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Exploratory study on wind-adaptable design for super-tall buildings

Jiming Xie* and Xiao-yue Yang[a]

College of Civil Engineering and Architecture, Zhejiang University, 866 Yuhangtang Road, Hangzhou, China

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Abstract. Wind-adaptable design (WAD) provides a new method for super-tall buildings to lessen design conflicts between architectural prerequisites and aerodynamic requirements, and to increase the efficiency of structural system. Compared to conventional wind-resistant design approach, the proposed new method is to design a building in two consecutive stages: a stage in normal winds and a stage during extreme winds. In majority of time, the required structural capacity is primarily for normal wind effects. During extreme wind storms, the building's capacity to wind loads is reinforced by on-demand operable flow control measures/devices to effectively reduce the loads. A general procedure for using WAD is provided, followed by an exploratory case study to demonstrate the application of WAD.

Keywords: wind-adaptable design; wind-resistant design; operable flow control; building aerodynamic optimization; wind effects; super-tall buildings

1. Introduction

Excessive across-wind response is the major challenge for super-tall building designs (Kareem 1982, Irwin 2007). This issue is different from wind drag effects commonly described in building design codes or standards. The across-wind response originates from the alternate vortex shedding from both sides of building and is intensified by super-tall building's lower frequencies and damping levels. Although the significance of across-wind response depends on many factors, such as local wind climate, terrain conditions, and building geometry, design wind loads for tall buildings of 300m or taller were found to be mostly governed by across-wind responses based on authors' engineering experience. A slender building less than 300 m height may also experience considerable across-wind loading. Compared to along-wind, the across-wind loads are much more sensitive to building's shape. Shape modifications within 10% of building width may result in a 25% reduction in overturning moment (Irwin 2007). Therefore, aerodynamic optimizations of building geometry have received great attention in design community (Hayashida *et al.* 1990, Kareem *et al.* 1999, Sharma et al 2018). Common approaches of aerodynamic optimization include building corner recessing or chamfering (Kwok 1988, Kwok and Isyumov 1998, Dutton and Isyumov 1990), tapering or setbacks (Kim *et al.* 2013, 2014), twisting (Xie 2014), and upper portion opening (Isyumov *et al.* 1989). A series of wind tunnel experiments on aerodynamic forces and wind pressures acting on square-plan tall buildings with various aerodynamic configurations, including corner chamfering, tapering, twisting, opening, etc. were reported (Tanaka *et al.* 2012, 2013), which led to comprehensive understanding on the effects of aerodynamic modifications. To assist the application of aerodynamic modifications in design practice, a practical approach was proposed to quickly assess potential effectiveness of various aerodynamic configurations (Xie 2014). Automated optimization procedure for reducing wind load on tall buildings was proposed and developed (Elshaer, Bitsuamlak and Damatty 2017).

However, in engineering practice, the above-mentioned aerodynamic optimizations can have some inherent drawbacks:

- Decrease of building's efficiency: A typical example is tapering. It has been recognized that in order to make tapering effective for aerodynamic purpose, the tapering ratio (i.e., the ratio between the width reduction and the building height) needs to be reasonably large (Xie 2014). However, this can cause considerable loss of usable space in building's upper floors (Tse *et al.* 2009). Building corner modification is another example that tends to have unfavorable impact on usable space for building's corner units.
- Increase of construction difficulties and costs: While twisting can largely reduce across-wind loads, the increase of costs in association with facade design and construction can be substantial.
- Contrary to architectural concept: An aerodynamically optimized shape may be unfit with the surrounding environment and/or may be contrary to the architectural concept. In engineering practice, this was often the leading cause that aerodynamic approach could not be accepted even after excessive across-wind responses were identified.

In this paper, an innovative design approach is proposed, which is basically to design a geometrically adjustable building to achieve aerodynamic optimization with less interference to architectural design. In other words, the proposed method is to take temporary measures to modify

*Corresponding author, Professor
E-mail: jiming_xie@zju.edu.cn
[a] Ph.D. Student,
E-mail: xiaoyue_yang@zju.edu.cn

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building's shape in extreme weather conditions, and these temporary measures are pre-designed and pre-installed. Compared to the conventional wind-resistant design method (WRD), the proposed method is to activate building's adaptability to winds rather than relying solely on structure's resistance to winds. Therefore, we named the proposed method "Wind-Adaptable Design" or "WAD" as an abbreviation. The following sections discuss the concept of the method in detail, followed by the general design procedure of WAD. An exploratory case study is given to demonstrate the application of WAD by utilizing wind fairings as flow control devices.

