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Structural responses of a high-rise building during three severe typhoons

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Abstract

This paper analyses 72-hour-long field measurement data collected by a long-term structural health monitoring (SHM) system at a 420-meter-high building in Hong Kong during the passages of three severe typhoons. In this study, wind characteristics of these typhoons over the monitored high-rise building are presented; structural dynamic properties of the building are discussed using random decrement technique and Bayesian spectral density approach (a probabilistic approach in the Bayesian framework); and the building's serviceability under typhoon conditions is evaluated against three comfort criteria. This study aims to further the understanding of wind effects on high-rise buildings so as to provide useful information for the wind-resistant structural designs.

Introduction

Since field measurements monitor structural responses from a prototype structure directly, it has been widely accepted as the most reliable and convincing approach to investigate wind effects on structures. Over the past few decades, numerous field measurements of dynamics responses of high-rise structures under wind actions have been conducted [3, 8, 12-13, 21, 23]. In particular, a full-scale monitoring program on three tall buildings in Chicago has been conducted [10]; a monitoring system in Burj Khalifa which is currently the tallest building in the world has been established [11]; structural performances of various super-tall buildings under typhoon conditions were evaluated [15-19]. However, the opportunities to conduct field measurements of wind effects on high-rise buildings during severe wind events such as tropical cyclones are still considerably rare, and more field studies are thus needed.

Based on 72-hour-long field measurement data collected by a structural health monitoring (SHM) system during three severe typhoons, this study investigates the structural performance of a 420-meter-high office building in Hong Kong under strong windstorms. The organization of this paper is as follows: Section 2 introduces the SHM system; Section 3 presents the wind characteristics of three monitored typhoons; Section 4 estimates structural dynamic properties of the monitored building with usage of random decrement technique (RDT) and Bayesian spectral density approach (BSDA), and evaluates the building's serviceability during these wind events.

Monitored High-rise Building

Building site

As shown in Figure 1, which is an aerial photo of Hong Kong city center, the monitored super-tall building is located on the northern coast of Hong Kong Island (geographic coordinates: 22°17'7"N, 114°09'33"E). A large number of tall buildings over 150 m in height are located closely to the monitored building to its east, south, and west. Victoria Harbor is located in the north of the monitored building, where is an open water terrain with a minimal width approximately 1 km. The southern part of Kowloon Peninsula in the north of Victoria Harbor is a densely built-up terrain with a great number of tall buildings over 100 m in height.

Figure 1. Aerial photo of Hong Kong city center and building site.

SHM system

The long-term structural health monitoring (SHM) system is installed in the high-rise building shown in Figure 2(a). The monitored structure is currently the second tallest building in Hong Kong with a height of 420 m. Its cross section is convex-square shaped, while its width tapers gradually from 57 to 39 m with its height. The right side of Figure 2(b) shows a data acquisition unit that recorded the field measurement data at a sampling frequency of 20 Hz, while in the meantime these measurements are visualized and displayed by a control panel software shown on the left side. The approaching wind speed and direction atop the building during the 3 typhoons were measured by a Young 05103 propeller anemometer (R. M. Young Company, Traverse City, Michigan), with an accuracy of wind speed within ±0.3 m/s and that of wind direction within ±3°. As shown in Figure 2(c), the anemometer was fixed on a mast at a height of approximately 14 m above the building roof, or equivalently, 419.32 m above mean sea level (AMSL). Meanwhile, structural responses of the high-rise building during these typhoons were measured by a pair of orthogonally placed accelerometers shown in Figure 2(d). These two accelerometers were located at the building center on the top floor (398.87 m AMSL) to measure accelerations in two orthogonal directions, namely X- and Y-directions as indicated in Figure 2(e), respectively.

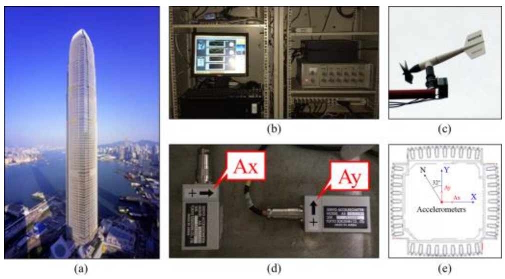

Figure 2. The monitored high-rise building and SHM system: (a) building exterior; (b) control panel of SHM; (c) propeller anemometer; (d) High-resolution accelerometers; (e) locations of the accelerometers and directions X and Y.

