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New Approaches of Supertall Building Design for Wind Effects

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Abstract

To optimize supertall buildings for wind effects, two new design approaches are proposed in this paper. The first approach, called wind-adaptable design (WAD), is to use operable scheme to optimize building's aerodynamic shape when needed, instead of permanently changing a building's geometry. The second approach, called modal interference approach (MIA) is to reduce across-wind building motions by utilizing multi-mode interference effects through the optimization of structural layout. The effectiveness of both approaches has been validated by wind tunnel tests on a typical square building.

Introduction

Excessive across-wind response is the major challenge that engineers commonly encountered in super-tall building designs. Therefore, designers and researchers gave great attentions on design optimizations in the past, which included aerodynamic approaches by optimizing building's geometry and structural approaches by optimizing building's structural system. While both approaches have been rewarded with some success stories, challenges still remain in the engineering practice.

For aerodynamic optimizations, the main drawbacks are the inherent conflicts with architectural designs [1]. Potential increase of construction costs and loss of usable spaces are also the issues. Only few supertalls were architecturally designed by taking aerodynamic aspects as a major objective in their preliminary design stage. Most supertalls were undergone aerodynamic mitigations in the later design stage when excessive across-wind responses detected.

For structural optimizations, the conventional approach is by strengthening the structural stiffness at the cost of increased project expense. In the last 15 years, supplemental damping system has gained attentions in building design communities as an optional structural solution for wind effects [2,3]. However, this approach has been used mainly to improve building's serviceability. The issues with the damping approach are both the costs and the available spaces, especially for mass dampers which require significant space at upper floors to accommodate the damper systems.

Therefore, the optimization of super-tall buildings for wind effects remains to be a demanding and interesting topic in wind engineering researches. In this paper, two new approaches are proposed, one is aiming at the aerodynamic optimization and the other one is focusing on structural optimization. In comparison with the current available methods, the proposed approaches have great benefit in terms of project costs.

Wind-adaptable Design (WAD)

Concept

The conventional wind-resistant design (WRD) is based on the same concept as for seismic loads: to design a structure with sufficient capacity against extreme natural disasters. Practically this is to consider an extreme wind event with very small probability of occurrence, such as 2% or 1% probability of annual occurrence (i.e., a 50-year or 100-year return period). In other words, the current method is to take a very rare event as design objective and pursues with "maintaining the status quo" approach to design a building for daily use.

This conventional design concept is reasonable in dealing with unpredictable disasters, such as earthquakes. However, for predictable disasters such as severe winds, the design method based on this concept seems not cost effective. As the current technology allows severe wind storms, such as hurricanes, being reliably forecasted at least several days in advance, it becomes feasible to design a building in a more resourceful way for extreme circumstances.

The proposed method is to make use of weather forecast information and to design a building that can adjust its aerodynamic shape when needed to adapt severe wind conditions. In most time with common winds, the building maintains its basic shape which is not necessarily to be aerodynamically optimized, because the structure is required only to handle moderate winds. When a severe storm is forecasted, the building can be transformed from its basic shape to an aerodynamically optimized shape by launching flow control devices over the building's facade.

Since the proposed design concept is to put emphasis on building's adaptability to winds rather than on resistance to winds, the authors refer the proposed method as "wind-adaptable design (WAD)", to conceptually distinguish it from the conventional wind-resistant design method. In application, the main difference of WAD from the conventional design is to involve a two-stage design procedure, as conceptually illustrated by figure 1.

In figure 1, the abbreviation "OPFC" stands for Operable Passive Flow Control which is used to aerodynamically modify the basic building shape during extreme winds. Most approved aerodynamic solutions, such as corner recessions, chamfering, and upper openings [4], can find their operable counterparts. Trigger speed is the reference wind speed at which the OPFC devices should be launched into service from their tucked positions. To have allowance for the uncertainties that may exist in weather forecast and fairing operation, the return period corresponding to the trigger speed should be shorter than that of the common speed.

