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A Survey on Hyperbolic Cooling Towers

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***Abstract*—**This study offers a comprehensive review of the research papers published in the field of cooling towers and gives an insight into the latest developments of the natural draught cooling towers. Different modeling, analysis and design techniques are summarized and the challenges are discussed. The 118 references included in this paper are mostly concentrated on the review of the published papers after 2005. The present paper represents a complete collection of the studies done for cooling towers and would give an updated material for the researchers and design engineers in the field of hyperbolic cooling towers.

***Keywords*—**Hyperbolic cooling towers, earthquakes, wind, nonlinear behavior, buckling, collapse, interference.

I. INTRODUCTION

COOLING towers constitute very important component of power generation systems they also contribute to environment protection. The hyperbolic cooling towers are associated with nuclear and thermal power plants, although they are also used to some extent in some large chemical and other industrial plants. From the structural point of view they are high rise reinforced concrete structures in the form of doubly curved thin walled shells of complex geometry and so is their analysis and design. The in-plane membrane actions primarily resist the applied forces and bending plays the secondary role in these special structures. Development of cooling towers goes back to the 19th century when the condensers were used with the steam engine (1902). The first hyperboloid shaped cooling tower was introduced by the Dutch engineers Frederik van Iterson and Gerard Kuypers and built in 1918 near Heerlen having 35 meter height. The first ones with 68 meter height in the United Kingdom were built prior to 1930 in Liverpool, England. Soon, heights and capacities increased, and the first cooling tower of height higher than 100 meter constructed in High Marnham Power Station in Britain. The cooling tower of 200 meter height built in 2002 in Niederaussem power station, Germany, was the world tallest hyperbolic cooling tower in the world until the construction of Kalisindh thermal energy plant in Rajasthan, India completed in June 2012. Two towers in this plant (Fig. 1) have a height of 202 meters with the base diameter of 142 meter each.


Fig. 1 Construction of Kalisindh thermal energy plant in Rajasthan, India

Cooling towers are classified by their use, build, heat transfer methods, air flow generation methods, and air-to-water flow mechanism. With respect to drawing air through the tower (air flow generation methods), there are three types namely as natural draft, mechanical draft and fan assisted natural draft cooling towers.

The present paper would concentrate on the researches done so far in the modeling, analysis, design and the latest theoretical and practical developments of such structures to bring to the light the better understanding of their behavior. The present work has more focus on the published research works between 2005 and 2014.

II. NATURAL DRAFT COOLING TOWERS (NDCT)

In NDCT, lower density of the moist air inside the chimney as compared to dry and cooler air outside at the same pressure makes the cooling process natural. The hyperbolic geometry has advantage of a negative Gaussian curvature which makes it superior in stability against external pressures than straight towers. The widened bottom of the tower accommodates large installation of fill to facilitate the evaporative cooling of the thin film of circulated water. Narrowing effect of the tower accelerates the laminar flow of evaporation and diverging top promotes turbulent mixing which increases the contact between hot inside air and cooler outside air. The entire structure is made of high-strength Reinforced Cement Concrete (RCC) in the form of hyperbolic thin shell standing on diagonal, meridional, or vertical supporting columns and radial supports. The shell is sufficiently stiffened by upper and lower edge members. In order to achieve sufficient resistance against instability, large cooling tower shells may be stiffened by additional internal or external rings which may also be used as repair or rehabilitation tool. The peripheral support at the base of the tower consists of either a number of single

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columns of varying or constant cross sections or pair columns of types A/V/X/Λ either joined at the tower base or foundation level (concentric) or not joined at any level (eccentric).

III. GEOMETRY AND OPTIMUM SHAPE OF THE TOWER

The hyperbolic form of thin-walled towers provides optimum conditions for good aerodynamics, strength, and stability. The only general ruled surface of revolution which can degenerate into a cylinder, a cone, or a plane is the hyperboloid. Rotation of a hyperbola $\frac{x^2}{a^2} - \frac{z^2}{c^2} = 1$, lying in the xOz plane having its convex toward the axis of rotation Oz, forms a hyperboloid in which the hyperbola becomes a meridian of this surface [1]. The other different formulas to define a hyperbola are given by equation $\frac{x^2+y^2}{a^2} - \frac{z^2}{c^2} = 1$, or by the parametrical equation:

$$x = -a\,sinu + a\,v\,cosu;\; y = a\,cosu + a\,v\,sinu;$$
$$z = c\,v$$

With regard to general hyperbola other forms of representation may also be used leading to the optimum shape of the tower against the different types of the loading conditions. Different geometries may found in the [2], [3]. Some studies have focused on selection of the optimum shape of the tower shell. Harte [4] gave a brief introduction into the shape optimization, design and construction of the 200 m high natural draught cooling tower shell at Niederaussem. Form of the tower is the result of optimization calculations with respect to a best possible load bearing behavior, lowest meridional stress and highest buckling safety, resulting in most economic concrete and steel masses. It has also been commented that the best possible load bearing behavior can be reached with continuous increase of meridian curvature from the base lintel to the throat level and thereafter continues without any drastic change. El Ansary et al. [5] following the flow chart given in Fig. 2 investigated the optimum shape of the tower corresponding to minimum weight assuming constant thickness and introduced the shell thickness as one of the design variables in order to achieve an optimum shape and design for the towers having B-spline geometric function. A number of computer optimization techniques were used by various researchers to solve shape optimization of cooling towers. Some are reported on [6]-[12].

IV. FINITE ELEMENT MODELING

In 1967, the first cooling tower shell analyzed by means of a shell bending theory [1]. Later, Antonov [13] neglecting the tangential displacements and their derivatives in the geometrical equations of a bending shell theory used a fourth-order ordinary differential equation for the normal displacement. Because of the complex geometry of the cooling towers and also the classical methods of analysis of shell structures, the most preferred method of the modeling and analysis of NDCT is Finite Element Method (FEM). In the 1970s, the FEM began to enter into the analysis of hyperbolic cooling tower shell structures. There are numbers of available finite elements to model and simulate the geometry and loading conditions of such complex structures. First, flat triangular finite elements were used. Lochner [14] applied a three-node curvilinear triangular shell element. A year later, using the FEM, Konderla considered the numerical solutions of symmetrical [15] and asymmetrical [16] problems of hyperbolic shells of revolution within the limits of a geometrically nonlinear shell theory. Detailed investigations on the finite element modeling and suitable elements applied in cooling towers analysis are covered in [17]-[20]. The latest researches done after 2005 are mostly related to the modeling and analysis considering the material nonlinearity, crack formation, use of multilevel elements and effect of large displacements using the FEM techniques.

