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Consideration of resiliency in the repair and completion of a damaged cooling tower

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Abstract

A successful repair and completion project for a large cooling tower shell damaged by a falling crane during a tornado in 1980 is re-examined from the standpoint of resiliency. One of the main benefits of increased resiliency is to provide resistance to unanticipated extreme loading situations beyond usual code requirements From the structural engineering standpoint judging by the current professional and technical literature, resiliency is a topic of considerable interest and is much encouraged for new designs. However the assessment of resiliency in existing structures is of similar importance and may present issues that are not present in new structures explicity designed for increased resiliency. The actual performance of such structures subjected to unanticipated extreme loading is an important contributer

This case is a prime example of resiliency assessment. It is intended to illustrate the process of determining the success of resiliency during an actual unanticipated event where there was contrary evidence from previous performance. While the assessment is focused on a particular structural type,the process might apply to other situations where a decisión to repair or rebuild is required.

Keywords: Resilience ,Cooling Tower, Tornado, Concrete Shells

1. Introduction

While performance of early cooling towers revealed a lack of resilience during extreme wind loading, the design and construction of a later generation incorporating improvements learned from earlier failures may have raised the level of resiliency. However for a particular type of structure such as a cooling tower or chimney, a main provider of resiliency *alternate load paths* may not be apparent since they are globally statically determinate. This is most directly determined by examination of the performance of an improved structure such as the Grand Gulf cooling tower in Mississippi, USA that was subjected to an unanticipated extreme load imparted by a collapsing crane during a tornado as shown in Fig.1. It is relevant to note that the shell was not far from completion at the time of the event. The engineering aspects of this project have been reported earlier [1] but the resilience issues were not addressed there.

Figure 1: The damaged cooling tower and the restored crane during repair [1].

For existing structures where repairs and modifications may be required for continued operation, the determination and provision of resiliency may be more complex than for new designs, involving issues of cost and serviceability along with structural integrity.This cooling tower project involved numerous stakeholders. In some cases their interests extend beyond the structural engineering issues and are discussed in the presentation along with some relevant aspects of resiliency, related performance of other cooling towers, assessment of damage and evaluation and repair methodology.

2. Resilience

The synonymous terms of *resilience* and r*esiliency* have become broadly used in the general as well as the technical media. In the realm of structural engineering, a somewhat narrower statement may be useful. Cary Kopczynski, a former president of ACI, stated that “structures must be designed with the resiliency necessary to resist extreme loading events even though these events seldom occur. Failure to plan for them can result in structural failure and the loss of life”. While this is an obvious requirement, members of a prominent engineering firm have provided an expanded statement that may better fit the case of industrial structures [2].

- Enhanced building design as stated above.
- Operational resilience: the ability of an organization to respond quickly and resume functionality.
- Site resilience: factors outside the structure envelope that may affect the operation.
- Risk assessment: evaluating how design and planning measures support functional recovery targets.

3. Performance of Failed Cooling Towers

In 1965 a group of cooling towers constructed in Ferrybridge, England was struck by strong straight-line winds and three of the eight towers collapsed as shown in Fig.2. This event attracted wide attention from utilities, builders, designers and researchers and resulted in improvements that are reflected in newer recommendations, codes and standards in Europe and the US [3]. Presumably adoption of these improvements enhanced the resiliency of newer cooling towers. The Ferrybridge failures were thoroughly investigated [4] and it is instructive to consider some of the findings from the standpoint of resilience.

