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Health Monitoring of High-rise Building with Fiber Optic Sensor (SOFO)

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Abstract

Structural health monitoring is becoming more and more important in the domain of civil engineering as a proper mean to increase and maintain the safety, especially in the land of earthquakes like Japan. In many civil structures, the deformations are the most relevant parameter to be monitored. In this context, a monitoring technology based on the use of long-gage fiber optic deformation sensor, SOFO is being applied to a 33-floors tall building in Tokyo. Sensors were installed on the 2nd floor's steel columns of the building on May 2005 in the early stage of the construction. The installed SOFO sensors were dynamic compatible ones which enable both static and dynamic measurements. The monitoring is to be performed during the whole lifespan of the building. During the construction, static deformations of the columns had been measured on a regular basis using a reading unit for static measurement and dynamic deformation measurements were occasionally conducted using a reading unit for dynamic measurement. The building was completed on August 2006. After the completion, static and dynamic deformation measurements have been continuing. This paper describes a health monitoring technology, SOFO system which is applicable to high-rise buildings and monitoring results of a 33-floors tall building in Tokyo from May 2005 to October 2010.

Keywords: Health monitoring, Fiber optic sensor, SOFO, Static deformation, Dynamic deformation, High-rise buildings, Long gage, Deformation sensor

1. Introduction

In recent years, many tall buildings have been constructed in all over the world. The advancement of structural analysis technologies has been playing an important role in this trend. In order to know the precise stress state of a building at the completion stage, it is desirable to measure deformations of structural members of the building during the construction stages because a construction goes ahead in many stages from lower story to upper story and there must be a difference between analysis results and the actual stress states accordingly. Measurement examples during construction stages are however very few in the world (Glisic et al., 2003). In addition, long-term health monitoring after the completion of a building is very important in order to confirm the integrity of it, especially in the land of earthquakes like Japan.

Long-term monitoring requires an accurate and very stable system. In many civil structures, the deformations are most relevant to be monitored. It is therefore desirable to perform health monitoring with strain sensors installed on main structural members during construction stages and after the completion. Conventional strain gages give only local information about the structural members. A complete understanding of the structure's behavior requires the measurement of deformations based on long-gage sensors. In this context, a long-gage-length fiber optic sensor system, better known by the acronym SOFO (Inaudi et al., 1996; Mikami et al., 2009) can be considered to be a significant achievement in the area of structural strain monitoring of civil engineering structures. The system has the capacity for monitoring structures over long periods of time, and has been successfully embedded or surface-mounted in a variety of materials such as concrete, steel, and mortar. The sensor, based on low-coherence interferometry, uses a Michelson interferometer. The SOFO V system is well suited for static and long-term measurements (Inaudi et al., 2000; Mikami et al., 2002). The SOFO Dynamic system enables dynamic measurements on structures. This system is based on heterodyne low-coherence interferometry (Inaudi et al., 2004; Mikami et al., 2006).

In order to demonstrate the effectiveness of fiber optic sensor system for the health monitoring of tall buildings, the SOFO V system is being applied on a 33-floors tall building with a height of 147 m in Tokyo. SOFO sensors were installed on five steel columns of the 2nd floor on May 2005 in the early stage of construction. The installed sensors were SOFO Dynamic compatible ones which enable both static and dynamic measurements. The main

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aim of monitoring is an evaluation of the structural condition after the completion of construction. Accordingly, the monitoring is being performed during the whole lifespan of the building, including the construction stage. The monitoring was initiated on May 2005. During the construction, static deformations of the columns had been measured on a regular basis using the SOFO V system and dynamic deformation measurements were occasionally conducted using the SOFO Dynamic system.

The building was completed on August 2006. After the completion, static and dynamic deformation measurements have been continuing.

2. The SOFO Fiber Optic Monitoring Systems

2.1. SOFO V

The SOFO V system (French acronym for Surveillance d'Ouvrages par Fibres Optiques - Structural Monitoring using Optical Fibers) is based on low-coherence interferometry in optical fiber sensors. It consists of long-gage-sensors, a reading unit and data acquisition and analysis software as shown in Fig. 1. The sensor contains two optical fibers called the measurement fiber and the reference fiber, both placed in the same protection tube (see Fig. 2). The measurement fiber is coupled with host structure and follows its deformation. In order to measure shortening as well as the elongation, the measurement fiber is pre-stressed to 0.5%. The reference fiber is loose and therefore independent from the structure's deformations. All deformations of the structure will then result in a change of length difference between these two fibers.