2. Concept of wind-adaptable design (WAD)

The conventional wind-resistant design is based on the same concept as for seismic loads: designing a structural system with sufficient capacity to withstand extreme natural disasters. Practically this is to consider an extreme wind event that has a 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 conventional method is to take a very rare event as design objective and pursues with "maintaining the status quo" approach to design a building for everyday use.

The above design concept is reasonable when dealing with unpredictable disasters, such as earthquakes. However, for predictable disasters, the design method based on this concept does not appear to be cost effective. For super-tall buildings, the wind-resistant designs are mainly governed by synoptic or mesoscale winds such as hurricanes. Current technology can reliably forecast these types of wind storms several days in advance (Stensrud *et al.* 2013). It is therefore feasible to design a building in a more resourceful way for extreme circumstances.

The proposed WAD method is to make use of weather forecast information and to design a building that can adjust its aerodynamic shape when needed to accommodate severe wind conditions. In most time with normal winds, the building retains its basic shape that is not necessarily to be aerodynamically optimized, because the structure only needs 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 activating flow control devices over the building's facade.

Compared to conventional wind-resistant design, the wind-adaptable design includes two distinctive aspects: flow control design and two-stage structural design.

The flow control design is to develop an operable aerodynamic control scheme that a building can be morphed from its basic shape to an aerodynamically optimized shape during severe storms. After the storm is over, the building can recover its basic shape by restoring the control devices. Given the relatively short duration of severe storms, the flow control devices will maintain their service positions for only a few days. The concept of WAD is shown in Fig. 1.

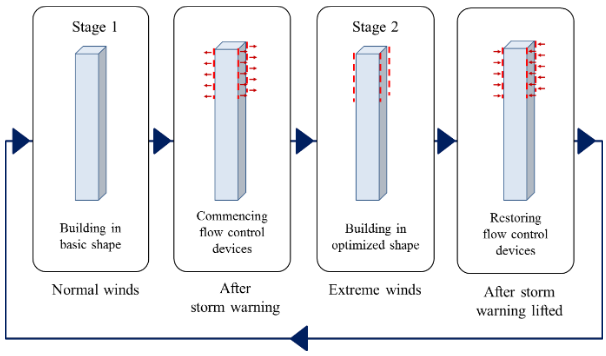


Fig. 1 Illustration of WAD concept

Generally, flow control schemes can be divided into two categories: passive control and active control. Although active control can be more efficient than passive control, the requirement for a reliable power supply is a major drawback of active control. As a result, almost all aerodynamic optimizations adopted in existing buildings are passive, including corner recessions, tapering or twisting. One of the objectives in WAD is to make the passive control operable. Use of operable wind fairings was found promising to create similar aerodynamic effects as corner recessing and chamfering (Xu and Xie 2018).

The two-stage design refers to a design with a basic building shape and a design with an aerodynamically optimized shape. Since the basic building is designed for normal winds and the optimized building is for severe winds, the two designs can be carried out consecutively in two separate stages, thereby avoiding the inherent conflicts between architectural prerequisites and aerodynamic requirements. In this way, architects can have more design freedom to achieve the best architectural appearance without excessive restraints due to aerodynamic requirements. On the other hand, since extreme wind storms are relatively rare and transient, the requirements for building's appearance during the storms are not a major issue, so more efficient and diverse aerodynamic measures/devices can be implemented on the building.

3. Procedure of wind-adaptable design (WAD)

To explain the procedures of wind-adaptable design, it is worth first reviewing the conventional procedure of wind-resistant design.

A typical procedure of wind-resistant design (WRD) for super-tall buildings consists of the following design steps, as summarized in Fig. 2.

Step 1: Estimate the wind loads for an architecturally designed building, usually by means of building codes or standards. Then conduct a preliminary structural design based on these estimated wind loads to determine the structural system and the structural dynamic properties.

Step 2: Based on the preliminary building shapes and structural properties, conduct wind tunnel tests to determine the accurate wind loads for structural design.