The Stage 1 of WAD actually represents a typical procedure of the conventional wind resistant design (WRD). The deviation between WAD and WRD starts after the checkpoint "*whether the actual wind loads are similar to those considered in the preliminary design*". If the results are "*No*", particularly in case of much higher, the WRD would require re-design of the structure. With WAD, however, the designers may accept the structure as it is and determine the reference wind speed corresponding to the assumed wind loads during preliminary design. This wind speed is then defined as "common wind", not rigorous from meteorological point of view but practically convenient because it is lower than the standard design wind speed such as of 100-year return period (named "extreme wind"). The insufficiency of the structure to meet the requirements for extreme winds is then compensated by the use of OPFC devices that reduce the wind loads through the improvement of the building's aerodynamic properties. The development of effective OPFC therefore becomes the key component in Stage 2 of WAD.

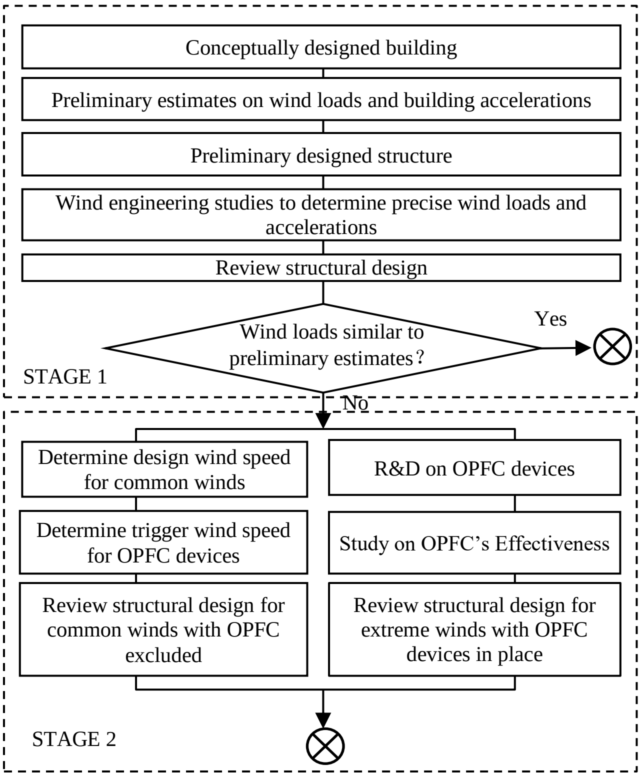


Figure 1. Procedure flow chart with wind-adaptable design (WAD)

Feasibility Study of Wind Fairings as OPFC

A set of wind tunnel tests and CFD simulations were conducted to investigate wind fairings for the potential OPFC devices [5]. By installing wind fairings along the building corners, it was expected that similar reductions on wind response could be achieved as corner chamfering. Comparing to the wind fairings commonly used for bridges, the applicable wind fairings for building's WAD have to meet the following special requirements:

a) Operable: With wind-adaptable design, wind fairings installed on a building have to be visually hidden during common wind conditions and be launched to service position during extreme winds. In comparison, wind fairings for bridges are normally designed as part of deck section

b) Omnidirectional: While wind fairings of bridges are mainly designed for horizontal winds, the wind fairings of buildings have to be effective for omnidirectional winds.

After selection process, the scheme of wind fairing shown in figure 2 was shortlisted as one of the candidates.

With the wind fairings in place, the flow separation was found remarkably weakened in comparison with a typical square section, as shown in figure 3. This was also observed with flow visualization tests in wind tunnel. From practical point of view, the wind fairings were only installed on the upper one-third height of the model, shown in figure 2.

Further studies were conducted by using high frequency force balance (HFFB) model to optimize the dimensions of the fairing.

Taking into account of both effectiveness and operability, the optimal fairing dimensions were recommended to have fairing width $b/B \approx 1/10$; fairing height $h/B \approx 1/5$; and fairing angle $\theta \approx 45^o$.

Wind fairings are considered to have potential to become prefabricated building elements so that the associated costs in application could be significantly reduced.