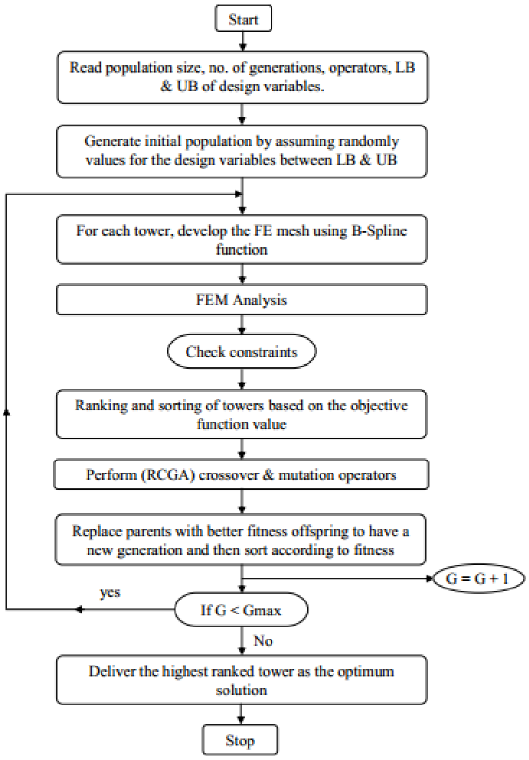

Fig. 2 Flow chart for optimum shape and design of cooling towers [5]

V. NONLINEARITY AND ULTIMATE LOAD

For the last four decades, tensile cracking in the concrete has been employed in the finite element analyses of RC structures. To this end, two distinct models being complex and time consuming have been generally employed: the discrete-cracking model and the smeared-cracking model. Determination of the ultimate strength of the cooling towers in the nonlinear static analysis subjected to the severe quasi-static wind loads is one of the objectives of the research for the structural engineers. Various nonlinear factors, such as the material nonlinearities in the concrete and reinforcing steel, tensile cracking, the bond effects between concrete and steel in the cracked concrete which is known as the tension stiffening, the large displacement effects, and so on; need to be taken into account to investigate the ultimate behavior of such structures.

Based on the Finite Element Method (FEM) a comprehensive numerical investigation of a RC hyperbolic cooling tower at Port Gibson, Miss. USA, was reported by Mang et al. [21]. They analyzed the cooling tower shell considering the large displacement, cracking in concrete, steel yielding and inelastic behavior of concrete. In their study, it was suggest that, in evaluating the ultimate strength of the cooling tower shell, the full nonlinear analysis must be performed since the ultimate load factor obtained by the nonlinear analysis is shown as considerably lower than that obtained by the buckling analysis. In fact, the linear buckling analysis gives ultimate load several times larger than that of nonlinear analysis. In this paper, it had been concluded that propagation of cracks in tensile zones would initiate the failure of the tower, followed by increased activation of the load-carrying capacity of the reinforcement and, finally, by yielding of the reinforcement. Milford and Schnobrich [22] obtained the load factor of 2.1 considering the tension stiffening effect, crack rotation and the geometrical nonlinearity. Later studies carried out by Hara et al. [23], Min [24] and Noh [25] reported the same conclusion. Thirty years later, Jia [26] employing another program, analyzed the same tower using the finite element method to find out whether the conclusions based on these results still hold if the concrete with much higher strength is used and geometric imperfections are considered. In this paper, ultra-high-strength-fiber concrete (UHSF-concrete) was used, the shell thickness was reduced and imperfections of the original geometry of the structure were also considered. The main conclusion of the study was that the cooling tower would still fail by loss of strength, characterized by the existence of an ultimate load and of yielding of the reinforcement which confirms the previous findings. However, Mahmoud and Gupta [27] obtained a load factor of 1.73 taking into account the large displacement effects. They concluded that the failure of the Port Gibson Tower at Mississippi was caused by the circumferential buckling in the vicinity of the throat rather than the yielding of the reinforcement, which contradicts the results of the previous researchers.

In the literature, many works such as Milford and Schnobrich [28], Gupta and Maestrini [29], and Harte and Kraatzig [4], have been given attention on the ultimate strength and causes of HPC towers failure. Noh [25] employing the layered degenerated shell element for modeling the reinforced concrete and taking into account the nonlinear behavior for the Port Gibson tower, obtained the ultimate load bearing capacity of cooling tower shell as 2.34 times that of design wind pressure. In this study for the concrete in compression, the work hardening plasticity was employed and the modified Drucker–Prager yield criterion written as a function of stresses given in (1) was used.

$$f(\sigma) = \{1.355[(\sigma_x^2 + \sigma_y^2 + \sigma_x\sigma_y) + 3(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)] + 0.355\sigma_0(\sigma_x + \sigma_y)\}^{1/2} \tag{1}$$

where σ_0 is effective stress equal to 30% of the compressive strength in which the initial yielding assumed to occur. For the tension stiffening effect, which is the contribution of the tensile stiffness from the cracked concrete due to the bond between concrete and reinforcement, the tension cut-off strategy was used. The schematic view of this model is given in Fig. 3. In this figure the degree of tension stiffening is controlled by ultimate strain ϵ_m which is given as constant n times the tension crack strain ϵ_t.

