Computer Based Optimization for Serviceability Design of Tall Steel Buildings

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Abstract: A computer based optimization technique and an aerodynamic wind tunnel load analysis routine based on the High Frequency Force Balance (HFFB) method have been coupled together to estimate the wind-induced acceleration, derive and update the equivalent static wind loads, and minimize the cost of the structures subjected to both the story drift and occupant comfort serviceability design constraints. The effectiveness of the proposed integration of an aerodynamic wind tunnel load analysis routine and numerical design optimization procedure is demonstrated through a full-scale 45-story symmetric tubular steel building example.

INTRODUCTION

The trend of increasingly slender and taller wind-sensitive buildings has led to serious concerns on the serviceability design problems, in terms of occupant comfort and lateral wind drift. While the advances in wind tunnel techniques have provided a satisfactory evaluation of the wind effects on tall buildings, there is still a lack of an effective optimization design tool for the serviceability design of tall buildings against wind excitation. In this study, occupant comfort has been shown to be effectively controlled through a computer based optimization technique in which the most optimal distribution of structural material is sought while stiffening the structure to a set of predetermined frequency targets, derived in accordance with the ISO Standard 6897 occupant comfort criteria [ISO 1984]. In addition, recognizing the fact that the equivalent static wind loads are a function of the dynamic properties of the structure, the static design wind loads for the example building will be automatically updated from the measured aerodynamic wind load spectra based on random vibration theory. Results indicate that not only is the optimization method able to produce the cost effective element stiffness distribution of tall building structures satisfying both the serviceability wind drift and acceleration design criteria, but a potential benefit of reducing the equivalent static wind loads can also be achieved by the stiffness optimization procedure.

DESIGN PROBLEM FORMULATION

Consider a 45-story tubular rectangular steel framework with the same geometry as the CAARC building model [Melbourne (1980)] having $i=1,2,\ldots,N$ members as shown in Fig.1.

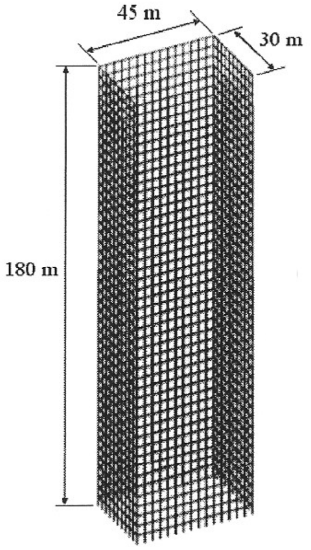

Figure 1: 45-story steel example building

The design optimization problem to minimize the structural cost of the steel framework subject to multiple natural frequency and story drift constraints can be stated as:

$$\text{Minimize } W\left(a_i\right) = \sum_{i=1}^{N} w_i a_i \qquad \text{(1a)}$$

subject to

$$n_j^L \le n_j \qquad (j = 1,2,...,L) \qquad \text{(1b)}$$
$$d_k \le d_k^U \qquad (k = 1,2,...,M) \qquad \text{(1c)}$$
$$a_i^L \le a_i \le a_i^U \qquad (i = 1,2,...,N) \qquad \text{(1d)}$$

where a_i is the cross-sectional area of member i; w_i is the cost coefficient associated with the member; a_i^L and a_i^U define the respective upper and lower members size in equation (1d). Equation (1b) defines the set of $j=1,2,..,L$ frequency constraints in which the current j-th modal frequency, n_j, of the building is required to be greater than its specified minimum targeted frequency, n_j^L to satisfy the stipulated occupant comfort criteria. Equation (1c) defines the k-th storey drift constraints.

OCCUPANT COMFORT DESIGN

A series of alongwind and crosswind load spectra for rectangular buildings of various height and depth-to-width ratios can be obtained from the aerodynamic load database of the NatHaz Modeling Laboratory at the URL address: http://www.nd.edu/~nathaz/database [Zhou et al (2003)]. As shown in Fig.3, the power spectral density of aerodynamic wind load attenuates rapidly with increasing frequency within the range of reduced frequency (*nB/V_H*) generally from 0.1 to 1.0 for serviceability checks. Within this range of reduced frequency, the load spectra can be approximated as a reciprocal exponential function of natural frequency. Assuming a building density of 125 kg/m^3, a damping ratio of 1% and a 5-year return period hourly mean design wind speed, V_H, of 25 m/s at the top of the building, the standard deviation of acceleration response can then be obtained by random vibration theory from the measured wind load spectra explicitly expressed in terms of frequency via regression analysis.

