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Deformation Analysis of a Chimney at Tripoli-West Power Plant

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Abstract—Chimneys are tall structures used to get rid of hot flue gases and combustion gases resulting from power plants. They are continuously under static and dynamic loads, thus it is important to study their behavior in order to avoid structural failures. In this paper, a chimney at Tripoli-West power plant is investigated. The excitation forces acting on the chimney are mainly due to wind, therefore data about wind velocities during a long period were collected from the National Centre of Meteorology in Tripoli. The maximum and average values of wind velocities were used in the analysis. The simulations were conducted using SolidWorks®, the finite element analysis software, and the wind flow was simulated using the flow simulation tool. Stress and deformation analyses were conducted, and the deflection at the top of the chimney was calculated and compared to international permissible standards. Another issue, regarding environmental protection, was also investigated. It was found that, due to the increasingly populated area around the plant, the chimney could still be made taller to protect the nearby buildings from hazardous emissions.

***Keywords*—deformation analysis, along wind, chimney, emissions, environment.**

I. INTRODUCTION

Chimneys, sometimes called stacks, are subjected to many types of loads, in the vertical and horizontal directions. Most of the loads are due to wind, earthquakes, and high-temperature changes. In Tripoli, chimneys suffer mainly from wind loads. The wind may cause high-stress distributions in some areas along with the stack, as well as high deformations. Wind load could also cause undesired stack vibration limits but this will not be investigated in this paper. Besides that, the effect of earthquakes will be ignored given that Tripoli is almost a seismic-free region.

Many research works worldwide were conducted on the static analysis of chimneys. These vary from steel-only chimneys to composite concrete structures. These vary from optimization studies to reduce the weight of chimneys [12], to reviewing the rationale for code standards regarding the basic dimensions of industrial steel chimneys. Explains the importance of engineering constraints in designing self-supporting steel chimneys [8].

References [9] and [2] have investigated the effect of wind stretching on Reinforced Concrete Chimneys (RCC) by studying a tall chimney, 150m high. In this study, the wind speed at 145m of height was not measured but rather estimated. The effect of wind speed considering turbulence was investigated by [1]. Various parameters were under study, such as chimney height, wind speed, and chimney wall thickness. Their results showed that the static and dynamic moments are minimum for a short chimney with the lowest wind speed and become higher for taller chimneys and higher wind speed, as would usually be expected. It was also concluded that the maximum deflections due to static wind forces are less compared to maximum deflections due to dynamic wind force.

The influence of using supporting rings along a chimney on its static behavior was studied by [6]. A miniature model of the chimney was made using fiber-reinforced plastic with a geometric scale of 1:150 representing a chimney with a height of 100m to illustrate the importance of wind interference between different buildings of the power station. It was also proven through the experimental model that using supporting rings in the upper two-thirds region of the chimney reduces the mechanical stresses and deflections. Reference [7] reviewed the along and across wind effects on a chimney, considering two regions with different wind speeds. The effect of vortex shedding on the chimney structure was also investigated. It was found that the across-wind calculation is directly proportional to the weight of the chimney, frequency, and mode shapes, but not to wind speed, such that across wind load is not increasing with the increasing wind speed.

Other research work, such as [11] and [4], have studied the dynamic behavior of tall chimneys, stress profile change due to wind load, the influence of along-wind and across-wind on the static and dynamic behavior of chimneys, and wind influence on the lateral deflection of top of the chimney, using ANSYS models.

It is worth mentioning that no other investigation has been conducted before regarding the deformation and stress analysis of the chimney located at Tripoli-West power plant. This study is concerned with the static and deformation analysis of this self-supporting reinforced concrete chimney, studying the maximum deflections at its top, the influence of using supporting rings along its length, and their location along the chimney. It finally highlights environmental issues regarding emissions and the necessity of making changes to the height of the chimney. Detailed data have been collected regarding the geometrical and material parameters of the chimney. Some dimensions were not available and have been measured on site. A finite element model was built on SolidWorks platform to study the influence of some of the above-mentioned parameters.