Monitored Typhoon Events

Typhoon No.	Typhoon name	Duration (hr)
1	0812 Nuri	36
2	1208 Vicente	18
3	1319 Usagi	18

Table 1. Monitored typhoon events.

This paper selects totally 72-hour-long field measurement data collected by the aforementioned SHM system, including wind speed, wind direction, and structural accelerations, during the passages of the three typhoons listed in Table 1. It is noted that structural performance of the monitored building during Typhoons ① (Nuri) and ② (Vicente) have been discussed in our previous studies [16 - 17]. As illustrated in Figure 3, all of these typhoons took a northwesterly path over the South China Sea towards inland and made landfall near Hong Kong. Especially, Typhoon ① passed over Hong Kong city center, and the closest distance between the typhoon eye and the monitored building was less than 2 km. Time histories of 10-min mean wind speed and direction atop the building are presented in Figure 4.

Figure 3. Tracks of monitored typhoons.

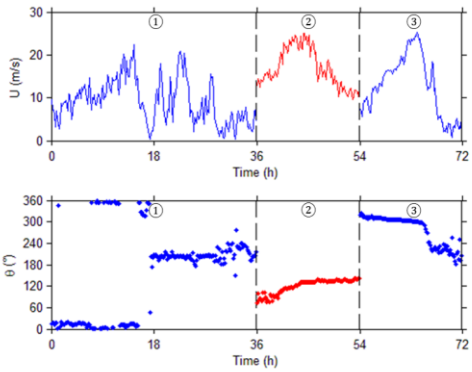

Figure 4. Time histories of 10-min mean wind speed and direction.

Structural Performance

Structural dynamic properties

Using the field measurement of accelerations, whose time histories are shown in Figure 5, the dynamic properties of the monitored high-rise building are estimated. This study employs the random decrement technique (RDT) [4] to describe the amplitude dependencies of building's natural frequencies as well as damping ratios, and the results are plotted in Figure 6 and Figure 7. In order to improve the reliability and accuracy of the RDT results, each random decrement signature (RDS) involved at least 500 segments as indicated in these two figures. It is shown that the fundamental frequency in X-direction gradually decreased from 0.141 Hz to 0.139 Hz as amplitude increased from 0 to 1.9 cm/s^2, while that in Y-direction dropped from 0.145 Hz to 0.143 Hz as amplitude raised from 0 to 1.7 cm/s^2. On the other hand, damping ratio in X-direction generally stabilized at 1.5% while that in Y-direction slightly increased from 1.2% to 2.0%. In previous studies, a number of damping predictors were proposed in terms of building height, natural frequency, and horizontal displacement. Figure 8 compares the damping ratios based on the measurements evaluated by the RDT with those predicted by six damping predictors [2, 5, 6, 8, 14, 22]. It is noted that in order to calculate the tip drift ratio corresponding to each RDS, the tip horizontal displacement was regarded as the double integral of the accelerations under the assumption that it is a sinusoidal vibration with equivalent viscous damping [3]. The results show that the models proposed by [2, 6], comparing with other models, showed the closest agreement with the field measurements. The model by [5], although it provided slightly conservative results, generally presented a similar tendency of the variation of damping with vibration amplitude. It is worth noting that building damping varies greatly among different buildings, and most of the existing damping predictors were derived using data collected from buildings with height less than 200 m.

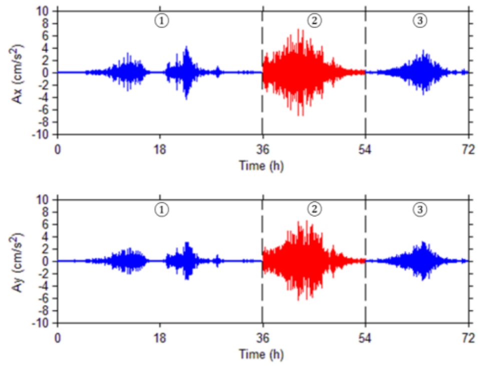

Figure 5. Time histories of building accelerations.

