Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
December 2023, Vol 12, No 4, 287-297
https://doi.org/10.21022/IJHRB.2023.12.4.287

Current Issues in Wind Engineering: A Review

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Abstract This paper briefly discusses current issues in wind engineering, including the enhancement of aerodynamic database and AI-assisted design, aerodynamic characteristics of tall buildings with atypical building shapes, application of computation fluid dynamics to wind engineering, evaluation of aerodynamic force coefficients based on a probabilistic method, estimation of tornadic wind speed (JEF scale) and effect of the Ekman Spiral on tall buildings.

Keywords Aerodynamic database, Atypical building shape, Computational fluid dynamics, Design fractile, Tornadic wind speed.

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1. Introduction

Tall buildings have to effectively resist horizontal loads such as wind loads and earthquake loads, because these loads are typically regarded as the dominant external design loads. Especially, it is well known that the history of tall building development was a record of fights with strong winds, because higher altitudes mean higher wind speeds, resulting in higher wind loads. Light and flexible buildings are favorable for resisting earthquake loads, while heavy and stiff buildings are favorable for resisting wind loads. Thus, tall buildings in regions that are both earthquake-prone and typhoon-prone have to satisfy these two completely opposite design criteria, and this can be one of the most challenging design issues. A comparative study using an earthquake load corresponding to 25 m/s ground velocity and a wind load corresponding to a 500-year return period for square buildings (50 m × 50 m, damping ratio of 2%) constructed in terrain category III reported that wind load becomes larger than earthquake load when building height exceeds about 200 m, as shown in Figure 1 (Kihara et al., 2000). Landmark Tower (296 m) in Yokohama and the World Trade Center (256 m) in Osaka are good examples of tall buildings designed mainly for wind load as the dominant horizontal design load.

Wind engineering is best described as the rational treatment of interactions between wind in the atmospheric boundary layer and man and his works on the earth's surface (Cermak, 1975). Cermak's work (1975) well summarized scientific and technological subjects at that time for wind engineering and indicated important unresolved research issues that needed to be highlighted in further research in both the structural and environmental

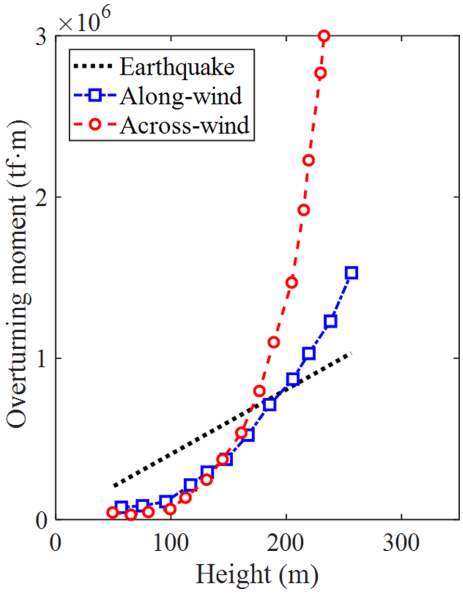


Figure 1. Comparison of earthquake loads with wind loads (Kihara et al., 2000).

wind engineering fields. These issues include wind-excited accelerations of tall buildings for serviceability and habitability design, wind-generated noise, wind-borne debris, pedestrian-level wind conditions, entrainment of solid and other solid debris, snow drifting, control of air-pollutant concentration, wind-generated power and wind characteristics at potential wind-power sites. Some of these issues are still popular topics, and considering its publication year, Cermark's work can be said to be quite pioneering.

In tall building projects, many of the above issues need attention in the maintenance stage as well as in the design

and construction stage. Without integrated and comprehensive care during these stages, satisfactory performance of a tall building cannot be expected (Tamura, 2009). The present paper introduces and reviews current issues that are mainly related to tall buildings.

2. Current Issues In Wind Engineering

2.1 Enhancement of aerodynamic database and AI-assisted design

Wind tunnel tests and computational fluid dynamics are the most frequently used techniques for evaluating wind-induced behaviors for tall buildings, but most wind load codes and standards only contain wind load estimation methods for buildings with regular and conventional building shapes. But in practical tall building projects, most of building shapes are atypical and unconventional. In the preliminary design stage, it is very important to have insights into the wind-induced responses and loading effects in easier and faster ways. One way to satisfy this requirement is to implement aerodynamic databases and related AI-assisted design. It is said that wind tunnel tests take a couple of weeks, LES calculations take a couple of days, RANS calculations take a couple of hours, and AI calculations take a couple of minutes.

Aerodynamic databases have been developed by several groups: the NIST Aerodynamic Database (http://fris2. nist.gov/winddata/) at the National Institute of Standards and Technology in collaboration with The University of Western Ontario, the NatHaz Aerodynamic Loads Database (http://www.nd.edu/~nathaz/ database/ index.html) at The University of Notre Dame (Zhou et al., 2003; Kwon et al., 2008), and the TPU Aerodynamic Database (http://db.wind.arch.t-kougei.ac.jp/) at Tokyo Polytechnic University (Quan et al., 2007; Tamura, 2009). This trend is expected to accelerate more and more, and efforts should be made to accumulate and develop more plentiful aerodynamic databases on various buildings and structures. Actually, the TPU Aerodynamic Database added wind forces acting on unconventional tall buildings, as shown in Figure 2, and many other experimental data on wind pressures and wind forces on unconventional tall buildings will be disclosed in the near future.