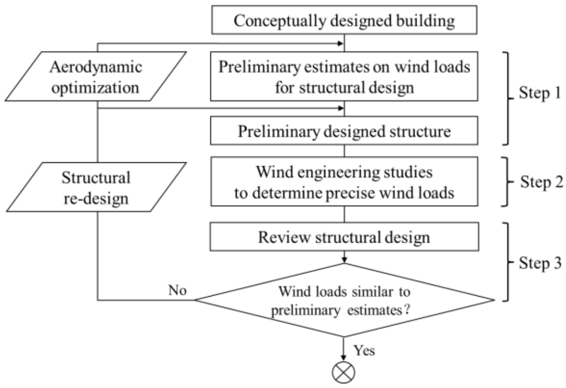


Fig. 2 Design flow chart with wind-resistant design

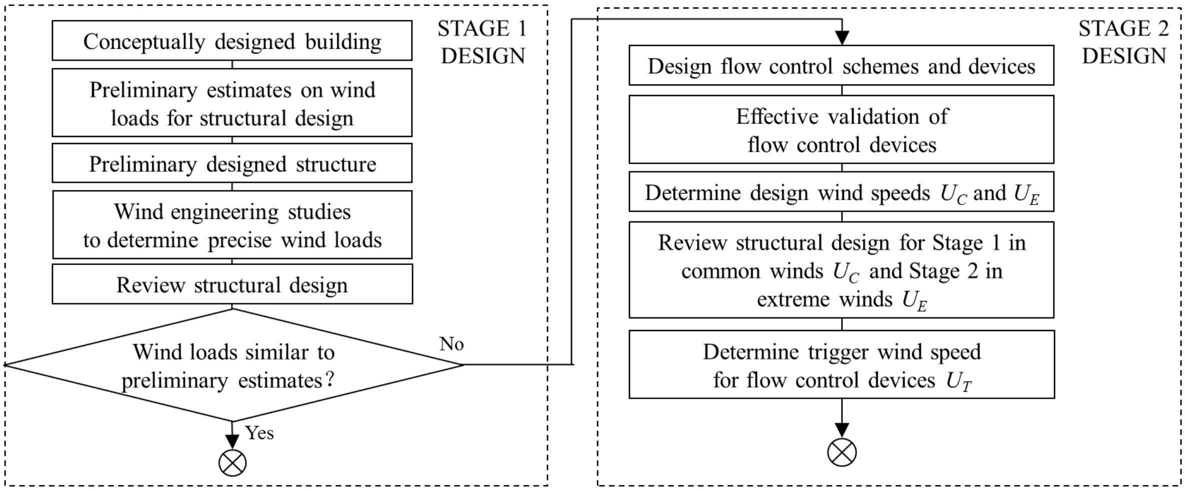


Fig. 3 Design flow chart of wind- adaptable design (WAD)

Step 3: Review the preliminary structural design using the accurate wind loads from the wind tunnel tests. If the accurate wind loads are not very different from the previous estimates, the designers may keep the original design with only minor adjustments. However, for flexible super-tall buildings, due to complexity of across-wind response, wind loads can be much higher than simple estimates from code calculations. In this case, the designers have to make a difficult choice between (1) re-designing the structural system to achieve higher wind-resistant capacity, and (2) modifying the building shape to reduce the design wind loads. The former may significantly increase the project cost, but the latter can conflict with the original architectural concept.

After several design iterations between Step 1 and Step 3, the final design is usually neither the most optimal structural design, nor the most favourable architectural design, but the best compromise between structural cost and architectural acceptance.

In contrast, Fig. 3 provides a flow chart of the proposed wind-adaptable design (WAD), where Stage 1 of WAD is similar to Step 1 through Step 3 of WRD. The deviation between the two methods starts after it is judged whether the design wind loads determined by wind tunnel tests are similar to those assumed in the preliminary design. If "No", the conventional WRD would need to reinforce the structural system or modify the building shape, but the proposed WAD offers an alternative solution: accept the designed structure as it is and apply flow control devices to reduce the design wind loads.

With WAD, the following three wind speeds need to be specifically determined:

- Extreme wind speed U_E: This is the structural design wind speed of Stage 2 for the building with flow control devices in place. In an ideal case with perfectly reliable flow control system, the extreme wind speed U_E is the same as the design wind speed U_D for conventional WRD, typically corresponding to a return period of 50 or 100 years. However, by considering the reliability associated with flow control devices, the extreme wind speed U_E should be higher than the design wind speed U_D, as discussed further in Section 3.1.

- Common wind speed U_C: This is the structural design wind speed of Stage 1 for the basic-shape building. The term “common” is relative to “extreme”, meaning that the corresponding return period of common wind speed U_C is much shorter than the extreme wind speed U_E. Note that the common wind speed in WAD is not defined by meteorology, but by the structural capacity to winds. A detailed discussion on common wind speed U_C can be found in Section 3.2.
- Trigger speed U_T: This speed is a reference for activating the operable flow control devices. In order to account for the uncertainties involved in weather forecasting and device operation, the trigger speed should be lower than the common wind speed.