To make an absolute measurement of this path imbalance, a low-coherence double Michelson interferometer is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path imbalance between its two arms. Because of the reduced coherence of the source used (the 1.3 micron of radiation of an LED), interference fringes are detectable only when the reading interferometer compensates for the length difference between the fibers in the structure.

If this measurement is repeated at successive times, the evolution of the deformation in the structure can be followed without the need of a continuous monitoring. This means that a single reading unit can be used to monitor several fiber pairs in multiple structures.

The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron (2/1000 mm), independently from the sensor length over more than 10 years. Even a change in the fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

The sensors are adapted to direct concrete/grout embed-

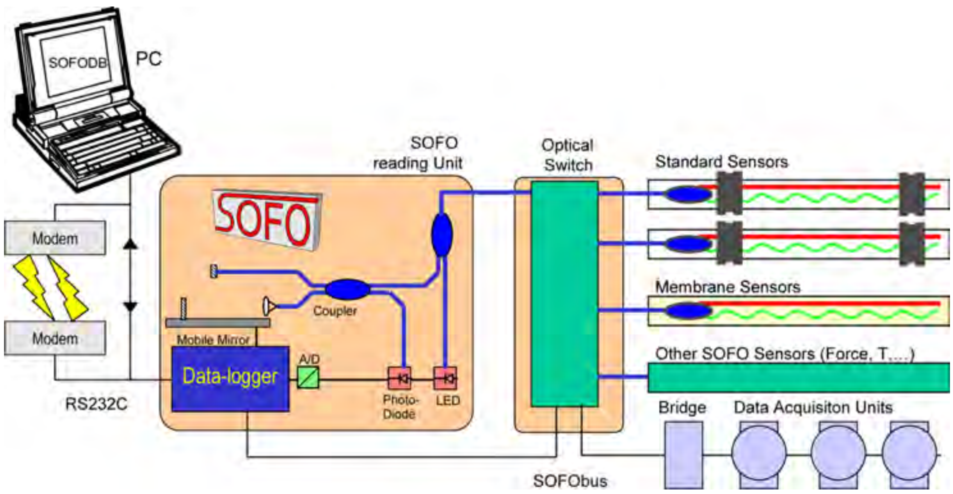

Figure 1. SOFO V system.

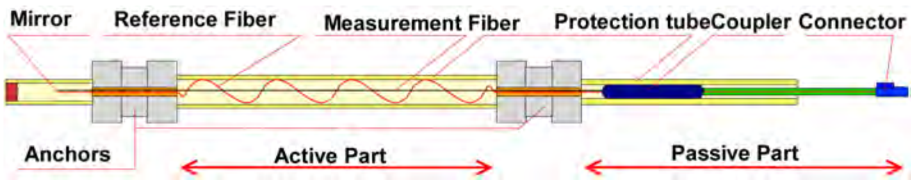

Figure 2. SOFO sensor setup.

Table 1. Specifications of SOFO V

Parameter	Characteristics
Gage length	200 mm to 10 m
Cable length	Up to 5 km
Resolution	2μm, independently from gage length
Dynamic range of the sensors	1 % elongation, 0.5% shortening for standard sensors
Waterproof	5 bars (50 m deep in water)
Calibration	None, not required
Precision	Better than 0.2% of the measured deformation
Measurement speed	Typically 6 to 10 seconds per measurement
Max number of channels	12 (up to 100 with separate switching unit)

ding or surface mounting on existing structures. The passive region of the sensor is used to connect it to the reading unit and can be up to a few kilometers long. The reading unit is portable, waterproof and battery powered, making it ideal for dusty and humid environments as found on most building sites. Each measurement takes about 7 seconds and all the results are automatically analyzed and stored for further interpretation by the external lap-top computer.

The measurements can be performed either manually by connecting the different sensors one after the other or automatically by means of an optical switch. Since the measurement of the length difference between the fibers is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors. A single unit can, therefore, be used to multiple sensors and structures at the desired frequency.