II. Description of Chimney

The Tripoli-West power plant is located ~15 Km west of Tripoli, situated on the seashore of Janzour. The chimney is part of a steam power plant generating 120MW, with an amount of gas flowing of about 400 m^3/s, at a temperature ranging from 40°C to 110°C. The chimney body consists of reinforced concrete and bricks for heat isolation, Fig. 1. The dimensions of the chimney are as follows:

- height of chimney: 105 m
- thickness of Reinforced concrete: 0.4m
- space between brick and wall: 0.1m
- thickness of brick: 0.4m
- outer diameter at the bottom: 9.3m
- outer diameter at top: 5m
- ½ of taper angle: 1.173°

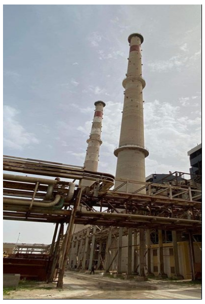

Fig. 1. The investigated chimney at Tripoli-west power plant.

The materials parameters used in modeling are defined by: bricks modulus of elasticity=11.146 GPa, bricks Poisson's ratio=0.156, bricks mass density=2000 kg/m^3. Steel modulus of elasticity=200 GPa, Steel Poisson's ratio=0.3, Steel mass density=7900 kg/m^3. The reinforced concrete parameters are calculated as follows ([13] and [14]),

$$E_{RCC} = \frac{E_S A_{S+} E_C A_{C+}}{A_S + A_C} \qquad (1)$$

$$\nu_{RCC} = \nu_S V_S + \nu_C V_C \qquad (2)$$

$$\rho_{RCC} = \rho_S V_S + \rho_C V_C \qquad (3)$$

where E_{RCC} is Young's modulus of reinforced concrete, E_S and E_C are Young's modulus of steel and concrete, respectively, A_S and A_C are the area fraction of steel and concrete, and V_S and V_C are the volume fraction of steel and concrete, respectively. In the same manner, Poisson's ratio ν_{RCC} and mass density ρ_{RCC} of the reinforced concrete are calculated. Thus, using these formulas, the reinforced concrete mass density is calculated to be 5320 kg/m^3, its Poisson's ratio equal to 0.21, and Young's modulus equal to 107 GPa.

III. Wind Load Calculations

Chimneys experience major loads coming from the wind from all directions and have different loads at different heights. The wind loads can be of two kinds; quasi-static load, which is the force acting on the chimney, calculated as time-averaged steady speed, and dynamic load generated because of gust and vortex shedding. The wind acting on the chimney in our case is considered the along wind type, which is the wind acting directly on the surface of the chimney.

As the wind speed changes according to many factors, mainly the height, the design wind speed can be calculated as a function of a few parameters, according to [15],

$$V_Z = V_b\, K_1\, K_2\, K_3 \qquad (4)$$

where V_Z is the design wind speed at any height, V_b is the basic wind speed at any height, K_1 is the probability factor (risk coefficient), K_2 is the terrain, height, and structure size factor, and K_3 is the topography factor.

The wind-induced forces acting on the chimney depend on many parameters such as the shape and direction of wind incident on the chimney surface, chimney height, influence of nearby structures, and the properties of the chimney itself. But for simplicity, it becomes convenient to consider equivalent static forces. The static force acting on the chimney, usually called drag force, creates along-wind shear forces and bending moments. The drag force acting on a body is calculated as [8],

$$F_D = \frac{1}{2}\rho_a v^2 C_D A \qquad (5)$$

where F_D is the drag, ρ_a is the density of air, C_D is the drag coefficient that depends on Raynold's number, shape, and aspect ratio of the structure, and A is the cross-sectional area normal to wind direction. The gust effect, due to fluctuations of wind speed, is neglected and an average wind speed is assumed to act. In addition, the flow state of air is considered laminar, Re<5.

