Optical Sensor Networks for Structural Health Monitoring of Canton Tower

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Abstract

Structural health monitoring (SHM) systems are crucial for modern civil structures such as high-rise buildings and long-span bridges in terms of operational safety and economical aspects. Fiber Bragg gratings (FBGs) sensing system is one of the optical fiber sensory systems with maturity in fabrication, comprehensive in functionality and effective in implementation. SHM systems based on FBG sensor networks are becoming popular in civil applications. FBG sensor also possesses salient features such as light weight, small size, immunity to electromagnetic interference, corrosion resistance, multiplexing capability over a single fiber for measuring different parameters such as strain, temperature, acceleration, wind speed, etc. These distinctive advantages make FBG sensor system a good candidate to serve as an integral part of a long-term SHM system. The small size (i.e. diameter of optical fiber with 125μm) of FBG sensors permit them to be used to monitor/measure even scaled-down model of civil structures. In this paper, a SHM system for the 610-m tall Canton Tower in Guangzhou, China integrates both in-construction and in-service monitoring, comprising about 800 sensors with over 200 FBG based sensors was successfully installed.

1. Introduction

Structural health monitoring (SHM) of civil structures such as bridges [1], historic and tall buildings [2] is critical to ensure the structures' safety and maintenance. SHM systems are also instrumental for refining models of civil structures for better performance and cost prediction.

Traditional electronic sensors using in SHM system have long history. Optical sensors as an alternative in this area is becoming attractive especially in large sensory system with more sensors and longer distance between the sensors and the interrogation unit. The SHM system of the Canton Tower is a good case for using optical sensor as it is one of the highest towers in the world with a height of 610m and, over 200 optical sensors were embedded in the structure and all these sensors are interrogated by a single optical unit.

Fibre Bragg grating (FBG) type optical sensor was used in this SHM system of the Canton Tower. Figure 1 shows the working principle of a FBG. A FBG is a short section (~1 cm) of single-mode optical fibre with its refractive index changes periodically inside the core of the fibre. Phase mask technique using a ultra-violet (usually 193nm or 248nm) laser to illuminate the fibre section under a phase mask is usually employed for FBG inscription. The refractive index of the fibre changes according to the pattern of the phase mask. As shown in Fig. 1, if the input light with a band of wavelengths λ1, λ2, λ3 and λ4 is fed into the fibre. Wavelength λB=λ3 will be reflected back by the grating that satisfies the Bragg condition of λB=2*n*Λ, where λB is the Bragg wavelength, *n* is the refractive index of the core material, Λ is the pitch of the grating which is defined by the phase mask during FBG inscription. The rest of the wavelengths λ1, λ2 and λ4 transmitted through the grating.

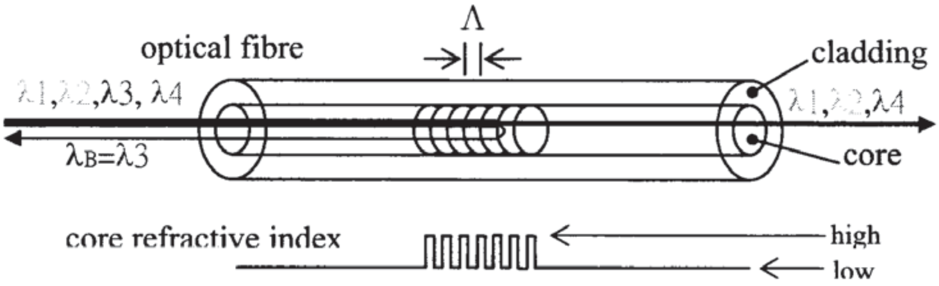

Figure 1: working principle of a FBG

FBG type strain sensor and temperature sensor are based on this working principle. As the refractive index of a FBG is sensitive to strain and temperature effects, a proper transducer design is required in order for the FBG to cope with different kind of measurement. In a FBG strain sensor, the FBG can be simply attached to the surface of the test material, tension or contraction of the material will be reflected by the changes of the Bragg wavelength of the FBG. However, temperature compensation [3] is also necessary to eliminate the thermal effect from the measurement result. On the other hand, in a FBG temperature sensor, the FBG can be placed closely to the measurement location and avoid any strain effect induced to the sensor.