3.1 Determination of extreme wind speed U_E

The relationship between expected structural response (e.g., wind-induced overturning moment) and the reference winds (e.g., return period speed at gradient height) can be established by accurate analysis based on wind tunnel results, taking account of building properties, wind climate and exposure conditions. In general, the peak value of wind-induced overturning moment can be approximately estimated by

$$\hat{M} = \frac{1}{2}\rho U^2 BH^2 \left(C_M + g_f \sqrt{\sum_j \left(\int_0^\infty \left(f/f_j \right)^4 S_{Fj}^*(f)df + \frac{\pi f_j}{4\zeta} S_{Fj}^*(f_j) \right) \int_0^H \left(\frac{m_z \varphi_{zj} z}{m_j H} \right)^2 dz} \right) K_d \quad (1)$$

where U = reference wind speed;
ρ = air density;
B = building’s typical width;
H = building height;
C_M = static coefficient of overturning moment, negligible for across-wind loads;
g_f = peak factor;
f = frequency;
f_j = the j-th modal frequency;
S_{Fj}^* = normalized spectrum of generalized aerodynamic force for the j-th mode;
ζ = damping ratio;
m_z = building mass at elevation z;
m_j = generalized mass of the j-th mode;
φ_{zj} = the j-th modal deflection at elevation z;
K_d = directionality factor due to wind climate.

Because the aerodynamic properties are different between Stage 1 and Stage 2, the generalized force spectra shown in Eq.(1) will be different, so does the relationship between the structural response and the reference wind speed. At the same reference wind speed, the response at Stage 1 and Stage 2 can be conceptually expressed by

$$\begin{aligned} &\text{Stage 1:} \quad r_1 = R_1(U) \\ &\text{Stage 2:} \quad r_2 = R_2(U) \end{aligned} \quad (2)$$

where R is the response function and r is the response.

At design wind speed U_D, it is desirable that the flow control devices be fully functional to satisfy the relationship of Stage 2. However, due to unpredictable malfunction, the flow control devices may not fully function. We conservatively assume that the relationship of Stage 1 applies to these fault conditions. As such, the structural response at design wind speed U_D is estimated to be

$$r_E = R_1(U_D) \cdot \left(1 - P_F(0|U_D)\right) + R_2(U_D) \cdot P_F(0|U_D) \quad (3)$$

where $P_F(0|U_D)$ is the probability of zero failure of the flow control devices during sever storm of U_D while 1-$P_F(0|U_D)$ represents the probability of at least one failure.

In WAD, the extreme wind speed is such chosen th at the response of Stage 2 at the extreme speed U_E is the same as the response predicted by Eq. (3) at the d esign speed U_D, i.e.

$$R_2(U_E) = R_1(U_D) \cdot \left(1 - P_F(0|U_D)\right) + R_2(U_D) \cdot P_F(0|U_D) \quad (4)$$

For simplicity of discussion, we assume the functions in Eq. (2) having the following expressions

$$r_1 = A_1 U^{\beta_1} \quad \text{and} \quad r_2 = A_2 U^{\beta_2} \quad (5)$$

where A_1, A_2, β_1 and β_2 are constants, representing the sensitivity of response to wind speed at Stage 1 and Stage 2, respectively.

By substituting Eq. (5) to Eq. (3), the extreme speed U_E is obtained as follows

$$U_E = \left[P_F(0|U_D) + \frac{A_1}{A_2}\left(1 - P_F(0|U_D)\right) U_D^{\beta_1 - \beta_2} \right]^{1/\beta_2} U_D \quad (6)$$

In general, we have

$$U_E = \gamma \cdot U_D \quad (7)$$

where γ is an adjustment factor for design wind speed.

It is apparent that the adjustment factor, being larger than or equal to 1.0, is not only determined by the reliability of the flow control devices but also by the effectiveness of the devices. Therefore, the adjustment factor could be slightly different for different responses of interest.

3.2 Determination of common wind speed U_C

If a preliminary designed structural system in Stage 1 cannot withstand the wind loads at the design speed U_D, it should still be able to withstand the wind loads at a lower speed. Denote U_{C0} the maximum wind speed in Stage 1 that the designed structural system can withstand. The corresponding response in Stage 1 can be expressed as

$$r_{C0} = R_1(U_{C0}) \quad (8)$$

The response r_{C0} represents the existing structural capacity.

One the other hand, the designed structural system i n Stage 2 should be able to withstand the wind loads in extreme speed U_E and the corresponding maximum response is calculated by

$$r_E = R_2\left(U_E\right) \tag{9}$$

The response r_E specifies the required structural capacity. There exist two possible cases in performing WAD:

Case 1: $r_E \le r_{C0}$, indicating that the existing structural system is sufficient;

Case 2: $r_E > r_{C0}$, indicating that the existing structural system is insufficient and therefore the measures need to be taken by either increase of the structural capacity or by increase of the efficiency of flow control devices until the condition $r_E = r_{C0}$ being satisfied.

