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ABAQUS Modeling and Investigation of Nuclear Central Cooling Tower Reinforced by CFRP

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Abstract

Concrete is recognized as the most ideal material for construction of cooling towers. Because it is a relatively durable material to certain chemical environments, gases and high temperatures but, being a brittle material, concrete is damaged when subjected to tensile and flexural stresses. In addition, tensile and flexural stresses in high structures such as towers are caused by horizontal loads such as wind loads. Therefore, it is important to examine the materials used in such serious structures and the repair materials to be applied after construction. In this study, it is aimed to simulate a super-large reinforced concrete cooling tower using ABAQUS program as a sheet, by considering previous studies on the structure of cooling towers. In the models, the strain and stress behaviors against the wind load were investigated by reinforcing the middle zone of the tower by carbon fiber reinforced polymer (CFRP) sheets in different thicknesses.

Keywords: Cooling Tower, ABAQUS Modeling, CFRP, Wind Load

1. INTRODUCTION

Cooling towers are heat removal units used for the purpose of obtaining chilled water in areas such as air conditioning systems, nuclear power plants, petrochemical plants, electricity generation systems and various production processes. In the system where the cooling tower is connected, some of the heated water is evaporated and cooled to the atmosphere, the remaining part is sprayed on the filling area under the tower with the sprinkler system over the tower and cools with the fans. Water flowing from top to bottom continuously along the tower accumulates in the base of the tower and is pumped back into the system as it is cooled down. Cooling towers are ideal areas for the development of microorganisms due to their working temperature [25-42 ° C], organic and inorganic substance content and wide wet surfaces. Aerosols originating from the towers have been known since the late 1970s, when Legionnaire's disease caused the Legionella bacteria and other microorganisms to spread easily to the environment (American Society of Heating and Engineers 2000, Şanli 2015). Therefore, the static investigation of the structure constructed for these conditions is also important.

Many scientific investigations have been presented related to cooling towers built from concrete, until today, and ways of solving problems related to this large structure are discussed(Gould 1984, Waszczyszyn, Pabisek et al. 2000).

Concrete core cooling system is an energy efficient alternative to the conventional mechanical cooling system. It provides better comfort due to direct absorption of radiation load, low indoor air velocity, apt vertical temperature gradient and absence of noise. It can be operated at relatively higher water temperature, which facilitates the use of passive cooling strategies (Leo Samuel, Nagendra et al. 2017). But because the concrete is a brittle material, it is damaged when subjected to tensile and bending (Bagherzadeh, Sadeghi et al. 2012, Dehghanpour and Yilmaz 2018). So it is important to examine the behavior of cooling Tower against such loads.

The historical development of natural draft cooling tower design and construction is presented with reference to the two towers of Lünen. Special attention is paid to new structural aspects which have come up during the last years such as acid resistant concrete, flue gas duct introduction, EMI platforms. An outlook to cooling towers of heights up to 250 m is given which are currently in conceptual design phase for new power plant projects (Lang and Strauß 2010).

In the present study, it was aimed to investigate the behavior of CFRP reinforced cooling tower against wind load. There are several researches in the literature about cooling towers under wind load reactions.

Wang et al (Wang, Cao et al. 2016) were investigated the wind-load characteristics of a cooling tower exposed to a translating tornado-like vortex. Wind load characteristics of a structure exposed to a swirling tornado are different from those in a boundary-layer-type straight-line wind. This paper presents wind pressures around a cooling tower caused by a translating tornado-like vortex with two different swirl ratios at three different translational velocities. The translational motion is scaled so that the durations of tornado force on both prototype and model structures are identical. The effects of translational motion are studied by comparing the pressure characteristics caused by a translating tornado-like vortex with quasi-steady results obtained for stationary tornado-like vortices located in different radial locations relative to the cooling tower model. Results of the present study show that translational motion does not significantly influence the peak external and internal pressures, although peak pressures and forces decrease slightly with translational velocity. A peak pressure coefficient does not necessarily appear after the passage of a tornado. The running-window cross-correlation analyses show that the correlation is actually lower than that of stationary tornadoes, although greater correlation occurs if it is calculated by the traditional steady analysis method that includes the effects of pressure variation trend.