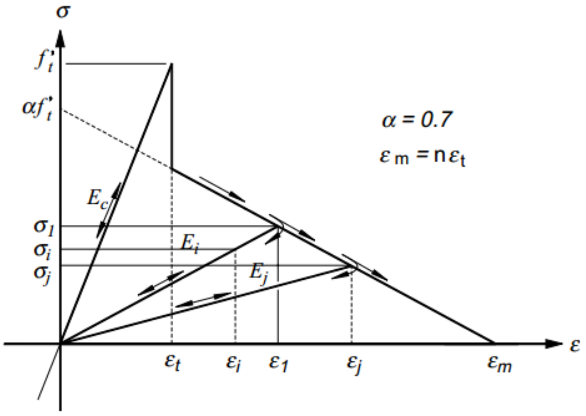

Fig. 3 Tension stiffening of concrete [25]

A year later, repeating more or less the same work, Noh [30] investigated the nonlinear behavior of the same cooling tower from unstressed state to the ultimate state. In this analysis, both the material nonlinearities in concrete (such as work-hardening plasticity, cyclic behavior to unloading and reloading, tension cracks and crack rotation, tension stiffening and shear transfer) and steel reinforcement, and the geometrical nonlinearities based on the Green–Lagrange strain tensor were taken into account. To represent the biaxial behavior of the concrete, again the work-hardening plasticity model was employed. The ultimate load bearing capacity of the cooling tower shell under consideration was obtained as 1.925 times that of the design wind pressure that corresponds to the wind velocity of 40.2m/s (90 mph). In this study, the nonlinear behavior reported to start by the formation of horizontal tension cracks in the windward meridian at the 43% height of the cooling tower shell. Then increasing the applied loading, cracks spread along meridional and circumferential directions. At the ultimate load, the yield of steel reinforcement in the windward meridian had occurred resulting in an abrupt increase in the along-wind displacement. Once the steel yielded, the yield zone propagated along the circumferential direction, resulting in the structural failure. The failure of the cooling tower was caused by the yielding of reinforcement in the windward meridian. The maximum crack width at the failure was over 3.0 mm in the part where the reinforcement yielded, however the bending cracks along the line of large curvature on the extrados were observed to be two orders lower to that of the maximum.

Deformation response and ultimate strength of RC shell structures are governed predominantly by material response of concrete and reinforcing steel, tensile cracking of concrete, bond between concrete and steel [31], [32]. Softening response of concrete due to quasi-brittle cracking in tension also significantly influences the nonlinear response by inducing loss of strength and stiffness [33]. Due to all these, analysis requires attention for realistic modeling of the layer of shell concrete confined between the reinforcement layers. Now a day's one of the most challenging areas for the researches is the modeling techniques using the layered elements. Gopinath et al. [2] presented integrated methodologies based on multilevel modeling concepts for finite element analysis of reinforced concrete hyperbolic cooling tower shell structure, with specific reference to account for nonlinear response behavior at ultimate capacity of cracked concrete. Geometric representation of the shell was enabled through multiple concrete layers. Composite characteristic of concrete was accounted by assigning different material properties to the layers.

After the successful linear or nonlinear analysis of the cooling towers for any types of loadings in which the finite element method is the most preferred, the designing process would be started. In the case of nonlinear analysis there are two different concepts for designing purpose [34]. A general cross-section design procedure according to EC 2 which is also used in linear analysis or an ultimate load design according to German standards DIN 1045-1 shown in Fig. 4.

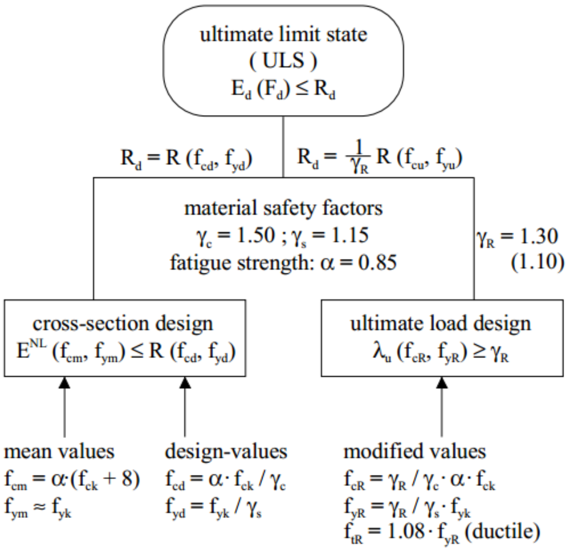

Fig. 4 Non-linear design procedure for ultimate limit state [34]

VI. LOADING, ANALYSES AND RESPONSES

The NDCT shell structures are submitted to environmental loads such as wind, earthquake and thermal gradients that are stochastic in nature. The dead loads, settlement, and construction load are the other common load conditions and various accidental loads, e.g., explosion often experience by hyperbolic cooling towers in their lifetime. The effects of the various loading conditions are combined and factored according to the available codes for the analysis and design purposes.

Dead load consists of the self-weight of the tower shell wall, the ribs, and the superimposed load from attachments and equipment. During the preliminary phase of the design process the results obtained from the self weight analysis are helpful to choose the most optimum shell-thickness variation. In the vicinity of the top edge, the self weight of the tower produces membrane tension however an axisymmetric and near-membrane state of compression are attained in the entire shell and in the vicinity of the supports, some bending may occur [35], [36]. The self weight for the towers of a general shape considering a number of different patterns of shell-thickness variation along a meridian was studied by Zingoni [35]. In this study, he developed explicit analytical results for resultant membrane stresses of the shell of revolution. The meridional directed forces developed in tower shell due to the self-weight of the tower may cause local (diamond-shaped) buckling or axisymmetric circular buckling [1]. For NDCT shell structures self-weight is always studied in combination with wind load in the areas of negligible seismic activity. Overall buckling of the tower shell may caused by combination of wind load and self-weight which takes place with large displacements. There is a considerable difference between design codes in criteria for buckling safety, requiring either the "snap-through" approach proposed by Der and Fidler [37] and used in British, Indian and German codes, the local or "buckling stress states" (BSS) approach proposed and developed by Mungan [38]-[40] and also used in German code, or the global approach which requires a full nonlinear buckling analysis of the shell and preferred in USA code [41].