IV. Wind Speed Profile

In order to collect wind speed data in the city of Tripoli, the Libyan National Meteorological Centre, and the Department of Climate Management and Climate Change were visited to acquire the necessary data. These data are the average wind speed and the maximum wind speed measured at 10m above sea level near the main seaport of Tripoli. The data collected covers the period from 1993 to 2009. The average wind speed in a certain month was calculated by taking the average over all days of the month, and the maximum wind speed is the highest recorded reading obtained for each month. It was observed from the data that the maximum occurred during the year 2001, as shown in Fig. 2. This was our basic wind speed used in this analysis.

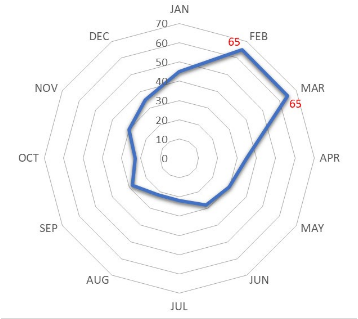

Fig. 2. Maximum observed wind speed during the year 2001.

The maximum values of wind speed were observed in the year 2001, about 65 knots (33.44 m/s), which is the basic wind speed V_b. The parameters K_1 and K_3 depend on the class of structure and wind speed. They were fixed at the values of 1.06 and 1.0 respectively, as in [9] and [15]. The parameter K_2 changes according to different categories of terrains and it varies with height. For our case, K_2 changes according to height, and accordingly the design wind speed also changes, as shown in Fig. 3.

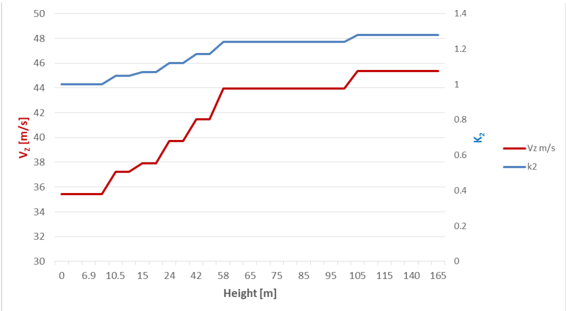

Fig. 3. The change of the design wind speed V_z and the parameter K_2 with chimney height.

To estimate the design wind speed for any given height, these data were curve-fitted using MS-Excel resulting in the following second order polynomial, with h being the height,

$$V_Z = -0.0007h^2 + 0.164h + 35.252 \qquad (6)$$

This equation is used in the model to specify the wind load acting on the chimney according to its height.

V. Modeling the Chimney

A finite elements model was created in SolidWorks® to investigate the effect of wind on the chimney. Static analysis is performed, in which the physical chimney model is divided into several elements, each with a specified number of nodal points, and the problem is mathematically summarized into a huge global system of the force vector, stiffness matrix, and nodal displacements, in the form [10],

$$\{F_g\} = [K_g]\{\delta_g\} \qquad (7)$$

where $\{F_g\}$ is the global nodal force vector, $[K_g]$ is the global stiffness matrix, and $\{\delta_g\}$ is the global displacements vector.

A. *Model of the original chimney on site*

The chimney is modeled in a way that it is fixed to the ground at the bottom, at its base. A mesh consisting of a total of 34462 triangular solid elements, and a total of 69188 nodes, as shown in Fig. 4.

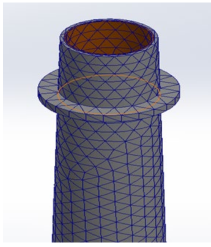

Fig. 4. Part of the Finite element mesh of the chimney using tridimensional triangular elements.

The static simulation was performed and solved, resulting in the following displacement and stresses profiles along the chimney, presented in Fig. 5. and Fig.6. As expected, the maximum deflection is observed at the top of the chimney of 4.965mm.

