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Field Measurements of Wind-induced Responses of Shanghai World Financial Center: Investigation of Amplitude-dependent Damping

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Abstract

Shanghai World Financial Center (SWFC) has a height of 492 m and is 101-stories tall. This paper describes the results obtained from the field measurements of wind effects on this super-tall building during the period from 2011 to 2016. According to acceleration responses at the top of SWFC to a large number of wind events, the damping ratios of this building are evaluated by the envelope random decrement technique. A linear regression model fitted by least square method is used to express the variations in damping ratios with vibration amplitude. The amplitude-dependent damping ratios of SWFC are compared with those of other super-tall buildings. It is found that damping ratios of SWFC for the fundamental mode in the x- and y-directions are small, and the damping ratios increase with the increase of vibration amplitude. The coefficients of linear regression model are approximately identical for SWFC and Canton Tower (432 m). Moreover, the increasing trend in damping with amplitude is consistent in buildings constructed with different material and under different wind conditions.

Introduction

With the advent of new materials, new technology, and innovative structural systems, a number of super-tall buildings have been constructed throughout the world in recent years. Because of high structural flexibility and remarkably increased wind speed at higher altitudes, wind resistance is one of the most important issues at the design stage for super-tall buildings. On one hand, the varied appearances and configurations may not only change the directional dynamic properties of these structures but may also lead to complicated fluid-structure interactions that are different from normal buildings with regular shapes [4],[16]. On the other hand, because of the shortage of credible wind records at high altitudes over land, most wind codes or design standards still use the traditional modes of atmospheric boundary layer. Consequently, they are not guaranteed to fully cover the wind-resistant design of super-tall buildings [7].

Field measurements have been regarded to be able to provide the most reliable evaluations of dynamic characteristics and wind effects. During the last two decades, a number of full-scale measurements of wind effects on tall buildings have been made throughout the world, including four Chicago tall buildings by Kijewski-Correa and Pirnia [10], Di Wang Towr by Fu et al. [2], TWO IWC building by Yi et al. [17], The Center by Li et al. [13], Canton Tower by Y.L.Guo et al. [17] and SWFC by An et al. [1], Quan et al. [15], He and Li [5]. Unfortunately, most field measurements of wind effects that have been published in the literature focus on responses and dynamic properties of super-tall buildings during only one typhoon. And most of the full-scale monitoring efforts have not been sustained long enough to observe responses under a wide spectrum of wind events.

Furthermore, with modern tall buildings becoming taller and more flexible, the determination of damping ratios is becoming increasingly significant to exactly estimate responses of high-rise structures at the design stage. And the damping ratios are usually chosen to be constants in the design phase. However, Damping is found as a nonlinear parameter and increases with increasing amplitude [11]. The differences between parameters of the real structure and those in the design phase would cause the structure's responses in the two situations to be different. Li et al. [11] have compared a building's dynamic responses computed using the measured damping characteristics to those computed with several constant damping parameters by a numerical simulation. Results showed that the predicted response using the amplitude-dependent damping characteristics were larger than those obtained adopting the constant damping ratios [6]. Therefore, conducting the filed measurements and identifying the amplitude-dependent damping ratios of real buildings are important for the parameter selection in structural dynamic analysis and design.

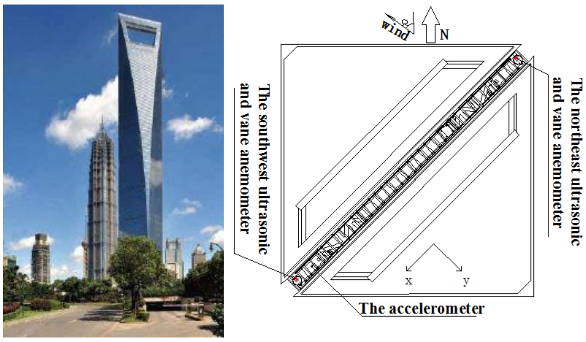
Therefore, in order to fully understand amplitude-dependent damping of super-tall buildings, this paper explores the field acceleration data of last six years, obtained through the field measurements at the top of the Shanghai World Financial Center. Firstly, damping ratios of SWFC are evaluated by the envelope random decrement technique [6], then a linear regression model fitted by least square method is used to analyse the variations in damping ratios with the vibration amplitude. Moreover, the damping ratios of SWFC under different wind conditions are compared. Lastly, the amplitude-dependent damping of SWFC are compared with those of other super-tall buildings, which are constructed with different material.