Canton Tower is the tallest tower in China with a height of 610m. The functionalities of the tower include broadcasting, sightseeing and catering. The architecture of the tower follows a tube-in-tube design. The structure comprises reinforced concrete in the inner tube and steel in the outer tube with concrete-filled-tube columns. The columns are uniformly spaced in an oval while inclined in the vertical direction. The oval decreases from 50mx80m at the ground to the narrowest of 20.65mx27.5m at the height of 280m. Then the oval increases to 41mx55m at the top of the tube at 454m. The columns are interconnected transversely by circular steel beams and braces. The shape of inner tube is oval too with constantly 14x17m in plan. The centroid of inner tube is offset from that of outer tube with different amount at different height.

2. Installation of FBG Sensors

The optical fibre sensors deployed by the SHM of the Canton Tower are "OS3110" optical strain sensor and "OS4100" optical temperature sensor, both of them are commercially available from Micron Optics Inc. The sensors are packaged by a thin stainless steel package which can be mounted by spot welding. Figure 2 shows the procedure of installing a FBG sensor onto the pillar.

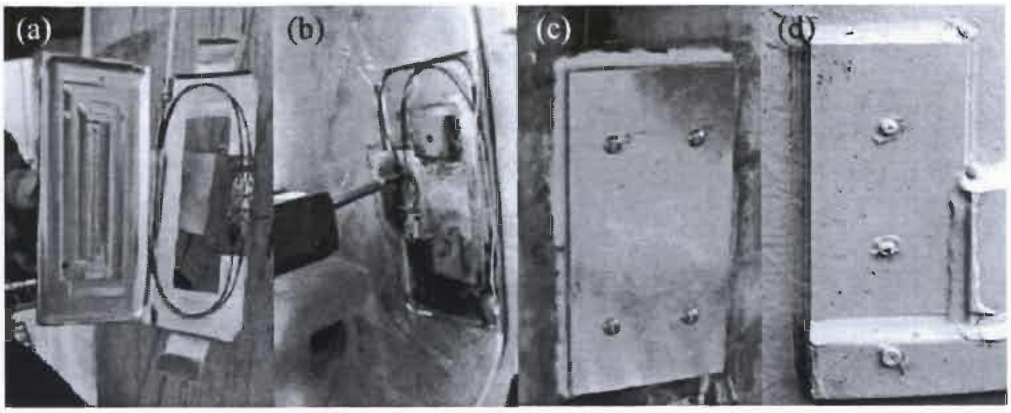

Figure 2: (a) FBG in stainless steel case, (b) spot-weld of FBG sensor on to a metal structure, (c) encapsulated FBG sensor with water proved sealing and (d) FBG sensor painted for anti-corrosion.

Sixteen groups of FBG sensor are mounted onto the tower body and each group is connected to one core of a multi-core optical cable as shown in Fig. 3(a). In the control room located on the ground floor of the tower, the sixteen fibres are connected to a 4-port FBG interrogator through a 4- to 16- port optical multiplexer. The sampling rate of all the sensors is 250 Hz. FBG sensors were also installed on the antenna section of the tower as shown in Fig. 3(b).