The selection of common speed U_C is to ensure that the designed structural system has sufficient capacity, which can be achieved by solving the following equation.

$$R_1\left(U_C\right) = R_2\left(U_E\right) \tag{10}$$

For the simplified relationship as of Eq.(5), the com mon speed U_C is given by

$$U_C = \left(\frac{A_2}{A_1}\right) U_E^{\beta_2/\beta_1} \tag{11}$$

3.3 Determination of trigger speed U_T

It is important to determine the trigger speed at which the building should be transformed from its basic shape to an aerodynamically modified shape by activating the operable flow control devices. To have some allowance for uncertainties involved in wind speed forecast, it is necessary to choose the trigger speed U_T lower than the common speed U_C. For example, if the common speed is the one at which the probability of occurrence is about 20 years, the trigger speed of 10-year return period sounds reasonable, the latter being four times more frequent than the former. Further studies are needed to have a better estimate on approximation in wind speed forecast. On the other hand, since the wind speed referred in conventional storm warning announcement is often different from that used in wind engineering studies, a correlation needs to be established between the wind speed that defines U_T and the wind speed commonly referred in weather forecast. This correlation can be preliminary estimated based on empirical analysis and averaging time conversion, and then be calibrated by on-site anemometers.

4. Exploratory case study with WAD

As an exploratory case study, a hypothetical 60-storey building was used to demonstrate the proposed method of wind-adaptable design (WAD), as shown in Fig. 4. The building, located in a typical urban area (power-law index of mean speed profile α = 0.22), has total height of 270 m (H=270 m) and a square floor plan of 45 m by 45 m (B=45 m). The fundamental frequency was assumed to be 0.13Hz in two sway directions and the structural damping ratio was assumed to be 1.5%. Typical nonlinear mode shapes in two sway directions were expressed by power-law curve with index 1.5. A mean wind speed of 65 m/s at roof height (U_H=65 m/s) was considered as the reference design speed (U_D= U_H), which corresponding to a return period of 100 years.

The 1:300 scale model of the study building was tested in the boundary layer wind tunnel at Zhejiang University, China. Fig. 5 shows the simulated mean wind profile, turbulence profile and wind spectrum at 2/3 of building height, in which the measured turbulence spectrum was compared to the von Kaman spectrum by assuming turbulence integral scale L_u=165 m.

For simplicity of discussion, the building's across-wind overturning moment was taken as the design objective. Detail analysis could be simply extended to different load effects at various wind directions.

Fig. 6 provides the predicted overturning moment M_y at design speed of 65 m/s based on wind tunnel tests and consecutive dynamic analysis. It is evident that the structural system should have a minimum capacity of 4.20×10^{10}N-m for overturning moment. Fig. 6(b) illustrates the across-wind loads as a function of wind speed. The critical speed, about 70 m/s in Fig. 6(b), corresponds to the Strouhal number of the building and in majority of engineering cases it is higher than the design wind speed so that the approximation of Eq. (5) is applicable.

In the case study, we selected wind fairings as operable flow control devices. The dimensions of the fairings are shown in Fig. 7(a). These fairings could be opened or closed by a sliding or rotating mechanism. The staggered arrangement of the fairings was to ensure their omnidirectional characteristics, i.e., the wind fairings are effective in all wind directions.

From a practical point of view, the operable fairings were only installed in the upper third of the building. The wind tunnel model with wind fairings in place was tested. Dynamic analysis were then performed by combining the wind tunnel data with structural properties to estimate the maximum overturning moments.