Shanghai World Financial Center and Measurement Instrumentation

Shanghai World Financial Center is 492 m high, with 101 stories, as shown in figure 1(a). The shape of it is a 58×58×492-m prism (aspect ratio is 8.48), which is chamfered along one couple of the across corners from the building top gradually to its bottom part, with a trapezoidal air-leaking tuyere at the upper part to reduce the wind loads [5]. Three parallel structural systems including mega-frame structure, reinforced concrete and braced steel services core, and outrigger trusses, are combined to resist vertical and lateral loads [14].

SWFC is located in the Lujiazui Financial and Trade district of Shanghai, which is often affected by typhoon-made landfalls in the eastern coastlines in China. In order to mitigate wind-induced vibration under strong winds, two identical active tuned mass dampers (ATMDs) are symmetrically installed on the north-eastern side and south-western side of the ninetieth floor (90F, 395 m). It is surrounded by a large number of tall and super-tall buildings such as the Jin Mao Building (421 m) and the Oriental Pearl TV Tower (468 m), making its surrounding terrain extremely complex.

The field measurement instrumentation installed in the SWFC mainly consists of one accelerometer on the 101st floor (492 m) of the building, one pair of ultrasonic anemometers and one pair of vane anemometers on the northeast and southwest corner (494 m). The direction of wind is defined as follows: its 0 degree mark points directly north and its values increase in a counter clockwise direction as viewed from the top, as shown in figure 1(b).



(a) (b)

Figure 1. (a) SWFC; (b) Location of the measurement instrumentation

The accelerometer is a LACC-1, ultra-low frequency, wireless, acceleration measurement instrument, whose sampling frequency is 25 Hz, range is milli-g (milli-g = millesimal gravitational acceleration) and resolution is 0.01 milli-g, as shown in figure 2(a). Its two horizontal orthogonal axes are parallel to the building's horizontal orthogonal x- and y-axes. The ultrasonic anemometer is Windmaster Proultrasonic anemometer (Gill Instruments, U.K.) and the measurement range of it is from 0.01 to 65 m/s, with a sampling frequency of 10 Hz, as shown in figure 2(b). Its two orthogonal axises are defined as the north and west directions of the ultrasonic anemometer respectively. The real-time storage of the acquired data is achieved by CR1000 data acquisition system program produced by Campbell Scientific, Inc. The vane anemometer is RM Young's Wind Monitors and the measurement range of it is from 0 to 100 m/s, with a sampling frequency of 1 Hz, as shown in figure 2(c).

(a) (b) (c)

Figure 2. (a) accelerometer; (b) ultrasonic anemometer; (c) vane anemometer

Data Analysis Procedure

In order to meet the requirement of the quantity of acceleration data in identifying damping ratios by Envelop RDT [6], 2 hour is chosen as the analysed time interval. Since the resolution of accelerometer is only 0.01 milli-g, the measurement error of low acceleration would be large. So this paper uses 2-h segments of acceleration if their RMS is larger than 0.01 milli-g. Also, when the wind-induced response of SWFC is large, ATMDs installed on the ninetieth floor will operate, increasing the total damping of SWFC. Thus, this paper does not consider 2-h segments of acceleration when ATMDs are on work. To meet these two requirements for segments of acceleration, 1610×2hr acceleration data in x-direction and 2330×2hr acceleration data in y-direction are selected in this paper.

For every 2-h segment of acceleration, the damping ratio of SWFC for fundamental mode is identified by the Envelop RDT [6] and the RMS of acceleration is regarded as the vibration amplitude. The relationship between the damping ratio and the vibration amplitude is analysed.

Results and Discussion

Figure 3 shows the variations in the damping ratios of the Shanghai World Financial Center for fundamental mode with vibration amplitude. Information on such amplitude-dependent damping obtained from acceleration response data of six years should be very useful, since similar measurements are still very limited for such super tall buildings. According to the measured data, it can be seen that the vibration in y-direction is larger than that in x-direction, but the damping ratios in both directions are approximately identical. When the vibration amplitude is low, damping ratios in the x- and y-directions are ranged from 2‰ to 6‰. He and Li [5] also estimated the damping ratios of SWFC for fundamental mode in x- and y-directions to be 5.84‰ and 4.10‰ respectively by the method of modified time-weighted RDT when ATMDs were turned off, which are within the range of damping ratios identified in this study. This validates damping ratios estimated by the Envelop RDT in this paper.

