Practical service life assessment and rehabilitation strategy development for hyperbolic shell natural draft cooling towers

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Abstract. Years of service in industrial plant operating environments can cause varying types and degrees of concrete deterioration on reinforced concrete hyperbolic shell natural draft cooling towers. Exposure to plant operating cooling water can potentially result in concrete material erosion and corrosion of embedded reinforcing steel and associated concrete delamination and spalling over time. Such deterioration can affect the integrity of the structure to the degree that repair programs are required to reliably maintain the towers for their required service life. Condition assessment of natural draft cooling towers is challenging due to their massive size, hyperbolic geometry, and plant operational considerations (i.e. schedule, risk and cost). A case history is presented illustrating a rational and targeted investigation approach that included a combination of field condition survey, laboratory materials testing, consideration of operational constraints, probabilistic-based concrete deterioration service life modeling, and structural analysis. Existing degradation as well as predicted conditions from service life modeling informed structural analyses that were performed to identify risk-based limit states over time. The multi-faceted approach provided information critical to understand degradation mechanisms, characterize structural health, and develop prioritized repair strategies to obtain the desired service life extension.

1 Introduction

Reinforced concrete, hyperbolic shell natural draft cooling towers are key to operations at major industrial plants due to their very large cooling capacity. These types of cooling towers are typically in operation for multiple decades and are utilized for dissipating heat generated by industrial production through means of a natural draft evaporative water-cooling process. Over time, cooling water and associated drift (mist) that pass through these towers can potentially lead to concrete deterioration associated with chemical, physical, or corrosive mechanisms that can also be intensified by environmental and weather conditions [1]. Like other plant infrastructure, cooling towers may be called upon to operate beyond their original intended design service life.

In order to reach a specific targeted operational service life, an Owner commissioned a comprehensive engineering assessment of their cooling towers to establish their overall structural condition, understand and project concrete degradation mechanisms, and develop prioritized repair interventions to obtain the desired service life extension. This paper describes the overall assessment program with general information using the Owner’s cooling towers as a basis to describe the assessment process.

Fig. 1. Overall view of a Cooling Tower
2 Tower Structure Description

The plant has several different towers associated with different plant processes. All the towers are of similar design and age. Each are large, thin-wall reinforced-concrete shell structures on the order of 150 m in height and follow a hyperbolic curve, which is rotated radially to produce a top diameter smaller than the bottom diameter. (Fig.1). The shell walls were cast in separate lifts and vary in thickness, being thicker at the bottom and top sections of the shell to provide overall stiffness and stability to the large diameter structure. Like many towers of their age and size, the majority of the shell wall is on the order of 200 mm thick and is reinforced with a mat of meridional (vertical) and circumferential (horizontal) mild steel reinforcing bars at both the interior and exterior faces with a concrete cover of 40 mm [2, 3]. Square reinforced concrete columns support the shell around its circumference and are founded on large concrete pedestals within a reinforced concrete cold-water basin.

3 Assessment Objectives and Scope

The Owner recognized that to have desirable value proposition whilst extending the operational life of the towers, a holistic and explorative in-depth condition assessment of the towers was required. This includes extended laboratory testing and utilization of recently developed technological solutions to arrive at a “techno-economical” solution.

The following three primary objectives were established by the Owner for the comprehensive assessment of the towers

1. Identify relevant risks and chemical reaction patterns associated with operating the towers utilizing the current water quality.
2. Evaluate the remaining useful service life of the cooling towers.
3. Develop remedial solutions to keep the cooling tower structures operable throughout the required targeted service life.

To achieve the above objectives, a project was launched, with the scope consisting of historical information review, field investigation, laboratory analysis, deterioration modeling, and structural analysis. The interrelated workflow and how it relates to achieving the project objectives can be visualized as shown in (Fig. 2).

4 Initial Work

Initial work included reviewing relevant historical information such as original construction documents, previous engineering reports prepared by others, and past repair construction records; discussions with plant engineering and repair contractor personnel; and conducting overall visual surveys of the exterior of all towers and limited visual review at the interior of several towers that were accessible during a maintenance shutdown.