Karakas and Daloglu (Karakas and Daloglu 2015) were studied on a comparative study for the responses of a cooling tower subjected to wind loadings described in accordance with Turkish Standard (TS 498) and Eurocode using harmonic solid ring finite elements. Nonaxisymmetric wind loadings around the circumference make the cooling tower problem three dimensional. However, using harmonic elements reduces the problem to a two dimensional problem by expressing the loading in the form of a Fourier series. Therefore, a finite element program is coded in Matlab incorporating harmonic finite element techniques. The wind analyses of the cooling tower are conducted using 9-noded harmonic solid ring finite element modeling. The harmonic finite element formulations in general terms are presented in the study. The vertical and circumferential distributions of the wind loading effective on the cooling tower according to both standards are compared. The circumferential distributions are expressed using Fourier cosine series and the coefficients indicate that while the wind loading mainly will cause undulating deformations according to Eurocode and beam like deformations according to Turkish Standard (TS 498). Moreover, it is realized that the circumferential distribution of wind pressure influenced the magnitude of displacements and stresses significantly as well as the region under tension along the circumference of the cooling tower (Karakas and Daloglu 2015).

2. AIM AND SCOPE

In this study, it is aimed to simulate a super-large reinforced concrete cooling tower with the ABAQUS program as a sheet, by examining the studies on the structure of cooling towers. In the models, the strain and strain behaviors against the wind load were investigated by reinforcing the middle zone of the tower with carbon fiber reinforced polymer (CFRP) sheets of different thicknesses. First of all, the behavior of a tower that is intended to be modeled to monitor how the cooling tower collapses was roughly examined at low frequencies and high frequencies. The behavior of the tower simulated was compared with a 20-year cooling tower that collapsed in a devastation explosion in Sichuan province of China (SINA 2009). The model images obtained at low and high frequencies are given in Fig. 1 for the actual collapse images. As seen in the figure, there is a good similarity between the images of the simulation and the actual collapse images. This, in turn, determines the accuracy of ABAQUS as a finite element program, in the simulation.

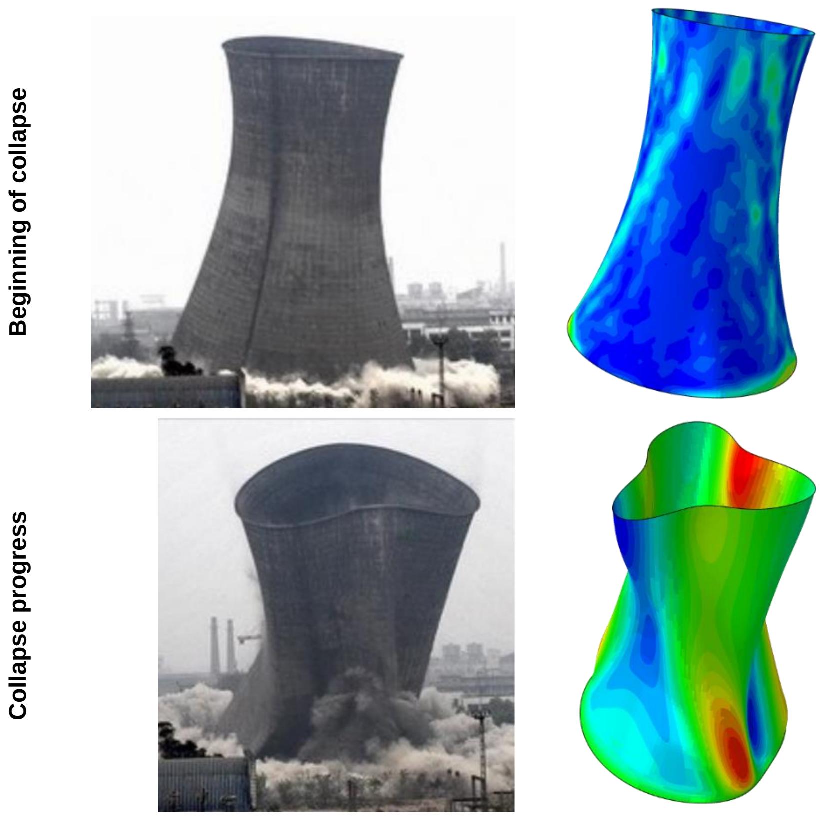

Figure 1. A cooling tower, in a demolition blast in Chengdu, southwest China's Sichuan province: Left, simulation results: Right

3. STRUCTURE OF THE COOLING TOWERS

Cooling towers should be made according to standards with the approved high quality structural elements in concrete. The coffin shell should consist of two reinforced layers (Fig. 2). Layers should be applied perpendicular to each other. Both sides should be covered with minimum 3 cm of concrete. The elements of the cooling tower must be reinforced with deformed steel. So the moments resulting from the combination of the tensile forces and the controlling load of the critical loading conditions must be provided. Shell walls can be proportionate to axial forces and rectangular sections subjected to bending. Tower Shell is connected with the columns as seen above Fig. 2. In addition, the thickness of the shell is applied at different thicknesses according to its height. However was assumed to be flat, to avoid geometric complexity in ABAQUS program (Gould and Krätzig 1998, Gu, Yu et al. 2017).