Although the scatter of damping ratios is large, it still can be seen from the measured data in figure 3 that when the vibration amplitude increases, damping ratios increase in both directions. P.Jeary [8] explained that with the increase of vibration amplitude, small elements increasingly undergo relative movement. In this regime the differential movement manifests itself as micro-crack elongation in the material of a structure, leading to energy being dissipated. Thus, the phenomenon that damping ratio increases with the increase of vibration amplitude is understandable.

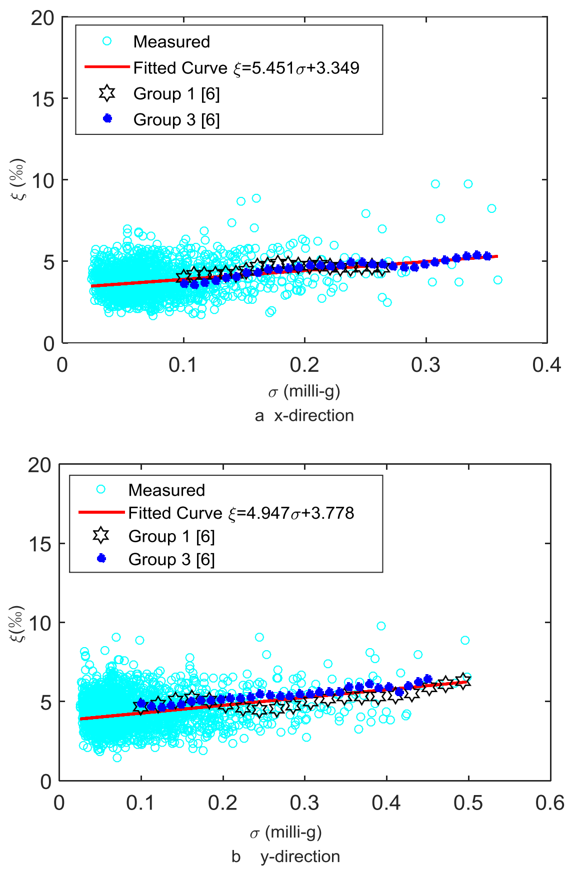


Figure 3. Variations in damping ratios for fundamental mode with vibration amplitude (a) x-direction (b) y-direction.

The measured data presented in figure 3 are fitted by least square method, and a linear regression model is used and expressed as follows,

$$\xi=\beta_0\sigma+\beta_1 \quad (1)$$

where σ is the vibration amplitude in milli-g; ξ is the damping ratio in ‰; β_0 and β_1 are the regression coefficients, where β_0 represents the change ratio of the damping ratio with the vibration amplitude and β_1 represents the damping ratio of building when its vibration amplitude is zero, which can be seen as the structural damping of the building.

Coefficients β_0 and β_1 of SWFC fitted by field data of this study are listed and compared with those of Canton Tower [3], as shown in table 1. It is showed that the range of β_0 is 5–7 (‰•milli-g^{-1}) (except the β_0 of Canton Tower in x-direction, which is larger), meaning the increasing trends in damping ratios with the increase of vibration amplitude are consistent among these two super-tall buildings; the range of β_1 is 3‰–5‰, meaning the structural damping of SWFC and Canton Tower is approximately identical and small.

According to the fitting curve in figure 3, when the vibration amplitude increases from 0.03 milli-g to 0.35 milli-g in x-direction and from 0.03 milli-g to 0.5 milli-g in y-direction, the damping ratios for fundamental mode increase from 3.51‰ to 5.27‰ and from 3.93‰ to 6.25‰ respectively. In figure 3, there is also an increase in damping ratios with the increase of the vibration amplitude based on field data of Group 1 and Group 3 measured on the top of SWFC during the typhoon Muifa [6].These data are on the fitting curve, validating the measured data in this paper. He and Li [5] also investigated the acceleration responses of SWFC during the typhoon Muifa by the method of RDT and found the increase of damping ratios with the vibration amplitude. When the vibration amplitude increased from 0.12 milli-g to 0.35 milli-g, the damping ratios for fundamental mode in y-direction increased from 5‰ to 17.8‰. Compared with the damping ratios obtained in this study, the damping ratios from the work of He and Li, are a bit larger. This is understandable because the field measurements by them were carried out when the ATMDs were in operation discontinuously. Therefore, both under moderate wind conditions and under typhoon Muifa, the increasing trend in damping ratios with amplitude is consistent.

