6th European Workshop on
Structural Health Monitoring - Tu.3.D.2

Prediction of Temperature Induced Deformation of a Supertall Structure Using Structural Health Monitoring Data

P. ZHANG, Y. XIA and Y. Q. NI

ABSTRACT

For supertall structures, temperature is one of the most significant factors to affect the structural responses. For example, the field monitoring exercise of Guangzhou New TV Tower (GZNTVT) has shown that the diurnal movement at the top of the main structure due to variation of temperature could be as large as 10 cm in magnitude, which is even larger than the typhoon-induced displacement. Therefore, monitoring and understanding the temperature effects on the super-tall structure are of practical importance. A long-term structural health monitoring (SHM) system consisting of over 700 sensors of sixteen types has been implemented on the GZNTVT for real-time monitoring of the structure at both construction and service stages.

For the supertall structures like GZNTVT, the non-symmetry, non-uniform, and twisted geometry configuration makes it not appropriate to develop a one-dimensional or two-dimensional finite element model like bridges to obtain the accurate temperature distribution. Consequently the temperature induced responses cannot be obtained. In this study, a method to predict temperature induced deformation of the supertall structures by using the measured strain data obtained from its SHM system is proposed. To verify the effectiveness, the predicted displacements are compared with the GPS-measured displacements. The proposed method can be extended to other supertall structures and bridges.

INTRODUCTION

In the recent years, numerous super-tall structures for commercial and residential functions have been built or are being constructed in many densely urbanized cities all over the world. For these super-tall structures of hundreds meters, changes in environmental factors, including temperature, have a significant influence on the overall deformation of the structures. In some situations, the temperature-induced

---

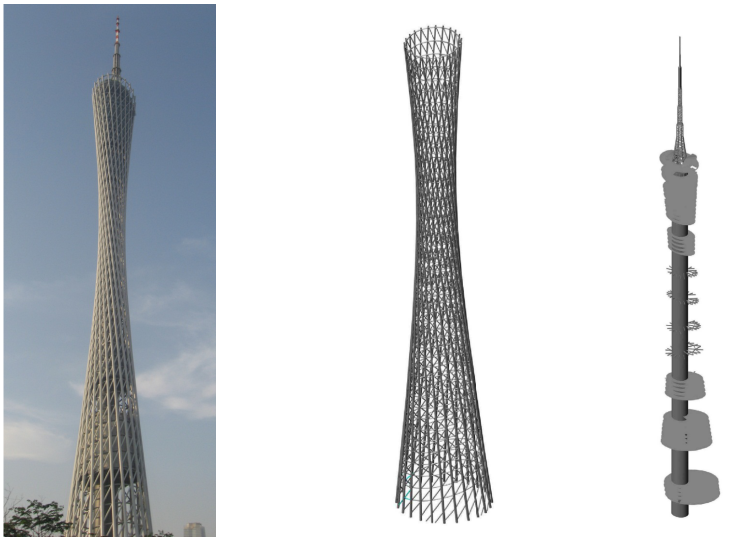
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. E-mail: peng.zhang@connect.polyu.hk (P.Zhang).

deflection at the top of a super-tall structure can reach over 20% of the drift caused by wind forces [1]. Structural health monitoring provides a situ-based laboratory experimental innovation to measure the loadings, environment factors, and responses of the structures. For example, 250 temperature sensors have been installed at six sections in the Confederation Bridge to monitor its time-temperature history hourly, together with the movements at expansion joints and strains [2]. Xia et.al studied the variation of temperature and temperature effect on the global responses of the Tsing Ma Bridge [3]. The temperature distribution on the external surface of the Stuttgart TV Tower has been recognized and the daily and seasonal drift of the tower top due to solar radiation and the daily air temperature variation have been acquired [4].