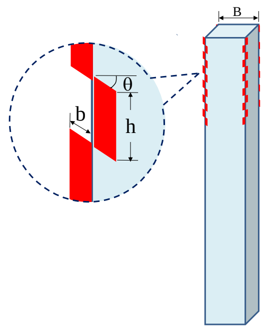
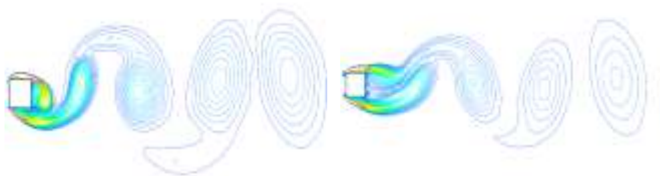


Figure 2. Wind fairings used as OPFC devices



a) square section without fairings b) square section with fairings

Figure 3. Effects of wind fairings observed in CFD simulations

Case Study of WAD

To illustrate the application of the proposed WAD, a typical square building was considered. The key parameters of the building are given below.

Height	270m	Width	45m×45m
Fundamental frequency	0.13Hz	Mode shape	$(z/H)^{1.5}$
Damping ratio	1.5%	Wind exposure	Typical urban

Table 1. Key parameters of the study building

A 1:300 scale HFFB model was tested with and without the proposed wind fairings. The fundamental frequency of the HFFB assembly was higher than 40 Hz which met the high frequency requirement. With wind tunnel test speed of 8.5 m/s, measurement duration of 90 seconds and sampling rate of 300 Hz, about one-hour time history of wind loading at full scale was recorded for analysis.

The analysis results indicated that the structural design wind loads were dominated by across-wind response, shown in figure 4. Since across-wind response was more sensitive to wind speed in comparison with along-wind, a big increase on across-wind loads were observed at 90° and 270° when wind speed increased from 20-years to 100 years.

Based on WAD, instead of designing the structural system for 100-year winds, we could consider the use of operable wind fairings to lessen the requirements on structural system during extreme winds.

The across-wind loading spectra of the building with and without wind fairings are given in figure 5. The spectra were measured at the wind direction normal to the building façade and normalized by reference wind pressures. It can be seen that the effectiveness of the wind fairing varies with the reduced frequency *fB/U*. In general, more severe are the across-wind loads, more effective the wind fairings would be. This is similar to what we observed on conventional approaches such as corner recession and corner chamfering.

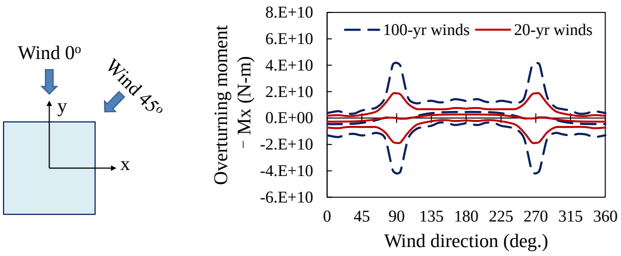


Figure 4. Base overturning moments on the study building without wind fairings

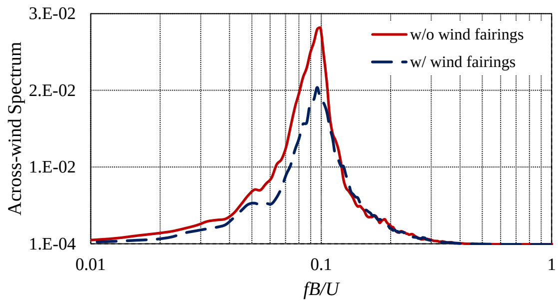


Figure 5. Comparison of across-wind loading spectra

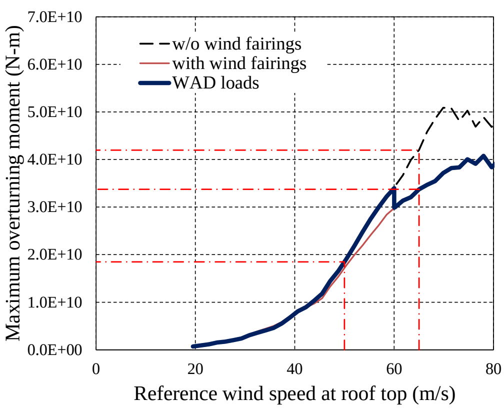


Figure 6. Illustration of design wind loads with WAD

The final design wind loads with WAD are illustrated by figure 6.