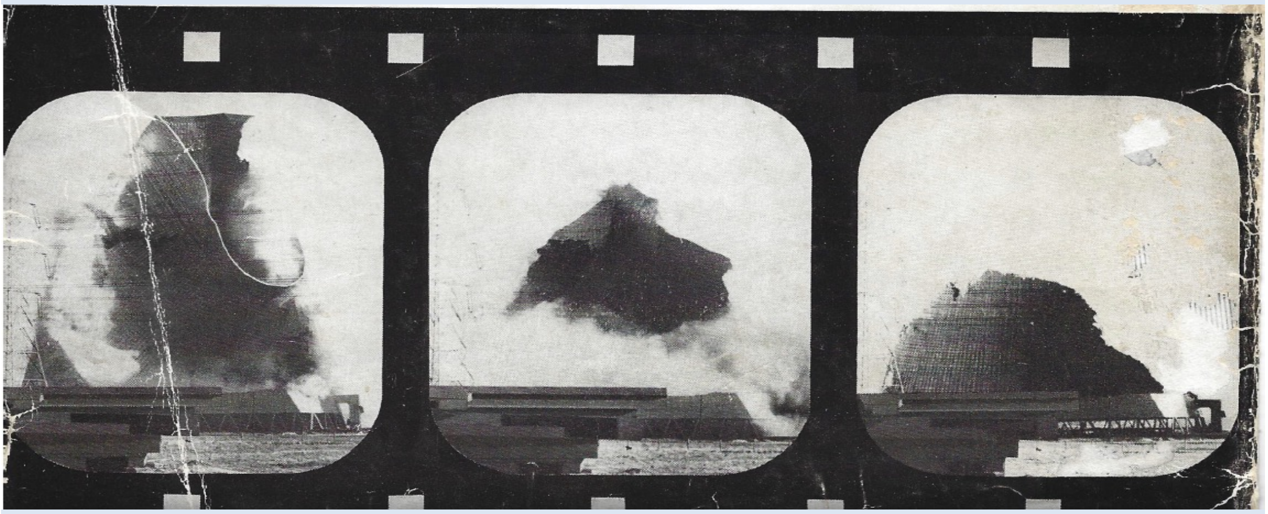


Figure 2: Collapse of Ferrybridge Tower [4]

HCT and Ferrybridge Shell

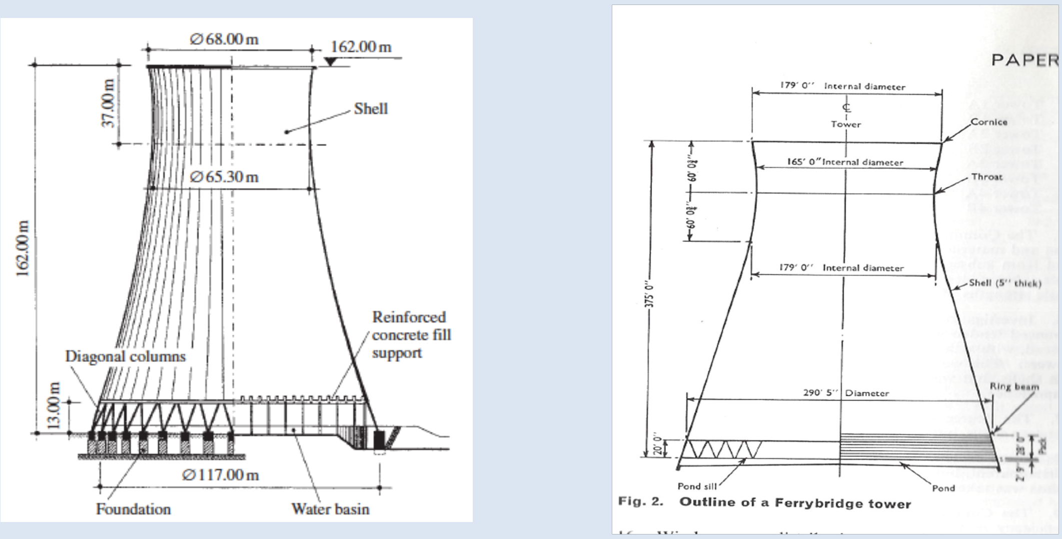


Figure 3: Comparison of Grand Gulf and Ferrybridge Towers [3,4]

- The Ferrybridge towers were subjected to a high but not extraordinary wind loading and those that failed were on the leeward side of the group.
- The failures were complete.
- The Ferrybridge towers were constructed as cone-toroids rather than the true hyperboloid of the Grand Gulf tower as shown in Fig.3. This resulted in significantly higher comparative stresses and apparently in somewhat different stress distributions.
- The Ferrybridge towers had only a single sheet of reinforcement in each direction, providing little bending resistance once the tension due to wind loading surpassed the dead load compression.

While some of these points were addressed in the later documents that were available for the design and construction of the Grand Gulf tower in 1978 , this does not insure that this tower would meet the modern criteria of resilience. In this regard it is important to emphasize a major difference between the hyperbolic shape and a typical framed structure. The hyperboloid is globally statically determinate and lacks the redundancy provided by obvious alternate load paths in frames.

It was apparent that a thorough physical and analytical study would be required to determine whether the tower could be repaired and completed to satisfy the project requirements or if it was too severely damaged. The lessons of Ferrybridge were obviously a part of the study.

4. Positions of stakeholders

For this discussion, four sets of stakeholders are considered, each with some similar and some with differing objectives. These objectives are observations of the author and not confirmed by the stakeholders.

4.1. Owners as represented by utility officials

The owners of the tower are a utility and their mission was to meet a commitment to bring their plant on-line into a regional grid by a certain date. Failure to do so would result in a major financial penalty. Therefore they would presumably accept either a repair and completion of the damaged tower or a total replacement within the time and budgetary constraints.