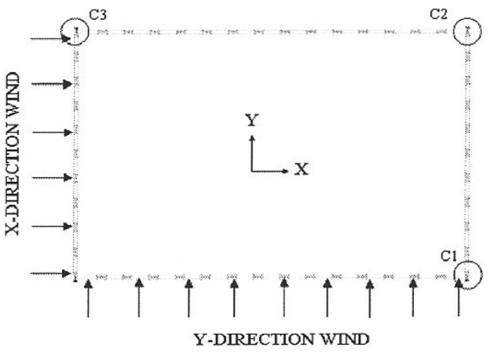

Figure 2: Plan view of the example

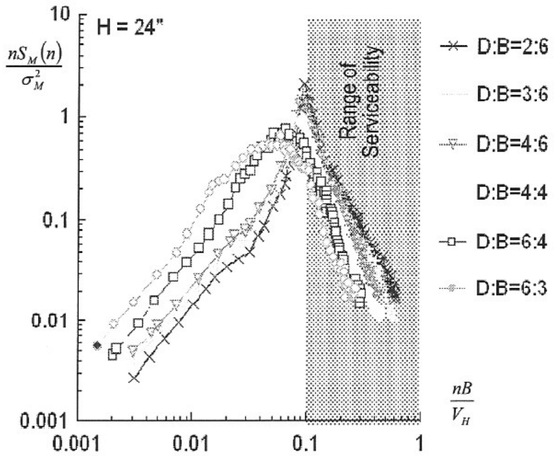

Figure 3: Typical crosswind force spectra

For wind along the X axis (B = 30m),
alongwind standard deviation acceleration:

$$\ddot{\sigma}_{ax} = 10.075 \times 10^{-3} n_x^{-0.682} \qquad \text{(2a)}$$

crosswind standard deviation acceleration:

$$\ddot{\sigma}_{ay} = 4.364 \times 10^{-3} n_y^{-1.513} \qquad \text{(2b)}$$

For wind along the Y axis (B = 45m),
alongwind standard deviation acceleration:

$$\ddot{\sigma}_{ay} = 5.107 \times 10^{-3} n_y^{-1.420} \qquad \text{(3a)}$$

crosswind standard deviation acceleration:

$$\ddot{\sigma}_{ax} = 8.040 \times 10^{-3} n_x^{-1.000} \qquad \text{(3b)}$$

When comparing Equations (2) and (3) with the following occupant comfort criteria stipulated by the ISO Standard 6897,

$$\ddot{\sigma}_a = \exp(-3.65 - 0.41\ln n) \qquad (4)$$

the targeted frequency should be 0.199 Hz along the Y axis and 0.200 Hz along X-direction. Once the targeted frequencies of the structure are obtained, the Optimality Criteria technique developed by Chan (1997) can then be utilized to optimally re-distribute the element stiffness of the buildings to satisfy the set of targeted frequencies.