Cooling tower shells are exposed to a relatively intense environment during their lifetime, which can last for decades and so special care must be taken to ensure a durable construction. During its lifetime, it may be exposed to severe frost in a saturated state, chemical attacks from harmful substances in the atmosphere, water and water vapor, biological attack from microorganisms and possible additional chemical attacks.

In this regard, concrete should be made from materials approved with high quality, including fly ash. It should have the following features (Eidiani 2015):

- High resistance against chemical attack
- High early strength
- High structural density
- High resistance to frost.

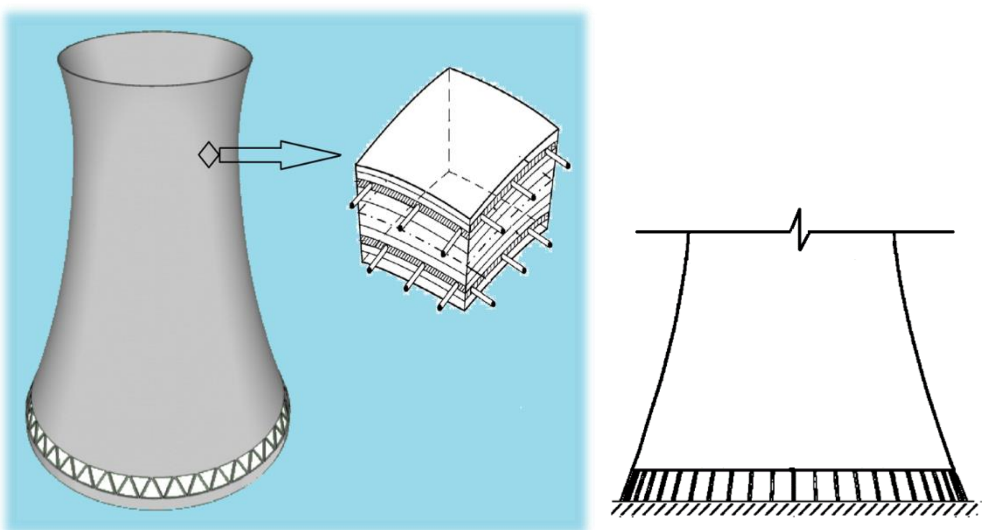

Figure 2. A schematic image of the structure element detail (left) and column connections (right) of cooling tower.

4. 3D SIMULATION

In recent years, FEM method is used to examine the materials and elements of construction with different geometry and dimensions for different purposes, extensively (Elsanadedy, Almusallam et al. 2013, Mahmud, Yang et al. 2013, Limazie and Chen 2016). In this study, by using ABAQUS program, the cooling tower of the reinforced concrete type is simulated with CFRP sheets of different thicknesses. The displacement and stress values were investigated under the wind load as horizontal load which are very influential on high structures. TS 498 Standard (TS498 1997) has been used to calculate the wind load. In this way, the absorption (velocity pressure) and the aerodynamic load factors in the most critical cases are taken (Eq. 1).

$$W = C_P . q \quad (1)$$

The information of the models is given in Table 1. In the models, CFRP thickness and mechanical properties were taken from an experimental study (Yin, Huang et al. 2016).

Table 1. The information of the models

Model NO.	0xCFRP	1xCFRP	2xCFRP	4xCFRP	6xCFRP	8xCFRP	10xCFRP
Number of layers	0	1	2	4	6	8	10
Total thickness (mm)	0	0.167	0.334	0.668	1.002	1.336	1.67

4.1 Mesh Generation & Boundary Condition

The geometric features of the model were chosen close to a study in the literature (Yu, Gu et al. 2016). In the ABAQUS program, the length units were machined with a 1/100 scale in m (Fig. 3-a). Boundary conditions and mesh generation of the concrete shell are given in the Fig. 3-b and Fig. 3-c respectively. As seen in the boundary conditions (Fig. 3-b), the cube is supported as an integral part of the lower section.

Typical mesh appearance (Fig. 4-a), and dimensions (Fig. 4-b) of the CFRP used as a reinforcing element against the tensile forces in the models, were given in the Fig. 4. In the models, CFRP of the same size was used in 6 different thicknesses. The connection between the concrete shell and the CFRP is provided by the constraint-Tie in the ABAQUS program.