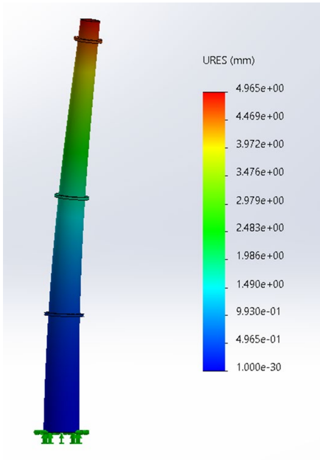

Fig. 5. The elastic behavior of the chimney, demonstrating the displacement profile.

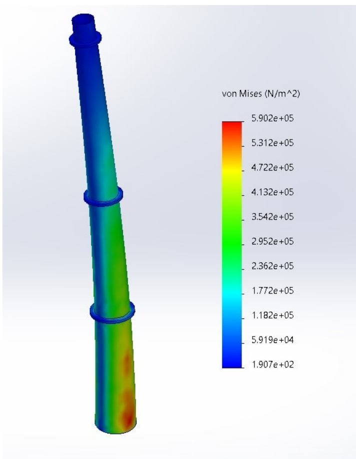

Fig. 6. The elastic behavior of the chimney, demonstrating the stresses profile.

B. *Model of the chimney with no rings*

For the sake of comparison, the three rings surrounding the chimney on three different levels were removed from the model. This was done to investigate the effects of these rings on the static behavior of the chimney. A new model was built and solved, and the elastic behavior and the distribution of stresses along chimney are shown in Figures 7 and 8 respectively.

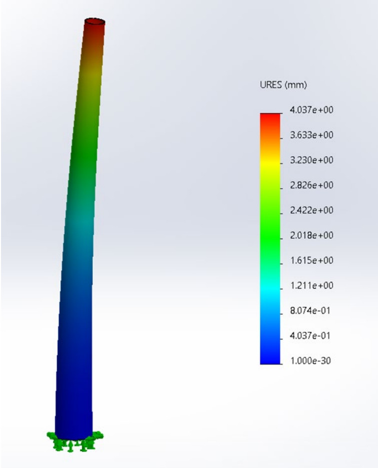

Fig. 7. The elastic behavior of the chimney with no rings.

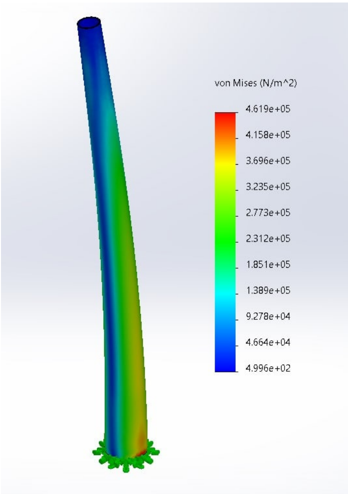

Fig. 8. Stresses distribution along chimney with no rings.

Observe that, in this case, the displacements along the chimney structure have decreased, especially at the top of 4.037mm. Moreover, one can see that the value of maximum stress in this model is decreased about 21% compared with the previous model. The rings have an effect on the static behavior, but due to the mass change, the dynamic behavior of the chimney is expected to be affected as well. To do a comprehensive study, modal vibration analysis has to be conducted, as the mass distribution on the chimney body has changed. This investigation of the dynamic behavior is not done in this paper.

C. Model of the chimney with rearranged rings locations

The use of the rings is important, used as “stitches” for possibly generated cracks, as structure supporters or fasteners, or needed for maintenance purposes. With that in mind, the positioning of the rings would have an effect on the elastic behavior of the chimney. For that, another model with rearranged positioning of the rings is performed. In this model, the rings are positioned and equally spaced, in the upper 1/3 part of the structure. Again a finite element model was built and solved. The resulting displacement and stress profiles are shown in Fig. 9. and Fig.10. The deflection at the top of the chimney has decreased to 3.798mm, and the stress on the chimney has decreased as well compared with the first model.