VII. RESPONSE TO THE EARTHQUAKE

The earthquake loads are dynamic in nature. In the NDCT the earthquake loading is produced by transmission of ground motions from the foundation through the supporting columns and the lintel into the shell. For a hyperbolic tower, the magnitude and distribution of the earthquake-induced forces in the meridional direction, is a function of the mass of the tower and the dynamic properties of the structure (natural frequencies and damping) and the acceleration produced by the earthquake at the base of the structure. In parts of the world wherein the wind is not the dominant load for the design, earthquake loading is an important consideration in the design of cooling towers. Back in 1967, closed-form expressions derived by Gould and Lee [42] for determining the resultant stresses in the shell and corresponding deformations under static seismic design load. Design aids were produced in the form of tables and charts. Acceptable results yielded by the proposed procedure for the static load case. For a tower fixed at the base and free at the top, on the basis of characteristic statistical data, Abu-Sitta and Davenport [43] investigated the effects of dynamic earthquake loading. In their study, the induced dynamic stresses were related to equivalent membrane stresses from static loads, resulting in the development of a simplified earthquake analysis procedure. Wolf and Skrikerud [44] had studied the Influence of geometry and of the constitutive law of the supporting columns on the seismic response of a hyperbolic cooling tower. To determine the optimum seismic design, the influence of the geometry of the columns was investigated parametrically. Bhimaraddi et al. [45] had studied the free vibration response of the column supported, ring stiffened cooling tower and concluded that under seismic excitation of the cooling tower the stiffening rings may not help to increase the resistance of the structure because these rings have no influence on the modal characteristics of structures under such excitations, however, the stiffening rings help to increase the load-carrying capacity of towers under wind excitations. Various attempts had been made to model the discrete columns and to incorporate their effects into the cooling tower analysis using different approaches of varying accuracy. Hara [46] had studied dynamic response of cooling tower considering two alternative types of the supporting column systems namely I-column supports and V-column supports. It had been concluded that the total structural responses of the shell with supporting columns strongly depend on the supporting column systems and were different from the conventional pin-supported ideal shell. Sabouri-Ghomi et al. [47] had carried out a numerical study of the nonlinear dynamic behavior of reinforced concrete cooling towers supported by columns under earthquake excitation and its influence on the integrity and stability of cooling towers. In this study, the locations of plastic hinges within the supporting columns were identified and assessed the ramifications of the plastic hinges on the stability of the cooling tower. Asadzadeh et al. [48] had studied the structural response of the hyperbolic cooling towers under static wind and pseudo static seismic forces. In this study, two types of supporting systems namely I type and I type of column supports at the base of the towers had been considered and the finite element analysis employing higher order Mindlin formulation for the shell elements have been undertaken. They have observed that the I type of supports create higher flexibility at the base of the tower as compared to the V type of supports which behaves in a manner similar to fixed support at the base. The structural response of the towers under wind and earthquake was found to be completely different for the towers supported on different columns. Asadzadeh et al. [49] have studied the effects of the inclination angle of the supporting columns on the dynamic response of the cooling towers. In this study, dynamic response, the location of the maximum displacements in the tower shell and the participation of the tower's stiffness in structural response of the layered cooling tower has found to be significantly dependent of the change of the inclination angle and even the types of the supporting columns. It has also observed that the stiffness of the structure increases with increase in inclination angle of the supporting columns resulting in decrease of the period therefore altering the resistance of the cooling tower against the earthquake loading. It have been concluded that the hyperbolic structure of the cooling tower can be optimized by finding the optimum inclination angle of the supporting columns.

VIII. WIND AND BUCKLING OF THE TOWER

Wind is the prime lateral load and its combination with self weight of the tower shell can cause the buckling instability leading to catastrophic failure. After the sudden collapse of three immense cooling towers at Ferry-Bridge Power Station in England in 1965, experimental and theoretical investigations had been done in the area of the stability of hyperbolic shells to study the parameters increasing the wind resistance and buckling safety of the cooling towers. Niemann et al. [50] assessed the wind loads on the cooling towers using a new approach with individual equivalent static loads, and presented the design of the reinforcement in the meridional /circumferential direction and the design against buckling. Karisiddappa, et al. [51] carried out the analysis of column supported cooling towers for unsymmetrical wind loads. Improved 3D finite element formulation of column supported hyperbolic cooling towers and the realistic circumferential wind pressure distribution was carried out. Consequently, for different wind pressure distribution profiles, meridian membrane forces were shown to exhibit more sensitivity towards the pressure variations. Buckling is one of the main failure considerations in design of the cylindrical and hyperbolic shells. Vaziri et al. [52] reported that the sensitivity of the buckling behavior of both plates and shells in the presence of defects such as cracks highly depends on the loading condition. The uniform external pressure at which a cylindrical shell buckles is very sensitive to the geometry of the cylinder. The buckling strength drops rapidly as the buckle becomes longer making longer cylinders have a lower critical buckling pressure. The buckling strength is also affected by the thickness of the cylinder and thinner cylinders have lower critical buckling pressures [53].

The wind-induced response of cooling tower is the key factor to improve safety and to reduce tower crack [54]. At present, the research on the large cooling towers is focused on the material properties of the shell structure of tower, such as multi-layered nonlinear concrete shell [30], [55], and the structural behaviour under external environment [56], [57] especially under wind loads.

Wind load analysis can be performed following three methods. One is from experiments wind pressure coefficient, the shape factors and the wind-induced vibration coefficient can be obtained [58], [59]. Two is the CFD (computational fluid dynamics) analysis, to calculate the wind pressure and velocity distribution directly with the appropriate turbulence models [60], [61]. And the three is, to perform spectral analysis with a variety of wind spectra of the tower.

Goudarzi et al. [62] investigated the effects of NDCT geometry features on formation of pressure field around the Kazerun power plant in Iran. In this paper, the effects of inside flow modelling on the external surface wind induced pressure and the effects of adding circumferential footing structures to the external Wind Induced Pressure Field (WIPF) distribution were numerically examined and results were compared with the German power plant guidelines VGB. It had been stated that modelling inside the NDCT had negligible effects on the external WIPF. Then modelling the two different geometrical characteristics of a full scale standard NDCT by omitting the footing attachments and by considering the footing with major geometrical difference with standard NDCT shape the comparisons were made. The circumferential WIPF diagrams were found to be similar with VGB trends at throat level. At upstream stagnation point (θ=0), identical positive WIPF were computed and at downstream part of the NDCT (110<θ<180) shell, the constant values of negative pressure were obtained. However, the circumferential WIPF presented different trends for the two models at footing levels. The vertical profiles of WIPF follow the VGB guideline in the vertical levels except the footing structure wherein some disturbances appeared.

Li and Cao [63] analysed the large cooling tower based on the iterative method for wind pressure. In this paper, three analysis methods of wind load were studied and compared, the proposed iterative pressure method with fluid-structure interaction, the design code based method and the rigid body method assuming the tower structure as a rigid body in CFD analysis without fluid-structure interaction. It had been concluded that the code based method is conservative, and the relative error between iterative method and code based method increases with the increase of the mean wind speed. According to the iterative method, the pressure coefficient Cp becomes uniform relatively at lee near the exit and bottom of the outside surface of tower because of turbulence, which is different from Chinese code.

