J. Wind Eng. Ind. Aerodyn. 155 (2016) 197–207

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Wind-induced response based optimal design of irregular shaped tall buildings

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form
2 June 2016
Accepted 2 June 2016

Keywords:
Tall buildings
Wind loads
Optimal design
Wind tunnel test
Wind-induced response
Optimality criteria method

ABSTRACT

This study takes sectional dimensions of structural members as basic design variables, total weight as objective function and wind-induced responses as constraint conditions. A mathematical tablmodel for the wind-resistant optimal design of tall buildings with irregular shapes is esished. Based on the Kuhn–Tucker conditions, the Optimality Criteria (OC) method is combined with a recursive algorithm to obtain the optimal solutions of the design variables. Wind tunnel testing results of an L-shaped tall building are used to validate the accuracy and efficiency of the optimal design model. The results of the case study showed that the total weight was decreased by 18.1% and the equivalent static wind loading (ESWL) in across-wind direction was reduced by 9.03% after the design optimization, thus demonstrating the effectiveness of the proposed optimal design method.

1. Introduction

With the increasing application of light-weight and high-strength materials, modern tall buildings tend to be more flexible and sensitive to wind excitations than those in the past. It has been widely accepted that the wind loads and wind-induced responses are the key factors in the structural design of high-rise structures, in particular in regions of high wind speeds. Wind effects on tall buildings are composed of two lateral components (along-wind and across-wind) and torsional moment. The along-wind dynamic responses of tall buildings can be theoretically analyzed by the gust factor approach (Davenport, 1967). On the contrary, it is quite difficult to estimate the wind-induced responses in across-wind direction and torsional moments by analytical approaches, due to their complex mechanisms (Foutch and Safak, 1979; Kareem, 1982; Solari, 1985). Several empirical formulas for estimating the across-wind forces and torsional moments have been proposed based on wind tunnel experimental results (Tamura et al., 1996; Liang et al., 2002, 2004; Liang, 2004; Gu and Quan 2004), although there are various limitations of the existing empirical models.

During the wind-resistant design process of a tall building, structural engineers firstly design the size of each member of the structure in accordance with relevant design codes and based on their engineering experiences. Then, they determine the dynamic properties of the tall building based on its finite element model. For wind-sensitive tall buildings, boundary layer wind tunnel (BLWT) tests are indispensable for evaluation of the wind loads (Cermak, 2003). Based on the overall aerodynamic forces obtained from BLWT tests, the wind-induced responses and the equivalent static wind loads (ESWLs) can be determined in combination with the dynamic properties. The safety and serviceability of tall buildings can be assessed accordingly (Zhou et al., 2003). The ESWLs of tall buildings can be divided into three components: mean, background and resonant components. Both the mean and background components are irrelevant with the dynamic properties of a structure, while the resonant component is closely related to the dynamic properties, especially the fundamental natural frequency. Therefore, the ESWLs of a tall building varying with its dynamic properties and its wind-induced responses depend on its damping, mass and stiffness (Vickery et al., 1983). Thus, it is possible to reduce the wind-induced responses and the ESWL through the optimal wind-resistant design such as adjustments of the cross-sectional sizes of structural members (equivalent to changing of structural dynamics properties) or taking the aerodynamic measures.

The majority of previous research works on the optimal wind-resistant design of high-rise structures have been focused on rectangular-shaped tall buildings (Chan et al., 1995, 2009; Chan, 2001; Chan and Chui, 2006; Huang et al., 2011; Li et al., 2011b). To

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http://dx.doi.org/10.1016/j.jweia.2016.06.001
0167-6105/

the best knowledge of the authors, there is still lacking of the wind-resistant optimal design method for tall buildings with irregular shapes. In recent years, numerous tall buildings with irregular and unconventional shapes have been built throughout the world. Therefore, there is a need to conduct more research works on this topic. In this paper, a mathematical model for the wind-resistant optimal design of tall buildings is firstly proposed. The model considers the sectional dimensions of structural elements as the basic design variables, the total weight as the objective function and the wind-induced responses as the constraint conditions. The optimal criterion (OC) method is adopted by using the Kuhn–Tucker condition. Then, the efficiency of the proposed optimal design method is demonstrated based on wind tunnel testing results of an L-shaped tall building.

2. Wind-induced responses based optimal design

Since many uncertain factors exist in the wind-resistant optimal design of tall buildings, it is difficult to establish a proper mathematical model of the design optimization when considering all the uncertainties (Chan et al., 2009). In this paper, only the sizes of structural members are considered in the optimization process.