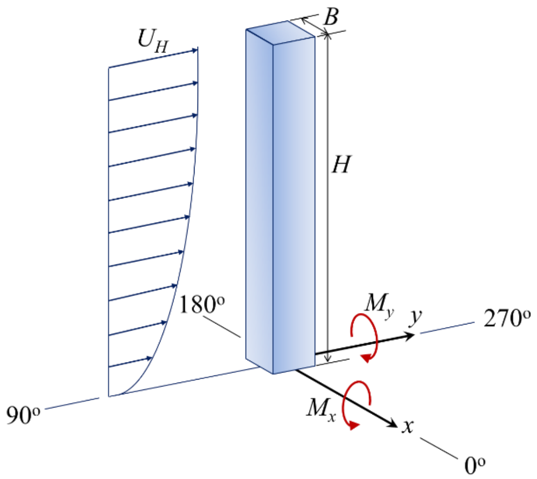


Fig.4 Study building

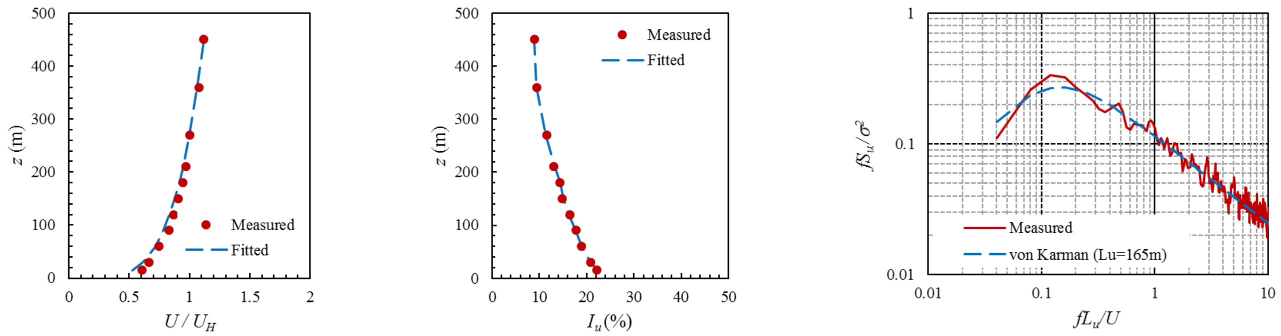
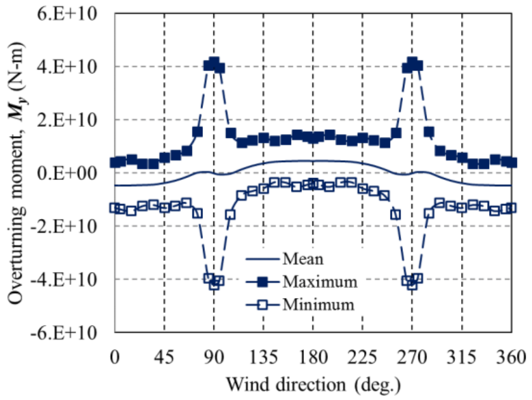
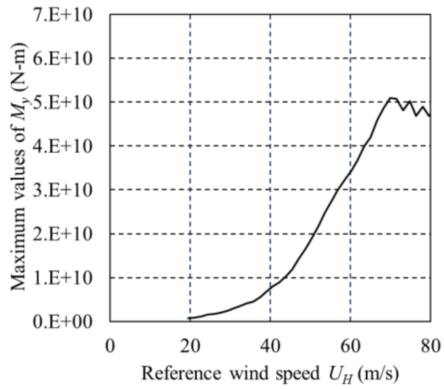


Fig. 5 Simulated wind properties for wind tunnel testing

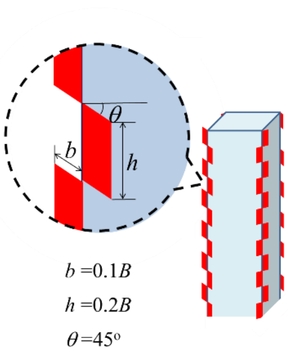


(a) Overturning moment for wind speed of 65 m/s

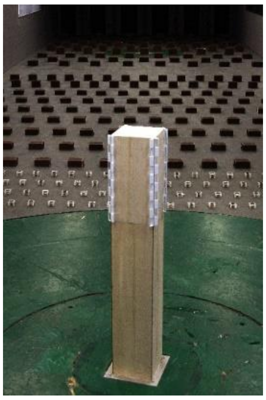


(b) Maximum across-wind overturning moment

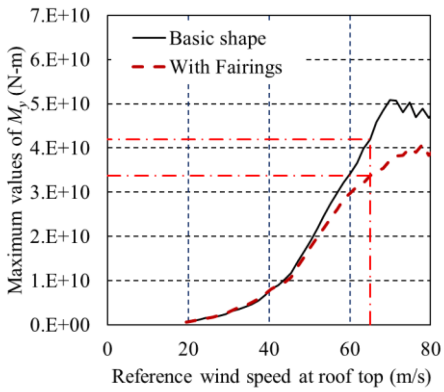
Fig. 6 Predicted overturning moment



(a) Fairing details



(b) Wind tunnel model



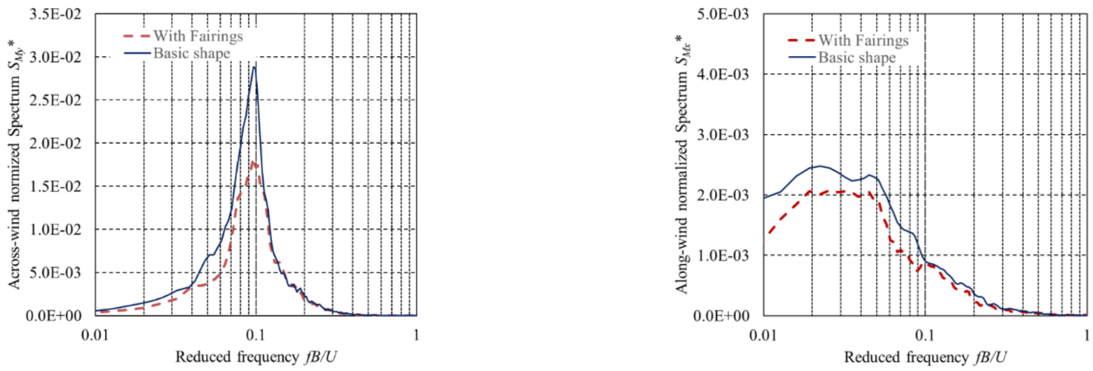
(c) Maximum across-wind overturning moment