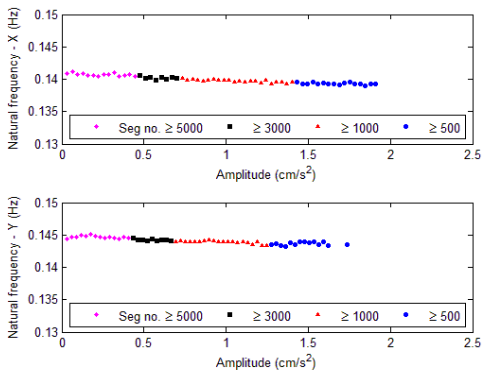

Figure 6. Amplitude-dependence of building natural frequencies estimated by the RDT.

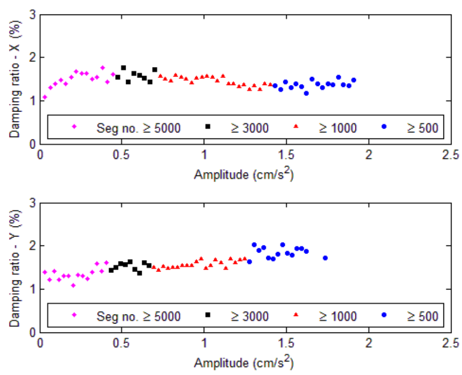

Figure 7. Amplitude-dependence of building damping ratios estimated by the RDT.

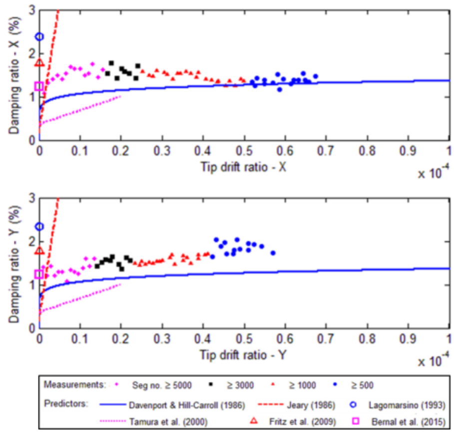

Figure 8. Comparisons between measured and predicted building damping ratios.

Traditionally, deterministic methods such as the RDT presented above are used to estimate modal parameters of a building, but these methods also lead to the neglect of the uncertainties of parameters. To take into account the uncertainties, this study employs Bayesian spectral density approach (BSDA) proposed by [9], which is a probabilistic approach in the Bayesian framework. Since the BSDA is applicable on the premise that external excitations are zero-mean Gaussian white noise, the data segments analyzed by the BSDA were first examined for their stationarities.

Figure 9 and Figure 10 present the building's natural frequencies and damping ratios estimated by the BSDA, respectively. The white circles represent the optimal estimations by the BSDA while the error bars indicate their associated confidence interval of 70%. The results show that the natural frequencies identified by the BSDA ranged from 0.138 Hz to 0.142 Hz in X-direction and from 0.142 Hz to 0.145 Hz in Y-direction, while the damping ratios in both directions varied between about 1% and 1.7%. As for the uncertainties, it is shown that the confidence intervals of 70 % for natural frequencies in both directions were less than 0.001 Hz, while those for damping ratios ranged approximately from 0.5% to 1%. In general, the estimations by the BSDA were in a good agreement with those by the RDT. Moreover, the BSDA is capable of estimating the modal forces applied on the building, and the results are shown in Figure 11. As expected, the variation of modal forces followed a similar tendency of the wind speed presented in Figure 4.

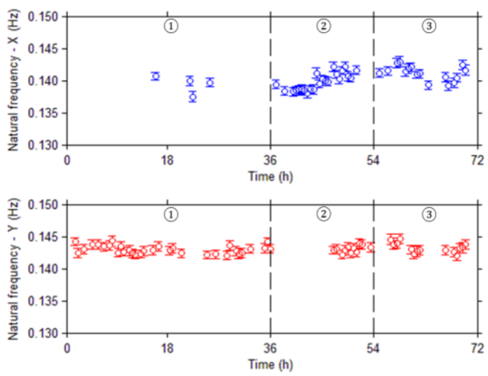

Figure 9. Natural frequencies estimated by the BSDA.

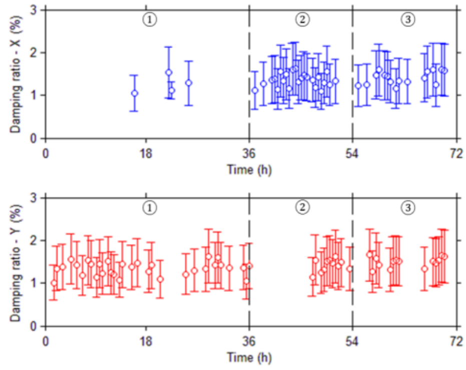

Figure 10. Damping ratios estimated by the BSDA.