2.2. Tall buildings with atypical building shapes

Construction of tall buildings started in the late 19th century in North America thanks to social, economic and technological development. At this time, building shapes were simple and regular such as square and rectangular prisms. However, recent tall buildings can be characterized as atypical building shapes and this trend has become more apparent as building heights have increased. Generally, tall buildings are very sensitive to wind and earthquake loads. For earthquake loads, tall buildings need to be light and flexible in order to lower the inertial forces caused by ground acceleration. Conversely, for wind loads, they need to be heavier and stiff to reduce the wind load and satisfy the serviceability design criteria. As wind and earthquake loads require opposite structural properties, designing and optimizing tall buildings is becoming more challenging for both architects and engineers, where these opposite requirements need to be satisfied. It seems that when a tall building is higher than 200 m, wind load is larger than earthquake load in Japan,

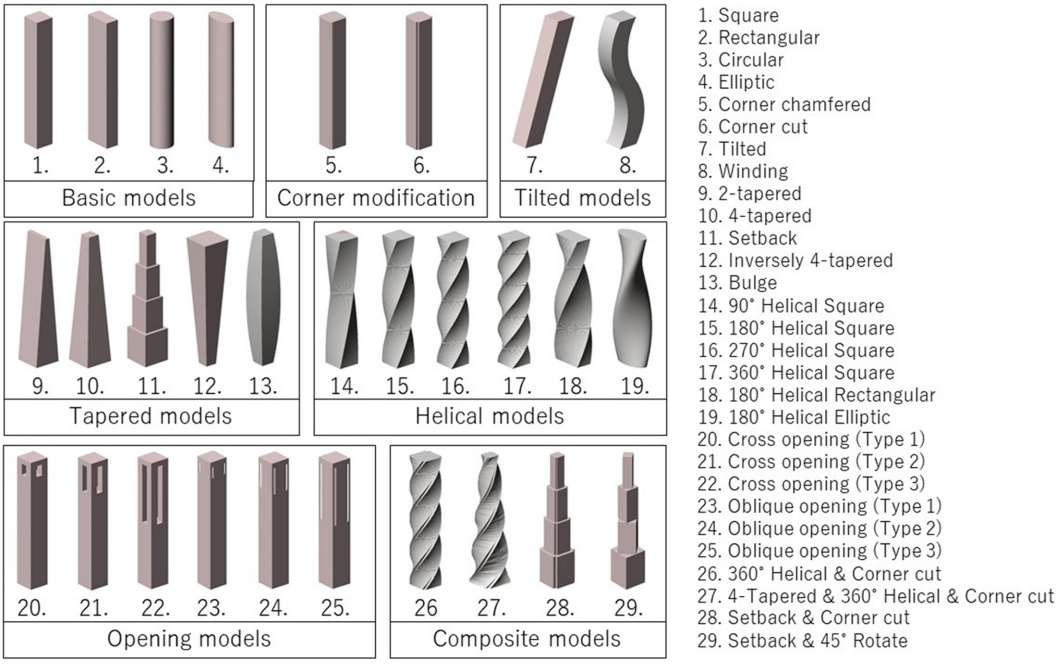
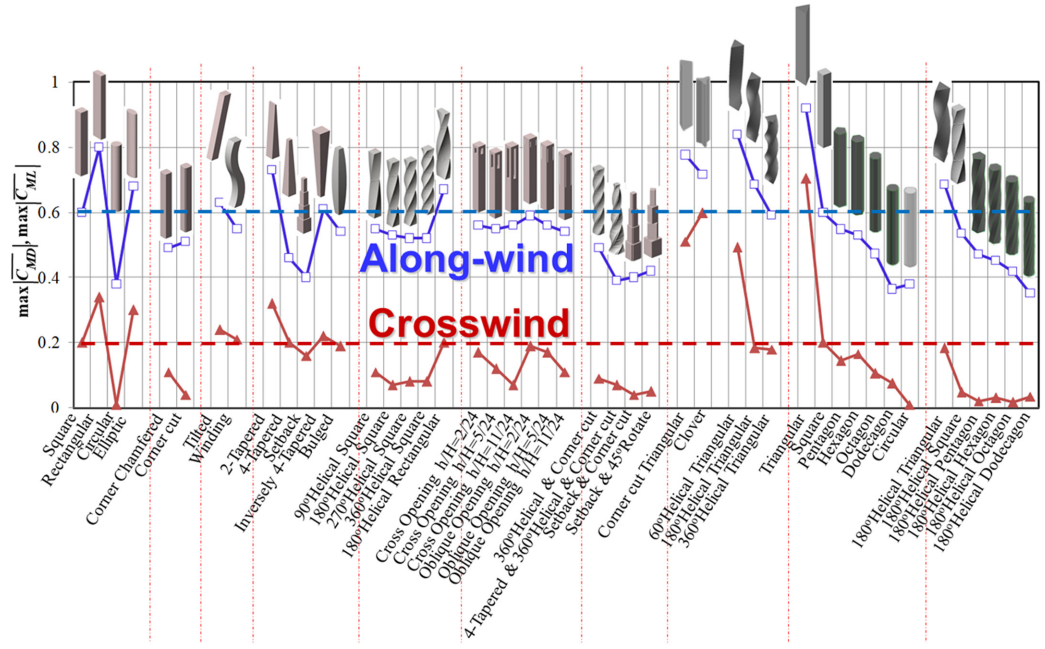