With conventional WRD, the structure needs to be designed for 4.20×10^{10}N-m at 100-year winds (i.e., at 65m/s). However, with proposed WAD, the structure can be designed for 3.37×10^{10}N-m by setting the trigger speed of launching wind fairings at 20-year winds of 50m/s. Since the wind speed corresponding to the load of 3.37×10^{10}N-m on the basic building (i.e., without wind fairings) is about 60m/s, the difference between the 60m/s and the trigger speed of 50m/s is served as the safety buffer for uncertainty that may contain in weather forecast and fairing operation.

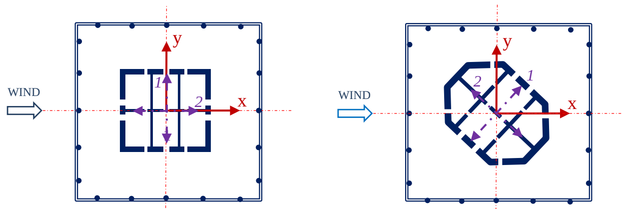
The most important advantage of WAD is to separate the architectural design and the aerodynamic design into two detached stages: common wind stage and extreme wind stage, thereby avoiding the inherent conflicts between architectural prerequisites and aerodynamic requirements. While the proposed wind fairings offer promising effectiveness, WAD is readily incorporated with many other flow control schemes.

Modal Interference Approach (MIA)

Concept

Structural systems of tall buildings are often conventionally designed in such a way that the structural directionality is coincident with the building directionality. Figure 7a shows a typical example. In this example, the most susceptible building directions for vortex shedding are along the *x*-axis and along the *y*-axis. Given the layout of the structural system, the two fundamental sway modes are also along the *x*-axis and *y*-axis. Therefore, when approaching winds are along the *x* direction and cause periodical vortex shedding forces in *y* direction, only the Mode 1, the sway mode in y-direction, will be excited which could potentially lead to an excessive motion.

The concept of modal interference approach (MIA) is to promote more-than-one modes to share the vortex shedding forces by stimulating modal coupling effects, so that a more complex building motion will occur which disturbs or suppresses the vortex-induced oscillations. Modal interference effects can be introduced in structural design by making the structural directionality deviate from the building directionality. Figure 7b shows a relatively straightforward scheme based on this concept. By rotating the centre core by 45°, both Mode 1 and Mode 2 will participate in the vortex-induced oscillations.



a) conventionally designed system b) structural system based on MIA

Figure 7. Conventionally designed structural system vs. modified structural system based on MIA

Analytical Description of MIA

For comparison, the variance of modal acceleration for the conventional system shown in figure 7a can be approximately expressed by

$$\sigma_{a_1}^2 = \frac{(q_r BH)^2}{M^2}\left(\int_0^\infty (f/f_1)^4 S_P^*(f)\,df + \frac{\pi f_1}{4\zeta} S_P^*(f_1)\right) \qquad (1)$$

where M=generalized mass; q_r=reference wind pressure; B=typical building width; H=building height; ζ=damping ratio; f_1=natural frequency of Mode 1; and S_p^*=normalized spectrum density of the generalized force. The first term in equation (1) represents the background contribution while the second term is the resonance. For across-wind response, the resonant component is normally dominant.

For the system of MIA shown in figure 7b, the variances of modal accelerations for both Mode 1 and Mode 2 can be calculated based on the component wind loads along the sway directions of Mode 1 and Mode 2, respectively.

The resultant acceleration caused by both modes can be expressed by

$$\sigma_R^2 = \sigma_{a_1}^2 \cos^2\varphi + \sigma_{a_2}^2 \sin^2\varphi + 2\sigma_{a_1}\sigma_{a_2}\rho_{12}\cos\varphi\sin\varphi \qquad (2)$$

where φ= the angle between the modal direction and the direction of the maximum resultant. ρ_{12} is the modal correlation factor between Mode 1 and Mode 2, ρ_{12}=0 if uncorrelated and ρ_{12}=1 if fully correlated. The authors have developed a method, CS method, to precisely estimate the modal correlation factor for wind-induced motions [6].

It can be proved that the background accelerations between the two structural systems remain almost the same if the corresponding frequencies between two systems are similar. However, the resonant components would be different depending on the cross-modal correlations. If the structure is such designed that not only the structural directionality deviates from the building directionality (such as the system shown in figure 7b) but also the modal frequencies are well separated from each other so that ρ_{12}=0, the maximum acceleration of MIA system (shown in figure 7b) can be smaller than that of conventional system of figure 7a.

