Damage, deterioration and the long-term structural performance of cooling-tower shells: A survey of developments over the past 50 years

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Abstract

The last 50 years have seen a gradual shift in trend in research on concrete hyperbolic cooling-tower shells, from the issues of response to short-term loading and immediate causes of collapse in the early part of this period, to the issues of deterioration phenomena, durability and long-term performance in more recent times. This paper traces these developments. After a revisit of some historical collapses of cooling-tower shells, and a brief consideration of condition surveys and repair programmes instituted in the aftermath of these events, focus shifts to the important question of damage and deterioration, and progress made over the past 30 years in the understanding of these phenomena. In particular, much research has gone into the modelling of cracking and geometric imperfections, which have a considerable effect on the load-carrying capacity of the shell, and are also manifestations of long-term deterioration. While structural monitoring of the progression of deterioration in cooling-tower shells, and the accurate prediction of this through appropriate numerical models, will always be important, the thinking now seems to be shifting towards designing for durability right from the outset.

Keywords: Cooling towers; Shell structures; Long-term performance; Damage modelling; Deterioration phenomena; Concrete cracking; Shell imperfections; Durability

1. Introduction

A large number of reinforced-concrete cooling-tower shells at power stations around the world are at an advanced stage of their service life, and exhibit signs of considerable structural deterioration accumulated since their construction. Evidence of gradual damage and deterioration over time includes severe cracking, rusting of steel reinforcement, spalling of chunks of concrete, irreversible deformation of shape, and global tilting of the cooling tower due to differential settlement of the foundations. One or a combination of these effects can provide the conditions for a total collapse of the structure even under moderate loads, hence comprehensive programs have been instituted in several countries around the world, to inspect and monitor the structural condition of cooling towers, and effect repair measures where necessary.

This paper traces the developments in research on concrete hyperbolic cooling-tower shells, which in the past 50 years has seen a shift in trend from the issues of response to short-term loading and immediate causes of collapse in the early part of this period, to the issues of deterioration phenomena, durability and long-term performance in more recent times. After a revisit of some historical collapses of cooling-tower shells, and a brief consideration of structural condition surveys and repair programmes instituted in the aftermath of these events, focus shifts to the important question of damage and deterioration, and progress made over the past 30 years in the understanding of these phenomena.

Cracking and geometric imperfections have long been recognized as having a considerable effect on the load-carrying capacity of the shell, and much attention has subsequently been devoted to the modelling of these
phenomena. Both meridional and circumferential geometric imperfections can result in severe stress localizations and cracking, and significant reductions in the buckling resistance of the shell. Cracking and imperfections can also deteriorate with time, so that any (nonlinear) model for long-term structural performance of cooling-tower shells has to be able to take into account the time-dependent nature of these and similar effects.

The paper ends with the issue of designing for durability. Structural monitoring of the progression of deterioration in cooling-tower shells, and accurate predictions based on good mathematical models, will always be important. However, for the large high-capacity cooling towers that are increasingly becoming necessary these days, the thinking now seems to be shifting towards designing cooling towers for durability right from the outset.

2. Loading considerations

In areas of negligible seismic activity, the two most significant loadings acting on a hyperbolic cooling tower are self-weight and wind [1,2]. Under the tower’s self-weight, a smoothly continuous shell of perfect hyperbolic profile achieves an axisymmetric and near-membrane state of compression everywhere except in the vicinity of the top edge, where some membrane tension is observed [3,4], and in the vicinity of the supports, where some bending may occur. It is this compressive self-weight prestress over most of the shell that beneficially counters the generally non-axisymmetric wind-induced tensile effects.

As early as 1961, Martin and Scriven [5] presented an exact calculation method for membrane stresses due to self-weight and wind, in which only steady wind was considered. Eight years later, Gardner [6] presented, on the basis of the finite difference method and model testing, a calculation method for the natural frequencies of a hyperboloidal shell, as well as for peak deformations due to turbulent wind. In 1974, Hashish and Abu-Sitta [7] developed a procedure (also supported by model tests) to predict both quasi-steady and resonant stresses. A year later, Cole and co-investigators treated the transient dynamic and stability problem for wind loading, and presented a summary of the understanding at that time of the buckling behaviour of cooling tower shells [8,9].