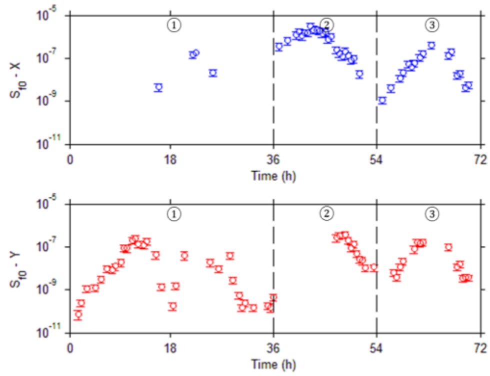

Figure 11. Building modal forces estimated by the BSDA.

Serviceability evaluations

Serviceability, or habitability, is of great concern in the design of wind-sensitive structures. This study employs three commonly adopted comfort criteria, namely AIJ Habitability Guidelines [1], ISO 10137 [7], and Melbourne and Palmer [20], to assess the serviceability of the monitored building. As presented in Figure 12, the building's peak responses were much lower than the criteria by [7, 20], and less than 70% of the habitant were able to sense the building vibrations during the most severe typhoon (Typhoon ②) according to [1]. Therefore, the serviceability of the monitored high-rise building during these three typhoons was satisfactory.

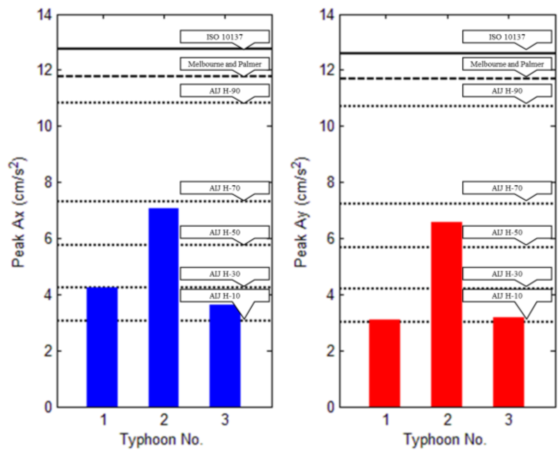

Figure 12. Comfort criteria and field-measured building's peak instantaneous accelerations.

Discussions

In this study, 72-hour-long field measurements of the wind effects on a 420-meter-high building in Hong Kong during the passages of three severe typhoons were analyzed and discussed; the random decrement technique (RDT) was employed to reveal the amplitude dependencies of natural frequencies and damping ratios; a recently proposed probabilistic method in Bayesian framework, namely the Bayesian spectral density approach (BSDA), was adopted to identify the modal parameters of the monitored high-rise building as well as their associated uncertainties; and the serviceability of the high-rise building during these typhoons was evaluated by three comfort criteria. As a time-domain method, the results by the RDT were significantly improved with the usage of a large amount of data, producing reliable and convincing estimations of amplitude dependencies of the modal parameters of this building. Meanwhile, as a probabilistic approach, the BSDA is able to identify the modal parameters with information of their associated uncertainties, and the results were in a good agreement with those obtained by the RDT. The serviceability of the high-rise building satisfied all the three comfort criteria during the monitored severe wind events.

Acknowledgments

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References

[1] Architectural Institute of Japan. Guidelines for the evaluation of habitability to building vibration. Japan, 2004.

[2] Bernal, Dionisio, Michael Döhler, Salma Mozaffari Kojidi, Kenny Kwan, & Yang Liu., First mode damping ratios for buildings. *Earthquake Spectra*, **31(1)**, 2015, 367-381.

[3] Campbell, S., Kwok, K. C. S., Hitchcock, P. A., Tse, K. T., & Leung, H. Y. Field measurements of natural periods of vibration and structural damping of wind-excited tall residential buildings. *Wind Struct.,* **10(5)**, 2007, 401–420.

[4] Cole, H. A. On-line failure detection and damping measurement of aerospace structures by random decrement signatures. NASA CR-2205, *National Technical Information Service, VA.* 1973.