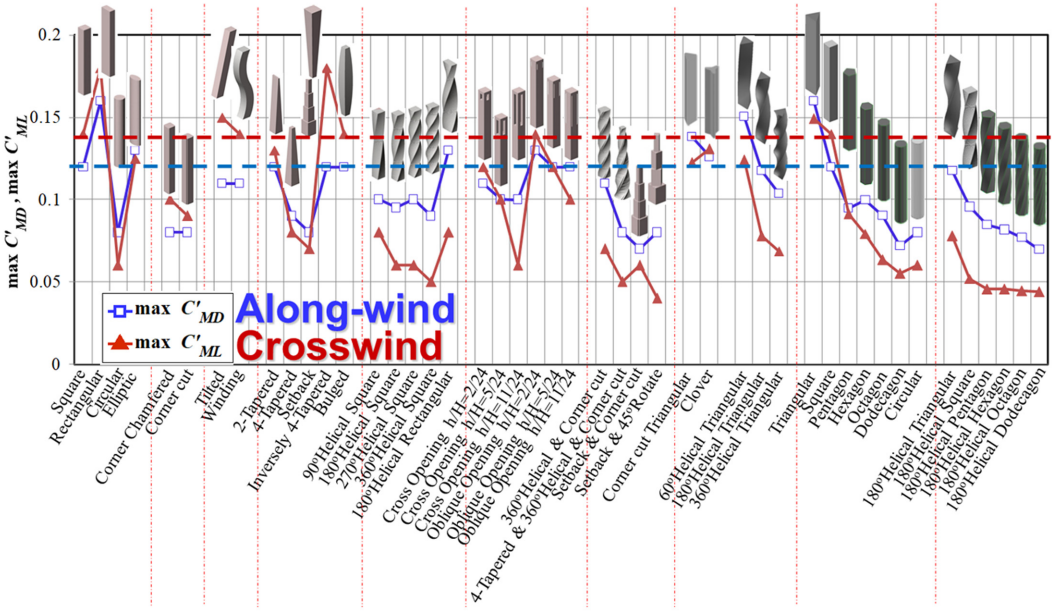
Figure 2. Unconventional building shapes in TPU aerodynamic database. http://db.wind.arch.t-kougei.ac.jp/aerodynamic/experiment/WindForce_UHB/)

but this varies depending on where the tall buildings are located. There have been many studies on mitigation of wind loads by changing building shapes from simple and regular to atypical or unconventional, i.e., taper, setback, helical, opening, modification of corner shape, and combinations of them.

Two major problems need to be solved in tall building projects (Tamura, 2009). The first is aerodynamic performance, especially mitigation of along-wind load caused by fluctuating oncoming flow and mitigation of across-wind load caused by periodic excitations due to vortex formation and shedding in the wake region. The second is pedestrian-level wind conditions around tall buildings. Wind speeds in side and downstream areas near the ground remarkably increase and occasionally provide unfavorable situations due to downdraft. Falling-down of people or damage to public facilities can occur in surrounding areas even under daily wind. Therefore, some local



(a) Mean overturning moment coefficients



(b) Fluctuating overturning moment coefficients

Figure 3. Comparison of maximum mean and fluctuating o.t.m. coefficients (Tanaka et al., 2012; Bandi et al., 2013; Kim et al., 2015; Kim et al. 2019).

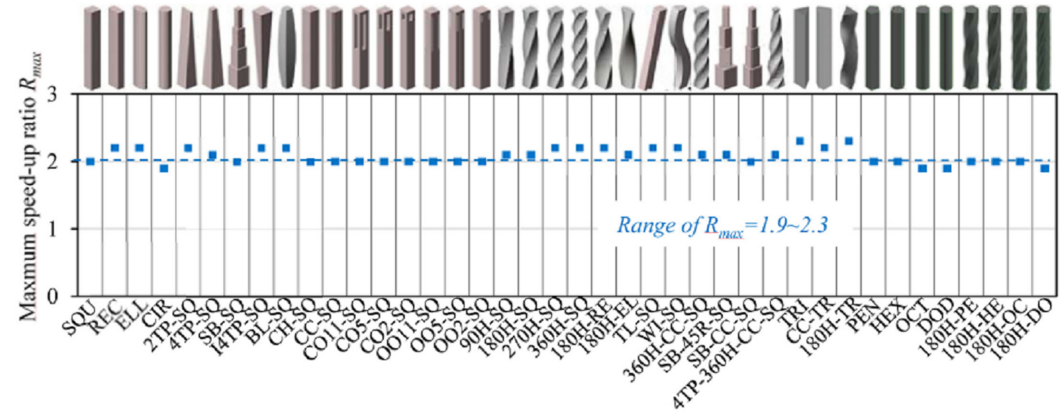
governments oblige building owners and developers to conduct wind environmental assessment studies before and after construction to secure safe living environments.