Ke et al. [64] presented a new approach for analyzing wind-induced responses and corresponding equivalent static wind loads (ESWLs) by a consistent coupling method (CCM) based on structural random vibration theory. In this work, the refined analysis method was firstly presented as a CCM to compensate the coupling component between background and resonant components. Then, to discuss the modal coupling mechanism of ESWLs, and to verify the precision of CCM for super-large cooling towers, a case study on a super-large cooling tower in Jiangxi nuclear power plant was made. In order to compute the dynamic response of the cooling tower, the fluctuating wind pressures acting on the shell surface were measured in a wind tunnel test. Then, based on a modified equivalent beam-net design method [65], the aero-elastic model for simultaneous pressure and vibration measurement was firstly put forwarded to check the validity of responses for a super-large cooling tower with CCM. The aero-elastic model consisted of 14 x 36 spatial thin steel sheets, which provide reduced-scale stiffness and truly simulated bending, torsion and axis stiffness components by modifying three-dimensional sizes of each thin sheet, such as depth and width, and of 12 x 36 pieces of copper additional masses, which simulate reduced-scale mass distribution. The computation results indicate that the coupling effects between resonant modes and cross term between background and resonant component are significant, and CCM is an effective method for calculating ESWLs on super-large cooling towers.

IX. STIFFENING RINGS

In new built and repaired NDCT the stiffening rings used to improve the stability of the total structure [66]-[73]. Meanwhile, contribution of stiffening rings to dynamic properties was also investigated in several parallel studies [67], [69]. Some preliminary instructive conclusions for the effects of the stiffening rings on dynamic properties are mentioned here. Compared with the original un-stiffened structure, stiffening rings' influences on eigenfrequencies could be classified into two separate series. For a specified mode, the stiffening rings' effect is related to its location: the eigenfrequency would be increased most if it locates at the maximum modal displacement, which is quite similar to the buckling problem [66]-[71]. For different modes, the stiffening rings' effect is related to the lattitude wave number: the mode which has more latitude waves will show more remarkable increase on eigenfrequency [67], [69].

Abbu-Sitta [74], presented ring-stiffened hyperbolic cooling towers under static wind loading and showed that the ring beam effect is local and influences mainly the meridional moment and the circumferential force. Form [67] found that the construction of the stiffening rings significantly influenced the buckling safety factor (BSF) and structural buckling stability of hyperbolic cooling towers. He showed that adding 2, 3, or 4 stiffening rings to the cooling tower increase the BSF of the R.C. shell by a factor of 1.65, 2.32, and 2.80, respectively. Bhimaraddi et al. [45] concluded that the stiffening rings may not increase the earthquake resistance of the HCT. Later on, in 1998, Boseman [75] evaluated the R.C. cooling towers of the Athlone power plant and showed that the addition of stiffening rings to cooling towers increased the BSF of the R.C. shell by a factor of 2.75. However, neither study addressed the details of stiffening ring design parameters such as quantity, location, and dimension. These design parameters are essential for effectively strengthening the R.C. cooling towers and achieving maximum buckling stability. Eight years later, Sabouri-Ghomi et al. [73] investigated the effect of stiffening rings on the buckling stability of R.C. cooling towers supported on X-shaped columns by considering the important design parameters such as the number, dimension, and location of stiffening rings and concluded that added stiffening rings increase the buckling resistance of the R.C. shell. The stiffening rings behaved flexibly or rigidly, depending on their dimensions. The number of flexible stiffening rings required to maximize the buckling safety factor was found to be higher than the number of rigid stiffening rings required to maximize it.

Zhang et al. [76] had also studied the effect of the stiffening ring on hyperboloidal cooling towers (HCT) to improve the dynamic properties and the wind resistance capability of such structures. In this study, they had proposed a participation degree of stiffening rings concept based on some fundamental perceptions on the dynamic properties of HCTs and free ring structures. The 'participation degree' is determined by the modal deform amplitude and latitude wave number of stiffening rings which was in good agreement with [67], [69]. In more detail, Zhang and his co-authors concluded that the higher modal deform amplitude and larger latitude wave number, which mean more modal energy, will give higher participation degree in the ring-shell structure and more improvement to the eigenfrequencies. They also found that the contribution of stiffening rings to a specified mode is related to the modal deform amplitude of the stiffened HCT. However, according to the earlier studies it was related to the modal deform amplitude of the unstiffened HCT. They also concluded that for the latitude and meridian directions, the stiffness in the latitude direction contributes more to the whole structure and finally, the location where the maximum modal displacement of the unstiffened HCT appears will not always be the most effective place for an additional stiffening ring unless the mode shapes of the unstiffened and stiffened HCTs are similar.

X. INTERFERENCE EFFECTS

In some power plant stations, the cooling towers are often in close distance with each other or the adjacent structures, consequently the wind-induced pressure on the towers of a cluster would be considerably different from the isolated one. The diversion of the air flow due to the vicinity of the tower to the nearby structures is known as interference. Though, there are no valid theoretical models for the correct evaluation of the interference effect [77], yet the experimental investigations on prototypes or boundary layer wind tunnel (BLWT) tests are used [78]. The BLWT tests are performed on flexible models by measuring the interference effects on strains with strain gauges placed on the inner and outer surfaces of the model and on rigid models by measuring the interference effects on pressure patterns [79]-[81]. The experimental studies involve the use of expensive wind-tunnel tests and data recording facilities, thus, requiring significant time and effort to obtain the desired results, therefore, there is growing interest among the researchers to use a relatively new technique known as Computational Fluid Dynamics (CFD) employing the FEM. The performance of the mathematical models used in CFD depends on the physical assumptions made for the turbulent component of engineering flows, thus, it has been proved to lead to a major errors in wind engineering simulations [82]. However, it does not mean that the results obtained by CFD are not reliable; it needs a careful effort and good knowledge of the modeling techniques. Orlando et al. [83] investigated the wind induced interference effects between two adjacent towers experimentally and numerically. First, the BLWT test performed for the rigid models of two adjacent towers of Italian power plant for varying distances and wind directions. Second, the interference effects on the structural responses of the towers were generated from the results of a computational model using the empirically obtained data by Orlando [84] and Borri et al. [85]. In this study the effects of resonance were neglected. It was concluded that the most significant interference effects are on the downwind tower and the largest interference effects on stresses were found for distances between 1.5 and 2 times that of base diameter and for flow angles less than 25°. The interference effects were found to be negligible for distances of greater than 2.5 times that of base diameter. Irtaza et al. [85] carried out a comprehensive numerical study for the determination of wind pressure coefficients on cooling towers considering the interference effects using the turbulence models of CFD. In this work, a cluster of three and five cooling towers having different wind incidence angle and spacing of two times the base diameter were simulated. Then the computed results on isolated and in single interference configurations of cooling towers were compared with the wind-tunnel tests data from Indian Institute of Technology, Kanpur, India [86] for Krishnapatnam thermal power plant in Andhra Pradesh, India and a good agreement on the windward face of the cooling tower was found using RNG k-ε turbulence method. In case of multiple cooling towers, both shielding and interfering effect leading to either reduction or enhancement in wind pressure coefficient values at different wind incidence angle observed. And because of interference and shielding effect the negative pressure sometimes found to increase by more than 33% to that of the isolated cooling tower.