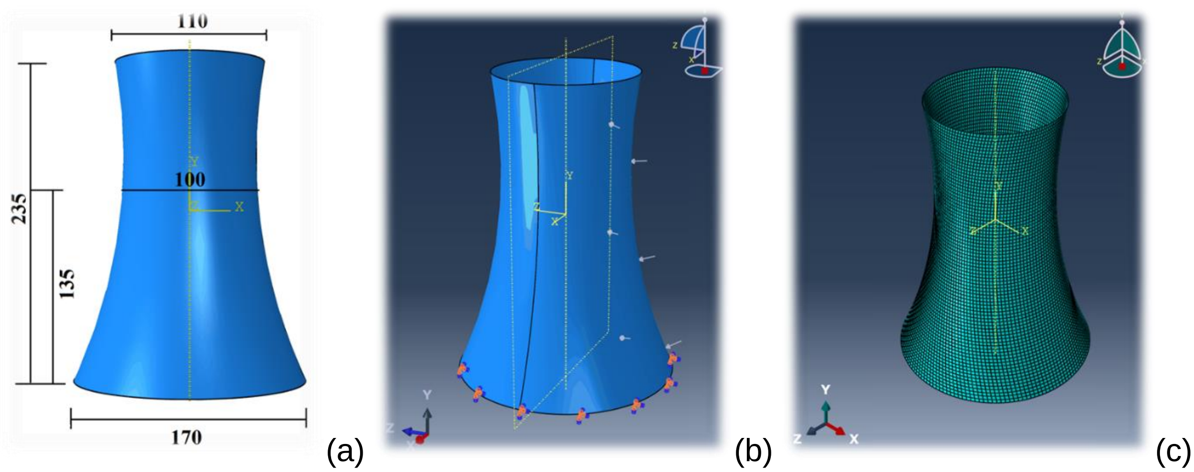

Figure 3. Dimensions (a), boundary conditions (b) and typical mesh appearance of cooling tower.

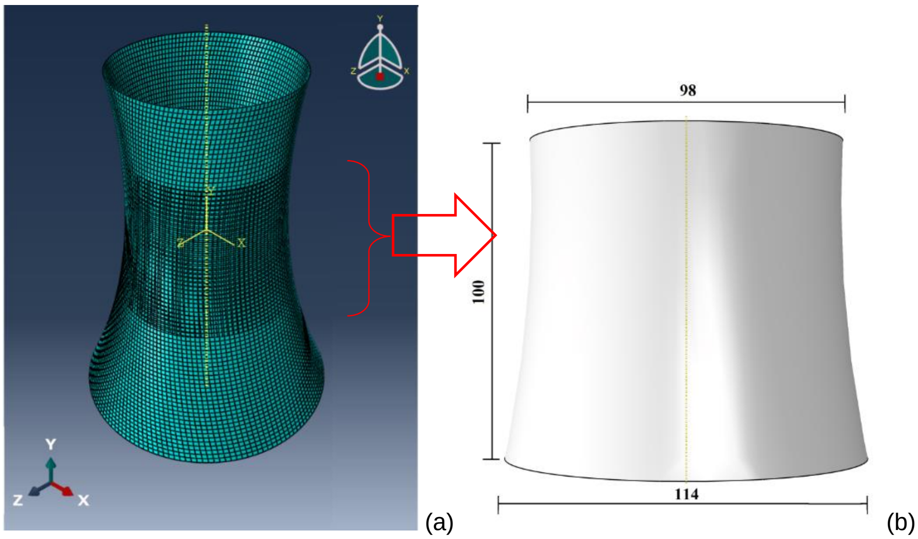

Figure 4. Typical mesh appearance (a), and dimensions (b) of the CFRP.

4.1 Material Properties

To represent inelastic behavior of concrete in the ABAQUS program, compressive and tensile strengths values of concrete were used in the concrete damage plasticity (CDP) settings in the property section (Hibbitt, Karlsson et al. 2011, Dehghanpour and Yilmaz 2018). The CDP model is proposed by Lubliner et al for semi-brittle materials such as concrete [38]. There are five additional parameters that need to be defined in the CDP in the ABAQUS model: dilation angle (in degrees), eccentricity (the flow potential eccentricity), fb0/fc0 (the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress), K (the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian), and viscosity parameter. Default values are accepted since the values of these parameters are not very effective in the results, i.e. respectively 33º, 0.1º, 1.16º, 0.66º and 0.0º (Mahmud, Yang et al. 2013, Dehghanpour and Yilmaz 2018). The density, compressive strength, modulus of elasticity and tensile strength of concrete were applied 2400 Kg / m^3, 35 MPa, 35 GPa and 3 MPa respectively.

