated by an equivalent cantilever without shell modes.
- Variation of shell thickness with height is difficult to include in closed-form solutions.
- Load combinations for dead, wind, seismic, and temperature are assembled manually.
- Deflection and buckling checks require separate, approximate calculations.
- Revision of geometry or thickness requires the entire calculation to be repeated.
- Results are not available in graphical form for checking force distribution.

Proposed System

The proposed approach models the complete cooling tower in STAAD.Pro using finite elements. Node coordinates of the shell are generated from the hyperbola equation at 36 circumferential divisions and 40 vertical divisions, with closer spacing near the lintel and top ring. The shell is represented by plate elements whose thickness varies with height, and the raker columns and ring beams are modelled as beam elements connected to the shell nodes. Supports at the column bases are taken as fixed on the ring foundation. Self-weight is generated automatically, wind pressure is applied as element pressure computed at each element centroid from the IS 875 (Part 3) height variation and the IS 11504 circumferential coefficients, and seismic load is

applied through a response spectrum analysis to IS 1893 (Part 1):2016. Load combinations for limit state of collapse and serviceability are defined according to IS 456:2000. The analysis yields membrane forces, bending moments, and displacements for every element, and reinforcement is designed at critical sections for combined axial force and bending.

Advantages of Proposed System

- The actual hyperbolic geometry and varying thickness are represented directly in the model.
- Discrete column supports and their interaction with the shell are captured.
- Both membrane forces and local bending moments are obtained for every element.
- Circumferential and vertical variation of wind pressure is applied accurately.
- Modal analysis identifies both beam-type and shell-type vibration modes.
- Load combinations are generated and evaluated consistently for all elements.
- Contour plots show the distribution of forces over the entire shell surface.
- Changes in thickness or geometry can be evaluated quickly by re-analysis.
- Column and foundation forces are obtained directly from the same model.
- Deflection under wind can be compared with serviceability limits easily.

IV. METHODOLOGY

The methodology begins with the fixing of the tower geometry, including total height, throat level, base, throat and top radii, and the equation of the hyperbola that passes through these points. Node coordinates are computed at each vertical level and circumferential angle using a spreadsheet and imported into STAAD.Pro. Plate elements are generated between adjacent nodes, and element thicknesses are assigned level by level. The raker columns are created from the lintel nodes to support points on the foundation ring, and the top ring beam is added. Materials are assigned, and supports are fixed. Self-weight is defined as the dead load case. Wind pressure at each element is computed from the design wind speed, the height factors of IS 875 (Part 3), and the circumferential coefficients of IS 11504, and applied as element pressure. The response spectrum case is defined for Zone III. Load combinations are formed as specified in IS 456:2000, and the model is analysed. Membrane forces and moments are extracted, reinforcement is designed at critical sections, and results are compared with membrane theory.

SYSTEM ARCHITECTURE

The workflow of the study progresses through a series of stages. The Data Collection stage fixes the functional requirements of the tower and the site data such as basic wind speed, terrain category, and seismic zone. The Geometry Generation stage computes shell coordinates from the hyperbola equation and defines the column and ring beam layout. The Finite Element Modelling stage creates plate elements for the shell with varying thickness and beam elements for columns and rings in STAAD.Pro. The Material and Support stage assigns M30 concrete and Fe500 steel and fixes the column bases. The Load Definition stage applies self-weight, wind pressure according to IS 875 (Part 3) and IS 11504, and seismic load according to IS 1893. The Load Combination stage forms the design combinations of IS 456:2000. The Analysis stage runs static and response spectrum analysis. The Design stage computes reinforcement in the shell, columns, and foundation, and the Result Comparison stage checks the finite element forces against membrane theory values.