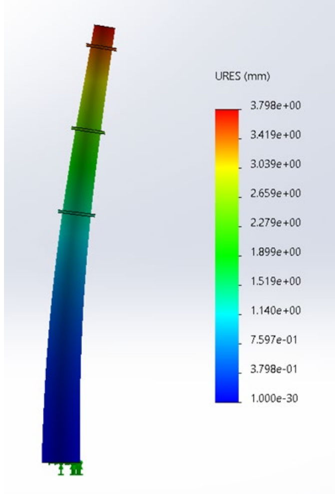

Fig. 9. The elastic behavior of the chimney with modified ring positions.

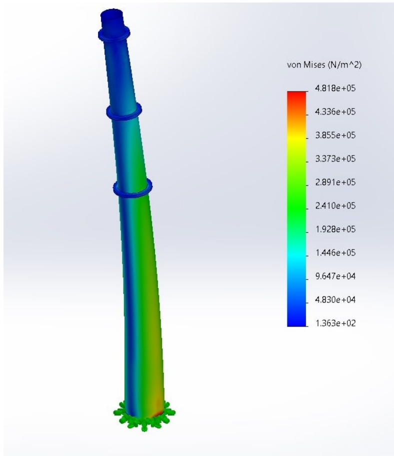

Fig. 10. Stresses distribution along chimney with modified ring positions.

VI. RESTRICTIONS ON CHIMNEY’S TOP DEFLECTION

There exist few standards worldwide restricting the maximum allowed deflection of the top part of a chimney. Among these are the Indian standards [5] and the American ASME standards [16]. These are standards made for steel chimneys but the ones specific for RCC are not available in hand, hence, we will use these two as a reference for our estimated calculations. The RCC is reinforced concrete, so our approximation is considered valid.

The Indian standards state that the maximum deflection at the top of the stack as a result of a wind load acting on the circular cross-section of the stack should not be greater than h/200, where h is the unsupported height of the stack. On the other hand, the ASME STS-1-2016 standards restrict the top deflection to a maximum of h/100 (12 inches per 100 feet).

Using these standards, and comparing them to the previous three configurations of the analysis, it is observed that the maximum deflection in the three cases was way below the limit values, as demonstrated in Table I.

TABLE I. MAXIMUM PERMISSIBLE DEFLECTIONS VS. CALCULATED DEFLECTIONS

MPD: ASME standards (mm)	MPD: Indian standards (mm)	Displacement at top of the chimney (mm)	Height of chimney (m)	Model
h/100	h/200			
1050	525	4.965	105	Original
1050	525	4.037	105	no-rings
1050	525	3.798	105	rearranged rings

MPD: Maximum Permissible Deflection.

VII. RECOMMENDATIONS ON CHIMNEY HEIGHT AND ENVIRONMENT PROTECTION

Utilizing the fact of very low deflections at top of the chimney, the height of the chimney could be increased if new chimneys of similar design are to be built in the power plant. The main reason for increasing the height is to protect the surrounding environment and nearby populated areas from hazardous emissions released from the stack.

Investigating the area around the power plant, it was observed that there is an urban development and an increase in civil construction. Satellite images were collected covering the period from 1976 to 2021 showing new constructions and eventually an increase in population density and a decrease in vegetation areas, Fig. 11.

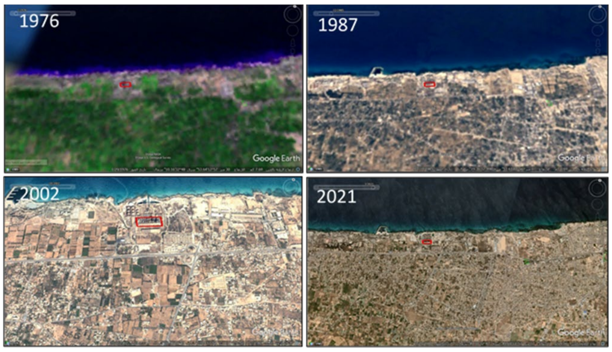

Fig. 11. Urban development near Tripoli-West power plant from 1976 to 2021. The red area is the stack location.

