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Rebar section loss and carbon fiber reinforced plastic reinforcement effects on nonlinear behavior and ultimate load of cooling towers

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ABSTRACT

The present paper quantifies the adverse effects that can generate rebar section loss, induced by corrosion, especially on the bearing capacity of nuclear power plant cooling towers under extreme wind conditions. Numerical simulations, taking into account, appearance of concrete cracks and their evolution via an appropriate material concrete law and rebar's yielding, are conducted. Different levels of corrosion are considered which are approximated by rebar section loss. Finally, to restore the integrity of these structures, composite material such as a carbon fiber reinforced plastic (CFRP) layer is modelled. The enhancement of the bearing capacity of the damaged structure compared to the undamaged structure is evaluated in the pre- and post-cracking regime. The main conclusion drawn from the numerical results is that the CFRP reinforcement is very effective for improving the integrity of RC cooling tower shells even when the latter present an advanced corrosion rate.

1. Introduction

Many numerical studies based on finite element method (FEM), where conducted in order to explain the origin of the disorders observed on reinforced concrete (RC) cooling tower shells as geometric imperfections and material degradations like localized or distributed cracks. In light of the obtained results, wind loads and soil settlements are the more sensitive. Progressive soil settlements induce geometrical imperfections, concrete creep in interaction with settlement enhancement explain their large amplitude evolution. But this kind of defects does not affect the bearing capacity [1]. In addition, other loads, such as cyclic thermal and hydro-mechanical effects, or regular operating loads or accidental overloads, can induce cracking damage [15,32]. This damage does not appear to affect drastically the bearing capacity [26,3] but result in the activation and acceleration of corrosion and concomitantly the degradation of the concrete material (see Section 3.1), and at least, decrease the structure's lifetime. Wind gusts are certainly the most severe solicitations to these structures, taking them into the nonlinear domain, and can induce or amplify cracking damage. Storms in France are common and according to Météo-France, the French national weather service, wind gusts higher than or equal to 100 km/h occur 15 or more times per year (averages over the 1981–2010 period) (http://www.meteofrance.fr/prevoir-le-temps/phenomenes-meteo/les-vents-violents) [6].

The authorities have planned to increase the lifetime of currently operating nuclear power plants, first meticulously evaluating ageing RC hyperbolic cooling towers and the impact on the bearing capacity calculated, to determine their lifetime and aid in deciding whether or not to strengthen these structures. Several studies have been conducted to investigate the ultimate strength of these structures under extreme wind conditions. For example, Mang et al. [17] presented a comprehensive numerical investigation of the cooling tower at Port Gibson MS (USA) and were the first to assert the representativeness of an incremental calculation concluding that the failure of wind-loaded cooling towers made of reinforced concrete is initiated by rapid propagation of cracks in the tensile zones of such shells followed by activation of the reinforcement until yielding occurs and not by buckling. In their damage analysis of a cooling tower shell, [10] mentioned that after many years in permanent service, shells show a considerable number of vertical cracks due to the low amount of reinforcement. The study reported by Baillis et al. [1], where undamaged and damaged cooling towers were analyzed through large parametrical analyses, confirmed the Harte and Kratzig study and demonstrated that in the case of wind load, initial cracks do not significantly reduce the strength because the structure works mainly in the meridional direction. These initial cracks regularly distributed throughout the

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shell start to affect the behavior only during the crack plateau and beyond, when the shell begins to work in the circumferential direction. Noh [25] addressed the nonlinear behavior from the unstressed virgin state to the ultimate state for a cooling tower shell and observed that the failure of the cooling tower is caused by the yielding of reinforcement in the windward meridian. The nonlinear behavior starts by the formation of horizontal tension cracks in the windward meridian. Increasing the applied load conducts to cracks spreading along meridional and circumferential directions. At the ultimate load, the yield of steel reinforcement in the windward meridian occurred, resulting in an abrupt increase in the along-wind displacement. Once the steel yields, the yield zone propagates along the circumferential direction, resulting in structural failure. All these studies have clarified the failure mechanisms of cooling tower shells and concluded that the reinforcing ratio plays an important role in the ultimate strength of RC cooling tower shells after cracking. Hara [9] concluded that the ultimate strength is determined by the amount of meridional reinforcement and that fiber reinforced plastic layer strengthening is effective.

