Engineering Structures 172 (2018) 141–153

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Wind-induced equivalent static interference criteria and its effects on cooling towers with complex arrangements

Lin Zhao, Yanyan Zhan*, Yaojun Ge

State Key Lab of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

ARTICLE INFO

Keywords:
Six-tower combination
Interference effect
Evaluation criteria
Reinforcement envelope
Multiple interference factors

ABSTRACT

Wind-induced interference is a controlling factor in the design of grouped cooling towers. To meet structural safety requirements, interference factor (*IF*) is commonly used to envelope the multiple complex static wind pressure distributions caused by it. However, the parameter turns out to be quite scattered for different evaluation criteria. To compare those criteria and study tower-group interference effects among complex arrangements, cooling tower groups with typical six-tower double-column arrangements were selected to perform wind tunnel tests and FEM calculation. Interference effects among classical rectangular and rhombic combinations were investigated, considering several typical center-to-center distances between towers. Wind pressure under 15 × 16 incoming flow conditions for 1:200 reduced-scale models was measured and corresponding 3-D quasi-static and static calculations were carried out to analyze the *IF*s. Totally, twenty-five kinds of *IF*s were compared based on criteria at three aspects: aerodynamic loading, structure response and reinforcement ratio. Some principal conclusions are synthesized as follows: the values of *IF*s for twenty-five criteria are quite different even for a same tower and their fluctuation under different cases is not the same as well, but those criteria are in accordance with each other in reflecting adverse interference conditions; the unified *IF* widely applied by loading codes cannot economically cover complex spatial wind pressure distributions caused by interference effects; multiple factors changing along the tower shell are recommended as a possible alternative, taking into account convenience, economy and rationality.

1. Introduction

As typical thin-wall structures, large cooling towers are greatly influenced by wind loads due to their mechanical properties such as flexibility and vulnerability. Interference happens when the distance between adjacent towers is within a particular range, strengthening or weakening wind effects. From the perspective of wind load, it changes flow field, making spatial wind pressure distribution more complex and quite different from that of an isolated tower. From the aspect of engineering application, it greatly influences reinforcement quantity for reinforced concrete structures and steel consumption for steel structures, which can be eventually reflected by economy efficiency. The effect cannot be neglected since the majority of cooling towers in China are increasingly high and they are usually arranged in group.

Since the collapse of cooling towers at the Ferrybridge Power Plant, interference effects among grouped buildings have attracted much attention. Wind tunnel tests and field measurements are powerful tools for evaluating the effects. Representative progress in recent decades is shown in Table 1. Previous studies focused mainly on two-, three- and four-tower arrangements, evaluating interference effects through different indexes and from various aspects. Criteria have been developed from wind pressures [19,10,22,23] to structure response, including membrane force [7,15,11], bending moment [14,23], shear force [14] and displacement [10]. In addition, research methods have evolved from rigid model tests that can measure wind pressure to aerodynamic model tests that can investigate structure vibration [13,17,18] and then to Computational Fluid Dynamics (CFD) [24,1]. For convenience in engineering application, *IF* is adopted by codes of many nations to amplify wind pressures without interference [6,4,2,20,5], but its accuracy and justifiability partly depends on criterion selection. To check each other, study results were often compared with relevant specifications in codes [8].

From above review, it can be summarized that there are mainly two problems about *IF*. One is which criterion it should be based on, and the other is which form it should be in. First, numerous criteria have been proposed and applied under particular condition, however, there has been no conclusion about which index is more reasonable and can be applied under more general conditions due to the lack of synthesized

---

* Corresponding author.
E-mail address: zhan_yanyan@126.com (Y. Zhan).

https://doi.org/10.1016/j.engstruct.2018.05.117
Received 8 December 2017; Received in revised form 30 May 2018; Accepted 31 May 2018

Table 1
Typical progress in interference effects among grouped buildings.

Reference	Year	Objects	Comparison criteria
Uematsu [21]	1986	A pair of thin circular cylindrical shells	Buckling pressure
Sun et al. [19]	1995	Two- and four-tower combination	Drag coefficient, lift coefficient, mean pressure distribution
Niemann et al. [7]	1998	Tower groups and adjacent buildings	Maximum tensile meridional force
Orlando [15]	2001	Two towers	Mean meridional force, mean hoop bending moment, maximum hoop and meridional normal stresses
Gu et al. [14]	2010	Groups of buildings with different dimensions	Mean base shear and moment
Zhao et al. [10]	2014	Two- and four-tower combination	Horizontal force coefficient, maximum shell displacement
Uematsu et al. [22]	2014	Open-topped oil storage tanks	Mean internal and external pressure coefficients, buckling loads
Kim et al. [23]	2015	Low-rise buildings	Average, peak and fluctuation of wind pressure coefficient, base bending moment, local wind load
Zhao et al. [11]	2016	Six-tower combination	Local buckling factor, circumference and meridian membrane force and bending moment, construction cost

comparison. Second, the unified *IF* has been introduced into codification twenty years ago when most cooling towers were no more than 165 m high and arrangement of tower group was relatively simple. However, cooling towers under construction and under plan in China are often over 200 m high and their arrangements become increasingly complex, which are far away from the situations twenty years ago. Consequently, it is necessary to compare existing evaluation criteria synthetically and recheck their applicability.