Fig. 7 Effects of wind fairings on overturning moment

The results are shown in Fig. 7. Fig. 7 also plots the maximum overturning moments of the basic-shape building to demonstrate the effectiveness of the wind fairings.
From Fig. 7, we first determined the overturning moments for both stages at design speed of U_D (U_D =65 m/s).

$$
\begin{aligned}
r_1(U_D) &= f_1(U_D) = 4.20\times10^{10}\,\text{N-m} \\
r_2(U_D) &= f_2(U_D) = 3.37\times10^{10}\,\text{N-m}
\end{aligned}
\tag{12}
$$

Then we estimated the failure probability of flow control devices. In fact, given the wind fairings, the probability of device failure during operation could be very



(a) Across-wind (b) Along-wind

Fig. 8 Power spectrum densities of overturning moments

small. For properly designed fairings, main cause of failure might be a mechanic malfunction in the opening operation. However, regular maintenance and adequate preparing time before severe storms could prevent failures.

For illustration purpose, we conservatively assumed a 10% probability of failure during severe storms. From Eq. (4), we calculated the predicted response for this estimated failure probability.

$$R_2(U_E) = 4.20\times10^{10}\cdot0.1+3.37\times10^{10}\cdot0.9 \\ =3.45\times10^{10} \tag{13}$$

From Fig. 7, the extreme speed was found to be $U_E = 66.5\text{m/s}$. The physic meaning of U_E is that the response of structure with intact wind fairings at design wind speed U_E is the same as the response of structure with possibility of wind fairing failures at design wind speed U_D.

According to Eq. (10), the common wind speed was determined $U_C = 60.2\text{m/s}$. It is evident that the maximum overturning moment in Stage 1 at wind speed U_D is the same as the maximum overturning moment in Stage 2 at wind speed U_E.

As a result of using WAD, the design overturning moment could be reduced from 4.20×10^{10}N-m to 3.45×10^{10}N-m, about 18% reductions.

A trigger speed was selected to be 51m/s, which corresponds to a 10-year return period. The operation of wind fairings was therefore adequately infrequent.

5. Further discussions about flow control devices

It is apparent that the success of WAD largely depends on the effectiveness of engaged flow control devices. Although the flow control devices can be of many types, the general principle of adequate devices for WAD should be to balance the efficiency, reliability and expected operating frequency.

High efficiency must be warranted by high reliability. In the proposed WAD, the requirement for device reliability is represented by the adjustment factor γ (=U_E/U_D). For higher efficient but lower reliable devices, the adjustment factor γ can be very high, leading to a higher design wind speed for Stage 2.

Operating frequency of flow control devices is another factor to consider in the design. In general, devices with high efficiency and high reliability permit the structure being designed more efficiently. However, the resulting lower trigger speed is in general associated with more frequent operation of the flow control devices. Wind fairings are fairly reliable and can be as effective as permanent corner modifications, such as corner recessing and chamfering. Fig. 8 shows the normalized power spectral densities of the overturning moments in across-wind and along-wind directions, each of them being defined by

$$S_{My}^* = \frac{fS_{My}}{\left(0.5\rho U_H^2 BH^2\right)^2}\ ;\ S_{Mx}^* = \frac{fS_{Mx}}{\left(0.5\rho U_H^2 BH^2\right)^2} \tag{14}$$

where S_{My} and S_{Mx} are the measured aerodynamic force spectrum for across-wind and along-wind overturning moments, respectively.

It can be seen that the given wind fairings not only reduce the across-wind loads but can also be effective in reducing along-wind loads.

It is important to note that the effectiveness of the wind fairings also depends on the reduced frequency *fB/U*. At the reduced frequency of about 0.1, the representative value of Strouhal number for the study building, the wind fairings can effectively reduce the across-wind response. However, when the reduced frequency reaches to 0.115 or higher, the wind fairings show no benefits. As a result, the wind fairings can significantly reduce the wind response in high wind speed, but are almost negligible in low wind speed, as shown in Fig. 7(c). The limitation of wind fairings in low speed region is virtually the same as the conventional aerodynamic approaches of corner modifications. Fig. 9 shows the experimental results by Tanaka (Tanaka et al 2013). It is evident that similar phenomenon occurs for corner chamfered and corner cut. This validates that the wind fairings are actually the operational version of these corner modifications. The difference in spectral magnitudes between Figs. 8 and 9 was mainly caused by the different building slenderness (=*H/B*). The study building of Fig. 7

has a slenderness of 6 while the building in Tanaka's experiments was 8. High slenderness normally results in more severe across-wind responses and also makes aerodynamic optimization more effective.