While all the cooling towers in the plant are of similar design and age, different towers have different operating exposures associated mainly with water chemistry. The initial work identified variable conditions across the different towers with apparent different deterioration mechanisms. Varying degrees of concrete spalling associated with corrosion of embedded reinforcing steel was observed at tower exteriors (Fig.3). Varying conditions were also observed at the accessible tower interiors (Fig. 4 and Fig. 5).

Fig. 2. Project workflow for tower asset analysis in satisfaction of project objectives.
These different conditions appeared to be influenced by differences in both “deterioration-driving” and “deterioration-resisting” factors. The water chemistry that circulates through the cooling towers in several towers creates a certain exposure environment (deterioration-driving factors) and reaction with the concrete could be more intense than other towers that are exposed to different water. In addition to the different chemical composition of the water, some towers with a similar water makeup appeared to be in a different condition. This is attributed due to a difference in construction quality (deterioration-resisting factors). With this understanding, the towers were grouped in pairs by similar water chemistry, as well as perceived construction quality for the purposes of defining the assessment program. To investigate the condition of all cooling towers and conduct a service life evaluation, a comprehensive assessment of one tower within each group was proposed to characterize its condition and a reduced assessment of the other tower in the pair was proposed to confirm that similar conditions are present. These towers are identified as the “exemplar” and “similar” towers(s), respectively.

With this information available, investigation work was prioritized on a tower group where the towers had an existing repair program in progress, as well as an access system including temporary suspended platforms (TSP) which facilitated close-up inspections. Assessment of this cooling tower group is summarized as a case history in the following section.

5 Cooling Towers Shell Case History

5.1 Condition Assessment

Condition assessment activities at the two towers covered by this case history included field investigation and laboratory analysis. These activities provided key information on the existing condition and degree of deterioration of the structure, the quality and composition of the concrete, and the concrete degradation mechanisms present. The inspections conducted on the outside of the tower could happen at any time, whilst the inspections required on the inside of the cooling towers were conducted during planned maintenance shutdowns whilst the towers were not operational.

5.1.1 Field Inspection

Four primary inspection and sampling types, summarized in Table 1, were performed at varying frequencies depending on the tower and element (shell or column).

Close-up access to perform the inspections was through a combination of working from the suspended work platforms available at one tower (Fig. 6) as well as by rope access performed by a specialty abseiling contractor (Fig. 7) with technicians trained specifically for the project needs at the other tower. Close-up assessment permitted gathering information via hands-on surveys, in-depth study areas, and extraction of through-shell thickness concrete cores.
Table 1. Field Inspection Type Summary

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<tr>
<th>Inspection Type</th>
<th>Objective</th>
<th>Approach/Information</th>
</tr>
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<tbody>
<tr>
<td>Wide-Field Survey</td>
<td>Quantify surface damage over a large area and beyond that which can be assessed visually from grade.</td>
<td>Visual survey via UAV (drone) Scanning technologies (Infrared Thermography for delamination identification)</td>
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| Hands-On Survey       | Identify surface conditions of the concrete and measure reinforcing bar cover depth. | Arms-length inspection and non-destructive test methods (from TSP scaffolding & rope access):  
  - Hammer Sounding  
  - Cover Meter Readings (rebar concrete cover)  
  - GPR Scanning (rebar concrete cover) |
| In-Depth Study        | Measure conditions internal to the concrete that influence concrete durability. | Detailed measurement of internal conditions of tower concrete through testing:  
  - Surface Resistivity (rebar corrosion potential)  
  - Carbonation Testing (rebar corrosion potential)  
  - GPR Scanning (rebar concrete cover correlation) |
| Core Sampling         | Sample representative concrete specimens for laboratory testing.          | Core drilling of shell and column concrete.                                           |

Laboratory analysis of the shell wall core samples included petrographic examinations, chloride testing, sulfate testing, ion chromatography, and x-ray diffraction analysis. Additionally, analysis of water chemistry data was analyzed using Langelier Saturation and Basson Corrosion indices [4] related to concrete degradation mechanisms. As the towers were in operation, laboratory analysis of through-wall thickness core samples was utilized to quantitatively evaluate the conditions at the interior face of the shell.