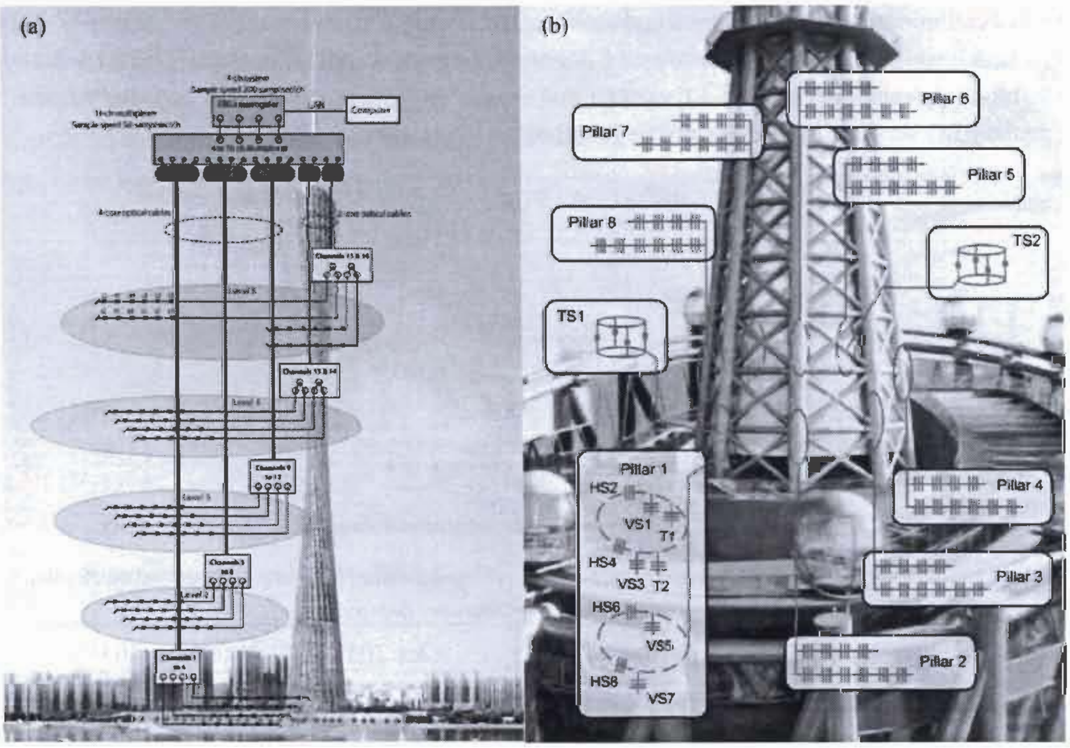

Figure 3: schematic of FBG sensor distribution (a) in tower body, (b) in antenna.

3. Result and Discussion

3.1 Strain and vibration modes

Figure 4 shows a 3-day strain measurement on Pillar-19 at Level-45. The strain follows the trend of temperature change of the tower body because of the thermal expansion of the material. The highest strain observed was between 2:00pm to 4:00pm while the lowest strain was at ~6:00am during sun rising period.

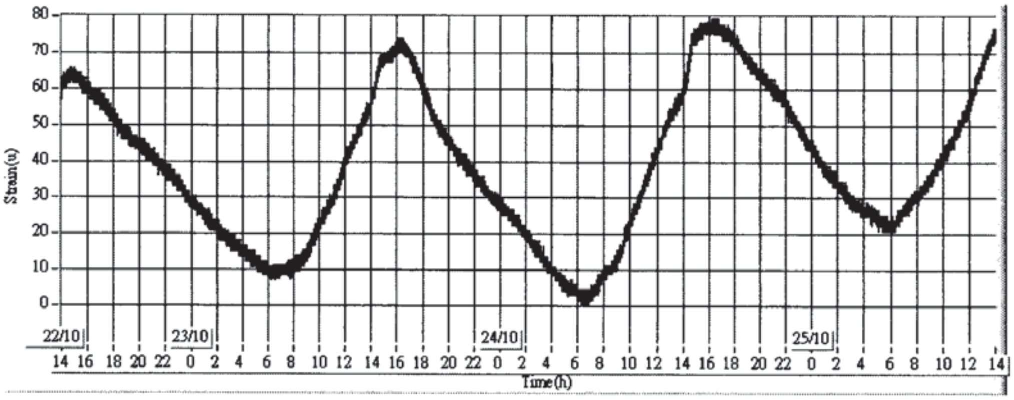

Figure 4: a 3-day long (14:00 22nd to 14:00 25th/Oct/2010) of strain on Pillar-19 at Level-45

Vibration modes of the tower can also be extracted by applying Fast Fourier Transform (FFT) analysis to the data measured by the FBG strain sensors. Figure 5 shows a strain sensor response in frequency domain over 1-hour measurement of column 13 at the height of 110m. Six out of seven fundamental vibration modes (designed values) are found in the FFT analysis, where the frequencies and vibration mode are 0.092Hz (1st mode), 0.138Hz (2nd mode), 0.371Hz (3rd mode), 0.462Hz (4th mode), 0.578Hz (6th mode) and 0.598Hz (7th mode). A detail comparison of the vibration modes are shown in Table 1. The first 7-vibration modes measured by a conventional electronic accelerometer at the height of 121m match well to the analysis results of FBG strain sensors. In addition, the 0.0952Hz vibration mode detected by the GPS [4] system and vision inspection system [4], are also similar to the FBG sensors and accelerometer founding.

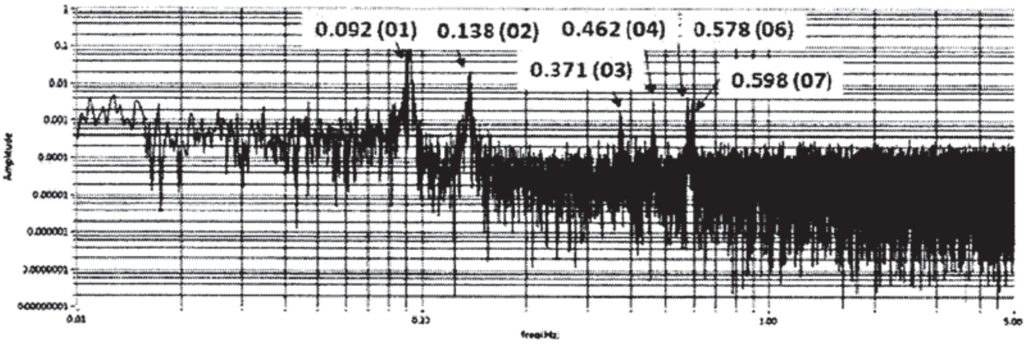

Figure 5: FFT analysis of FBG strain sensor located at column 13 and height of 110m.