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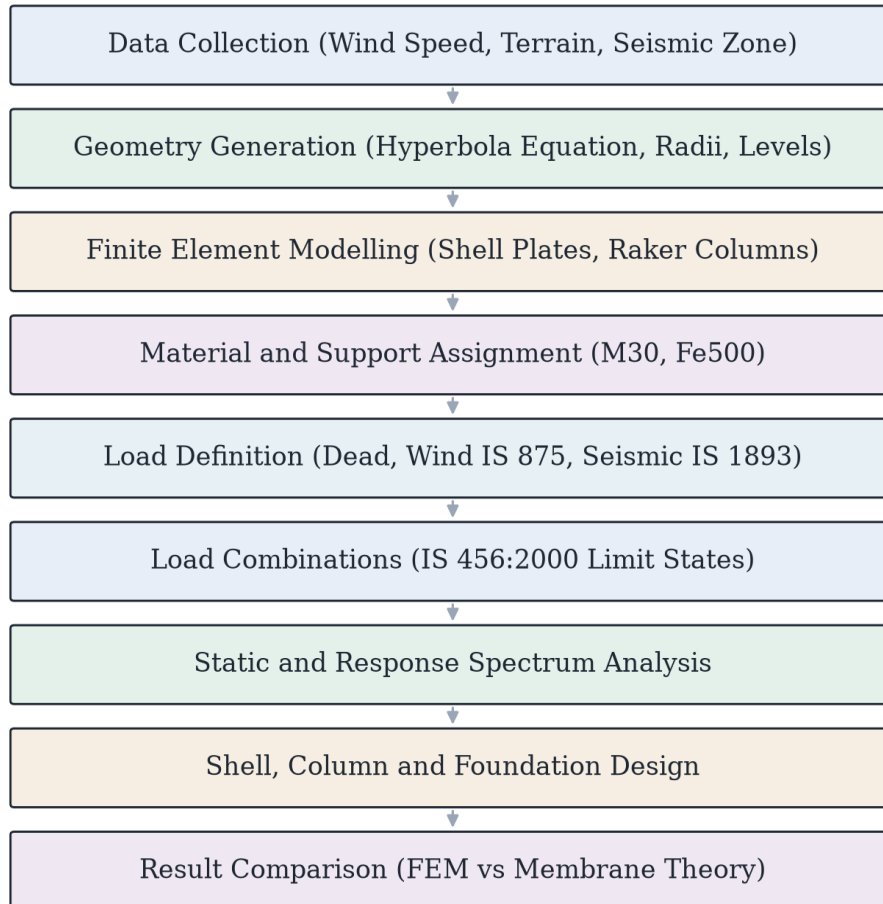
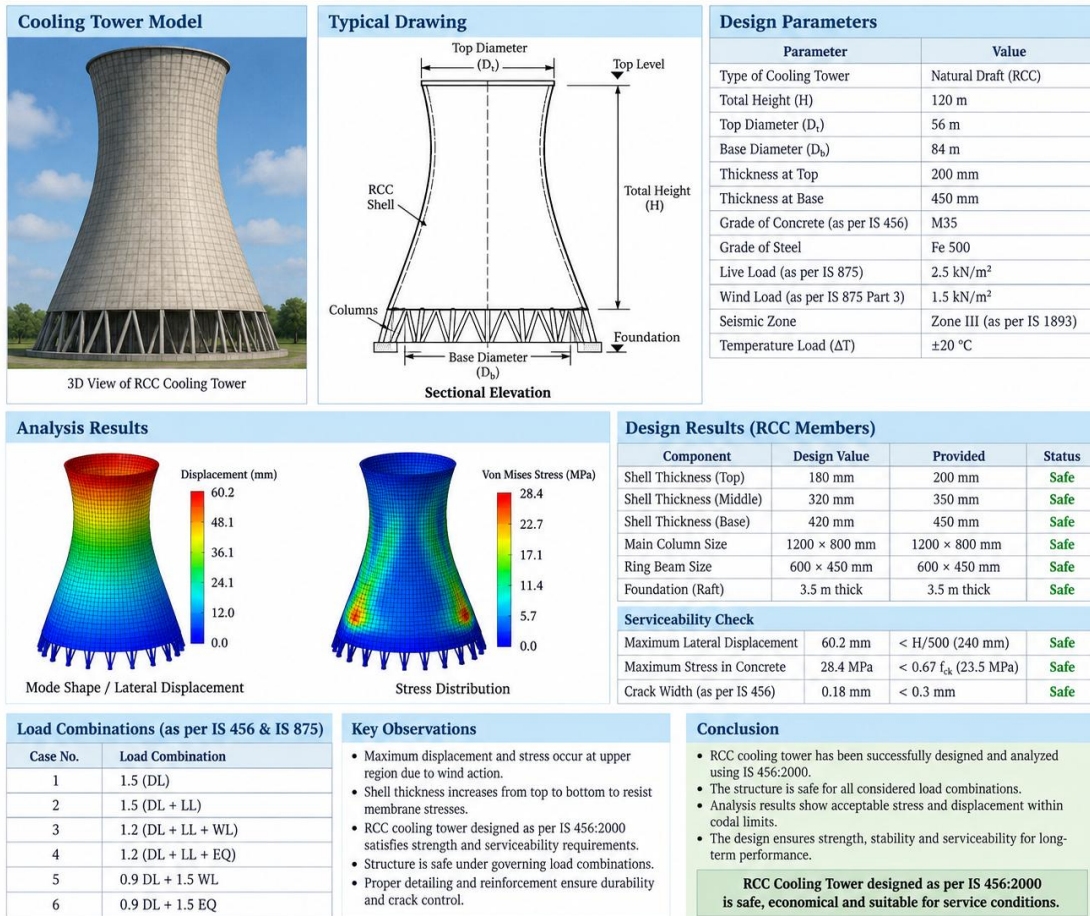


Fig. 1 System Architecture

V. RESULT AND OUTPUT

Design and Analysis of Cooling Tower (IS 456:2000)

Structural Design of RCC Cooling Tower as per IS 456:2000



VI. CONCLUSION

This study presented the analysis and design of a 120 m reinforced concrete hyperbolic cooling tower using finite element modelling in STAAD.Pro and the design provisions of IS 456:2000. The shell, raker columns, and ring beams were modelled together, and the structure was analysed for self-weight, wind load according to IS 875 (Part 3) and IS 11504, and seismic load according to IS 1893 (Part 1):2016. The approach gave the distribution of membrane forces and bending moments over the entire shell rather than at a few selected points.

The results showed that wind load governs the design of most of the shell. The windward meridian develops meridional tension, while the flanks at about 70 degrees from the windward direction develop the highest compression. Hoop forces vary around the circumference in accordance with the pressure distribution. The finite element results for meridional and hoop forces agreed closely with membrane theory over the middle height of the shell, but bending moments near the lintel and top ring were considerably larger than membrane theory can predict.

Reinforcement in the meridional and circumferential directions was designed for combined axial force and bending, and minimum steel was found to govern over a large part of the middle height. Additional reinforcement was required near the column supports and the top ring. The raker columns were found to be governed by combined wind and dead load, while seismic load in Zone III produced smaller

column forces. The lateral deflection at the top under wind was within the serviceability limits adopted, confirming adequate overall stiffness.

Future work may include buckling analysis of the shell under wind pressure, detailed thermal analysis for operating and shutdown conditions, and interference effects due to neighbouring towers in a group. Nonlinear analysis that accounts for cracking of concrete in tension zones and soil-structure interaction at the ring foundation would further improve the understanding of the tower's behaviour.

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