Comprehensive and excellent reviews summarizing the above issues can be found in Kim et al. (2019). Aerodynamic and response characteristics of super-tall buildings with various configurations have been investigated by Tamura et al. (2010), Tanaka et al. (2012; 2013), Bandi et al. (2013), and Kim et al. (2014; 2015; 2016). Figures 3 shows one of the experimental results for maximum mean and fluctuating overturning moment coefficients (o.t.m. coefficient) (Kim et al., 2019). For mean o.t.m. coefficients of corner modified models, helical models, tapered models and setback models in Figure 3(a) show much better aerodynamic behaviors than the square straight model. In particular, composite models, polygon models and helical polygon models show significant reductions in mean o.t.m. coefficients. Figure 3(b) shows the maximum fluctuating o.t.m. coefficients and a similar tendency is observed for the mean components. Especially, helical square models, composite models and helical polygon models show significant reductions of maximum fluctuating o.t.m. coefficients. It should be noted that the aerodynamic characteristics of the composite models with multiple modifications are better than those of the models with single modification.

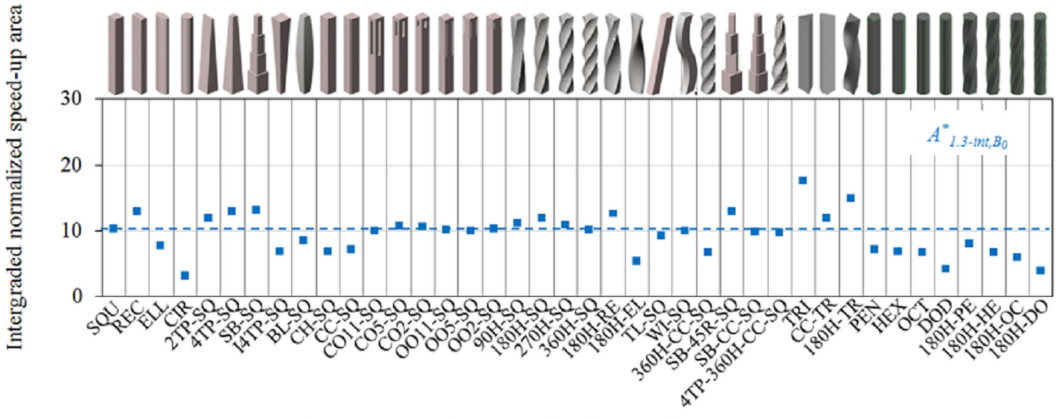
Figure 4 shows pedestrian-level wind conditions obtained from wind tunnel tests. As shown in Figure 4(a), the maximum speed-up ratio is not largely influenced by building shape. The maximum speed-up ratio ranges from 1.9 to 2.3, and the differences among different models are roughly ±10%. The circular, octagon and dodecagon models show better pedestrian-level wind conditions than the square model (Xu et al., 2017). For integrated normalized speed-up area of each building shape shown in Figure 4(b), the circular model shows the smallest values and models without sharp corners show superior pedestrian-level wind conditions. Generally, models having a larger projected width near their bottom parts show worse results than the square model (Xu et al., 2017).

2.3. Computation fluid dynamics and computation wind engineering (CFD and CWE)

The remarkable growth in hardware/software technology and the development of computational methods has enabled increasing application of Computational Fluid Dynamics (CFD). CFD is a method of discretizing and solving the Navier-Stokes equation and the continuity



(a) Maximum speed-up ratios



(b) Integrated normalized speed-up area

Figure 4. Comparison of pedestrian-level wind conditions (Xu et al., 2017, Kim et al., 2019).

equation describing flow and pressure fields. Computational Wind Engineering (CWE) is defined as the application of CFD to wind engineering in both the structural (wind pressure distribution on building/structures by synoptic and/or non-synoptic wind) and the environmental fields (pedestrian-level wind condition and/or pollutant dispersion). In the past 50 years, CWE has undergone a successful transition from an emerging research field to a well-established application field. A number of excellent reviews summarizing the state-of-the-art in CFD and CWE can be found in Cochran and Derickson (2010), Tamura (2010), Blocken (2014) and Kataoka et al. (2020).

CWE offers some particular advantages compared with field measurements and wind tunnel tests. It can provide detailed information on the flow variables in the whole calculation domain, which are one of the main concerns in conducting wind tunnel tests. However, the accuracy and reliability of CWE are of concern and V&V (verification and validation) are of importance. In addition, it is widely recognized that the results of CWE simulations can be very sensitive to the wide range of computational parameters that have to be set by the user. This implies the need for best practice guidelines for CWE.

In Japan, currently two guidelines have been published by the Architectural Institute of Japan (hereafter, AIJ): Guide for Numerical Prediction of Wind Loads on Buildings (AIJ, 2005) and Guidebook for CFD Application to Wind Environment in Urban Area (AIJ, 2007). The first one discusses the numerical accuracy of wind pressures and forces on buildings (Tamura et al., 2008) and the second one discusses the numerical accuracy of pedestrian-level wind conditions in urban areas (Yoshie et al., 2007; Tominaga et al., 2008; Mochida and Lun, 2008).

The present study briefly introduces some of the recent trends and advances in CWE (Kataoka et al., 2020).

CWE is becoming the most practical tool for assessing pedestrian-level wind conditions inside urban areas. To conduct CWE successfully, reading and modeling of building shapes and their surroundings from maps or CAAD drawings and generating a computational mesh should be simplified without losing solution accuracy. The advent of digital maps and geographic information systems has made the process effective. In addition, recent numerical techniques have made mesh generation straightforward. An example of 3D building models from GIS data and computed flow fields around buildings is shown in Figure 5 (Kataoka et al., 2002).