Fiber-reinforced polymer (FRP) materials have been widely used in the civil engineering industry in recent years. Due to its high tensile strength, good corrosion property and electric conductivity, FRP plate is successfully used to improve existing reinforced concrete structures by winding the surface of the structure.

The geometric and mechanical properties of the CFRP material used in the models were taken from the study of Yin et al: thickness (one layer of CFRP) = 0.167 mm; ultimate strength, f_{fu} = 3,200 MPa; ultimate strain, e_{fu} = 0.0150; modulus, E_{fu} = 213 GPa; and density = 1800 Kg / m^3. (Yin, Huang et al. 2016).

5. RESULTS

Deformation Contours of unreinforced and CFRP reinforced tower models are given in Fig. 5. As shown in the figure, strain values are lower in all CFRP reinforced models, especially in the middle region, in the region where CFRP is wound, compared to unreinforced model. This is due to the fact that CFRP has a very high tensile strength compared to concrete, most of the stresses under the influence of wind load were carried by the CFRP and therefore the tower was less stressed.

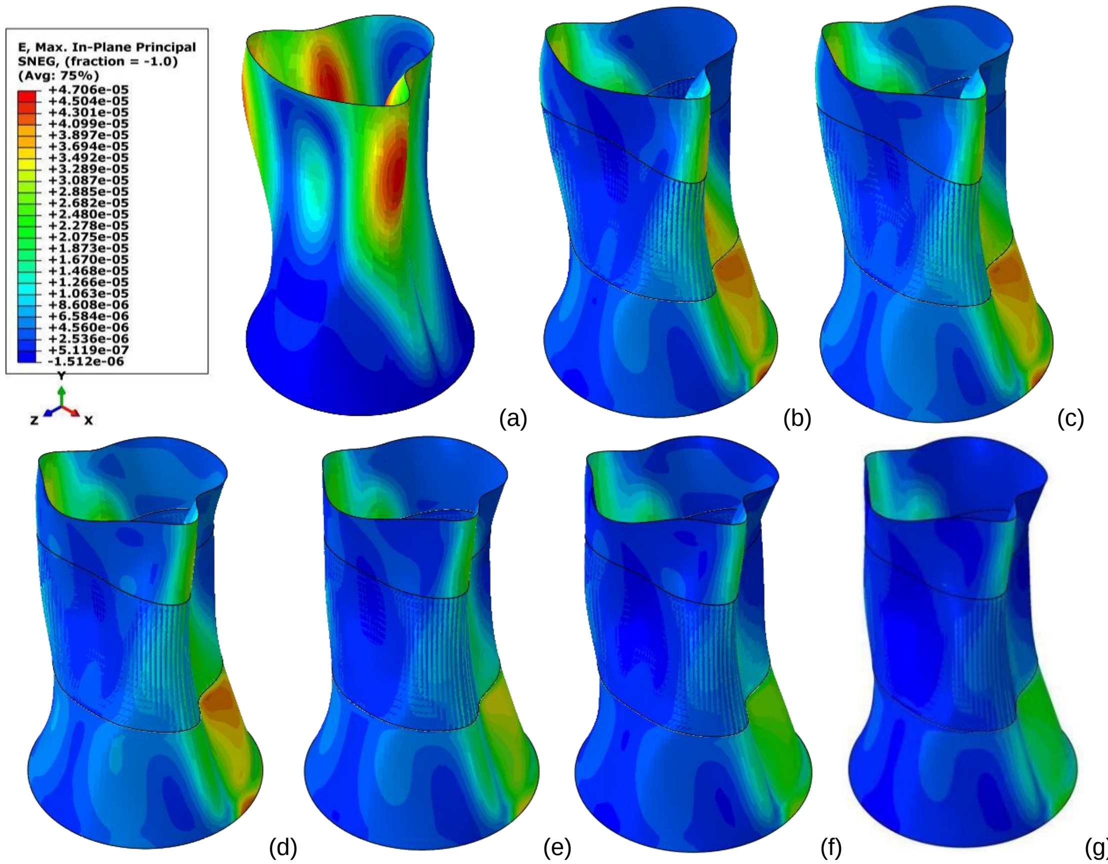

Figure 5. Deformation Contours of unreinforced and layer CFRP reinforced tower; (a); unreinforced, (b); 1xCFRP, (c); 2xCFRP, (d); 4xCFRP, (e); 6xCFRP, (f); 8xCFRP and (g); 10xCFRP reinforced.