The stack height at Tripoli-West power plant might have been sufficient in the 70s when it was commissioned, but nowadays it is not anymore. From an environmental point of view, higher stacks are better to get rid of air pollutants such as sulfur dioxide and nitrogen oxides [17].

Taking that into account, an increase in chimney height is recommended. Different scenarios were investigated and modeled using different heights. The chimney top deflection is again calculated to check if it is within the recommended limits, as given in Table II.

TABLE II. MAXIMUM PERMISSIBLE DEFLECTIONS VS. CALCULATED DEFLECTIONS FOR MODIFIED DESIGNS

MPD: ASME standard (mm)	MPD: Indian Standard (mm)	Displacement at top of the chimney (mm)	Height of chimney (m)	No. of rings/model
h/100	h/200			
1250	625	9.09	125	3/(a)
1450	725	12.93	145	3/(b)
1650	825	25.97	165	3/(c)
1650	825	26.61	165	4/(d)

MPD: Maximum Permissible Deflection.

The obtained results are demonstrated in Fig. 12. The model of 165m height was also modeled with 4 supporting rings instead of 3, to study its effect, as shown in Fig. 12. a thorough investigation should be conducted concerning the number of rings and their influence on chimney's performance.

It has been stated that "it is difficult to isolate the exact contribution of stack height to the spreading of pollution because of the complexity of the process that involves several variables" [17]. Nevertheless, it is still considered a good engineering practice to make stacks higher. On the other hand, Table 2 demonstrates that the deflection at top of the stack for a higher height of 165m is still under the maximum permissible deflection. The fact that a 165m high stack with 3 rings has a lower deflection of the top than the 165m with 4 rings needs extensive research to define the optimum number of rings and their locations along the stack.

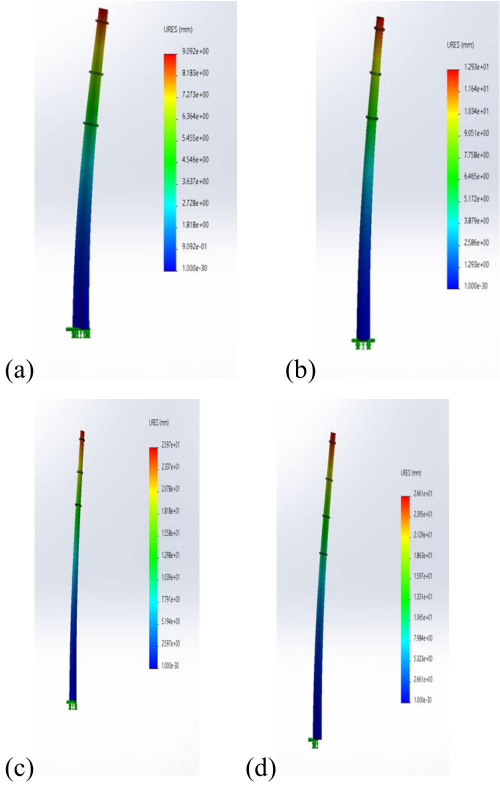

Fig. 12. The elastic behaviour of the chimney with modified rings positions: (a):height=125m, (b):height=145m, (c):height=165m, (d):height=165m with 4 rings.

VIII. CONCLUSIONS

The main objective of this paper is to investigate the effect of wind on a self-supporting reinforced concrete chimney at Tripoli-West power plant. The deflection at top of the chimney was found within the maximum permissible limit, as a matter of fact way below the limits. Because of increasing urban development and civil construction around near the power plant area, it is highly recommended that new stacks are to be built higher than the existing ones, conforming with the restrictions on maximum deflections at top of the chimney. This is highly recommended taking into account the environmental issues and protection of the surrounding population nearby the power plant from the hazardous emissions. It is not the intention of this paper to optimize the positioning of rings on the chimney, but it is recommended for future work.

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