Prediction of dust dispersion is an example of the expanding application of CFD to wind engineering. This simulation is very challenging because there is only one simple prediction method for the dust dispersion rate, and it is difficult to verify and validate the quantitative accuracy of the simulated results at the construction site (Kataoka et al., 2020).

The area where the use of LES is expected to be most useful is in the structural wind engineering field. As the fluctuating characteristics of oncoming flow dominates the aerodynamic and response characteristics of tall buildings, the vertical profiles need to be simulated exactly. There are two methods for generating the time-dependent oncoming flow: the Semi-Periodic Method (SPM) and the Synthetic-Eddy Method (SEM). An SEM result is shown in Figure 6, showing good agreement with experimental results (Kataoka and Tamura, 2015).

An examination of the pressure characteristics on a complicated building façade using LES together with an unstructured grid system was conducted in Enoki and Ono (2016) and Kataoka et al. (2017). An example is shown in Figure 7, which compares the pressure coefficients for 5 wind directions. Even though the negative peak pressure coefficients deviate from the experimental results at a wind direction of 270°(open square symbol), the negative peak pressure coefficients for other wind directions show good agreement. Detailed examination shows that the difference is caused by an insufficient number of ensemble averaging times, and it was found that even a small discrepancy in the evaluation location and the building shape between the experimental model and the computational model may cause a significant difference in the pressure coefficients.

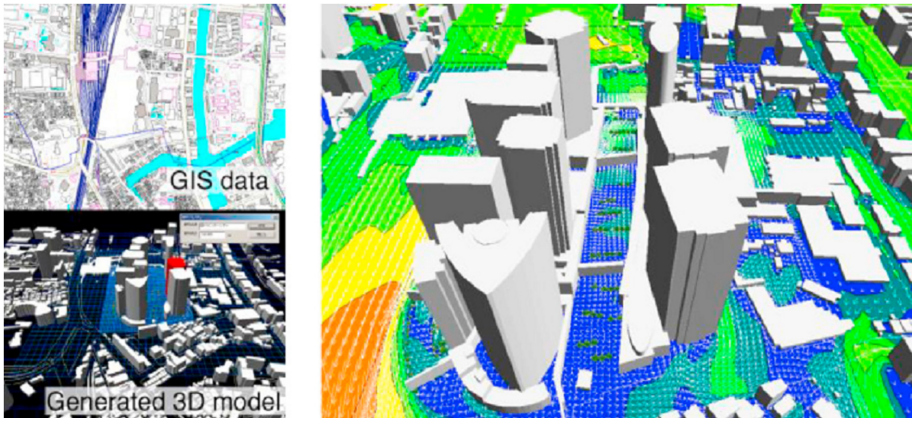
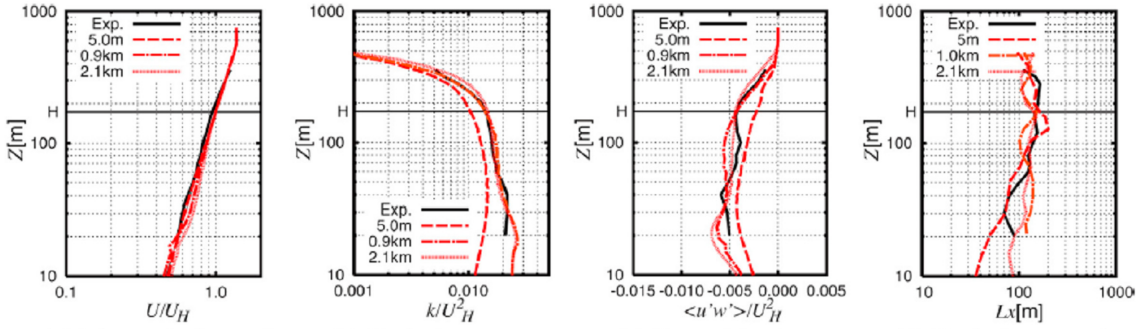
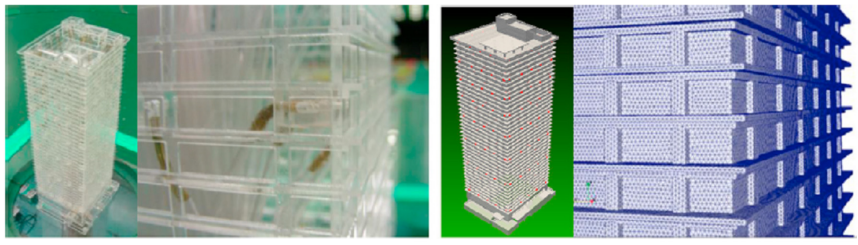


Figure 5. 3D modeling from GIS data and results near ground (Kataoka et al., 2020).