The above limitation of aerodynamic optimization has been well recognized in engineering practice. A typical example is Taipei 101 Tower. Although the corner recessions brought about 25% reduction on the structural design wind loads, a huge 660 ton tune-mass damper had to be installed to further reduce the accelerations in low speed to meet the serviceability requirement. In fact, many popular aerodynamic approaches share the same limitation. Tapering and stepping along building height, for example, can reduce the design wind loads at high wind speeds, but at low wind speeds it may cause an increase of the building acceleration (Xie 2014).

In engineering practice, it is often found that a single method is not sufficient to solve all wind-related problems. The proposed WAD adds a new approach to deal with wind issues. Notably, the proposed WAD makes it possible to employ various types of innovative flow control measures in building design. For example, if the design of a building allows certain floors or corner units to be shut down in an emergency, the WAD design can be performed by temporarily opening these floors or units as airflow control measures in extreme wind conditions, as illustrated by Fig. 10. Functional building features can sometimes be found to have favorable aerodynamic effects (Aly *et al.* 2017).

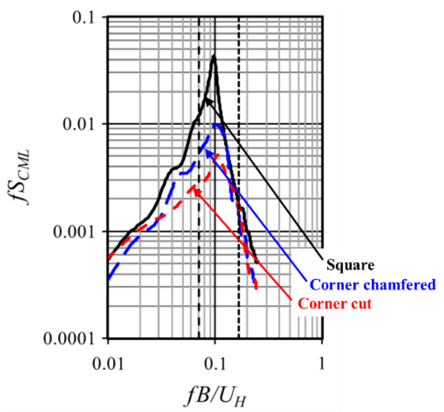


Fig. 9 Power spectrum densities of overturning moments (Tanaka *et al.* 2012)

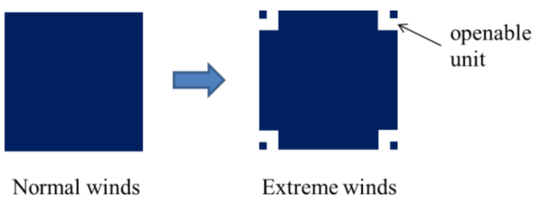


Fig. 10 Illustration of openable unit as a measure of flow control in WAD design

It should be noted that the proposed WAD is a design concept and procedure, and is therefore not limited to a particular method of flow control. Most existing measures for building shape optimizations can find their operable counterparts, but the selection of a specific measure is a case-by-case practice. It is evident that the success of WAD design is strongly dependent on the adopted flow control measures. High efficiency, high reliability, low cost and low maintenance are the important parameters for the flow control measures/devices. Therefore, research and development of high quality flow control measures should be a promising direction for future studies.

5. Conclusions

To solve conflicts between architectural prerequisites and aerodynamic requirements in super-tall building design and to further improve the efficiency of structural system**,** a new design method is proposed in this paper. The proposed WAD method is based on the fact that extreme wind events, such as hurricanes, can be reliably predicted with modern technology in weather forecast. As such, conventional aerodynamic modifications for super-tall buildings can be achieved by using operable flow control devices, rather than permanently changing building shapes. This method brings benefits to both architectural design and structural design.

A general design procedure with WAD is provided that involves calculations of three key design speeds, the extreme speed U_E for the aerodynamically modified building, the common speed U_C for the basic building, and the trigger speed U_T at which the flow control devices should be put into service position. The concept of the proposed WAD procedure is to ensure that a structure designed with operable flow control devices has the same safety reliability as its counterpart designed in the conventional way. To clarify the proposed WAD procedures, an illustrative flow chart is provided.

An exploratory case study demonstrates the application of WAD to a 270 m high building. By using staggered wind fairings as flow control devices in WAD, a reduction of about 18% on structural design wind loads was achieved. Compared to conventional wind-resistant design and permanent shape modification, the reduction on design loads with WAD was achieved under the condition that the originally designed building shape remains unchanged for most of the time.

The limitations of WAD are discussed, primarily due to the selected flow control devices. For the wind fairings shown in the exploratory case study, the wind fairings have almost the same functions as the chamfered corners. Therefore, the same limitations as the chamfered corners are also shown in the wind fairings, i.e., high efficiency at high wind speeds but low efficiency at low wind speeds.

The proposed WAD can be considered as a new approach to solve wind issues in addition to the conventional building shape modifications and supplementary damping solutions. In many engineering cases, a single method is not sufficient to solve all wind-related problems.

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