In 1980, Sollenberger and co-investigators [10] carried out site experiments to measure wind pressure on a cooling tower, and concluded that the values generally used in design are significantly higher than actual measurements. At about the same time, Niemann [11] conducted wind-tunnel tests on tower models to assess quasi-static wind pressure on cooling towers. Tower response to turbulent wind was split into quasi-static and resonant components. Once quasi-static pressure distribution was defined, gust factors to simulate response to turbulent wind were introduced. Further experimental tests [12] confirmed the observation that dynamic stresses are not always correctly assessed by assuming a static design wind load. At this time, cooling-tower design practice in Germany [13,14] reflected wind pressure distributions which were reasonably in line with research findings up to that time. In 1983, Hayashi and Gould [15] proposed a simple elastic method to determine a tower’s cracking wind load. There now seems to be reasonable agreement among researchers on procedures for determining quasi-static wind pressure distribution on cooling towers.

Design codes, on the other hand, differ considerably in criteria for buckling safety, requiring either the “snap-through” approach, the local or “buckling stress states” (BSS) approach, or the global approach. The snap-through criterion was first proposed by Der and Fidler in 1968 [16]. Based on results of wind-tunnel tests, this approach prescribes design for a critical wind-buckling pressure, which is a function of shell geometry and material strength. The Der and Fidler formula is incorporated in the British, Indian and German codes. The BSS approach, proposed and developed by Mungan [17–19], is based on the hypothesis that buckling starts locally and is primarily dependent on the strength of the shell material as well as the presence of geometrical imperfections. It is also incorporated in the German code. On the other hand, the global buckling criterion requires a full nonlinear buckling analysis of the shell, and is the preferred approach in the USA [1].

In parts of the world, earthquake loading is an important consideration in the design of cooling towers. Back in 1967, Gould and Lee [20] derived closed-form expressions for determining shell stress resultants as well as corresponding deformations under static seismic design load. Design aids in the form of tables and charts were also produced. The proposed procedure yielded acceptable results for the static load case, but did not account for dynamic effects. In 1970, Abu-Sitta and Davenport [21] investigated the effects of dynamic earthquake loading, on the basis of characteristic statistical data for a tower fixed at the base and free at the top. Induced dynamic stresses were related to equivalent membrane stresses from static loads, resulting in the development of a simplified earthquake analysis procedure. In the approach adopted by researchers in Germany [14], the response-spectrum method is applied to the tower, which is discretized into a beam-like model. This approximate approach yields an acceptable estimate of seismic response.

There are, of course, other possible load effects on cooling towers. Thermal loading, which has generally been ignored in early designs due to lack of adequate knowledge, was considered by Meschke and co-investigators in 1991 [22], in their assessment of the residual safety of an old and cracked cooling tower located in Ptolemais, Greece. In their finite element analysis, a smeared crack model was adopted, taking into account cracking of the shell and corrosion of the reinforcement. Through appropriate simulation of thermal load history, it was possible to estimate the contribution of thermal effects to overall structural damage.
3. Some historical collapses and lessons from the past

Information on cooling-tower collapses is often not readily available, but the examples mentioned here have been well documented, and the lessons from these are still as valid as they were at the time of the collapses. The examples are drawn mostly from the UK, but this does not suggest that only cooling towers constructed in the UK were particularly vulnerable to collapse. Rather, these case studies have been the subject of particularly detailed and well-publicized investigations.

In November 1965, three out of a group of eight reinforced-concrete cooling towers were blown down in strong winds at Ferrybridge Power Station in the Yorkshire county of the UK. Details of the collapse have been reported extensively in the literature [23,24]. The committee of inquiry into the collapse cited, as the cause of the collapse, tension failure of the meridional reinforcement resulting from a gross underestimation of wind loading, combined with a limited contemporary knowledge of the adverse effects of turbulence and tower grouping. The situation was aggravated by the use of inadequate factors of safety in the design. Following the recommendations of the committee, the Central Electricity Generating Board (CEGB) of the UK commissioned a series of wind-tunnel tests on tower models, which resulted in a more realistic assessment of wind-induced stresses.

In September 1973, a single 137 m tall cooling tower collapsed under moderate winds at Adeer Nylon Works power plant just off the southwest coast of Scotland. Formal investigation into the collapse [25] concluded that meridional curvature imperfections in the shell were responsible for the failure. High circumferential stresses due to the imperfections were shown to have caused yielding of horizontal steel, resulting in collapse. Some years later, a number of researchers [26–28] investigated the influence upon shell stresses of small cooling-tower shape deviations, and came up with results which confirmed the findings of the Adeer Nylon committee of inquiry.