Typical sensor gage-length ranges from 200 mm to 10 m. The accuracy of measurement is 0.2% of the measured value (linear correlation between the optical signal and the deformation). The dynamic range of the sensors is 0.5% in compression and 1.0% in elongation.

The main characteristics of the SOFO V system are shown in Table 1.

2.2. SOFO dynamic

The SOFO Dynamic system is designed to allow a full compatibility with the SOFO sensors already installed several structures. This also guarantees the possibility of using the same sensors with the SOFO V reading unit, optimized for long-term stable measurements.

The SOFO Dynamic system relies on interferometric demodulation as shown in Fig. 3. The emission of a coherence-collapsed Laser diode is injected in the passive part of the sensor through a coupler. The light is then passed in the Michelson interferometer composed by the two fibers in the SOFO sensors and is reflected back to the demodulation system.

A Mach-Zehnder interferometer with an active phase modulator is used as demodulation interferometer. The modulator is driven at about 50 kHz frequency. Finally the light intensity is collected by a photodiode and digitalized. The resulting fringe pattern is analyzed using an Optiphase DSP board that provides the corresponding

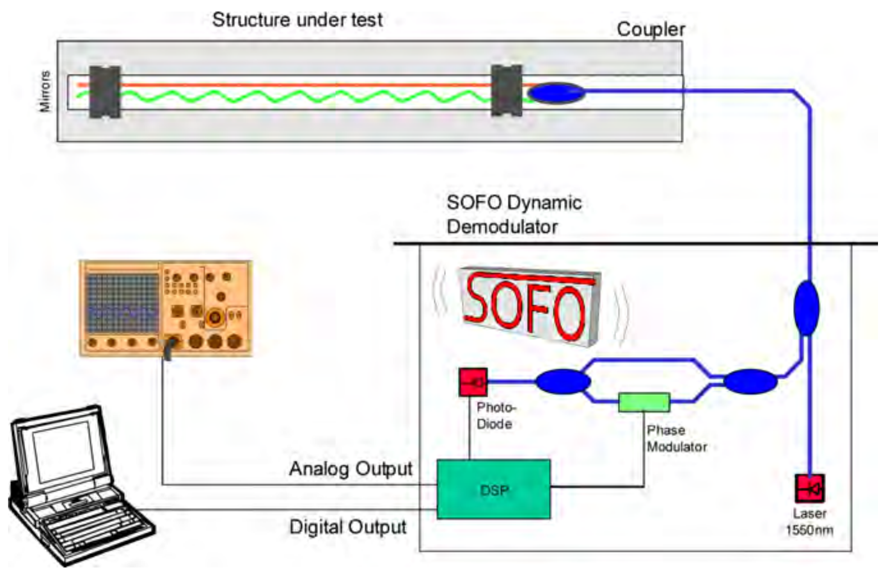

Figure 3. SOFO Dynamic system.

Table 2. System performances of SOFO Dynamic

Parameter	Characteristics
Bandwidth	0 to 10 kHz (up to 10 kHz on special request)
Resolution	0.01μm
Measurement range	± 5 mm (maximum deformation)
Velocity range	Max. 10,000 μm/s
Drift	< 0.003 μm/s (after 1 h warm-up time) < 0.5 μm/day using drift compensation (reduces the number of channels to 7)
Max. Number of channels	8 (7 with drift compensation)
Acquisition	Simultaneous
Digital readout	USB 2.0, 1 kHz, 32 bits
Analog output	8 channels, 10 kHz, 20 bits, adjustable gain

cumulated phase in digital and analog formats.

In the final system the light from the same laser is split with a 1×8 coupler to allow simultaneous demodulation of 8 channels, each with a dedicated DSP board. The system performances are shown in Table 2.

As shown in Table 2, SOFO Dynamic has a remarkable resolution which is extremely better than conventional strain gages. Very small dynamic strains which are not detected by strain gages can be therefore detected by SOFO Dynamic.

3. High-rise Building Monitoring

3.1. Structure's short description

A 33-floors tall building with a height of 147 m was constructed at Toyosu region in Tokyo. The Toyosu region is land reclaimed from the sea. Evaluation of structural condition after earthquake or strong wind and ground sinking is considered to be a matter of importance for this building. Its construction started on June 2004 and was completed on August 2006. Fig. 4 shows a photo of the building taken on August 2006 soon after the completion.