The GZNTVT located in the city of Guangzhou, China, is a tube-in-tube structure with a total height of 600 m. In order to assess the structural safety, a sophisticated SHM system has been implemented in parallel with the construction process for on-line monitoring of the GZNTVT at both construction and service stages. A total of 48 temperature sensors and 144 vibrating wire strain gauges have been embedded at 12 selected cross-sections of the reinforced concrete inner structure and 96 temperature sensors and 144 vibrating wire strain gauges have been embedded on the surface of the corresponding rings of the outer tube. In this paper, a method to estimate the temperature induced deformation of the supertall structures by using the measured strain data obtained from its SHM system is proposed. To verify the effectiveness, the predicted displacements are compared with the GPS-measured displacements.

GZNTVT AND ITS SHM SYSTEM

As shown in Figure 1, the GZNTVT is a concrete-steel composite structure, consisting of a main tower (454 m) and an antennary mast (146 m). The main tower of 454 m high comprises a reinforced concrete inner structure with an ellipse cross-section of 14 m × 17 m and a steel lattice outer structure. The outer structure is

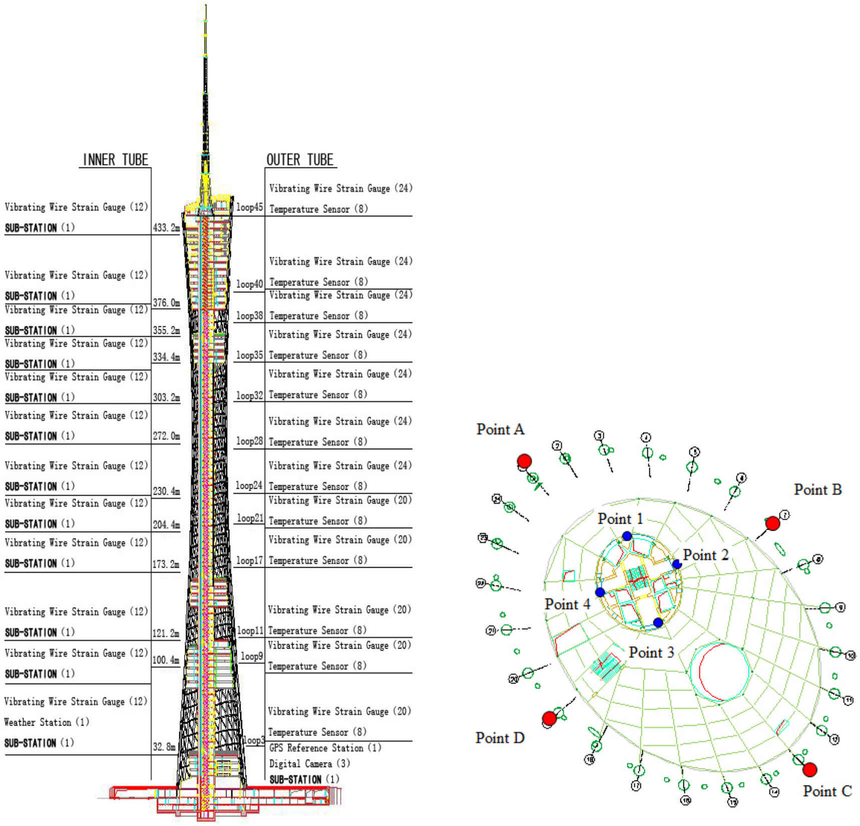


(a) Perspective view of GZNTVT (b) Outer steel structure (c) Inner concrete structure

Figure 1. Guangzhou New TV Tower (GZNTVT).

a varying oval which decreases from 50 m × 80 m at the ground to the minimum of 20.65 m × 27.5 m at the height of 280 m (waist level), and then increases to 41 m × 55m at the top of the main tower (454 m). There are 37 floors connecting the inner and outer structures which serve for various functions.