A third incident of a cooling-tower collapse in the UK occurred in the Lancashire county in January 1984, when one tower at Fiddlers Ferry Power Station collapsed in wind gusts exceeding 125 km/h [24,29]. Construction of the 114 m tall tower, which was already in progress at the time of the collapse at Ferrybridge, had been stopped briefly to consider possible improvements in design. Although the design had been slightly improved, the tower did not fully meet the design recommendations of the Ferrybridge inquiry, since the lower part of the shell (already completed at the time of the Ferrybridge collapse) only had one layer of reinforcement. With the knowledge gained from both the Ferrybridge and Adeer Nylon collapses, and in the light of subsequent research since then, the committee of inquiry into the Fiddlers Ferry collapse concluded that an axisymmetric external bulge imperfection built into the shell just above the lower ring beam caused the collapse.

At Bouchain in France, there is also one cooling tower reported to have collapsed in 1979 under minimal winds, after ten years of service [24]. This tower was known to have had serious dimensional errors right from the beginning, and it is now suspected that the collapse could have been caused by progressive deterioration. In addition to cooling towers which actually collapsed, there is on record a number of those that had deteriorated to the extent that they had to be demolished because they posed a very high risk of collapse. Examples include the towers at Pont sur Sambre and Ansereuilles in France [30].

4. Structural condition surveys and strengthening

Following the collapses at Ferrybridge, Adeer Nylon and Fiddlers Ferry, the Central Electricity Generating Board of the UK instituted an extensive programme for inspection, repair and maintenance of the 139 towers they had in service. More than half of these were of height in excess of 100 m, and 13 were constructed after the Ferrybridge collapse. The first phase of the programme comprised a detailed shape-imperfection and structural-condition survey. Pope [24] described the survey techniques devised specifically for this program, and summarized the observations made at selected power stations. For instance, for one cooling tower at Ratcliffe Power Station, the change in radial deformations around the circumference over a 10-year period was monitored. This tower was among the larger towers (of height exceeding 100 m) which showed considerable structural defects in the form of deformations and/or vertical cracks. From such monitoring data gathered over a period of time, a risk assessment for each tower was performed, and the towers prioritised for repair and strengthening. Defective towers were strengthened using a number of techniques, depending on the nature and cause of the defects. For instance, the cooling towers at the Ironbridge Power Station near Birmingham had an additional concrete mantle cast on the outside surface of the shell [31]. Some of the severely cracked shells were repaired by injecting resin into the cracks.

In South Africa, similar structural surveys of existing cooling towers were also being undertaken at about the same time. Here, cooling-tower design practice had fortunately been quite conservative, requiring the shells to be reinforced with two layers of steel rather than one. All existing cooling towers were found to be structurally sound, with the exception of two towers at Kelvin Power Station in Johannesburg [32], where considerable vertical cracking was detected. Strengthening of the towers was carried out in 1985 and 1986 by adding cast-in-situ concrete stiffening rings. A finite element analysis enabled an optimum spacing of these rings to be determined. This repair method was used again in South Africa in 1993, when a further two cooling towers were strengthened at Athlone Power Station in Cape Town [32]. Vertical cracks had developed in the lower part of the then 35-year-old towers, which according
to contemporary codes, were dangerously under-reinforced. In addition to the rings, all large cracks were filled with low viscosity epoxy resin.

Details on various methods for the survey of the shape and structural condition of cooling-tower shells, and for the practical repair of damaged shells, may be seen in the Proceedings of the 4th International Symposium on Natural Draught Cooling Towers [33].

5. Damage and deterioration phenomena

5.1. Cracking and ultimate strength

Cracking of concrete as a damage or deterioration phenomenon has received considerable attention over the past 30 years. Owing to the brittle nature of concrete, it is often the rapid propagation of cracks in tensile zones, followed by yielding of the steel reinforcement, that results in ultimate failure [34]. As shown by Gupta [35], significant redistribution of stresses occurs after yielding of the reinforcement, which has the beneficial effect of increasing the ultimate load-carrying capacity of the shell. Cracking itself may, of course, initiate as a result of buckling, or quite independently. Studies of the ultimate strength of cooling-tower shells after initial cracking confirm the importance of a correct amount of reinforcement steel in ensuring maximum structural resistance against wind load [36]. The various numerical models for simulating cracking and reinforcement-yielding phenomena in structural concrete will not be discussed in detail in this survey.