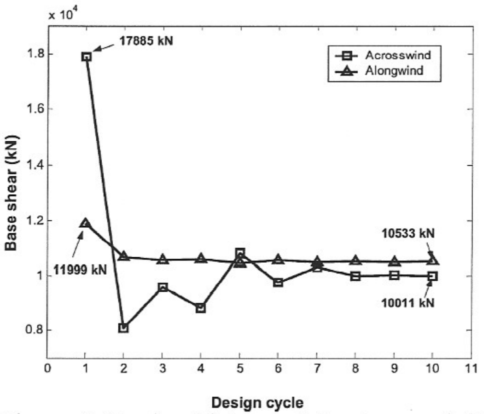

Figure 4: Design history of structure weight

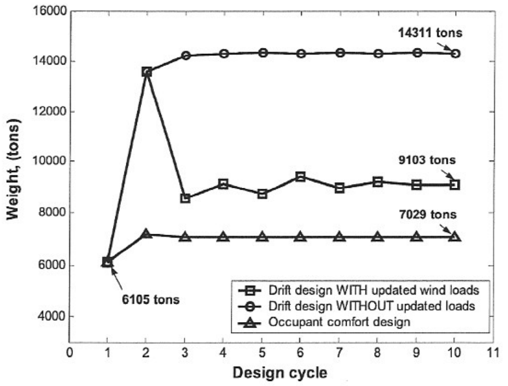

Figure 5: Design history of base shear

Results and discussions

The total steel tonnage required for the optimized structure is increased from 6105 tons to 7029 tons. Compared with the result of 10890 tons calculated based on the conventional simple scaling method, when the first mode frequency of the initial strength-based designed structure is increased from 0.149 Hz to the targeted minimum frequency threshold of 0.199 Hz, the proposed optimization design method has achieved a significant savings of about 34.9% in the structural steel quantity. Upon reaching the set of targeted frequencies, the crosswind standard deviation acceleration of the optimized structure under both wind load cases has been reduced to an acceptable level as shown in Table 1, in which up to 35.5% reduction in the crosswind standard deviation acceleration can be achieved.

Table 1:Standard deviation acceleration of the example(m/s^2)

Before optimization				
	X-direction wind		**Y-direction wind**	
	Alongwind	**Crosswind**	**Alongwind**	**Crosswind**
RMS Acceleration	0.0313	0.0778	0.0549	0.0538
ISO Standard 6897	0.0513	0.0567	0.0567	0.0513
After optimization				
	X-direction wind		**Y-direction wind**	
	Alongwind	**Crosswind**	**Alongwind**	**Crosswind**
RMS Acceleration	0.0302	0.0502	0.0404	0.0502
ISO Standard 6897	0.0503	0.0504	0.0504	0.0503

WIND LOADS UPDATING AND WIND DRIFT DESIGN

For the wind drift design of the example framework, a 50-year return period wind speed of 41 m/s at the top of the building is considered. A typical interstorey drift limit of 1/400 is imposed at the three critical corner columns of the building (as shown in Fig. 2) under the equivalent static alongwind, crosswind and torsional wind loads derived from the measured wind load spectra.

Results and discussions

The alongwind, crosswind and torsional equivalent static wind loads are updated when the frequencies of the building in the respective directions are modified. The optimized structure weight with updated wind loads is compared with that without updated wind loads, the result of the design history of the structure weight is shown in Fig.4. A reduction of 36.4% in the structural weight is found while a 43.6% reduction in the crosswind base shear is shown in Fig.5. It is found that the conventional structural optimization based on a given fixed set of derived wind tunnel loads may lead to conservative design since the reduction of these loads due to the increase in the building stiffness is generally not explicitly taken into account in the design synthesis process.

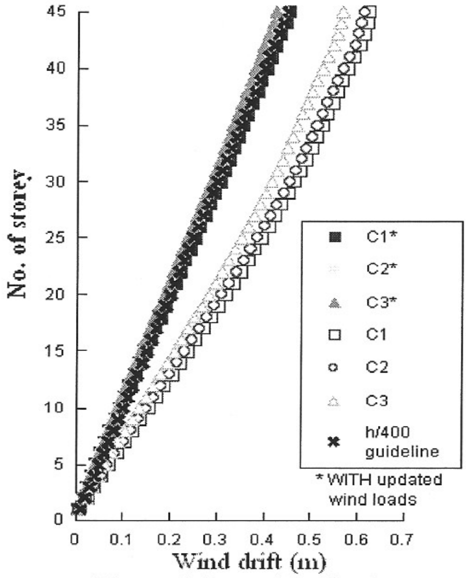

Figure 6: Lateral Deflection

CONCLUDING REMARKS

This paper proposed an integration of an aerodynamic wind tunnel load analysis routine, based on the high frequency force balance method, and an optimal resizing technique for element stiffness design of tall steel building structures subject to occupant comfort and lateral wind drift serviceability design criteria. Wind-induced vibrations have been successfully controlled by optimally resizing the structural elements to appropriately stiffen the building structure to meet a set of targeted frequencies derived in accordance with the motion perception design criteria of ISO Standard 6897. Updating the equivalent static design wind loads during the process of stiffness optimization allows for significant reduction in the wind loads received by the structures, resulting in further savings in the total steel tonnage required. Encouraging results are found in the serviceability design of the full-scale 45-story symmetric tubular steel building framework with uncoupled wind-induced motions. Rapid convergence to the optimal element stiffness design of tall building structures is generally achieved in a few design cycles. It is envisaged that the methodology developed can be further extended to the design optimization of asymmetric tall building structures with complex mode shapes.

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