3.2. Installation of the sensors

We installed SOFO sensors on the second floor's columns on May 2005. The main area of the second floor is a machinery room (57 m×50 m) having 33 steel columns. These columns are not furnished with tiles and are therefore ideal to install the sensors. Not all columns were monitored. Five representative columns were selected for monitoring as shown in Fig. 5. The monitored columns were named as X4Y2, X4Y5, X6Y5, X7Y9 and X8Y6 corresponding to their positions in the building. Here, the positions were expressed as X-Y coordinates (X, Y are transverse and longitudinal directions respectively). The dominant load in each column is compressive axial force and it is therefore supposed that the bending effect on the deformation of the column can be neglected. Only one sensor is considered to be enough to monitor a column load consequently. One sensor was installed on the surface center of each column accordingly.

Figure 4. High-rise building (Toyosu in Tokyo).

The position of the sensor on the column: X7Y9 is shown in Fig. 6 as an example. The length of the sensor was determined with respect to the height of column (3 m) and on-site conditions. Hence one-meter long sensors were installed.

Thermal expansions of the columns were considered to be significant during construction and we installed a thermocouple near the center of each SOFO sensor in order to monitor a column temperature as shown in Fig. 7.

In addition, a conventional small strain gage was installed on each column as a reference (see Fig. 7). The columns were to be covered with insulating material at the final stage of the construction. All the leading cables of the sensors installed on each column were therefore led to a small connection box on each column. The connection box was provided with an opening so as to be able to access the cable connectors of the SOFO sensor, the thermocouple and the strain gage after the completion as shown in Fig. 8. Each thermocouple was connected to a small data logger operated by small batteries. The data logger was contained in the connection box and a temperature data was taken in PC at every measurement.

3.3. Results and analysis

The installation of the SOFO sensors and etc., was completed on May 18th, 2005. The first measurements by SOFO V were performed on that day. This measurement

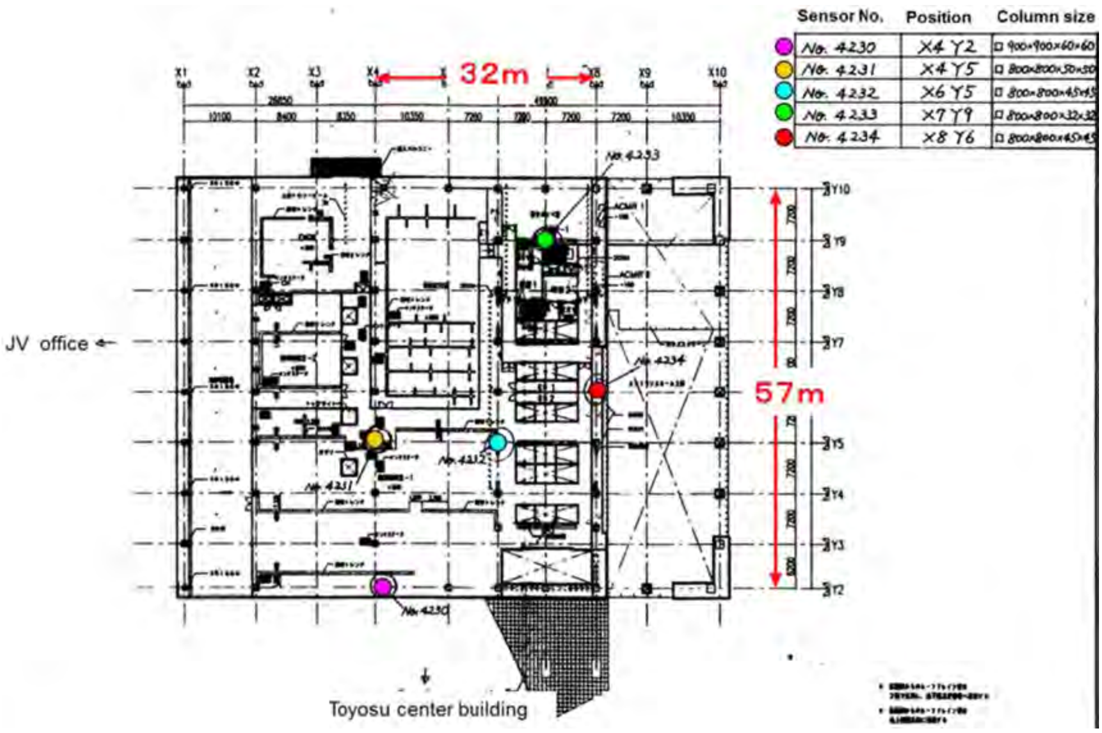

Figure 5. Sensor arrangement in the 2nd Floor.

