

# Wind-resistant structural optimization of a mixed steel and concrete supertall building

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**Abstract.** Wind load is a type of the controlling horizontal loads for the structural design of mixed steel and concrete supertall buildings. Performance-based wind resistant structural optimization can effectively reduce the material cost of supertall buildings in the premise of ensuring the structural safety and serviceability. Most of investigations in this area are concerned with relatively simple structural systems and use the optimal criterion (OC) method to perform the wind-resistant structural optimization. For actual supertall buildings with complex structural systems, the structural optimization problem is much complicated in formulation, and the conventionally-used OC method is difficult to converge stably to the global optimal solution to such a large scale nonlinear optimization problem. This study presents a new framework for wind-resistant structural optimization of supertall buildings with complex structural systems. Firstly, the optimization problem is formulated by taking various types of frame members and area members into account, especially the concrete filled steel tube (CFST) column and the shear wall which are often used in supertall buildings but have seldom been discussed in the current optimization studies. Secondly, the interior point algorithm, which is propitious to large scale nonlinear optimization, is used to seek the optimal design solution. An actual supertall building with a height of 432 m, the Guangzhou West Tower, is taken as an example to examine the effectiveness of the proposed framework. It is shown that the proposed method can work effectively in the wind-resistant structural optimal design for supertall buildings with complex structural systems.

**Keywords:** structural optimization; wind effect; complex structural system; tall building

## 1. Introduction

With the advances of design and construction techniques, more and more mixed steel and concrete supertall buildings are under construction or planned to be built throughout the world. Supertall buildings are usually sensitive to wind excitations, and for those located in the region affected by strong typhoons, wind load usually becomes the dominant horizontal load for the structural design of supertall buildings (Bandi *et al.* 2013, Xu *et al.* 2014a,b, Xu *et al.* 2015a,b).

There are several major ways available to enhance the wind-resistant performance and reduce the constructional cost of a supertall building, including some aerodynamic measures (Bandi *et al.* 2013, Zhang *et al.* 2008), the vibration control method, and the performance-based structural design optimization (Beck *et al.* 2014, Chan and Chui 2006, Chan *et al.* 2009, Chan *et al.* 2010). The aerodynamic measure is conventionally performed by changing the global or local design of a building to reduce the aerodynamic wind load and the consequent structural response (Kawai 1998). Sometimes this treatment is

difficult to be endorsed by the architects and the owner of the building. The vibration control method usually adds a damper system, for example a tuned mass damper or a tuned liquid damper, to the structure to reduce the wind induced response, at the expense of extra cost of building and maintaining the damper system. The structural optimization method doesn't need to change the shape of the building or the basic structural system, but only adjusts the cross-sectional sizes of frame members and thicknesses of area members to make the structure more efficient to resist external loads (Huang *et al.* 2011a,b, Huang *et al.* 2012, 2015, Chan and Chui 2006, Chan *et al.* 2010). Without any extra expense and changes of architectural design, the approach of structural optimization is more acceptable by architects and structural engineers than the first two methods.

Performance-based structural optimal design has been widely studied throughout the world for decades. Some researchers conducted systematic studies on the optimal seismic performance-based designs of reinforced concrete high-rise buildings and tall steel structures (Chan 2001, Zou and Chan 2005, Zou *et al.* 2007, Xu *et al.* 2017a,b, Kang and Zong 2004, Kaveh 2002, Gong *et al.* 2006, Fragiadakis and Lagaros 2011, Liu *et al.* 2005). In these studies, the basic procedure was established and some key methodologies, such as the methods to explicitly formulate the constraints and seek the solution to the optimal design problem, were developed. The methods were widely adopted in the subsequent research and applications of

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structural optimization and were extended to the wind-resistant optimal design of supertall buildings.