The two mentioned problems are actually what this paper focuses on, whose key points are as follows. Point One is about comparison of interference effect evaluation criteria, which is discussed in Section 4. Through the comparison, it is found out that *IF*s are different and scattered, and criterion of weighted internal force combination (reinforcement ratio) is proposed. It can reflect the contribution of various internal forces and reinforcement is closely related to engineering practice. Point Two is about proper form of *IF*, which is discussed in Section 5. Due to conservatism and uneconomic of the unified *IF*, multiple *IF*s that change along the shell height are proposed as possible alternatives. Advantage and disadvantages of the two forms are compared. Point One and Point Two supplement each other and are linked through the new-recommended evaluation criterion, namely reinforcement ratio.

Typical six-tower arrangements are selected to perform case study. The research can be divided into two steps. First, wind tunnel tests were performed on a rigid model for various cases and wind pressure around the shell surface was measured. Second, finite element analyses were carried out to calculate structure response and shell reinforcement. *IF*s for twenty-five criteria at three aspects were comprehensively compared. Reinforcement envelopes under multiple *IF*s and different unified *IF*s are analyzed and discussed. Interference effects influence average and fluctuating wind pressure simultaneously. However, due to the complexity of the problem, the former was determined as study purpose here and the contribution of the latter was simplified through wind-induced vibration factor β referring to the Chinese loading Codes.

2. Wind tunnel test

A series of wind tunnel tests were carried out on rigid models to investigate spatial wind pressure distribution outside the tower shell. The tests were performed in TJ-3 (an atmosphere boundary layer wind tunnel at Tongji University), whose testing segment is 14 m long × 15 m wide × 2 m high. Flow characteristics of Type B terrain was simulated during the tests. Simulated mean wind velocity profile and turbulence intensity profile are given in Fig. 1. In Fig. 1, U represents average wind speed at the height Z, U_G is average wind speed at a selected reference height Z_G, which was set as 975 mm high from the bottom of tower model; I_Z is a non-dimensional value defined as the ratio of standard deviation of fluctuating wind speed to average wind speed at height Z. As can be seen, mean wind velocity profile and turbulence intensity profile agree well with the loading code [5]. Along-wind velocity spectrum distribution is illustrated in Fig. 2 and is compared with some commonly used ones, where nZ/U is non-dimensional reduced frequency and $nS_u(n)/u_*^2$ is non-dimensional reduced power spectrum density. Due to dimensions of the wind tunnel, turbulence scale was not fully consistent with the geometric scale, but that is permitted in Chinese Code JGJ/T 338-2014.

The prototype cooling tower is 250 m high and its other typical dimensions are shown in Fig. 3(a). Considering both blockage ratio limit and Reynolds number effect simulation, six rigid models with a 1:200 reduced-scale were adopted. Under this condition, max blockage ratio was 6.79%, meeting the requirement of corresponding specification [9]. The model was made of organic glass with enough stiffness to guarantee that wind-induced vibration would be within the permission. As shown in Fig. 3(b), there were 12 × 36 = 432 pressure taps on the external surface of the model, *i.e.* 12 layers along the meridional height and 36 taps arranged evenly around the circumference in every layer. No internal pressure tap was arranged because internal wind pressure is relatively stable, according to previous study [16] and corresponding items from Chinese Loading Codes [6,4]. Reynolds number effect simulation was realized through simultaneous adjustment of paper ribs and testing wind velocity. Thirty-six paper ribs were pasted uniformly around the circumference. They were 12 mm wide and 0.1 mm thick, stretching from shell bottom to top. The Reynolds number effect compensation method can be verified in two aspects, *i.e.* average and fluctuating wind pressure distribution [12].

Interference effects are influenced by many factors, including structure dimensions, incoming flow directions and neighboring buildings. During the tests, group tower arrangement, tower-to-tower distance and wind direction were selected as variables and they were set as follows (see Fig. 4): six towers were in rectangular and rhombic arrangements; the ratio of L (center-to-center distance between adjacent towers) and D (base diameter of the tower) were 1.5, 1.75 and 2.0; and wind direction θ ranged from 0° to 360° in increments of 22.5°. Considering symmetry of tower arrangements, there were only 2 and 3 actually observed towers for every rectangular and rhombic arrangement, respectively. The measured towers were named T1, T2 and T3. Considering different arrangement forms and L/D, the number of measured towers totaled fifteen, and they are summarized in Table 2. Towers located in the left column are taken as examples in following measurement, analyses and discussion.

3. Finite element analysis and evaluation criteria

3.1. FEM modeling

The whole process of modeling and calculation was based on a commercial FEM software and a self-developed software. The two are applied together to perform FEM calculation and reinforcement design. To consider pile-soil interaction, foundations and piles were simulated by equivalent soil springs with 6 dimensions. The tower shell was simulated by an element that has both bending and membrane capabilities and permits both in-plane and normal loads. Bottom-supported