To ensure the safety of construction progress and long-term service, a long-term SHM system has been implemented on the GZNTVT by a team from The Hong Kong Polytechnic University and Sun Yat-sen University. This system is a pioneering SHM practice of integrating in-construction monitoring and in-service monitoring [5][6]. As shown in Figure 2(a), 12 critical sections are chosen at elevations of 32.8 m, 100.4 m, 121.2 m, 173.2 m, 204.4 m, 230.4 m, 272.0 m, 303.2 m, 334.4 m, 355.2 m, 376.0 m, and 433.2 m for the concrete inner structure. These elevations correspond to Ring Nos. 3, 9, 11, 17, 21, 24, 28, 32, 35, 38, 40, and 45 of the outer tubular structure. At the inner tube, as shown in Figure 2(b), four points (denoted as Point 1 ~ Point 4 in Figure 2(b)) at each critical section are installed with a 45-degree strain rosette, each consisting of three vibrating wire strain gauges to measure the strain and temperature of the concrete wall. For the outer structure, four points (denoted as Point A ~ Point D in Figure 2(b)) are monitored at each section with vibrating wire strain gauges as well. Each monitoring location has six strain gauges: three of them are used to monitor the strain at the external surface of the CFT, one for strain and temperature of concrete inside the CFT, one for the ring member, and one for the brace (inclined supporting member). In addition, two thermal sensors are installed at the opposite surface of the four CFTs to measure the



(a) elevation ***(b) Cross Section***

Figure 2. Layout of the strain and temperature monitoring system.

surface temperature of the CFTs while inside temperature is obtained through the vibrating wire temperature sensor. The sampling rate for each sensor is set as one data per minute in normal circumstances and can be switched to one data per second during typhoons and other extreme events.

PREDICTION OF TEPMERATURE INDUCED DEFORMATION FROM MEASURED STRAIN DATA

According to the the Bernoulli-Euler beam theory, the extensional strain ε_x is related to the local radius of curvature $\rho(x)$, by the following strain-displacement equation

$$\varepsilon_x = -\frac{y}{\rho(x)} \tag{1}$$

where y is the distance from the neutral surface.

When the beam deflect laterally, the deflection curve is characterized by a function $v(x)$.When the deflection and slope is small, we get

$$\frac{1}{\rho} = \frac{d^2 v}{dx^2} = v'' \tag{2}$$

By using Eqs.1 and 2, the relation between deflection and flexural strain can be stated as

$$v'' = \frac{d\theta}{dx} = \frac{d^2 v}{dx^2} = -\frac{\varepsilon_x}{y} \tag{3}$$

The deformation of a beam subjected to linear temperature gradient could be calculated by using the method of virtual work. As illustrated in Figure 3 (a), a cantilever beam which is divided into several parts based on their different temperature difference. Figure 3(b) shows the plot of the bending moment M_u^1 due to a unit virtual load at the top, corresponding to a horizontal deflection of the beam. Figure 3 (c) shows an element of length dx, the varying temperature will cause a displacement, the angular rotation of the section is

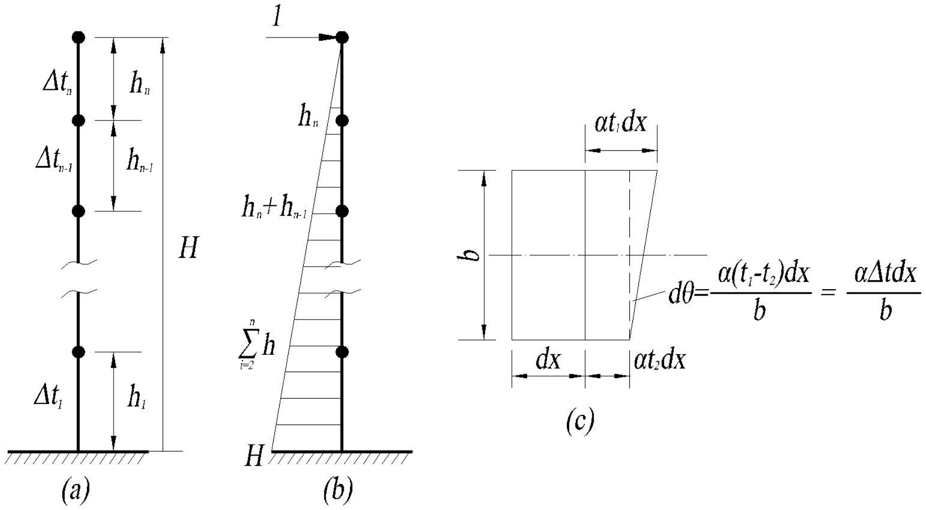
$$d\theta = \frac{\alpha(t_1 - t_2)dx}{b} = \frac{\alpha \Delta t dx}{b} \tag{4}$$

Where α is the thermal expansion coefficient of the material, t_1 is the temperature of the top surface, t_2 is the temperature of the bottom surface, b is the height of the section.