5.2. Imperfections

The presence of imperfections in the geometry of the cooling-tower shell often provides the conditions that precipitate failure of the shell. Geometric imperfections (which may occur in the meridional section or the horizontal section, as kinks in the smooth profile, or deviations in the radius of curvature of the profile) could be present from the outset as initial constructional errors, or may develop gradually with time as a result of the service loads and other operational conditions, or may arise at some particular point in time during the life of the cooling tower as a result of sudden damage. As far as constructional errors are concerned, studies by Soare [37] of a cooling tower under construction in Romania had shown, as early as 1967, that small changes in the radius of the horizontal circles of the shell of revolution can cause significant changes in the meridional radius of curvature, which in turn cause relatively large changes in hoop stresses.

Of meridional and circumferential geometric imperfections in cooling-tower shells, it appears that the former attracted the attention of researchers first, since with meridional imperfections, the assumption of axisymmetry could be preserved for simplicity. In 1969, by conducting parametric analyses on varying geometric shell shapes, Croll demonstrated the sensitivity of membrane-stress distribution in hyperbolic shells to even smooth overall variations in the meridional profile [38]. Seven years later, Kemp and Croll [39] analyzed a cooling-tower shell similar to the one that collapsed at the Adeer Nylon Power Station, and in agreement with Soare [37], demonstrated that “even moderate imperfections induce hoop stresses in the vicinity of the imperfection that are of the same order of magnitude as the meridional stresses”. In 1979, Croll and co-investigators estimated the elastic stresses around cooling-tower imperfections by analysing a perfect shell with the imperfection replaced with an equivalent localised band of applied pressure [27], and also on the basis of a piecewise model of the imperfection [26]. Although neither approach could account for nonlinear effects, they nevertheless permitted a rational set of guidelines on construction tolerances to be proposed [40]. In the sense of rationalisation, this approach was therefore an improvement on the then existing guidelines [41,42]. In papers published in 1979 and 1982, Al-Dabbagh and Gupta [43,44] presented the results of an analysis of the effects of wind load on a cooling-tower shell with an axisymmetric imperfection, and these reflected marked increases in both hoop forces and meridional bending moments. Reduced hoop stiffness due to meridional cracking was taken into account in later models of meridional imperfections [45].

As for circumferential imperfections, survey data has revealed that these generally assume a wave-like pattern around the circumference, with varying modes at different heights of the tower [46,47]. Such radial imperfections can give rise to flexural stresses in the shell high enough to cause vertical cracking. In 1980, Ellinas and co-investigators [46] modelled a radial imperfection as an equivalent pressure load following the method of Croll and co-investigators [27]. For a nonlinear numerical assessment of such effects, it is evident that the local–global finite-element technique proposed by Gould [48] would be appropriate. In a relatively recent publication, Waszczyzyn and co-investigators [49] also employ a nonlinear FE analysis to account for large geometric imperfections in the form of deviations in the horizontal radius of the shell. Their observation that such imperfections do not significantly influence the load-carrying capacity of the shell seems to be at variance with the observations of earlier investigators [46,47].

A general insight into how imperfections change the state of stress in cooling-tower shells, and into the possible analytical methods for such problems, may be seen in the work of Godoy [50]. As regards causes of imperfections, constructional errors and accidental damage have already been mentioned (Godoy [51] points out some fundamental similarities in the respective mechanisms of stress redistributions). It is also interesting to note that a correlation between existing imperfections and dead-load buckling modes has been observed by some investigators [52], suggesting that some of the measured imperfections may in fact be buckles in the shell profile.
that occurred during construction as the dead weight of the tower increased. Evidence also suggests that imperfections can deteriorate with time. There seem to be a good number of models that are aimed at predicting the state of stress in the shell due to a geometric imperfection or a pattern of imperfections at any given time, but clearly, models that account for the gradual variation of imperfections with time are necessary, for a more reliable assessment of the long-term performance of the shell.