Zhang et al. [87] studied the interference effects for group hyperboloidal cooling towers under static wind loading. In this paper the mechanical performance of hyperboloidal cooling tower (HCT) shell was illustrated according to some basic properties drawn from horizontal rings and cantilever beams under circular pressure. To better understanding of the mechanical performance, the cooling tower regarded as the coupling of horizontal rings and meridian cantilever beams. To pursue the relationship between different C_P (θ) and wind-induced responses they have adjusted the mean external latitude wind pressure distribution, C_P (θ). It was found that the maximum responses in hyperboloidal cooling tower shell are primarily dominated by the non-uniformity of C_P (θ) but not the local pressure amplitude C_P or overall resistance/drag coefficient C_D. They had also found that the latitude wind pressure shows great local effects on internal forces and deformation. The internal forces and deformation of HCT shell are primary dominated by wind pressure in sideward and windward which act as assistants for each other. In this study, the maximum amplitude of meridian axial tension was selected as an indicator to evaluate the influence of C_P (θ) on responses because it is the controlling force in design of structure. Since the interference effects on the cooling towers originate from the change of the wind pressure distribution along the circumference of the tower, the more realistic study would be the consideration of the dynamic wind effects.

In 2013, Ramesh Babu et al. [88] conducted wind-tunnel tests on aero-elastic model of an isolated cooling tower and the cooling tower with surrounding structures. The cooling-tower model made to a reduced scale of 1:300 from the geometric coordinates and good-quality aluminium material was used. In order to reliably predict the behaviour of the prototype cooling tower, similarity laws, namely, both dynamic and geometric were satisfied in this research. The total height of the model was 577 mm with the throat height as 432.5 mm. The top and bottom diameters were 246 and 413 mm, respectively, and the throat diameter was 236 mm. The wind-tunnel study was carried out on the model with raker columns. To obtain the velocity scale ratio as unity, base flexibility was provided at the base of the cooling tower by mounting it on a circular plate of 600-mm diameter and connected it at its periphery through a series of bolts to the turn table. Interference structures include the rigid models of a second cooling tower, power house block, boiler structures, electrostatic precipitator building, and a chimney stack. The details of the experimental programme, measurements, analysis, and results for both the isolated and interference cases completely presented in this paper. Wind-tunnel measurements on an isolated cooling tower were carried out to obtain meridional and hoop stresses at four different levels, namely, at top, throat, middle, and bottom, along a meridian using strain gauges. The interference factors also evaluated due to the presence of surrounding structures. A maximum interference factor of 1.3 observed at the top level. At other levels, the interference factors were observed to be in the range of 1.08–1.16.

XI. SOIL-STRUCTURE INTERACTION

Consideration of the soil–structure interaction is one of the challenging factors in the analysis of the cooling towers and it is extremely important when the soil or the foundation medium is not very firm. During lifetime of the cooling towers under the applied dynamic loadings, the structure interacts with the surrounding soil imposing soil deformations. These deformations, in turn, cause the motion of the supports or the interface region of the soil and the structure and consequently change the response of the structure. Noorzaei et al. [57] analyzed the cooling tower–foundation–soil system under vertical and lateral load generated due to self-weight and wind loads. In this study, the unsymmetrical wind pressure distribution in terms of Fourier series given in (2) was taken into account:

$$c(\emptyset) = \sum_{n=0}^{\infty} a_n \cos n\emptyset + \sum_{n=0}^{\infty} b_n \sin n\emptyset = a_0 + (a_1 \cos x + a_2 \cos 2x + a_3 \cos 3x + \cdots) + (b_1 \sin x + b_2 \sin 2x + b_3 \sin 3x + \cdots) \qquad (2)$$

where, $c(\emptyset)$ is the coefficient for circumferential distribution of wind pressure, n the number of harmonics, a_n and b_n the harmonic constants, and $\emptyset$ the horizontal angle measured from windward meridian. The response of the structure was investigated with respect to displacement and stresses. It was seen that the interactive analysis of the cooling tower–foundation–soil media plays a major role in releasing the stresses in the cooling tower, particularly at the bottom ring beam. Viladkara et al. [56], carried out the numerical modeling of a column supported hyperbolic cooling tower and its supporting annular raft–soil system to study the soil–structure interaction response under the influence of symmetrical wind load acting upon the tower. They highlighted that significant alteration of radial displacements and design forces and moments had occurred in the tower shell and supporting columns. It had been observed that the presence of a relatively stiff stratum at the base does not alter the design forces significantly. However, absence of a stiff layer at the bottom of the soil strata causes significant alteration in the values of forces and moments in the structure and the foundation. In this study, the annular raft with a thickness of 5.0 m behaved as a flexible foundation.