In the several studies related to the cooling towers under the effect of wind load, stress and strain values that have occurred along the height of the tower were investigated (Noh 2006, Karakas and Daloglu 2015, Yu, Gu et al. 2016). Depending on the height of the tower, the change in the amount of displacement in the tower shell is shown in Fig. 6. In the diagram, displacements along the elevation are compared for all models. CFRP effect is very clear at the middle and top of the height. In an FE study (Karakas and Daloglu 2015) conducted under the wind loads of the cooling towers (with 125 m height), the maximum displacement value along the axial direction of a bucket made of normal concretes was determined to be about 0.5 mm. this value confirms the displacement values, taking into account the height of the models (235 m) in the current study.

With increasing CFRP sheath thickness, the maximum displacement values of the tower shell are decreasing. But as the thickness increases, the results are very close to one another, especially in the last three models. According to the increase in CFRP thickness, the maximum displacement values are summarized in Fig. 7. In an FEM study (Karakas and Daloglu 2015) conducted under the wind loads of the cooling towers, the maximum displacement value along the axial direction of a bucket made of normal concretes was determined to be about 0.5 mm.

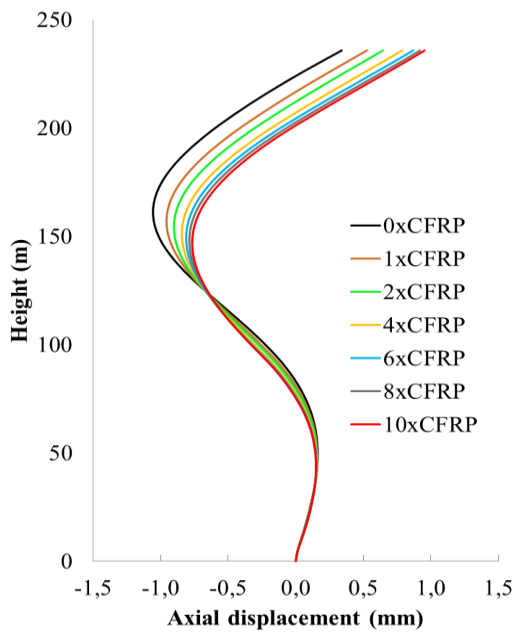

Figure 6. The change of the displacement amount in the tower shell in the height of the tower

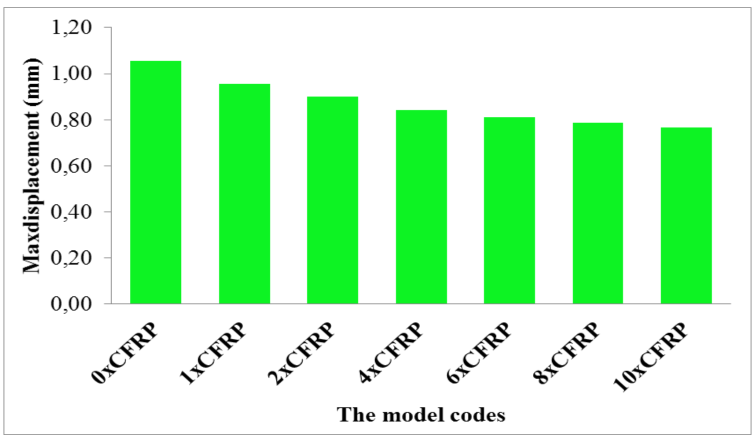

Figure 7. Maximum displacement values with CFRP thickness

The state of stress in the structure is the most critical information in a typical finite element analysis. For all models, large stresses resulting from wind load are visible in the base zone in the lower regions of the cooling tower. The increase in the CFRP thickness has led to a decrease in stress, which confirms that a certain portion of the stresses are carried by the attached CFRP. Depending on the height of the tower, the change in the amount of stress in the tower shell is shown in Fig. 8. In the same FEM study, stresses under the effect of wind load were studied and their maximum values were determined to be around 500 KPa. In the present study, the maximum stress value was found to be around 700 KPa, which is due to the higher structure.

In the present study also distribution of pressure of wind symmetrically alone has been investigated. The wind pressure distribution on the outside of the shell is assumed to be symmetrical about the center line in the direction of wind (Murali, Vardhan et al. 2012). Research has been conducted on Indian Standards and different studies on the distribution of wind pressure (Murali, Vardhan et al. 2012, Wang, Cao et al. 2016). Fig. 9 shows the amount of pressure in the shell of the towers along the height. The pressure distribution was obtained between 0.2 and 1.6 MPa in the unreinforced model and in CFRP reinforced models, the pressure distribution type was obtained in parallel however the maximum pressure value decreased from 1.6 to 0.7 MPa. In CFRP reinforced models, the decrease in pressure distribution confirms that a certain portion of the stresses are carried by the attached CFRP. Also, as seen from the figure, the maximum pressure values of all models are in the regions of the tower 90 and 270 according to the wind direction.