5.3. Long-term deterioration

A numerical scheme based on the theory of linear viscoelasticity has shown that in cooling towers, the distributions of both stresses and displacements can change considerably over 30 years [53]. Progressive damage (as opposed to sudden impact damage) is an aspect of structural deterioration, and this can manifest itself as an increase in the number, size and distribution of cracks, an increase in the severity of geometric imperfections, or an increase in the extent of rusting of steel. There is still limited knowledge of the factors influencing long-term structural deterioration in cooling towers. In 1991, Aflak and co-investigators [54] studied a number of damaged towers in France with the object of establishing parameters governing the aging process. Observations made pointed to the development of modal deformations, accompanied with cracking, as the most dominant phenomena characterizing deterioration in cooling-tower shells. Numerical computations produced buckling modes under self-weight similar to those observed in the field.

Understanding the basic mechanisms behind initiation of cracks as well as their propagation is vital to the interpretation of observed long-term structural deterioration of structures. Clearly, the simplistic model of a material which is homogenous, isotropic and perfectly elastic must be dropped, and replaced with more realistic models capable of determining the processes of crack initiation, propagation, and associated stiffness degradation. Apart from wind, seismic and self-weight effects, such cracking may be induced by thermal and moisture gradients. Both the amount of moisture in concrete and its thermal properties govern the formation of cracks as well as the subsequent crack propagation. All these effects and their dependence on time would require to be accounted for in a good model for deterioration.

Kratzig and co-investigators [55] have proposed an elasto-plastic simulation technique for damage processes in reinforced-concrete cooling-tower shells. This is quite elaborate, and employs nonlinear modelling at the material/point level, element/micro level and structural/macro level. In their 1998 publication, Zahnten and Borri [56] also present a nonlinear model representing wind loading stochastically, and capable of accounting for gradual deterioration, loss of stiffness and changes in the dynamic behaviour. Other investigators have used Fourier series to reduce the three-dimensional nonlinear damage model to a two-dimensional one [57].

Recognizing that cooling-tower failure occurs at the global or structural level, Kratzig and co-investigators [58] have recently proposed deterioration models at the structural level. As the global stiffness softening that results from material degradation is a good measure of structural damage, the change in the global tangent stiffness matrix with time may be taken as a direct measure of structural damage. Of course, for such models to be effective in simulating the progress of damage up to and including structural failure, appropriate material models must be adopted [59]. The main shortcoming of the global approach for estimating damage seems to be that it is not concerned with identifying the actual location or distribution of damage, information which is vital in the implementation of any remedial measures.

6. Designing for durability

Nearly 20 years ago, Niemann and Zerna [60] pointed to the need for durability improvements in the design of cooling towers, noting that most research up to that time had focussed on short-term effects of wind and buckling phenomena. As demonstrated more recently by Wittek and Meiswinkel [61], nonlinear analysis can be used successfully in the designing of new cooling towers for durability, and the checking of existing towers. As cooling towers become very large and expensive [62], longer service lives will be demanded, and in this regard, the combination of high-performance materials and good repair programmes can be effective.

In Germany, new measures are being taken to address the question of long-term durability of concrete against chemical attack in those designs where flue gas is introduced into cooling towers. One such example, described by Harte in a recent paper [63], is the cooling tower at Niederaussem, built with a special high-performance concrete made of densely packed aggregate and cement combined with fly ash and microsilica.

7. Concluding remarks

This review has traced developments in the understanding of cooling-tower response to various loadings, and causes of shell collapse. In any assessment of the long-term performance of cooling-tower shells, the role of cracking and geometric imperfections as deterioration phenomena must be appreciated, and appropriate models developed to accurately simulate the time-dependent nature of these effects.

In the past, structural inspections of cooling towers have been employed as a tool for assessing the condition of the shell at a particular point in time, deciding whether or not repair interventions are necessary, and selecting the most appropriate repair method. Structural monitoring of
cooling towers, on the other hand, allows the assessment of deterioration, such data being vital not only in providing information about the state of the structure at any given time, but also of its likely state at some other instant in the future.

Evidently, a number of material and structural models of deterioration have been proposed by various investigators, but clearly, the merit of these depends on how well they can predict the progression of damage. Accurate modelling of damage progression and deterioration phenomena allows appropriate interventions to be made on time, thus prolonging the life of the cooling tower. As with weather forecasting, structural monitoring can provide regularly updated input for these diagnostic models, tremendously improving the accuracy of predictions in the short to medium term.

On the other hand, if durability and long-term performance criteria are incorporated in the design of cooling towers right from the outset, structural deterioration will progress more slowly than would normally be the case, and the need for close monitoring would become necessary only at an advanced stage in the life of the structure. This thinking is already reflected in some of the largest cooling towers constructed in the very recent past.

References