5.1.2 Findings
A key finding of the initial work was the observed presence of widespread erosion of the interior face of the cooling tower shells (Fig. 4). Measured in the field as the depth from protruding aggregate to sound paste between aggregate, the erosion was measured to be around 20 mm deep.

In addition to reinforcing steel corrosion-induced concrete delamination and spalling deterioration (Fig 3), a zone of variable quality concrete was identified in areas spread throughout the approximately upper third of one of the tower shells. This zone was characterized by areas of concrete surface flaking and loss of concrete paste, and in many areas, exposed coarse aggregate around 20 mm deep (Figs. 8 and 9) that appeared to vary by individual original construction concrete batch (Figs. 10 and 11).
Through-thickness core samples exhibited concrete paste erosion at the interior face of the shell also up to 20 mm deep. This condition was observed to exist over the entire interior shell of this specific tower. Petrographic examination of core samples confirmed progressive paste erosion, softening and alteration at the shell interior (Fig. 12).

WJE analyses concluded that deterioration at this group of tower shells is primarily related to both erosive and corrosive mechanisms:

1. **Erosive Mechanisms:** Loss of concrete shell thickness at the interior and exterior faces of the shell are both driven by exposure to cooling water that reacts with the concrete cement paste. These mechanisms are more prevalent in, but not limited to, the upper approximately 40 percent of the towers.
   a. At the interior face, paste erosion is caused by decalcification starting at the interior surface of the shell (an “outside-in” phenomenon at that surface).
   b. At the exterior face, exfoliation is caused by physical salt attack from diffusion of water through the shell (“inside-out” phenomenon at that surface).

2. **Corrosive Mechanisms:** Environmental exposure at both interior and exterior faces of the shell contribute to corrosion of the embedded reinforcement.
   a. At the interior face, corrosion is primarily due to pH-change associated with decalcification and contribution from chloride infiltration, especially near the top of the shell.
   b. At the exterior face, corrosion is caused by carbonation throughout the shell, and also by chloride infiltration near the top and bottom of
the shell from exposure to falling drift (mist) that exits from the top of the tower.

5.2 Deterioration Modeling, Structural Analysis and Service Life Evaluation

Service life evaluation was conducted for the “exemplar” tower. In general, conditions at the “similar” tower validated the assumption of similar overall conditions within this tower pair. Based on the data obtained from field and laboratory assessments regarding existing conditions (including concrete quality, concrete cover over reinforcement, existing deterioration extent, and deterioration mechanisms), the deterioration was characterized in its current condition and modeled to project conditions through the service life target. The projected extent of deterioration was then incorporated into structural analysis to assess the impact on tower performance.

5.2.1 Deterioration Modeling

The relevant deterioration mechanisms were examined separately for the interior and exterior faces of the shell. To make engineering interpretation of the deterioration mechanisms, the laboratory characterization of conditions (described above in Section 5.1.2.), labeled the “scientist” model, was simplified to represent durability; and strength-influencing properties to generate an “engineer” model of conditions (Fig. 13).

A statistical analysis was performed to establish an average profile of current concrete conditions over the height of the tower. Conditions were idealized in their present conditions and then projected every 10 years through the service life target based on calibrated modeling of deterioration rates using WJE proprietary service life modeling software, WJE CASLE™.

5.2.2 Structural Analysis

The projected conditions were then incorporated into structural analysis of the deteriorated tower. A finite element model (FEM) of the tower served as the primary structural analysis tool (Fig. 14). The FEM was first analyzed based on the as-designed geometry and properties to demonstrate that the tower’s design satisfied strength and stability criteria for reinforced concrete design based on South African standards [5, 6] and other established design criteria for hyperbolic natural draft cooling towers [7]. The FEM was then adjusted to reflect changes in shell’s geometric and material properties. The erosion of concrete reduces the thickness of the shell, reduces the concrete cover over the reinforcement, and reduces the strength and stiffness of the near-surface concrete that remains. As such, to assess the deteriorated tower limit states of tower stability (i.e., buckling), strength (i.e., material overstress), and reinforcement development (i.e., loss of effective reinforcement encapsulation in concrete due to reduced cover and concrete strength) were evaluated for current and projected conditions.