2.1. Design variables

Rectangular cross section is usually employed for beams, columns and shear walls in engineering practice. Figs. 1 and 2 show the coordinate systems and internal forces of beams (columns) and shear walls, respectively. The natural frequency of a tall building can be determined with the total weight and stiffness of all the structural members. When neglecting the effects of reinforcements in concrete members, the weight and stiffness of beams, columns and shear walls can be determined from their dimensions. Therefore, the depth h, breath b of the beams (columns) and the thickness t of the shear walls are chosen as the basic independent design variables for the optimal design.

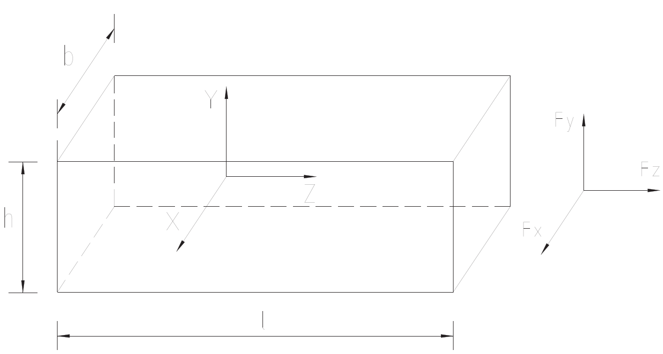

Fig. 1. Coordinate system and definition of internal forces of beams (columns).

The sectional properties of beams (columns) including A, A_X, A_Y, I_X, I_Y and I_Z can be calculated by the design variables as follows.

$$A = bh \quad A_X = A_Y = \frac{5}{6}bh \tag{1}$$

$$I_X = \frac{1}{12}bh^3 \quad I_Y = \frac{1}{12}hb^3 \quad I_Z = \beta h^3 b \tag{2}$$

where, A is the cross-section area; A_X, A_Y are shear areas in X and Y directions, respectively; I_X, I_Y, I_Z are the flexural and torsional moments of inertia of each member. β is the torque coefficient and it is approximately equal to 0.2 for typical rectangular sections and 0.3 for thin wall sections (Chan et al., 2001) .

2.2. Objective function

The aim of the optimal design is called as the objective function. The total cost or total weight is usually taken as the objective function of structural optimization. The total cost of a building is related to the cost of each member. Since the material price is quite different in various areas and may not be determined directly, the total weight of a tall building is selected as the objective function in this study. Considering an M-floor reinforced concrete tall building with a given geometry, it has N_l kinds of beams (columns) and N_w kinds of shear walls. The number of the ith beams (columns) is K_{i1} while the number of the jth shear walls is K_{j1}. The objective function with basic independent design variables can be expressed below:

$$W = \sum_{i=1}^{N_l} (w_{i_l} b_i h_i) + \sum_{j=1}^{N_w} (w_{j_w} t_j) \tag{3}$$

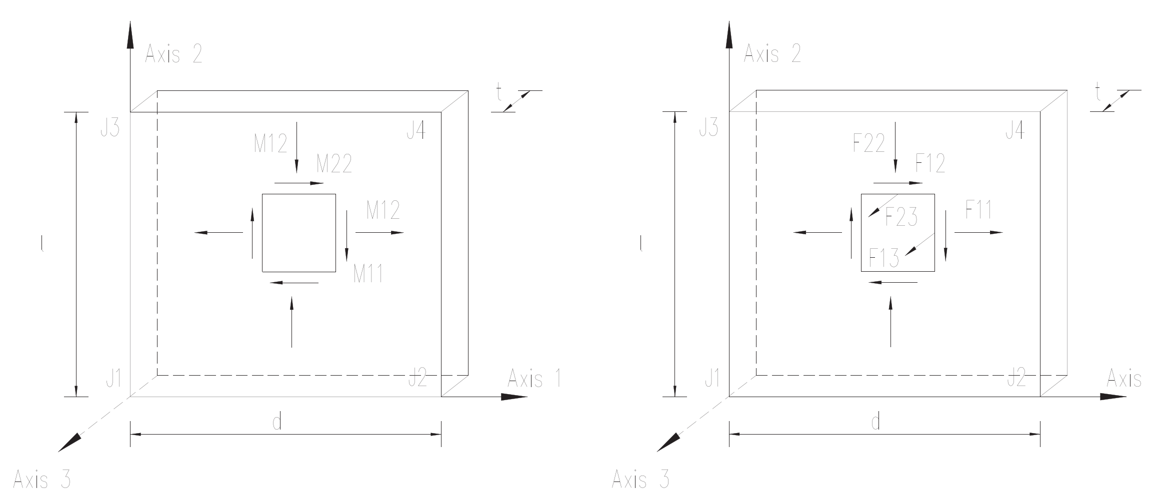

Fig. 2. Coordinate system and definition of internal force of shear walls (a) bending moment and twisting moment (b) plane force.