According the method of virtual work, the displacement at the top of the beam in Figure 3 (a) can be stated by

$$\begin{aligned} v_{top} &= \sum \int_l M_u d\theta = \sum \alpha \frac{\Delta t}{b} A_{M_u} = \frac{1}{2b}((\varepsilon_1^l - \varepsilon_1^r)h_1(H + (H - h_1)) + \\ &(\varepsilon_2^l - \varepsilon_2^r)h_2((H - h_1) + (H - h_1 - h_2)) + \cdots\cdots + (\varepsilon_n^l - \varepsilon_n^r){h_n}^2) \end{aligned} \tag{5}$$

where ε_n^l is the strain of the left surface at the height of h_n, ε_n^r is the strain of the right surface at the height of h_n.



(a) Cantilever beam (b) M_u^1 *diagram (c) Deformation of element of length dx*

Figure 3. A cantilever beam subjected to different linear temperature gradient.

For GZNTVT, in the inner tube, four points (denoted as Point 1 ~ Point 4 in Figure 2) at each critical section are installed with a 45-degree strain rosette, each consisting of three Geokon vibrating wire strain gauges to measure the strain and temperature of the concrete wall. With the strain gauges, the real-time strain data of four points are obtained. For a daily 24-hour monitoring, the variation of the vertical strains of the four measuring points in the inner-tube could be obtained by the vibrating wire strain gauges.

Among the 12 critical sections of the inner-tube, the strain data measured by the surface-type temperature sensors allocated on sections 1 and 2 are quite noisy and these data will not be used to predict the deformation of the tower. The measured strain data of sections 3 to 12 on which the embedment-type sensors installed will be used to estimate the temperature induced deformation of the tower top. The height of the 10 sections denotes to h_1 to h_{10}. Based on Eq.5, the daily relative displacement in the short and long axis direction of the tower top can be obtained by using the measured daily variations of the strain data.

COMPARISON BETWEEN THE PREDICTED AND GPS-MEASURED DISPLACEMENT OF GZNTVT

A GPS system has been installed and operated during the construction period. The sampling rate of the system is 1 Hz (one data per second). One GPS observation point is located at the top of the inner structure. During the period from September 2007 to March 2009, the deformations at the top of GZNTVT were measured by GPS system at different stage of the construction period. Among all these GPS-measured data, the data measured on 3rd December 2008 were chosen to compare with the predicted data based on the proposed method in the last section. Up to December 2008, the GZNTVT had been erected to the height of 454 m with the completion of the reinforced concrete inner structure. According to the temperature data for the surrounding air and velocity of wind provided by Guangdong Meteorological Administration, the amplitudes of daily temperature fluctuation of the surrounding air are approximately 17 ℃ and the wind speed was very low on that day. There are also no special loadings acted on the structure. Therefore, the deformation of the GZNTVT on that day can be deemed to be induced by temperature.

The deformation at the tower top of the concrete inner-tube on 3rd December 2008 could be calculated using the measured strain data. Figure 4 compares the predicted and GPS-measured temperature-induced displacements at intervals of 0.5 hour. It is observed that the predicted displacement track has the same pattern of west-north-east-south as the GPS-measured path. The maximum predicted displacements towards west and north occurred around 10:30 am and 2:30 pm, respectively, which are a little different from that GPS-measured. The maximum predicted displacement towards west is about 10.2cm, which is 1.3cm larger than the GPS-measured displacement. While the maximum predicted displacement towards north is about 4.6cm, which is 2.5cm smaller than the GPS-measured displacement. The daily maximum shift distance of the predicted and GPS-measured in the north-south direction are approximately 10.3cm and 9.1cm. The daily maximum shift distance of the predicted and GPS-measured in the east-west direction are approximately 7.6 cm and 10.7 cm.