5.2.3 Service Life Evaluation

The identified deterioration mechanisms cause the tower to degrade from its original condition, generating risk associated with decreased structural reliability. When this risk reaches an intolerable limit, the tower structure is judged to have reached its end of service life. Four end-of-life limit states were established and evaluated for the
shell structure associated with 1) structural stability, 2) structural section strength, 3) embedded reinforcement development, and 4) corrosion damage.

Based on these analyses, the following conclusions were drawn relative to the tower shell:

1. Risks associated with continued degradation of the shell include:
   a. Instability of the tower shell, resulting in structural buckling collapse.
   b. Loss of effective reinforcement engagement within the concrete, resulting in reduced structural section capacity for shell tension and out-of-plane bending.
   c. Corrosion damage, resulting in reduced structural capacity and increased overhead hazards from spalled concrete dislodging and falling off the tower.

2. Remaining service life of the shell:
   a. The remaining service life of the tower shell was predicted.
   b. Extending the service life of the tower shell can be achieved through various different remediation program strategies.

5.3 Remediation Strategies

Many different intervention actions are potentially applicable as components of a remediation program strategy for the maintenance and repair of the tower shell. These actions were broadly classified under four groups based on their objective:

   Monitoring to observe trends over time. Such actions include periodic inspection and survey of tower conditions over time; monitoring of water chemistry; and site-specific hazard monitoring to establish site-specific hazard probability (e.g., site-specific wind in lieu of codified 50-year wind).

   Hazard Mitigation to reduce the risk associated with adverse conditions when they happen. Such actions would include building netting or a canopy to catch or deflect falling concrete debris; establishing a safety perimeter; or periodically removing loose delaminated concrete before it falls.

   Materials Deterioration Mitigation to slow or stop deterioration. Such actions would include surface sealers and coatings; reinforcement protection, galvanic (passive) cathodic protection, impressed current (active) cathodic protection, and process controls such as adjusting the water chemistry.

   Concrete Repair/ Strengthening to restore or supplement the structural capacity of the tower. Such actions would include restoring the eroded interior face of the shell; partial- and full-depth concrete repairs; partially demolishing and rebuilding the tower shell; or partially demolishing the shell and converting it to a forced draft tower.

To achieve the target service life, various remediation strategies are technically applicable. While specific remediation strategies are not presented in this paper, different repair program strategies for consideration were arranged by combining proposed intervention actions. The selection of remediation program strategies is generally based on the following approach:

1. Identify when end-of-life limit states are violated.
2. Select an intervention action to address the earliest occurring limit state violation.
3. Reevaluate the next occurring limit state violation.
   a. This can be either a different limit state not addressed by the previously selected intervention action or can be a recurrence of a previously violated limit state based on the effectiveness or maintenance interval of a previously selected intervention action.
4. Select the next intervention action. This may be a repetition of the prior action if the durability of the action is less than the desired service life.
5. Repeat steps 3 and 4 until the next occurring limit state violation occurs after the target end of service life.
6. The combination of the selected intervention actions form the overall remediation strategy. Note that the same target service life can be achieved through different remediation strategies.

6 Summary

Cooling towers are operationally-critical infrastructure assets for industrial facilities. Repair of such structures are challenged by difficult access conditions, specialty labor needs, and operational and site constraints. Founded on condition-based assessment and technical merit, many different remediation strategies are possible to address deterioration in these structures. Investing in the remediation interventions of a cooling tower asset and selecting the most appropriate program strategy is part of complex business decisions that consider many factors. However, for the investment to yield long term benefits, it is essential that the selected strategy be grounded in a comprehensive technical understanding of the mechanisms and extent of that deterioration.

The Owner realized the need to increase the range of technical investigations and laboratory testing to optimize and refine their asset management strategy for the cooling tower assets presented in this case study. WJE and the Owner established a comprehensive condition assessment program that 1) characterizes the deteriorated conditions of the tower in its current condition, 2) projects the deteriorated conditions of the tower through the target service life, 3) assesses the structural and operational risk over time, and 4) identifies additional repair methodologies and strategies that meet Owner objectives.

Effective execution of such a program requires collaboration between the Owner, consulting engineer, and assisting contractors and vendors. The scientifically rigorous testing and analyses of the assessment program
provides a rational basis on which the Owner can make informed asset management decisions.

References