Many other researchers also investigated amplitude-dependent characteristics of damping ratios of super-tall buildings and found that damping ratios increased with the increase of vibration amplitude [2]. The increasing ranges of vibration amplitude and corresponding damping ratios of SWFC are compared with those of other super-tall buildings, as shown in table 2. C1 and C2 are two super-tall buildings in the Chicago Full-Scale Monitoring program undertaken by Notre Dame University [10], and P1 is a super-tall building in Busan, Korea [9].

From table 2, there is no obvious changing trend in damping with the height or with the type of material of different buildings, since damping ratios are related with many characteristics of buildings. However, the increasing trend in damping with the amplitude is consistent in these ten super-tall buildings, even though they were constructed with different types of material such as concrete, reinforced concrete, steel and steel reinforced concrete. It is seen that for Central Plaza, when its vibration amplitude in x-direction increases from 0.03 milli-g to 0.14 milli-g, its damping ratio increases by 30% from 4.82‰ to 6.27‰ and when its vibration amplitude in y-direction increases from 0.03 milli-g to 0.10 milli-g, its damping ratio increases by 35% from 3.57‰ to 4.83‰; Similarly, for CITIC Plaza with small change range of vibration amplitude, its damping ratios in x- and y-directions grow by 41% and 74% respectively; For other super tall buildings, the change range of vibration amplitude in x- and y-directions are 0.03–0.35 milli-g and 0.03–0.5 milli-g respectively, and their damping ratios grow by 50%–200% in both directions. The damping ratios of these ten super tall buildings for fundamental mode are nearly lower than 10‰.

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Building	Height/ (m)	Material	x-direction β_0/ (‰•milli-g^{-1})	x-direction β_1/ (‰)	y-direction β_0/ (‰•milli-g^{-1})	y-directionβ_1/ (‰)
Canton Tower[3]	454	Steel	16.32	4.14	6.54	5.08
SWFC(this paper)	492	Steel Reinforced Concrete	5.45	3.35	4.95	3.78

Table 1. Comparison of coefficients β_0 and β_1 between Shanghai World Financial Center (SWFC) and Canton Tower.

Building	Height/ (m)	Material	x-direction σ/ (milli-g)	x-direction ξ / (‰)	y-direction σ (milli-g)	y-direction ξ / (‰)
C1[10]		Steel	0.04-0.35	4.00-7.75	0.04-0.50	2.75-8.50
C2[10]		Concrete	0.04-0.35	8.40-12.84	0.03-0.25	15.31-22.96
P1[9]	134	Reinforced Concrete	0.03-0.35	5.79-11.65	0.03-0.35	8.32-13.54
Di Wang[2]	325	Steel Reinforced Concrete	0.03-0.35	2.60-4.90	0.03-0.50	3.08-5.36
The Center[13]	350	Steel	0.03-0.35	2.19-3.29	0.03-0.50	2.58-3.39
Central Plaza[12]	374	Concrete	0.03-0.14	4.82-6.27	0.03-0.10	3.57-4.83
CITIC Plaza[2]	391	Concrete	0.03-0.20	3.69-5.22	0.03-0.15	3.02-5.26
TWO IWC[17]	420	Steel Reinforced Concrete	0.08-0.35	5.00-13.00	0.08-0.50	4.90-13.00
Canton Tower[3]	432	Steel	0.03-0.35	4.63-9.85	0.03-0.50	5.28-8.35
SWFC1[6]	492	Steel Reinforced Concrete	0.10-0.35	4.00-5.00	0.10-0.50	4.80-6.30
SWFC3[6]	492	Steel Reinforced Concrete	0.10-0.35	3.60-5.30	0.10-0.45	4.80-6.40
SWFC(this paper)	492	Steel Reinforced Concrete	0.03-0.35	3.51-5.27	0.03-0.50	3.93-6.25

Table 2. Comparison of increasing ranges of vibration amplitude and corresponding ranges of damping ratios between Shanghai World Financial Center (SWFC) and other super-tall buildings.

Conclusions

Based on the field measurement data of acceleration on the top of SWFC over the last six years, damping ratios were obtained by the envelope random decrement technique and the variations in damping ratios with the amplitude were analysed. The conclusions from this study are summarized as follows.

(1) Despite of the large scatter of damping ratios, there were increasing trends in damping ratios in x- and y-directions when the vibration amplitude increased. Most damping ratios of SWFC in both directions were ranged from 2‰ to 6‰ when the vibration amplitude was small.