Table 1. Comparison in vibration modes of tower designed value, FBG strain sensor and electronic accelerometer in frequency domain.

Measurement period		Oct 2010	Nov 2010
Vibration mode	Designed value (Hz)	FBG strain sensor (Hz)	Accelerometer (Hz)
01	0.1102	0.092	0.0929
02	0.1590	0.138	0.1404
03	0.3466	0.372	0.3768
04	0.3682	0.464	0.4652
05	0.3995	N/A	0.5025
06	0.4606	0.578	0.5797
07	0.4850	0.598	0.5991

3.2 FBG Temperature sensor

Temperature is one of the reference factors for evaluating the structural data which may cause material expansion and induce strain. The majority construction materials of the tower are metal and concrete in which the metal have a relatively high coefficient of thermal expansion (CTE). Therefore, it is necessary to have precise temperature measurement in order to obtain the strain accurately.

The locations of the FBG temperature sensor in Canton Tower are distributed over the minor axis and major axis of the four main pillars (1, 7, 13 and 19)at the height of 32.8m, 121.2m, 272.0m, 334.4m, 433.2m as well as the antenna section. Traditional electronic temperature sensor was used to compare the measurement obtained by the FBG temperature sensor. All the FBG temperature sensors deployed in the tower have same CTE and their wavelength change to temperature sensitivity is28.9 pm/°C [5]. To evaluate the performance of the FBG temperature sensors, the temperature difference of each sample, the maximum difference, the phase difference as well as the correlation coefficient between the FBG sensor and the traditional sensor were considered.

Figure 4 shows the temperature measurements of both FBG sensor and the electronic based temperature sensor in one day. The result measured by FBG temperature sensor is identical to the result measured by traditional temperature sensor and there is a one hour lagged for the FBG measurement as shown in Fig, 5. The reason of the phase difference is that the two sensors are not installed at the same location but only close to each other and there the shape of the two curves is very similar.

The maximum temperature difference between the two measurements was less than -0.001 °C if the one hour lagging is considered. These two measurements are highly correlated and the correlation coefficient is 0.97925.

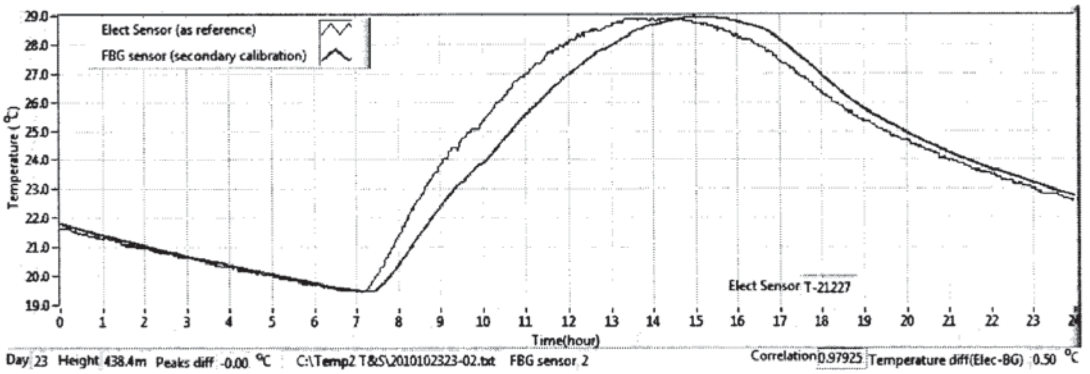

Figure 4: Temperature measurement obtained by the traditional and FBG temperature sensors with one hour phase lag