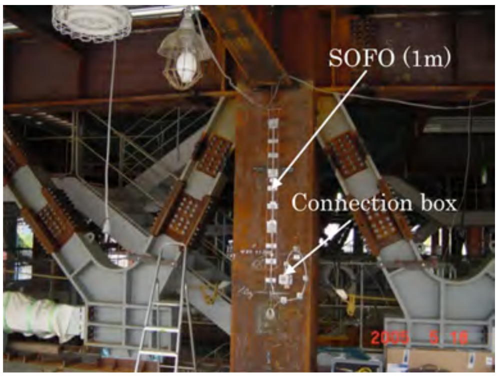

Figure 6. SOFO sensor on column X7Y9.

Figure 8. Connection box.

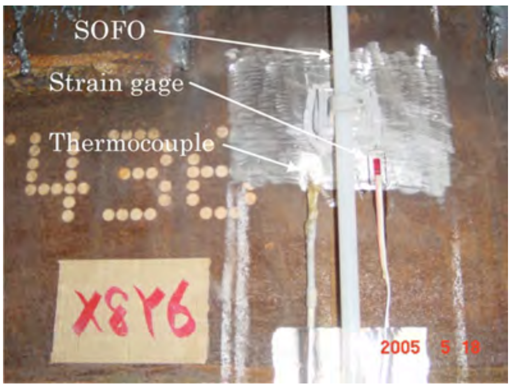

Figure 7. Thermocouple and strain gage.

was a reference for all further measurements. The measurements were performed every one month until the completion of construction on August 2006 and were performed every 2 months until the end of 2007 after the completion and have been performed generally every 2 to 6 months from January 2009. A general view of the building during the construction is shown in Fig. 9.

The result of temperature measurements is shown in Fig. 10. Because the SOFO sensor and the thermocouple on X7Y9 were broken mistakenly just before the completion of construction, the temperature data on this column has been cancelled. Temperatures on the four columns have not been the same because of the heating effect by sunshine. After the completion, the temperature on X8Y6

Figure 9. Pictures of high-rise building during construction.

has been different from others. This is considered to be an effect of air conditioning in the building.

The SOFO sensor installed on a vertical column measures an average strain of the column over the sensor length including a strain due to thermal expansion at the position where it is installed. Table 3 shows the dimensions and the section areas of the instrumented columns.

Table 3. Column dimensions and areas

Column name	Column dimension	Section area
X4Y2	900*900*60*60mm	$0.202m^2$
X4Y5	800*800*50*50mm	$0.150m^2$
X6Y5	800*800*45*45mm	$0.136m^2$
X7Y9	800*800*32*32mm	$0.098m^2$
X8Y6	800*800*45*45mm	$0.136m^2$

The average strain measured by a SOFO sensor excluding thermal effect is given by the following equation:

$$\varepsilon=\frac{(d_{sm}-d_{s0})-d_t}{l_s} \tag{1}$$

Where

ε : Average strain over a SOFO sensor length excluding thermal effect;

d_{sm} : Deformation measured by a SOFO sensor;

d_{s0} : Initial deformation measured by a SOFO sensor on May 18, 2005;

d_t : Deformation by thermal expansion;

l_s : Length of a SOFO sensor (= 1000 mm);

d_t is expressed as follows.

$$d_t=\alpha_t \Delta t\, l_s \tag{2}$$

Where

α_t : Coefficient of thermal expansion of a steel column;

Δt : Column's temperature change from an initial temperature measured on May 18, 2005;

The axial force of a column can be calculated by the following equation.