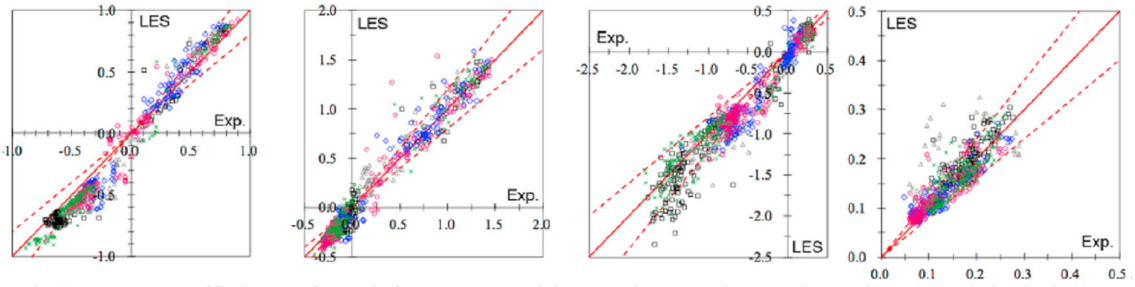


(a) Mean wind speed (b) Turbulence energy (c) Reynolds stress (d) Turbulence scale

Figure 6. Comparison of oncoming flow profiles (Kataoka et al., 2020).



(a) Building façade (left: experimental model, right: computational model)



(b) Pressure coefficients (from left: mean, positive peak, negative peak, and standard deviation)

Figure 7. Building façade and comparison of pressure coefficients (Kataoka et al., 2020).

Recently, tornado-like flows have been simulated successfully to investigate flow characteristics and instantaneous pressure and force characteristics. A result is shown in Figure 8, which shows the vortex core and changes in the wind pressure distribution on the building surfaces. When a vortex reaches the building, a positive pressure is generated on the windward surface, while a large negative pressure is generated on the right side eave in the traveling direction (left in Figure 8). While passing the roof, local negative pressure occurs when the flow crosses the eave (middle in Figure 8). After that, it moves away the building while generating a negative pressure owing to a conical vortex at the right eave edge (right in Figure 8) (Kataoka et al., 2020).

As seen earlier, the accuracy of CWE can be equivalent to that of wind tunnel tests if the calculation is conducted properly by experts or experienced engineers. CWE is an alternative tool to field measurements and wind tunnel tests. However, with current technology, CWE cannot fully replace them. The high quality and reliability of CWE have been a concern because of an increasing variety of choice in commercial codes. This can be a blessing or a curse (Blocken, 2014). It is a blessing because everyone can use it easily, and it is a curse because it can

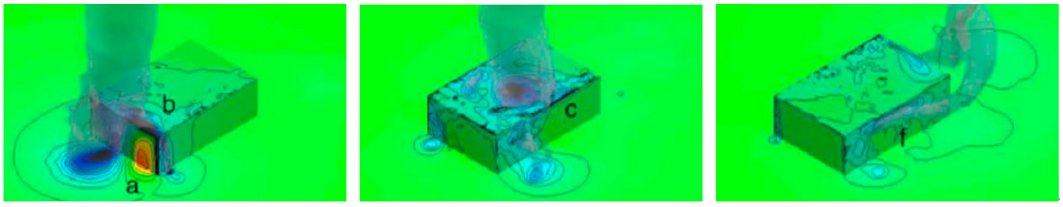


Figure 8. Relationship between vortex core and wall pressure distribution (Kataoka et al., 2020).

be used without the required basic knowledge and experience. However, although CWE is still incomplete and needs to be developed, applications of CFD to wind engineering have become widespread and essential in almost all areas of wind engineering.

2.4. Evaluation of aerodynamic force coefficients based on probabilistic method: Design fractile

The peak pressure coefficients and aerodynamic force coefficients in most codes and standards are prescribed based on the results of wind tunnel tests such as high-frequency force balance tests and/or simultaneous multi-channel pressure measurements. The prescribed values are an ensemble average of at most ten and/or twenty 10-minute samples. This means that an inherent randomness of 10-minute samples was not considered at all, and this makes it difficult to evaluate the exact probability density function and cumulative density function of the prescribed pressure coefficients and aerodynamic force coefficients.

Randomness in wind loads has been discussed since the late 1970s by Cook and Mayne (1979; 1980). They discussed how wind speed and peak pressure coefficient can be used together to arrive at a design load with a qualified risk of exceedance. They examined the value of a loading coefficient that results in a design wind load with the desired design risk, given a wind speed with the same risk. This question implies that the randomness of wind speed and loading coefficient need to be considered in the evaluation of design wind load. Here, the loading coefficients can be aerodynamic force coefficients for evaluating horizontal wind loads on structural frames (mean and fluctuating force coefficient) and peak pressure coefficients for evaluating wind loads on components and cladding. The optimal design fractile and comparison with the studies by Cook and Mayne were well summarized in Kasperski's studies (Kasperski, 2003; Kasperski, 2009). Lo and Tseng (2017) examined the effects of surrounding buildings on peak pressure coefficients, focusing on the tail characteristics of extreme value distributions and coefficients of variation (c.o.v.) of extreme values.

Recently, Kim and Kinoshita (2023) and Kim and Cao (2023) investigated the probability density distributions of peak pressure coefficients and aerodynamic force coefficients, and evaluated the values corresponding to the specific non-exceedance probabilities or cumulative probabilities based on the probabilistic method. Kim and Kinoshita (2023) evaluated the peak pressure coefficients on a low-rise building corresponding to the three non-exceedance probabilities and proposed adjusting factors based on each low-rise building zone as shown in Table 1. Kim and Cao (2023) also evaluated the probability density functions of mean and fluctuating force coefficients on three tall buildings with aspect ratios of 4, 6, and 8 and evaluated the adjusting factors corresponding to the three non-exceedance probabilities. They found that the probability distributions of all the mean and fluctuating aerodynamic force coefficients follow a normal distribution, and the adjusting factors were less than 2% even for the non-exceedance probability of 0.999. The effect of c.o.v. of annual wind speed on the adjusting factor is larger than that of the annual non-exceedance probability of wind load for both local force and generalized force coefficients. And, as shown in Figure 9, the adjusting factors from the Gumbel distribution were larger than those from the normal distribution.