Effectiveness of MIA

For effectiveness study, we considered two cases: Case 1 has the structural system similar to figure 7a with two sway frequencies being the same, denoted by f_a. Case 2 has the structural system similar to figure 7b with rotation angle of 45º and two well-separated sway frequencies of f_{b1} and f_{b2}.

Scenario 1: $f_{b1} = f_a$ and $f_{b2} > f_a$

This represents the structural optimization using MIA in combination with increased stiffness in Mode 2 direction. The RMS ratio (root-mean-square) of the resultant acceleration between Case 2 and Case 1 is given by

$$Ratio = \frac{\sigma_R(Case2)}{\sigma_a(Case1)} = 0.5\sqrt{1+\frac{f_{b2}S_P^*(f_{b2})}{f_{b1}S_P^*(f_{b1})}} \quad (3)$$

In most practical cases, the spectrum value decreases or keeps the same with the increase of frequency within the frequency range of interest. Therefore the ratio in equation (3) is less than 0.707.

Scenario 2: $f_{b1} < f_a$ and $f_{b2} = f_a$

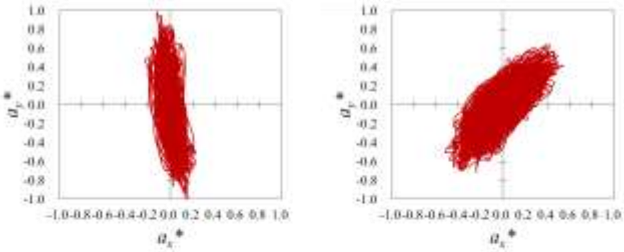
This represents the structural optimization using MIA in combination with decreased stiffness in one direction. The RMS ratio is given by

$$Ratio = \frac{\sigma_R(Case2)}{\sigma_a(Case1)} = 0.5\sqrt{1+\frac{f_{b1}S_P^*(f_{b1})}{f_{b2}S_P^*(f_{b2})}} \quad (4)$$

Equation (4) reveals one of the most impressive advantages of using MIA, i.e., wind-induced building acceleration can be potentially reduced by weakening the structural stiffness as far as

$$f_{b1}S_P^*(f_{b1}) \big/ f_{b2}S_P^*(f_{b2}) < 3 \quad (5)$$

To further validate the effectiveness of MIA, a stick aeroelastic model was wind tunnel tested. The building stiffness system was modelled by a rectangular flexure that provides the frequency ratio of 1.1 between the second and the first sway modes. The direction of the flexure was first set in line with the building axis to simulate the system of figure 7a, and then set along the building's diagonal direction to simulate the system of figure 7b. For both cases, the maximum accelerations were found when wind approaching in a direction parallel to the x-axis. However, the vibration traces were found much different in two cases, as shown in figure 8. The accelerations shown in figure 8 have been normalized by the maximum value of the two cases. It can be seen that due to the modal interference effects, the peak acceleration of figure 7b was about 30% lower than that of figure 7a.



a) conventionally designed system b) structural system based on MIA

Figure 8. Wind-induced building accelerations on conventionally designed structure and on MIA optimized structure

Conclusions

Two new approaches have been developed for building optimization design against wind effects.

The proposed wind-adaptable design (MAD) method is to aerodynamically optimize the building shape in an operable manner instead of permanently changing the building's geometry. With MAD, the architectural design and the aerodynamic design can be considered in two separate stages: common wind stage and extreme wind stage, so that the inherent conflicts between architectural design and aerodynamic requirement can be avoided. The use of wind faring with MAD was further investigated and was proved to be effective.

The proposed structural optimization method using modal interference approach (MIA) is to reduce vortex-induced building motions by stimulating multi-mode responses. The major benefit with MIA is not to solely rely on the increase of structural stiffness but to rely on the efficiency improvement of the structural system, so that the reduction of wind-induced building motions can be achieved at lower cost. Analysis and experiment results verified the effectiveness of MIA in reduction on wind-induced building accelerations.

Acknowledgments

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