(2)A linear regression model fitted by least square method was used to express the increasing trend in the damping ratios with the increase of vibration amplitude. The regression model in x- and y-directions were ξ=5.451σ+3.349 and ξ=4.947σ+3.778 respectively.

(3)From the fitting curve, when the vibration amplitude in x- and y-directions increased from 0.03 milli-g to 0.35 milli-g and from 0.03 milli-g to 0.5 milli-g, the damping ratios for fundamental mode increased from 3.51‰ to 5.27‰ and from 3.93‰ to 6.25‰ respectively.

(4) Both under moderate wind conditions and under the typhoon, the increasing trend in damping ratios with amplitude is consistent. This trend for super-tall buildings is also consistent in different types of material such as concrete, steel, reinforced concrete and steel reinforced concrete.

Acknowledgments

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References

[1] An, Y., Y. Quan, & M. Gu., Field Measurement of Wind Characteristics of Typhoon Muifa on the Shanghai World Financial Center, *International Journal of Distributed Sensor Networks*, **1–3**, 2012, 34-63.

[2] Fu, J. Y., et al., Field measurements of boundary layer wind characteristics and wind-induced responses of super-tall buildings, *J. Wind Eng. Ind. Aerodyn.*, **96**, 2008, 1332-1358.

[3] Guo, Y. L., et al., Performance evaluation of Canton Tower under winds based on full-scale data, *J. Wind Eng. Ind. Aerodyn.*, **104–106**, 2012, 116–128.

[4] Hayashida, H., and Y. Iwasa, Aerodynamic shape effects of tall building for vortex induced vibration, *J. Wind Eng. Ind. Aerodyn.*, **33**, 1990, 237-242.

[5] He, Yun Cheng, & Q. Li., Dynamic responses of a 492 - m - high tall building with active tuned mass damping system during a typhoon, *Struct. Control Health Monit.*, **21**, 2013, 705-720.

[6] Huang, Zifeng, & M. Gu, Envelope Random Decrement Technique for Identification of Nonlinear Damping of Tall Buildings, *J. Struct. Eng.*, **142**, 2016, 04016101.

[7] Irwin, Peter A., Wind engineering challenges of the new generation of super-tall buildings, *J. Wind Eng. Ind. Aerodyn.*, **97**, 2009, 328-334.

[8] Jeary, A. P., The description and measurement of nonlinear damping in structures, *J. Wind Eng. Ind. Aerodyn.*, **59**, 1996, 103–114.

[9] Ji, Young Kim, et al., Calibration of analytical models to assess wind-induced acceleration responses of tall buildings in serviceability level, *Engineering Structures*, **31**, 2009, 2086-2096.

[10] Kijewski-Correa, Tracy, & J. D. Pirnia, Dynamic behavior of tall buildings under wind: insights from full-scale monitoring, *Struct. Design Tall Spec. Build.*, **16**, 2007, 471–486.

[11] Li Q S, Yang K, Wong C K, et al, The effect of amplitude-dependent damping on wind-induced vibrations of a super tall building, *J. Wind Eng. Ind. Aerodyn.*, **91**,2003, 1175-1198.

[12] Li, Q. S., Y. Q. Xiao, & C. K. Wong, Full-scale monitoring of typhoon effects on super tall buildings, *Journal of Fluids & Structures*, **20**, 2005, 697-717.

[13] Li, Q. S., et al., Typhoon effects on super-tall buildings, *Journal of Sound & Vibration*, **313**, 2008, 581-602.

[14] Lu, Xilin, et al., Shaking table model test on Shanghai World Financial Center Tower, *Earthquake Engng Struct. Dyn.*, **36**, 2007, 439-457.

[15] Quan, Yong, et al., Field Measurement of Wind Speeds and Wind-Induced Responses atop the Shanghai World Financial Center under Normal Climate Conditions, *Mathematical Problems in Engineering*, **1056**, 2013, 469-481.

[16] Tanaka, Hideyuki, et al., Experimental investigation of aerodynamic forces and wind pressures acting on tall buildings with various unconventional configurations, *J. Wind Eng. Ind. Aerodyn.*, **107–108**, 2012, 179–191.

[17] Yi, J., J. W. Zhang, & Q. S. Li, Dynamic characteristics and wind-induced responses of a super-tall building during typhoons, *J. Wind Eng. Ind. Aerodyn.*, **121**, 2013, 116-130.