In this paper, the ultimate strength of RC hyperbolic cooling towers is re-investigated. To take into account damage identified on these structures, especially steel corrosion, cooling towers are reanalyzed using the same assumption as [21] and [7], which consists in reduction of the steel section using the FEM. Various nonlinear factors are taken into account, such as the material nonlinearities in the concrete and reinforcing steel, tensile cracking, tension stiffening. Several numerical simulations were carried out to study the bearing capacity of three RC hyperbolic cooling towers with different dimensions in the presence of different levels of corrosion which are approximated by rebar section loss. The influence of wind cycles on the behavior of the shell is also evaluated. Moreover, to restore the integrity of these structures, and therefore to increase their lifetime, the carbon fiber reinforced plastic (CFRP) strengthening technique is explored. Real and proposed configurations were assessed by quantifying the contribution of CFRP strengthening in terms of stiffness and strength in pre-cracking and post-cracking on a perfect shell or a damaged shell by steel corrosion under extreme wind conditions.

2. Nonlinear analysis

In this paper, three RC hyperbolic cooling towers in French nuclear power plants are modelled. These cooling towers are about to reach 30 years of service. The concrete hyperboloid of revolution shell reinforced with double-layer rebar grids, is supported on a V-shaped support system for towers I and II and X-shaped for tower III. They are reinforced at the top and the bottom by lintels, which are here modelled by stiffening rings with a high ratio of reinforcement. Table 1 lists the dimensions and characteristic thicknesses of each shell. After the mesh sensitivity study, shells are discretized into several elements in the circumferential and meridional directions. Table 2 lists the number of elements in each shell FE model.

Table 2
Number of elements.

Variant	I	II	III
Shell	19,440	22,032	20,304
Rebar	39,096	44,280	40,824
Supports and foundations	216	144	252
Total	58,752	66,456	61,380

2.1. Finite element representation

The numerical study was conducted using the finite element program Cast3M, developed at the French Atomic Energy and Alternative Energies Commission (CEA) [31]. Elements used in 3D modelling (see Fig. 1) are three-node elements, have 6 degrees of freedom per node and 3 Gauss points for integration in the plan. These elements are a superposition of a classical triangular membrane element CST (constant strain triangle) and a compatible triangular plate called DKT (discrete Kirchhoff triangle) developed by Batoz et al. [2], which deals with the flexion of thin structures within the framework of Kirchhoff theory, which assumes the conservation of normal to the section. The transversal shear effect is neglected. For each element, the thickness representing the concrete is divided into several layers, working with a concrete model, to describe the progression of damage accurately, in particular crack propagation through the thickness of the shell. Therefore, every shell element is constituted of 11 layers working in plane stress, as shown in Fig. 2. The support system is modelled by Timoshenko beam elements with consideration of transversal shear. The boundary conditions of the three towers corresponds to a clamped end. Details of the concrete and steel models used in this study will be given in the following Sections 2.2 and 2.3.

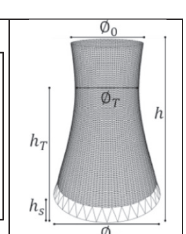
2.2. Concrete constitutive laws

Two concrete models were used for the analysis; results from each model are compared with each other and also with the results of other studies conducted on this type of structures (see Section 3). In both models, the behavior of cracked concrete is covered by the concept of distributed cracking considering the cracked material as a continuum (smeared crack approach).

The first concrete model used was developed by Nahas [24] within the framework of plasticity theory. In both the tension and compression regimes, this model presents a linear elastic zone followed by a linear softening behavior (decrease of stress as strain increases) (see Fig. 3). The cracking of concrete is managed by a

Table 1
Characteristic dimensions of RC hyperbolic cooling towers.

Variant	I		II		III	
Φ_o [m]	53.40	$e_0 = 0.60$	84.08	$e_0 = 0.60$	87.56	$e_0 = 0.55$
Φ_u [m]	83.20		135.75		117.20	
Φ_T [m]	49.23	$e_T = 0.16$	84.11	$e_T = 0.23$	83.80	$e_T = 0.21$
h_s [m]	7.46		17.35		27.70	
h_T [m]	93.04		131.36		123.20	
h [m]	121.70	$e_u = 0.80$	165.00	$e_u = 1.07$	165.50	$e_u = 1.09$



Φ_o: Top diameter, Φ_u: Base diameter, Φ_T : Throat diameter, h_s: Supports height, h_T : Throat height, h : Shell height, e_0: Top thickness, e_u: Base thickness, e_T: Throat thickness.