XII. COLLAPSE AND GROUND VIBRATION

The collapse of three natural draft cooling towers at the Ferry bridge power station in 1965 invited the attention of the researchers to work on the collapse and subsequent effects. These towers collapsed due to the inadequate design for the wind forces [89]. Krätzig and Zhuang [90] numerically simulated the collapse of a cooling tower subjected to both gravity load and wind load. This research only evaluated the safety and reliability of the cooling tower and did not consider the entire process of the collapse. In recent years, with the rapid development of computational technology, numerical simulation method has been applied to describe the collapse of structures, e.g., the collapse of cooling towers under blasting demolition [91] and the collapse of the World Trade Center after being hit by the planes [92]. In the coming years, a new cooling tower with an overall height of 235 m would be built as a part of the construction of a planned nuclear power station in southern China. Feng et al. [93] followed a comprehensive approach for prediction of the ground vibration due to the collapse of this super large tower caused by various accidental loads. In this investigation, firstly, the falling weight tests were conducted by the authors on the construction site near Hangzhou, China, using the dynamic compaction method by a falling weight of 12 tons with a diameter of 2.5 m and made of a concrete-filled steel shell slowly slung to a height of about 6 m and then freely dropped, impacting the soil surface and, consequently, inducing ground vibration. Then using the acceleration sensors the ground vibrations were measured in the form of acceleration time histories of the vibration points in the vertical and radial directions and not in tangential directions. Then the results of four typical test cases presented in the form of accelerograms at distances of 80m, 100m, 120m, and 150m with falling heights of 5.917m, 5.968m, 5.903m, and 5.97 m, respectively. A comparison on the maximum acceleration amplitudes showed that, a) the wave forms were typical vibration responses under a heavy impact, b) the maximum acceleration amplitude occurred in the radial direction and, c) the maximum acceleration amplitudes in the radial direction were larger than the corresponding ones in the vertical direction in the considered ground region are, similar to the results observed by Kwang and Tu [94]. Then using the ANSYS/LS-DYNA, a finite element method based “falling weight-soil” model of the four test cases were developed for the prediction of the impact-induced ground vibration. Comparing the simulation results and the test data satisfactory agreement was achieved both in the acceleration amplitudes and vibration durations. Although the simulated curves did not fit the ones obtained from test very well, their dominant frequency band was quite similar.

Meanwhile, the simulated collapse processes of the cooling tower supported by 120 columns of 18m at the bottom under two accidental loads that may cause the tower to collapse were considered in a parallel study. The accidental loads considered were the sudden removal of 60 columns which could be a result of a bomb attack or foundation settlement and the other was an extremely strong wind load with 44.3 m/s velocity. The details of the cooling tower, the structural model as well as the collapse simulation were described by Li et al. [95]. The simulations indicated that the cooling tower collapsed and the collapse modes of the tower exhibited different characteristics under the two load cases. The tower shell began to incline in the "removal" direction after the sudden removal of the columns, sinking in integrity, almost without changing the profile of the whole tower shell. Meanwhile, the residual 60 columns were crushed into pieces sequentially, due to the action of the tower gravity. The tower shell then contacted the ground surface with an inclination angle of about 3°. Subsequently, the tower strongly struck the ground and finally disintegrated. This collapse mode is labelled as "collapse in integrity" in this study. Dissimilarly, after the extremely strong wind load was applied, a large part of the upper shell became concave and cracked. The tower then disintegrated, broke into fragments and finally dropped on the ground. However, the lower portion of the shell did not break. This collapse mode is labelled as "collapse in fragments". Furthermore, based on the "falling weight-soil" model, "cooling tower-soil" models were developed for the prediction of the ground vibrations induced by two collapse modes of the cooling tower. The ground vibrations were obtained in the form of acceleration histories of vibration points at various distances in the vertical and redial directions.

In practice to reduce the ground vibration generated by various factors an open or filled isolation trench is often used. This method of vibration isolation can be classified into two categories: source isolation and receiver isolation [96], [97]. The former is used to reduce the vibrations at their source; whereas, on the other hand, the latter is usually built away from the source, surrounding the structure to be protected. A good deal of research efforts, both experimental and numerical have been devoted to the vibration screening by open trenches in [96]-[99]. These studies concluded that using an open isolation trench could reduce the ground vibrations significantly. Generally, the effect of vibration reduction depends mainly on the depth and width of the trench. The trench depth is the governing factor compared to the trench width. An analytical approach has rarely been used; because its solutions are usually limited to ideal conditions using an open isolation trench could reduce the ground vibrations significantly. Generally, the effect of vibration reduction depends mainly on the depth and width of the trench. The trench depth is the governing factor compared to the trench width. An analytical approach has rarely been used, because its solutions are usually limited to ideal conditions. Feng et al. [93] in the last part of their study, for a deep understanding of the vibration characteristics, conducted a parametric study with consideration of different collapse profiles, site or soil geologies as well as the arrangements of an isolation trench. For the collapse profile of the tower shell the inclination angle and vertical velocity were considered as two critical factors when it just reached the ground surface. For the three considered inclination angles (i.e., 0^0, 3^0, 6^0), it was found that the case with an inclination angle of 0°, led to the most intensive ground vibration having the maximum acceleration amplitude. However, its vibration duration, i.e., of about 5.7 s, was the shortest one of the three. Two types of site geology were considered in this paper to study the vibration characteristics. One was a solely rock foundation; and the other was a "soil-rock" foundation, i.e., overlying soft soil to a depth of 10 m with the same rock foundation underneath. It was found that the ground vibration was dramatically reduced for the soil-rock foundation and that the vibration duration became shorter, compared to those of the solely rock foundation. From the viewpoint of application, this finding also suggests an efficient method for vibration reduction. In the last part of the parametric study, two different open isolation trenches, both with a length of 220 m and a width of 5 m and 10 m, were set in the model as a method of source isolation. It was seen that the ground vibrations were significantly reduced by adding an isolation trench and the vibration durations of the considered cases had almost no significant change which was in agreement with the numerical study carried out by Adam and Estorff [97]. Considering the whole study, it was found that severe ground vibration occurred in the vicinity of the cooling tower when the collapse happened. However, the vibration attenuated rapidly with the increase in distance from the cooling tower. Moreover, the "collapse in integrity" mode and the rock foundation contributed to exciting intense ground vibration. By appropriately arranging an isolation trench, the ground vibration can be significantly reduced. This study has indicated that, with the increasing height of the cooling tower and the relatively small distance between the nuclear island and the cooling tower, the effect of collapse-induced ground vibration on the nuclear-related facilities cannot be ignored.

A year later, in 2014, Yi and his co-authors [100] continued their study on the same tower considering the accidental loads. Dynamic finite element analysis considering the nonlinear material models carried out and the focus made on the modes and mechanisms behaviour of the collapse of the towers subjected to accidental loads. Vehicle collision, airplane impact, local explosion and missile attack were the four simulated accidental loads to study the failure of the tower. It was found that vehicle collision, missile attack and small TNT equivalent explosives (2 kg, 20 kg, and 200 kg) might result in local failure of the cooling tower; however, the tower can still keep stable. On the other hand, large TNT equivalent explosives (2000 kg, 4500 kg) could cause severe damages in the inclined columns of the cooling tower, and lead to progressive collapse of the entire cooling tower. The two kinds of TNT equivalent explosives caused the same collapse mode while the collapsing duration was different. The airplane impacted at the throat of the cooling tower caused the local failure of shell structure of the tower, and then the progressive collapse of the cooling tower happened due to the gravitational action. The resulting collapse mode was different from that triggered by the local explosion.