[5] Davenport, A.G., and Hill-Carroll, P., Damping in tall buildings: Its variability and treatment in design, *Proceedings of Building Motion in Wind, a session of the ASCE Convention*, Seattle, Washington, April 8, 1986, 42-57.

[6] Fritz, William P., Nicholas P. Jones, and Takeru Igusa., Predictive models for the median and variability of building period and damping. *J. Struct. Eng.,* **135(5)**, 2009, 576-586.

[7] ISO. Bases for design of structures - Serviceability of buildings and walkways against vibrations. *ISO 10137*, International Organization for Standardization (ISO), 2007, Geneva.

[8] Jeary, A. P., Damping in tall buildings, a mechanism and a predictor. *Earthquake Eng. Struct. Dyn.*, **14(5)**, 1986, 733–750.

[9] Katafygiotis, L. S. & Yuen, K. V. Bayesian spectral density approach for modal updating using ambient data, *Earthquake Eng. Struct. Dyn.*, **30(8)**, 2001, 1103-1123.

[10] Kijewski-Correa, T., Kilpatrick, J., Kareem, A., Kwon, D. K., Bashor, R., Kochly, M., Young, B. S., Abdelrazaq, A., Galsworthy, J., Isyumov, N., & Morrish, D. Validating wind-induced response of tall buildings: Synopsis of the Chicago full-scale monitoring program. *J. Struct. Eng.*, **132(10)**, 2006, 1509-1523.

[11] Kijewski-Correa, T., Kwon, D. K., Kareem, A., Bentz, A., Guo, Y., Bobby, S. & Abdelrazaq, A. SmartSync: An integrated real-time structural health monitoring and structural identification system for tall buildings. *J. Struct. Eng.*, **139(10)**, 2013, 1675-1687.

[12] Kuok, S.C. & Yuen, K.V. Structural health monitoring of Canton Tower using Bayesian framework. *Smart Struct. Syst.*, **10(4-5)**, 2012, 375–391.

[13] Kuok, S. C., & Yuen, K. V. Structural health monitoring of a reinforced concrete building during the Severe Typhoon Vicente in 2012. *Scientific World J.*, 2013, doi: 10.1155/2013/509350

[14] Lagomarsino, S. Forecast models for damping and vibration periods of buildings. *J. Wind Eng. Ind. Aerodyn.*, **48(2-3)**, 1993, 221-239.

[15] Li, Q. S., Fang, J. Q., Jeary, A. P., & Wong, C. K. Full scale measurement of wind effects on tall buildings. *J. Struct. Eng.*, **74–76**, 1998, 741–750.

[16] Li, Q. S., Li, X. & He, Y.C. Monitoring Wind Characteristics and Structural Performance of a Supertall Building during a Landfall Typhoon. *J. Struct. Eng.*, **142(11)**, 2016, 04016097.

[17] Li, Q. S., Li, X., He, Y. & Yi, J., Observation of wind fields over different terrains and wind effects on a super-tall building during a severe typhoon and verification of wind tunnel predictions, *J. Wind Eng. Ind. Aerodyn.*, **162**, 2017, 73-84.

[18] Li, Q. S., Xiao, Y. Q., Wu, J. R., Fu, J. Y., & Li, Z. N. Typhoon effects on super-tall buildings. *J. Sound Vibr.*, **313(3)**, 2008, 581–602.

[19] Li, Q. S., Zhi, L. H., Yi, J., To, A., & Xie, J. Monitoring of typhoon effects on a super-tall building in Hong Kong. *Struct. Control Health Monitor.*, **21(6)**, 2014, 926–949.

[20] Melbourne, W. H., & Palmer, T. R. Accelerations and comfort criteria for buildings undergoing complex motions. *J. Wind Eng. Ind. Aerodyn.*, **41(1)**, 1992, 105-116.

[21] Tamura, Y., Suganuma, S., Evaluation of amplitude-dependent damping and natural frequency of buildings during strong winds. *J. Wind Eng. Ind. Aerodyn*., **59(2–3)**, 1996, 115–130.

[22] Tamura, Y., Suda, K., & Sasaki, A., Damping in buildings for wind resistant design, *Proc. Int'l Symp. on Wind and Structures (Cheju)*, Techno-Press, Korea, 2000, 115-130.

[23] Yuen, K.V. and Kuok, S.C. Ambient interference in long-term monitoring of buildings. *Eng. Struct.*, **32(8)**, 2010, 2379-2386