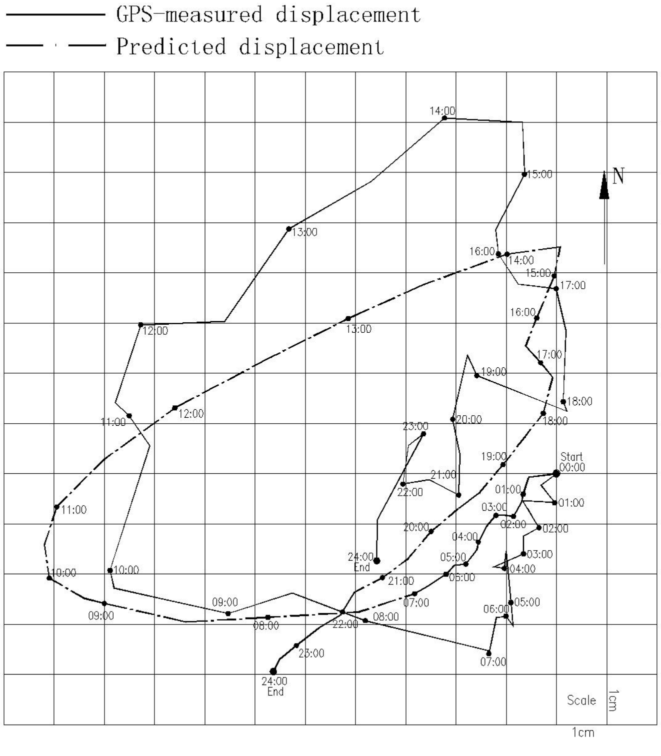


Figure 4. Predicted and GPS-measured temperature-induced displacement track at top of inner structure on 3rd December 2008.

CONCLUSIONS

In this study, a method to predict the deformation of the structures by using the measured strain data obtained from its SHM system is proposed. Since the inner tube of the GZNTVT could be simplified as a cantilever beam and the temperature-induced deformation can be regard as quasi-static deformation, the method is applied to predict the temperature-induced horizontal displacement at the top of the GZNTVT. To verify the effectiveness, the predicted displacements are compared with the GPS-measured displacements. The results show that the predicted moving path has the same pattern with the GPS-measured path. Therefore, the proposed method is able to satisfactorily predict the temperature-induced deformations of the inner concrete core. When there is no GPS system installed in the structure or the GPS system data are not collected continuously, the proposed method can be used to predict the static deformations of high-rise structures by using the measured strain data obtained from the sensors permanently installed on the symmetric axis of the section.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by The Hong Kong Polytechnic University (Project Nos.A-PJ14 and 1-BB6G) and the scholarship provided to the first author.

REFERENCES

1. Smith, B. S., and Coull, A. 1991. *Tall Building Structures: Analysis and Design*, Wiley, New York, USA.
2. Dilger, W. H. 2000. “Temperature Effects in Concrete and Composite Bridges.” *Proceedings of the Workshop on Research and Monitoring of Long Span Bridges*, Hong Kong, China, 1-13.
3. Xia, Y., Chen, B., Zhou, X. Q., and Xu, Y. L. 2012 “Field Monitoring and Numerical Analysis of Tsing Ma Suspension Bridge Temperature Behavior”, *Structural Control and Health Monitoring*, accepted.
4. Breuer, P., Chmielewski, T., Gorski, P., Konopka, E., and Tarczynski, L. 2008. “The Stuttgart TV Tower-displacement of the top caused by the effects of sun and wind.” *Engineering Structure*, 30(10), 2771-2781.
5. Ni, Y.Q., Xia, Y., Liao, W.Y. and Ko, J.M. 2009. “Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower”, *Structural Control and Health Monitoring*, 16(1), 73-98.
6. Xia, Y., Ni, Y. Q., Zhang, P, Liao, W. Y. and Ko, J. M. 2011, “Stress Development of a Super-tall Structure during Construction: Field Monitoring and Numerical Analysis”, *Computer-Aided Civil and Infrastructure Engineering*, 26 (7), 542-559.