4.2. Designer and constructor of the tower

The tower was designed and constructed by an experienced firm that had completed numerous similar projects. Possibly as a business opportunity, they seemed to be attracted to demolition of the partially completed shell and rebuilding the entire structure. They supported an independent engineering study that suggested that there could be many problems in repairing and completing the shell. One example would be the inability to detect and repair internal damage using the technology of the times (early 1980s), when only visual mapping and epoxy crack repair were commonly available. They also expressed a concern that such an event had apparently not happened before, so the repair and completion option would be breaking new ground. Of course, they owned the scaffolding that was damaged but probably repairable and could be used to complete the tower once the repairs were completed. It is likely that the demolition and rebuilding option would come up against the time deadline.

4.3. Other contractors including foreign firms

The project attracted the interest of some additional contractors who had apparently encountered some similar problems but the owners apparently were not attracted to their proposals.

4.4 Insurance providers

While all major built works may be subject to interruptions during their design and construction and perhaps for many years of their lifetime, this reality does not usually drive the engineering aspects. Of course this may be changing with the recent focus on resiliency. In any case owners, contractors and engineers rely on insurance to assist in resolving difficulties that may arise.

When there is an event that affects the operation of a facility, the engineering aspects may be strongly influenced by the time required to restore the operation and in turn by the insurance provided. This is perhaps even more acute when the cause of the delay is beyond the code requirements. Apparently, the insurance providers were active participants in the decision for this project**.**

5, Completion of project

In the case of the Grand Gulf tower, the decision was made to proceed with the proposed repair and completion of the tower following state-of the art design procedures and repair and reuse of the scaffolding. The completed shell is shown in Fig. 4. The purpose of the added intermediate rings is discussed later.

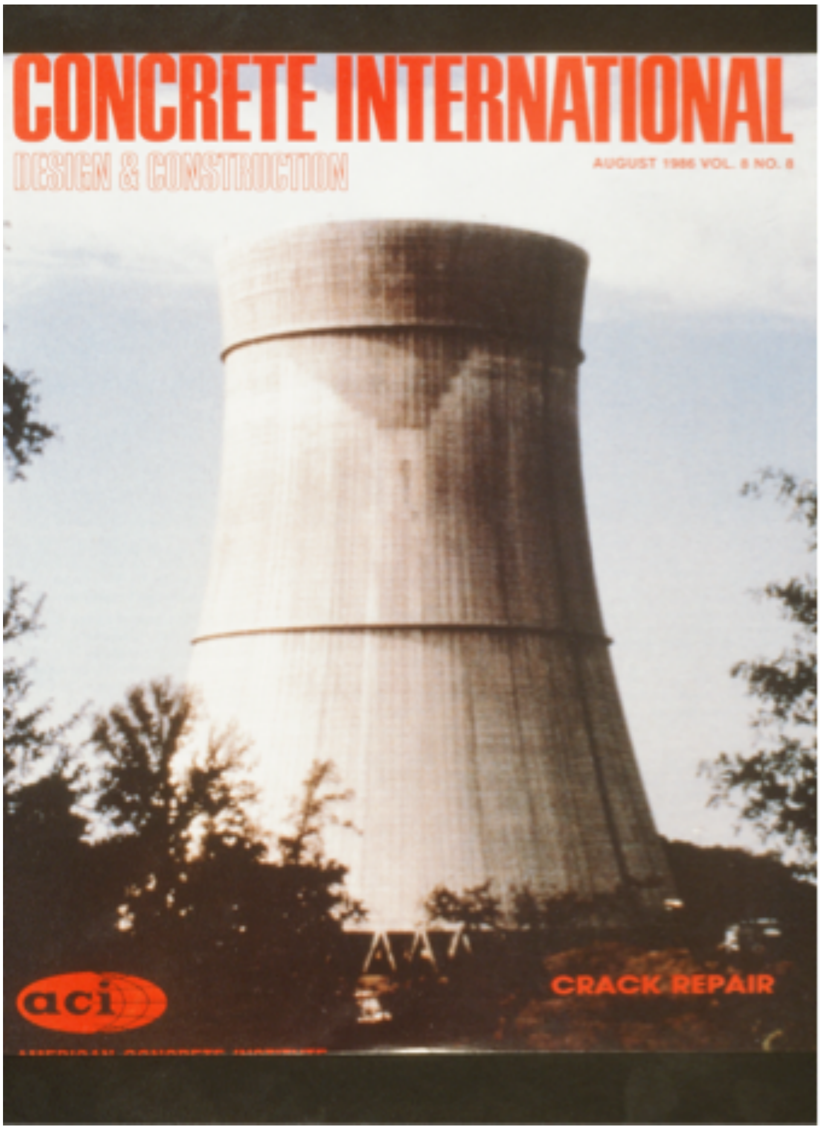
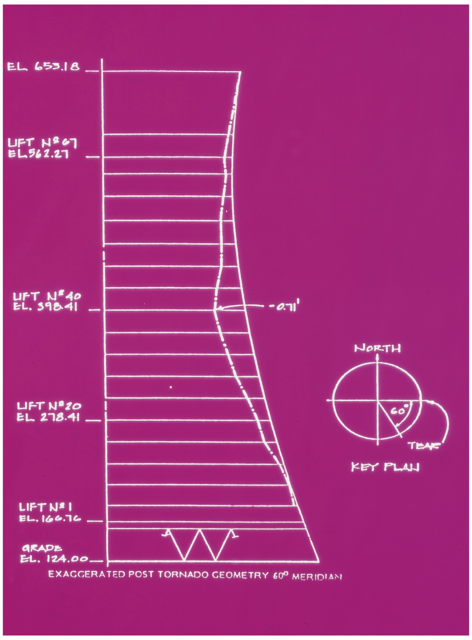


