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ORIGINAL ARTICLE

Foundation analyzing of centrifugal ID fans in cement plants

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Abstract This research was based on a finite-element model (FEM) of large foundations such as induced draft (ID) fans. Three-dimensional (3D) linear analyses were performed under arbitrary static and dynamic loads for various modulus of elasticity of concrete (E_c) (20, 25, 28 and 30 GPa) and reinforcement (E_s) (200, 250, 300 GPa). FEM results were compared with the existing ID fan foundations (laboratory-based evidence) to assess the accuracy of simulations made by the FEM. This study validated what constitutes a major departure from current thinking regarding material properties modeling of concrete under various loads to increase foundation for lifetime.

1. Introduction

Fan vibrations may lead to operational problems, shutdowns, and curtailed operations. Therefore, the analysis of large structural concrete foundations for induced draft (ID) fans presents a challenge to a wide variety of industrial plants [1]. Concrete foundation cracks result not only from mechanical defects which cannot be completely resolved by plant personnel (e.g. imbalance and misalignment), but also from type of loading, speed of rotors, and cyclic and dynamic loading (Fig. 1). Fan vibration, caused by the mentioned reasons as well as the frequency resonance of the dynamic load, can reduce the safety factor of an ID fan foundation [2,3]. Simply checking the validity of the foundation design for the stationary situation (as it often happens in practice) might not be enough to produce a proper foundation design [4].

Many researchers have attempted to increase the life span of ID fan foundations by identification of the reasons for their higher sensitivity. In the beginning of the 20th century, the analysis of large concrete foundations was limited to static calculations based on vertical loads comprising dead load plus machine weight multiplied by three-five. However, it is now obvious that such designs with the first order natural frequency alone are not sufficient to characterize the dynamic behavior of large concrete foundations. In other words, a better understanding of the involved processes requires a dynamic analysis [5]. Serious challenges posed by increasing heights of towers and foundations along with concerns about design concepts, life cycle, environmental impacts, and dynamic load necessitate the revision of the existing production and assembling solutions [6]. The finite element model (FEM) is a beneficial method to include all parameters without the construction of a full-scale foundation [7]. Research has shown that the first and second natural frequencies obtained from a stiffness

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Figure 1 Typical concrete foundation of induced draft fan systems in which cracks occur.

matrix with coupled lateral behavior provided very good correspondence with the FEM of the foundation, especially when the effects of inertia on the foundation were negligible [8]. Operating deflection shape (ODS) models are also applied to identify the weaknesses of the foundation at a large ID fan. These models have indicated that adding mass and stiffness with more piles and concrete could be reliable except when resonance is involved. The reliability of such models can be obtained from Newton's second law of motion ($F = m \times a$) which implies that the acceleration levels (a) would generally be reduced by increasing the mass (m). Hooke's law ($F = k \times x$), on the other hand, suggests that increased stiffness (k) is generally associated with lower displacement levels (x) [9]. Therefore, isolation systems can be useful to reduce foundation vibration [10–12]. Meanwhile, the resonant frequencies of the rotor and support system may cause very high amplitude vibrations [13]. The mass of the foundation block should also be adequate. The adequacy and dimensions of foundations, particularly the more complex ones, can be best evaluated by detailed analysis of the existing stresses and strains [14].

Various standards and approaches have used the types of loading (based on the coefficient of load), material properties, and safety factor to determine the appropriate design of ID fan foundations under static and dynamic loads [15–19]. While several studies have assessed some parameters of ID fans subjected to static or dynamic load, the deformation and stress caused by fan vibration and mass have not been well evaluated. These factors are affected by the shape and size of the foundation and the strength of the materials. The characteristics of the duct of screws and bolts used to connect the machine to the foundation should also be accurately designed and specified. Precise design and implementation of fan foundations can diminish the stresses and strains they receive and hence increase their longevity.

As the prediction of foundation behavior under various conditions can improve its structural performance, the present work aimed to use the FEM to accurately estimate the behavior of the concrete foundation under static and dynamic loads with different frequencies. It is noteworthy that due to the possible imbalance of the fan, the load applied to the foundation is generally dynamic unless a damper or isolator is used. We, therefore, tried to evaluate the structural behavior of the fan foundation under various types of loads, i.e. static and dynamic loads with rotor speed of 400, 800, 1200, and 1800 rounds per minute (rpm). We also used different material strengths, e.g. compressive strength of concrete and reinforcement, to determine the critical points of foundation structures in terms of displacements and stresses imposed and to predict the actual behavior of the structure and the likelihood of further damage. We finally compared our predictions with the actual cement foundation of a plant.

2. Load cases

Foundation analysis requires the proper consideration of machine loads, categorized as static and dynamic loads and those exerted during operation, provided by the manufacturers. The main static load is generally caused by the dead load of the equipment. The magnitude of the moments produced by the driving mechanism, typically calculated as a vertical force couple, depends on both the rotational speed and power output.

Imbalance, created when the rotating part's center of mass does not match the center of rotation, is responsible for major dynamic loads during operation. Although these loads are commonly presented by the machine manufacturer, they can also be computed based on the balance quality grade of the rotor.

The resultant imbalanced load $F(t)$ (N) is calculated with the rotating mass m (kg) as follows:

$$F(t) = me\omega 2 \tag{1}$$

where e (mm) is permissible eccentricity and ω (rad/s) is rotor velocity.

Since such an imbalance increases over the course of operation, the $F(t)$ obtained from Eq. (1) has to be multiplied by a factor which should typically, but not always, be greater than 2 [20].

Dynamic analysis is performed based on the vibration modes of similar structures and the vibrations measured at various fan speeds (e.g. 400, 800, 1200, 1500, and 1800 rpm). According to Eq. (1), the total $F(t)$ caused by fan rotation at all bolts would be respectively 10, 20, 30, 40, and 50 tons for the above-mentioned rotational frequencies. Based on the direction of fan rotation, the concentrated force should be considered tensile at one side and compressive at the other side. The static load exerted on the surface by the weight of the equipment was considered 60 tons.

3. Model explanation and parameters

A three-dimensional (3D) numerical model was developed to investigate the behavior of the concrete foundations of ID fans under combined loading conditions. Finite element programming was performed with Abaqus Unified FEA 6.13 (Dassault Systèmes, France) [21]. The Poisson's ratios of 0.2 and 0.3 and densities of 2400 and 7850 kg/m^3 were entered into the software. Concrete components and steel bars were first generated by the software (based on actual practical details) and then assembled at their appropriate locations. The steel bars were attached and completely embedded in the concrete structure. Since proper meshing of the obtained structural components is critical to the accuracy of the results, a 10-node quadratic tetrahedron (C3D10) mesh and a 3-node quadratic beam in space (B32) mesh were considered for the concrete structure