Compared to the structural optimal design problem of conventional tall buildings or structures, the wind-resistant optimal design of supertall buildings is facing some new challenges. Firstly, wind load is a kind of random load that distributes randomly on buildings and structures in both time and space, generating not only the bearing capacity problem but also the serviceability problem (conventionally associated with the acceleration response atop a certain building). Besides, wind load has directional effects depending on the wind climate of the building site (Xu *et al.* 2014b). To some degree, wind load is more complicated than the seismic load. Secondly, modern supertall buildings usually have much more complicated structural systems which are much more complicated than the conventional or hypothetical buildings and structures such as reported in the literature (Li and Hu 2014, Spence and Giofrè 2012). A real supertall building usually consists of a huge number of frame and area members as well as the element types. On one side, some nonrectangular cross-sectional frame members such as concrete-filled steel circular tube (CFST) are widely used in the construction of supertall buildings. The optimal design of a structure with various types of members requires all constraints being explicitly formulated, but most of the current studies involved only rectangular cross-sectional members (Zou and Chan 2005, Zou *et al.* 2007, Huang *et al.* 2015, Chan *et al.* 2010), and relevant formulations for nonrectangular cross-sectional members have rarely been reported. On the other hand, for most cases with relatively simple structural systems, the optimality criteria (OC) method can converge rapidly and stably. Therefore, the OC method is widely used to seek the optimal solution in the current optimization research. However, previous studies by the authors show that for actual supertall buildings with much more element types and numbers, the OC method would sometimes fail to converge to an optimal solution (Xu *et al.* 2016), indicating that the OC method may be unsuitable for solving large scale nonlinear optimization problems. It's necessary to adopt a suitable algorithm to seek the solution to such a large scale nonlinear optimization problem.

In this study, the explicit objective function and the constraint functions for mixed steel and concrete super-tall buildings with various types of structural elements, are derived. An interior point algorithm, which is suitable for large scale nonlinear programming, is then employed to seek the solution of the optimization problem. The Guangzhou West Tower, an actual supertall building with a complex frame-core tube structural system, is taken as the example to show the effectiveness of the deduced formulae and the whole

optimization strategy in this study.

## 2. Methodology

For a deterministic algorithm of optimal design, all objective functions and constraint functions must be explicitly formulated before the optimal iteration computation can be performed. An actual supertall building with a complex structural system usually consists of various types of area and frame members, making the explicit formulation more difficult than simple structures.

### 2.1 Explicit formulation of the objective function

Conventionally, the objective of optimal design is to minimize the total material cost of a building or structure in the premise of guaranteeing its safety and serviceability, which can be formulated as

Minimize

$$C = \sum_i c_i A_i L_i + \sum_j c_j A_j t_{shj} \quad (1)$$

subject to

$$u_{top} \leq u_{top}^U \quad (2)$$

$$\Delta u_i / \Delta H_i \leq \delta^U \quad (1, 2, \dots, n) \quad (3)$$

$$a_{top} \leq a_{top}^U \quad (4)$$

$$x_i^L \leq x_i \leq x_i^U \quad (5)$$

where  $C$  is the total material cost of the building;  $c_i$  and  $c_j$  are the unit material costs for the  $i$ th frame member and  $j$ th area member, respectively;  $A_i$  and  $L_i$  are the cross-sectional area and length of the  $i$ th frame member, respectively;  $A_j$  and  $t_{shj}$  are the area and thickness of the  $j$ th area member, respectively;  $u_{top}$  and  $a_{top}$  are the peak wind-induced displacement and acceleration response with  $u_{top}^U$  and  $a_{top}^U$  being their upper bounds;  $\Delta u_i$  and  $\Delta H_i$  are the interstory lateral drift and level height between the  $i$ th and  $(i-1)$ th floor, respectively; and  $\delta^U$  is the maximum tolerated lateral drift angle which is determined by codes or standards.

The total material cost of a building is the sum of the material cost of all the structural members. Considering a structure with various cross-sectional types of frame members as shown in Figs. 1 (a-e), and shear wall members as shown in Fig. 1 (f), the material cost for each frame member can be written with the design variables as

$$c_i A_i L_i = \begin{cases} \left( c_{si} (\pi D_i^2 v_i (1 - v_i)) + c_{ci} \left( \frac{\pi D_i^2}{4} (1 - 2v_i)^2 \right) \right) L_i & \text{for CFST element} \\ c_i B_i H_i L_i & \text{for rectangular cross-section} \\ c_i (h_{fi} t_{wi} + 2(b_{fi} - t_{wi}) t_{fi}) L_i & \text{for I-section cross-section} \\ c_i (2H_{bi} t_{wbi} + (B_{bi} - 2t_{wbi}) t_{fbi}) L_i & \text{for box section} \\ c_i (0.25\pi D_{ci}^2) L_i & \text{for circular section} \end{cases} \quad (6)$$