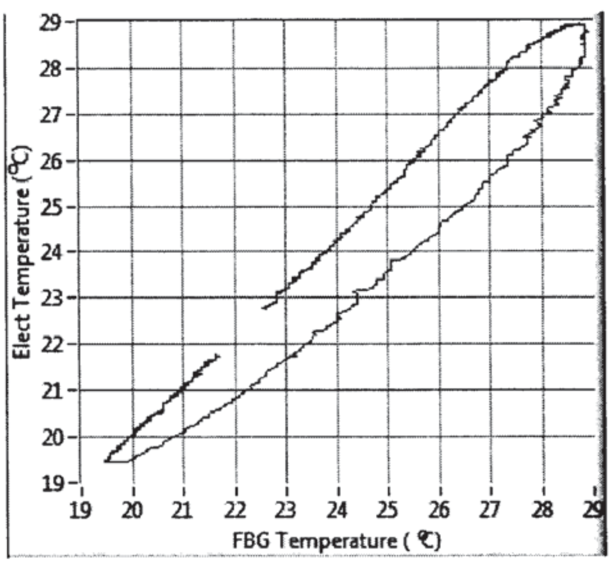

Figure 5: Traditional temperature sensor against FBG temperature sensor shows a large phase difference

Figure 6 shows another measurement location with both FBG and electronic sensors installed. The temperature difference at the highest temperature points is 0.057 °C and their correlation coefficient is 0.99790. The temperature difference in Fig. 4 is less than that in Figure 6 whereas the correlation in Fig. 44 is smaller than that of Fig. 6. This is because the phase difference in Fig. 4 is more significant than that in Fig, 6. The correlation is higher in Fig. 7 which is indicated by the smaller area enclosed by the plot of the two curves. In contrary, Figure 6 had a larger enclosed area which is due to less correlation coefficient between the curves.

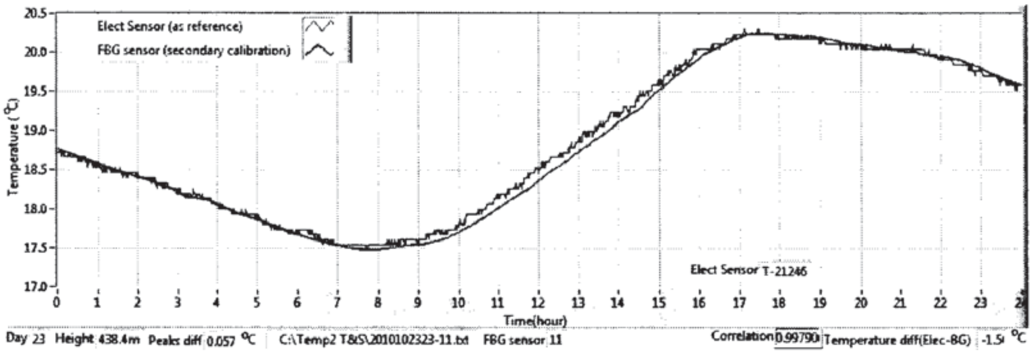

Figure 6 Measurement taken from traditional and FBG temperature sensors with less phase difference

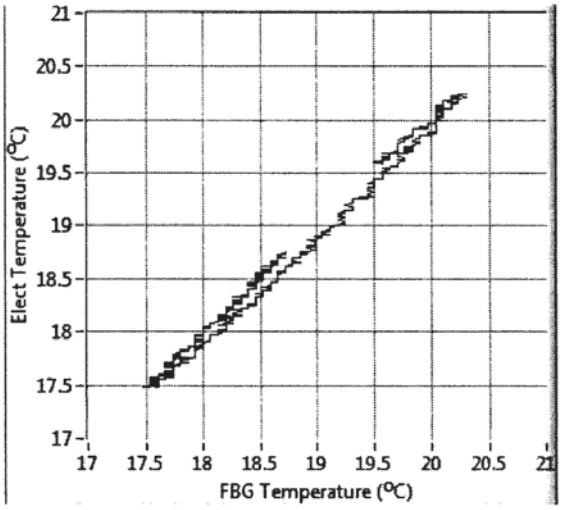

Figure 7 Traditional temperature sensors against FBG temperature sensors

During this test, 16 pairs of FBG temperature sensors and electronic sensors were used for comparison. The result shows that the maximum temperature difference of less than 1°C compared to the electronics sensor was measured by 13 FBG sensors.

4. Conclusion

This research demonstrated a successful case of applying 208 FBG sensors in the 610_m tall Canton Tower. The sensors are distributed over the tower body and antenna which are connected to the interrogation system located in the ground floor without any active electronic element in-between.

Three types of FBG sensors had been applied in the SHM. A 3-day strain measurement agreed well with the temperature cycle of the tower which implies that the strain experienced by the tower is mainly caused by thermal effect. The vibration frequencies of the tower e were obtained by FFT frequency analysis of the dynamic strain measurement. The frequencies matches well to the vibration modes of the design model. In additional, the measurement also matches the result obtained by other technologies such as vision and Global Positioning System (GPS).

References

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