It can be said that studies conducted so far have been

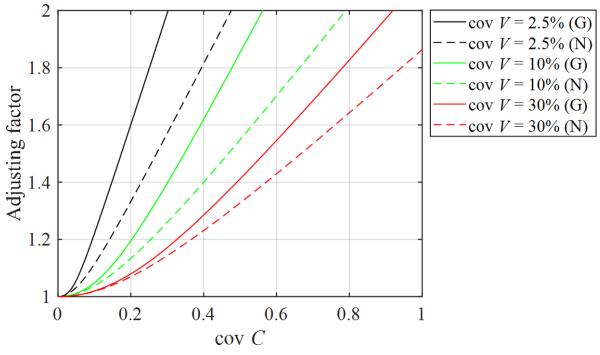
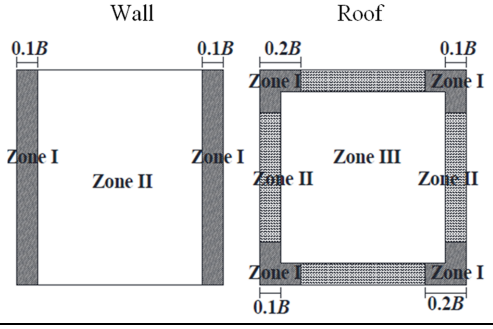


Figure 9. Adjusting factors for different probability distributions of aerodynamic force coefficients (G indicates Gumbel distribution and N indicates Normal distribution, Wind speed was assumed to follow a Gumbel distribution and $P_{W,target}$ = 0.999) (Kim and Cao, 2023).

Table 1. Adjusting factors for positive and negative peak pressure coefficients for design (Kim and Kinoshita, 2023).

$P_{W,target}$	Positive	Negative					Zones for peak pressure coefficient on low-rise building
		Wall		Roof			
		Zone I	Zone II	Zone I	Zone II	Zone III	
0.98	1.05	1.1	1.1	1.1	1.05	1.1	
0.99	1.05	1.1	1.1	1.1	1.05	1.1	
0.999	1.1	1.1	1.1	1.1	1.1	1.1	



very limited. (i) For low-rise buildings, only a flat-roof low-rise building was used. But gable and hip roof low-rise buildings are also common, and rectangular and irregular cross-sectional low-rise buildings should also be considered. (ii) For tall buildings, only mean and fluctuating force coefficients were considered. In the design of tall buildings, both horizontal wind loads on structural frames (mean and fluctuating force coefficients) and wind loads on components and cladding need to be considered, and the peak pressure coefficients determine the wind loads on components and cladding. Similar to the low-rise building in Kim and Kinoshita (2023), adjusting factors based on the zone of a tall building need to be evaluated.

2.5. Estimation of tornadic wind speed: Japanese Enhanced Fujita scale (JEF scale)

Tornadoes are known to be the most violent and damaging meteorological phenomena, and 40~50 tornadoes occur per year in Japan, most of them near the coastline (Tamura et al., 2015). Lots of studies discussing characteristics of tornadic wind, tornadic load, and impact loads by tornado-borne debris have been conducted based on field measurements, wind tunnel tests and computational fluid dynamics. But the present study focuses on the recent development of an estimation of tornadic wind speed using the Fujita scale.

As tornado wind speeds are difficult to determine with existing ground-based anemometers, Fujita (1971) developed the Fujita scale to support wind speed estimation for strong-wind phenomena based on damage to buildings and structures. However, considering the issues as (i) correspondence between damage descriptions and wind speeds has not been adequately verified, (ii) a limited number of indicators are available, the Enhanced Fujita (EF) scale was developed in the US in 2006, Canada in 2013, and Japan in 2015.

The Japanese Enhanced Fujita (JEF) scale was formulated on the basis of cutting-edge expertise in wind engineering with reference to the US EF scale to enable more accurate estimation of tornado intensity in Japan (Japan Meteorological Agency, 2015). While each class in the Fujita scale corresponds to a wind speed range, each combination of DIs and DODs in the JEF scale corresponds to wind speed values.

On the JEF scale, damage and its severity used for rating wind speed are described using two factors, Damage Indicator (DI) and Degree of Damage (DOD), and thirty types of buildings and structures including vehicles and trees are used as DI, and multiple DODs are defined for each DI. DIs in JEF scale are shown in Table 2, and currently many other indicators of damage such as ships, various kinds of claddings, and roadside trees are under consideration.