XIII. RELIABILITY ANALYSIS

Due to the complexity of the building procedure, uncertainties in the material properties as well as differences between the theoretical and the real geometry also exist [101] therefore the reliability analysis is also seems to be indispensible part of the investigation in the cooling towers. Numbers of researchers have been paid attention to the random responses of cooling towers; they are seldom related to the buckling bearing capacity with consideration of random factors. Recently, Xu et al. [102] analyzed the stochastic response of cooling towers with fluctuating wind by Pseudo-excitation method, and compare simulated and experimental results. Li and Chen [103], [104] proposed the generalized probability density evolution method for random structures analysis in terms of the formal solution of dynamic system and the probability conservation theory. Then, Xu and Bai [105] introduced a virtual time variable to construct a virtual stochastic process for the random buckling problem, so that the probability density function of random buckling bearing capacity, i.e. the first order random buckling eigenvalue, described as a dynamic process as well. Thereafter the joint probability density evolution equation derived for the buckling bearing capacity. In this paper, they developed a probability density evolution method for the analysis of the random structural buckling problem and they have analyzed a super large cooling tower of 250 meter height employing the same. To partition the random parameter space in terms of given probability models tangent spheres method or spherical sieving technique [106] was employed. In this paper, the random material properties and wind loads are considered and three random variables are introduced including the elastic modulus of concrete, the wind speed at height of 10 m and the ground roughness. They reported that, the random buckling capacity obeys normal distribution in the case of elastic modulus as the sole random variable following normal distribution. But as extreme value distribution of wind speed at height of 10 m and the log-normal distribution of ground roughness were considered, the simulated probability density functions of buckling capacity were distorted and quite different from normal distribution. They also found that, as far as the first order and the second order statistical moments were concerned, the mean values of the analyzed cooling tower considering both random material properties and random wind loads were close the deterministic buckling bearing capacity. But the standard deviation and the coefficient of variability of random buckling bearing capacity increase when the random wind loads (non-normal random factors) are taken into account.

XIV. COOLING TOWER EFFICIENCY

Cooling tower is normally designed for stagnant ambient air condition, but experimental observation showed that cooling efficiency was changed as a function of cross-wind velocity. Cooling efficiency of a natural draft cooling tower (NDCT) is significantly affected under cross-wind condition and might decrease to 75 percent in the range of moderate to high wind-velocity condition. Separated flow occurring at the rear radiators, along with deflected plume exiting tower stack, reduces the cooling efficiency [107]. Experimental and numerical observations identically showed that heat transfer capacity of the cooling tower proportionally increased with wind velocity up to 3 m/s, and then decreased for higher wind velocity [108]. Various researchers have studied the effect of the wind on cooling tower's efficiency and the methods of the improvements. The first numerical study was performed by Du Preez and Kroger [109] to illustrate the wind effect on air flow field through the cooling tower. Other researchers identically showed that there were two causes which reduced the cooling efficiency; flow acceleration near the sideward radiators trailing with a flow separation beside the rearward radiators, and plume deflection at the exit plane of the tower stack [110], [118]. The same unfavorable cross-wind effects were reported in [111]-[113] on the thermal performance of a natural draft wet cooling tower.

Many researchers have given their attention on the accelerated flow near the side ward radiators. They used wind breakers which were extended normal to the wind direction, to decelerate the air flow velocity. The idea of using the wind breakers was firstly suggested by Du Preez and Kroger [109], but it was not tested by them. This idea then was tested numerically by some other researchers [110]-[115] and reported that, windbreakers improved cooling efficiency up to 16% at generally investigated wind velocity of 10 m/ s. Al-Waked and Behnia [110] simulated the flow field in the presence of different wind breakers under the wind condition. They computed the air mass flux through the radiators. Also, they computed the heat flux from the radiators and concluded that in the presence of wind breakers both the mass and heat fluxes increased under the high wind velocities. Three years later in 2007, the same authors [115] illustrated that, windbreakers could also increase the thermal performance of a natural draft wet cooling tower. Also, Wang et al. [116] qualitatively showed that guiding channels improved the thermal performance of a small scale model of natural draft wet cooling tower. Goodarzi and Keimanesh [117] used radiator type windbreakers instead of usual solid type windbreakers in their numerical simulation and showed that their proposed windbreakers improved cooling efficiency more than solid ones. Although the wind breakers improve the cooling efficiency, designers have never used them practically.

Goodarzi [107] has proposed a new exit configuration for tower stack to improve the cooling efficiency attempting to reduce the throttling effect of the plume deflection. In this study by crossing an oblique plane of 27 and 45 an elliptical exit plane for the tower had been created and was studied numerically. It had been concluded that, in the regions of invariant wind direction, the proposed geometry can be used to reduce the throttling effect. Because of the fact that the wind direction may alternatively change, it has been suggested that, the tower stack can be fabricated by two parts; the fixed lower part, and the upper part which must be suitably rotated with respect to the wind direction. But the problem arises here because of the practical implementation and the constructability of such additional rotating parts. It was also stated that the proposed geometry cannot improve the cooling efficiency as large as the wind breakers, but the combined use of proposed geometry and wind breakers will significantly improve the cooling efficiency under the wind condition. In another study, Goodarzi and Ramezanpour [117] proposed alternative shell geometry with elliptical cross section cooling tower instead of usual shell geometry with circular cross section. Thermal performance and cooling efficiency of the two types of cooling towers are numerically investigated. Numerical simulations showed that cooling tower with elliptical cross section improves the cooling efficiency compared to the usual type with circular cross section under high-speed wind moving normal to the longitudinal diameter of the elliptical cooling tower. According to the fact that the wind direction is not always the same efficiency of proposed elliptical configuration must be studied for the different blowing angles of the wind.

XV. CONCLUSION

The latest theatrical and experimental improvements and new achievements in the analysis and design of the natural draft hyperbolic cooling towers are briefly discussed. The various factors in the analysis and design of the cooling towers have been tracked in this study. This review is a complete collection of the studies done for cooling towers and would give the updated and sufficient materials for the researches in this field.

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