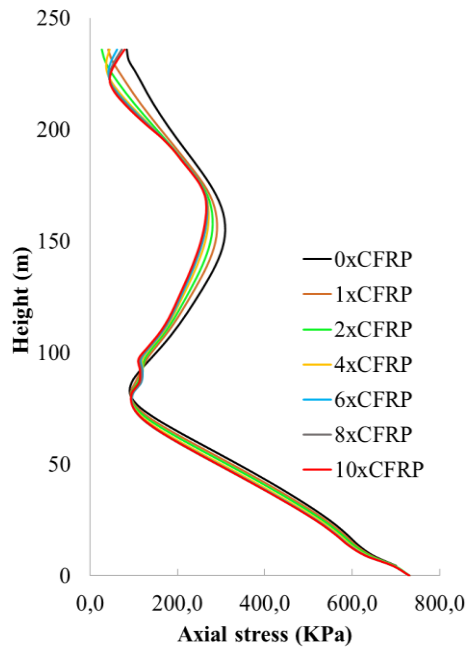

Figure 8. The change of the stress amount in the tower shell in the height of the tower

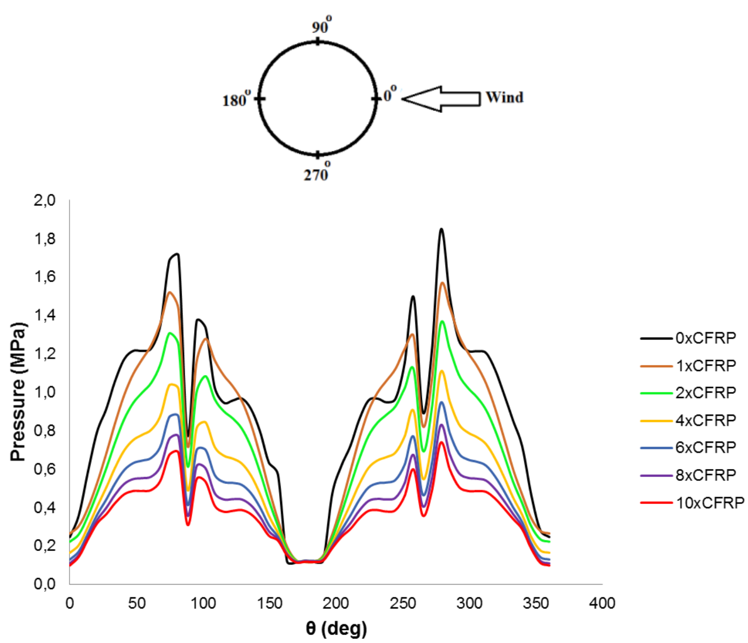

Figure 9. The change of the stress amount in the tower shell in the height of the tower

6. CONCLUSIONS

In this study, a high scale cooling tower was simulated in 3D with the ABAQUS program. The towers reinforced with CFRP plates in different thicknesses were examined under wind load. The summary and conclusions of the study are presented as follows,

According to the deformation results, strain values are lower in all CFRP reinforced models, compared to unreinforced model. This is due to the fact that CFRP has a very high tensile strength, most of the stresses were carried by the CFRP and therefore the tower was less stressed. Displacements along the elevation are compared for all models. CFRP effect is very clear at the middle and top of the height. With increasing CFRP sheath thickness, the maximum displacement values of the tower shell are decreasing. But as the thickness increases, the results are very close to one another, especially in the last three models. For all models, large stresses resulting from wind load are visible in the base zone in the lower regions of the cooling tower. The increase in the CFRP thickness has led to a decrease in stress, which confirms that a certain portion of the stresses are carried by the attached CFRP. The pressure distribution was obtained between 0.2 and 1.6 MPa in the unreinforced model and in CFRP reinforced models, the pressure distribution type was obtained in parallel however the maximum pressure value decreased from 1.6 to 0.7 MPa. In CFRP reinforced models, the decrease in pressure distribution confirms that a certain portion of the stresses are carried by the attached CFRP. Also, as seen from the figure, the maximum pressure values of all models are in the regions of the tower 90 and 270 according to the wind direction.

7. ACKNOWLEDGEMENTS

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REFERENCES

[1] American Society of Heating, R. and A.-C. Engineers (2000). ASHRAE Guideline 12-2000: Minimizing the risk of legionellosis associated with building water systems, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta.

[2] Bagherzadeh, R., A.-H. Sadeghi and M. Latifi (2012). "Utilizing polypropylene fibers to improve physical and mechanical properties of concrete." Textile research journal 82(1): 88-96.