Figure 4: Completed Structure.[Concrete International,ACI]



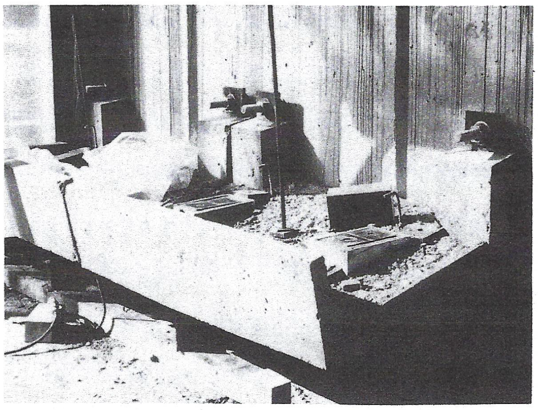


Figure 5: Bulge Profile [1]

Figure 6: Precast ring segment [1]

The repair and completion were specified to meet but not exceed the original design specifications. As stated earlier, the detailed structural design of the tower is described in [1]. However since this publication appeared long ago, it is worthwhile to describe a few key points related to resilience. It is helpful to consider the *strength* and *stability* requirements individually.

- The original design specifications likely presumed an idealized theoretical geometry with some allowance for construction tolerances. However, the shell was repaired and completed based on the post-tornado geometry. This consisted of the measured geometry, including a significant bulge along one meridian shown Fig 5, up to the region of significant damage, the modified -as -necessary geometry in the damage area and the theoretical geometry to completion.
- From a shell theory classification standpoint, the model was converted from an axisymmetric shell of revolution to a non -axisymmetric general thin shell. Also this analysis considered the tensile strength of the concrete, which is especially beneficial in resisting circumferential tension. Another generalization was the consideration of the direction of the wind, which was not an issue for the axisymmetric model but was important in relation to the aforementioned bulge as shown on Fig 5. The computer software required to address the general shell case was considerably more sophisticated than required for the axisymmetric case but the original design specifications for strength were met using state-of the art FE software .
- On the completed structure in Fig.4, the main damage surface is clearly shown by the shading change below the upper intermediate ring . While the damage penetrated into a rather large region of the shell as indicated by the crack pattern, it appears that alternate load paths were developed, a hallmark of resilience. The hyperbolic geometry provides two sets of straight line paths that may have aided this process.

- In contrast to the strength analysis described above, the consideration of buckling under increasing wind load was not as straightforward. The widely used design criterion for thin shells in this era was a factor of safety λ =5 applied to the dead load plus wind load, i.e. λ(DL+WL) , instead of the logical (DL + λW). The λ (DL+WL) criterion was attributed to earlier roof shell design practice. While that requirement was met for the new shell geometry, a (DL + λWL) calculation showed a slight decrease in the factor of safety. The decrease was compensated by the addition of the circumferential stiffeners based on published research [5]. Four stiffener locations were identified, the top cornice, the bottom thickened shell atop the columns, and two added precast post-tensioned rings as shown in Fig.6. The lower ring was installed in the vicinity of the máximum bulge while the upper ring provided a transition between the most damaged región and the to-be completed top portion.

6. Conclusion

Examples of past projects that survived unanticipated extreme events can be a valuable guide for the current and future inclusión of resilience as an explicit design objective in a restoration. While increased resilience can often be incorporated in a new design at some cost and perhaps prevent total destruction, it is likely that physical damage and loss of functionality will remain. Also it may be possible to determine the repairability of the structure with the assistance of technology that perhaps was not accessed or available for the original design.

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