2.6. Effect of Ekman Spiral on tall building

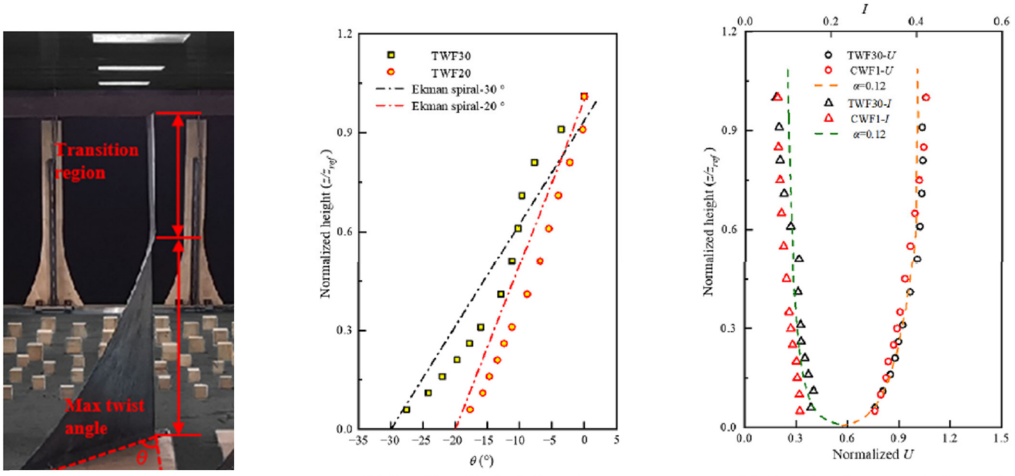
Current wind-resistant designs of tall buildings are based on a conventional model of atmospheric boundary layer (hereafter, ABL) winds which assumes that the wind direction remains constant with height. However, the direction of ABL winds actually varies with height due to the Coriolis force and surface roughness, and such twisted wind is known as the Ekman spiral. Additionally, twisted wind may also occur because of topographical features such as mountains and hills, which can redirect the wind direction horizontally. As shown in Table 3, although previous studies demonstrated that the wind

Table 2. Damage Indicators in JEF scale

No.	Damage Indicators	No.	Damage Indicators
1	Wooden houses and stores	16	Railway vehicles
2	Industrialized steel-framed houses (prefabricated)	17	RC utility poles
3	RC apartment buildings	18	Ground-based billboards
4	Temporary buildings	19	Traffic signs
5	Large eaves	20	Carports
6	Steel-framed warehouses	21	Hollow concrete block (HCB) walls
7	Small non-residential wooden buildings	22	Wooden, plastic, aluminum or mesh fences
8	Greenhouses, gardening facilities	23	Windbreak or snow break fences for roads
9	Wooden livestock sheds	24	Net fences
10	Small sheds	25	Broad-leaved trees
11	Shipping conditioners	26	Coniferous trees
12	Vending machines	27	Gravestones
13	Light vehicles	28	Road surfaces
14	Ordinary vehicles	29	Temporary scaffolding (with wall ties)
15	Large vehicles	30	Gantry cranes

Table 3. Summary of past studies on twisted angle in ABL

Literature	Height above ground	Twisted angle
Dyrbye and Hansen (1997)	1 to 1.5 km	Around 10° to 30°
Mendenhall (1967)	-	Oceans: about 10°, Land: about 20°
Tamura et al., (2007)	50 and 340 m	Around 20°
Liu et al., (2018)	over the first 1000 m	Around 5° to 40°
He et al., (2016) and Shu et al., (2018)	within the first 1.0 km	Around 20° to 40°



(a) Setting of guide vane (b) Profile of wind direction (c) Profile of mean wind speed

Figure 10. Shape of guide vane and profiles of oncoming flows (Yan et al., 2022).

direction definitely changes with height within the ABL, its effect on tall buildings has seldom been considered in current wind-resistant design. It can be intuitively understood that the wind pressure distribution on tall buildings under twisted wind may significantly differ from those predicted using the conventional ABL model. Hence, failure to take into account the twisted wind effect may lead to inaccurate estimates of wind load on tall buildings and even have a negative impact on wind-resistant performance. In order to understand the wind effect on tall buildings more comprehensively, the effect of twisted wind needs to be further investigated.

Consideration of twisted wind in wind tunnel tests first began with sail aerodynamics in the 1990s. By arranging guide vanes at upstream locations, Flay (1996) and Flay et al., (1996) made one of the first successful attempts to simulate twisted winds that are consistent with field measurements. Since then, guide vanes have been commonly employed for the generation of twisted winds as shown in Figure 10, usually with certain modifications of their shape to satisfy specific purposes (Tse et al., 2016; Liu et al., 2019; Zhou et al., 2021 and 2022; Yan et al., 2022).

However, characteristics of Ekman spiral flow need to be investigated in more detail in the future, and its effect on tall and super-tall buildings becomes very significant, when considering that lots of tall and super-tall buildings higher than 300 m are still under construction around the world.

3. Concluding Remarks

This paper has discussed some of current issues in wind engineering and it is very difficult to draw definitive concluding remarks because they are very subjective ones. However, it can be generally concluded that recent growth of application of computational fluid dynamics to wind engineering (CWE) is remarkable on account of both development of computer technology and computational methods. In the future, the application of CWE is expected to become a more reliable option, but many other problems should be solved beforehand. And as wind tunnel tests and LES calculations take a lot of time and energy, the need for enhancement of aerodynamic databases such as for tall buildings with atypical building shapes, and related AI-assisted design should be increased and accelerated. Lastly, there are many issues that current codes and standards cannot cover, and the author hopes that these issues will be solved in the near future, even though sometimes it is very challenging to find solutions and directions.

4. Acknowledgments

This research was supported by the State Key Laboratory

of Disaster Reduction in Civil Engineering, Tongji University (Project No. SLDRCE21-05). The authors gratefully acknowledge this support.

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