[3] Dehghanpour, H. and K. Yilmaz (2018). "Mechanical and Impact Behavior on Recycled Steel Fiber Reinforced Cementitious Mortars." Russian Journal of Building Construction and Architecture (3(39)): 67-84.

[4] Eidiani, M. (2015). An overview of energy strategies in the diagnosis of transient stability by the example of the closest unstable equilibrium point-persian, Technical Report· December 2015, DOI: 10.13140/RG. 2.1.

[5] Elsanadedy, H. M., T. H. Almusallam, S. H. Alsayed and Y. A. Al-Salloum (2013). "Flexural strengthening of RC beams using textile reinforced mortar–Experimental and numerical study." Composite Structures 97: 40-55.

[6] Gould, P. L. (1984). Natural Draught Cooling Towers: Proceedings of the 2. International Symposium, Ruhr-Universität Bochum, Germany, September 5-7, 1984, Springer Verlag.

[7] Gould, P. L. and W. B. Krätzig (1998). "Cooling tower structures." Handbook of structural engineering. Boca Raton, FL: CRC Press Inc: 473-504.

[8] Gu, X.-L., Q.-Q. Yu, Y. Li and F. Lin (2017). "Collapse process analysis of reinforced concrete super-large cooling towers induced by failure of columns." Journal of Performance of Constructed Facilities 31(5): 04017037.

[9] Hibbitt, H., B. Karlsson and P. Sorensen (2011). "Abaqus analysis user’s manual version 6.10." Dassault Systèmes Simulia Corp.: Providence, RI, USA.

[10] Karakas, A. I. and A. Daloglu (2015). "A Comperative Study on the Behavior of Cooling Towers Under Wind Loads Using Harmonic Solid Ring Finite Elements." Uluslararası Mühendislik Araştırma ve Geliştirme Dergisi 7(2): 20-29.

[11] Lang, C. and J. Strauß (2010). "Natural Draft Cooling Tower Design and Construction in Germany-Past (since 1965), Present and Future."

[12] Leo Samuel, D., S. S. Nagendra and M. Maiya (2017). "Simulation of indoor comfort level in a building cooled by a cooling tower–concrete core cooling system under hot–semiarid climatic conditions." Indoor and Built Environment 26(5): 680-693.

[13] Limazie, T. and S. Chen (2016). "FE modeling and numerical investigation of shallow cellular composite floor beams." Journal of Constructional Steel Research 119: 190-201.

[14] Mahmud, G. H., Z. Yang and A. M. Hassan (2013). "Experimental and numerical studies of size effects of Ultra High Performance Steel Fibre Reinforced Concrete (UHPFRC) beams." Construction and Building Materials 48: 1027-1034.

[15] Murali, G., C. V. Vardhan and B. Reddy (2012). "Response of cooling towers to wind loads." ARPN Journal of engineering and applied sciences 7(1): 114-120.

[16] Noh, H. C. (2006). "Nonlinear behavior and ultimate load bearing capacity of reinforced concrete natural draught cooling tower shell." Engineering Structures 28(3): 399-410.

[17] SINA. (2009). "A cooling tower, which is 20 year old and 105 meter high, at a local thermal power plant falls in a demolition blast in Chengdu, southwest China's Sichuan province."

[18] Şanli, N. Ö. (2015). "Soğutma Kulesi Dezenfeksiyonunda İş Sağlığı Ve Güvenliği." Tesisat Mühendisliği(146): 13-23.

[19] TS498 (1997). "Yapı Elemanlarının Boyutlandırılmasında Alınacak Yüklerin Hesap Değerleri (TS 498)." Türk Standartları Enstitüsü, Ankara.

[20] Wang, J., S. Cao, W. Pang, J. Cao and L. Zhao (2016). "Wind-load characteristics of a cooling tower exposed to a translating tornado-like vortex." Journal of Wind Engineering and Industrial Aerodynamics 158: 26-36.

[21] Waszczyszyn, Z., E. Pabisek, J. Pamin and M. Radwańska (2000). "Nonlinear analysis of a RC cooling tower with geometrical imperfections and a technological cut-out." Engineering structures 22(5): 480-489.

[22] Yin, P., L. Huang, L. Yan and D. Zhu (2016). "Compressive behavior of concrete confined by CFRP and transverse spiral reinforcement. Part A: experimental study." Materials and Structures 49(3): 1001-1011.

[23] Yu, Q.-Q., X.-L. Gu, Y. Li and F. Lin (2016). "Collapse-resistant performance of super-large cooling towers subjected to seismic actions." Engineering Structures 108: 77-89.