$$F=E\varepsilon S \tag{3}$$

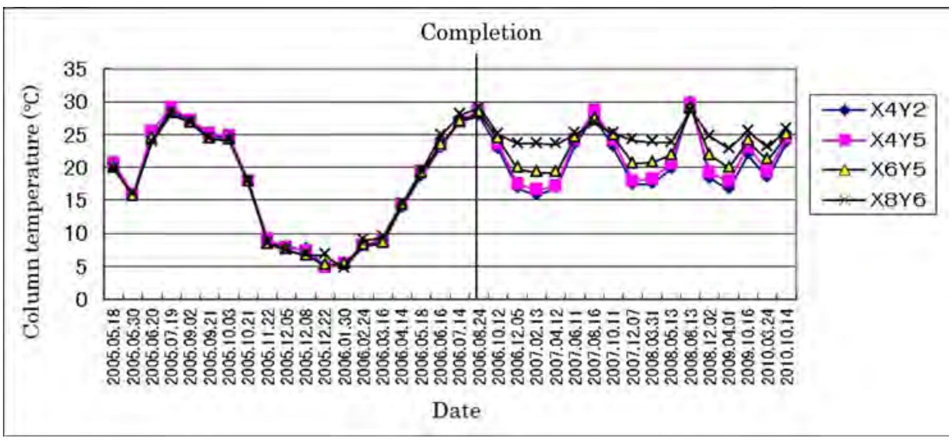

Figure 10. Result of temperature measurements of columns.

Where
F : Calculated an axial force of a column;
E : Young's modulus of a steel column;
S : Sectional area of a column (see Table 3);

Because the temperature change of the column is relatively large, an evaluation of the strain due to thermal expansion is of importance. In order to obtain the coefficient of thermal expansion of the steel column, a thermal expansion test was carried out using a steel pipe which has the same material as the columns on which SOFO sensors were installed. Because a SOFO sensor is installed on a measurement object through two L-brackets with an adhesive or bolts, tests were conducted within the parameters of materials of the L-bracket (Aluminum or SUS), directions of the L-bracket and methods of fixation (an adhesive or bolts).

A square steel pipe (120W×60H×1000L×5t) was selected as a specimen and four 0.3m-SOFO sensors (serial NO: 6742~6745) were installed on it as shown in Fig. 11. In addition, three thermocouples were installed on the pipe to measure steel temperatures (Temp-1~Temp-3) and one thermocouple was put near the specimen to measure an ambient air temperature (Temp-4). This specimen was exposed in outdoor for four days and measurements were conducted automatically every 10 minutes. In this exposure test, because any external load was not applied, the specimen was expected to expand freely depending on the temperature change.

The test results are shown in Fig. 12. Because of the heating effect by sunshine, the temperature of the steel pipe is much higher than that of the ambient air. Even in the steel pipe, there is a temperature distribution because of the sunshine effect. If we plot the measured strains with SOFO sensor versus measured temperatures of the steel pipe, we can obtain a regression line and consequently the slope of the line would become the coefficient of thermal expansion of the steel pipe. In this health monitoring of

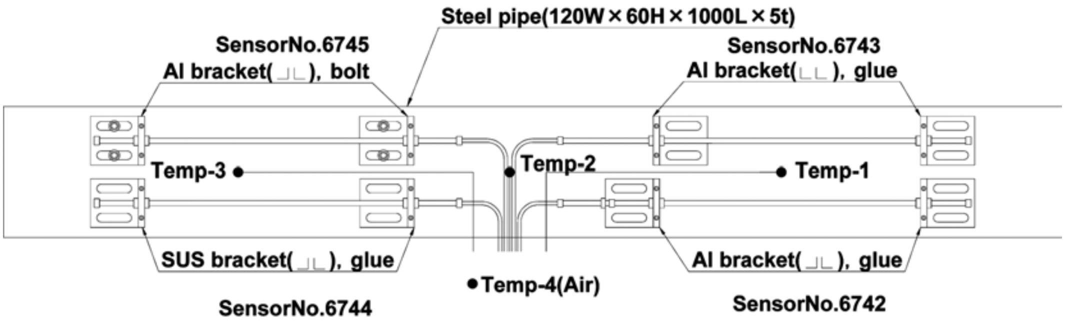

Figure 11. Thermal expansion test of a steel pipe.

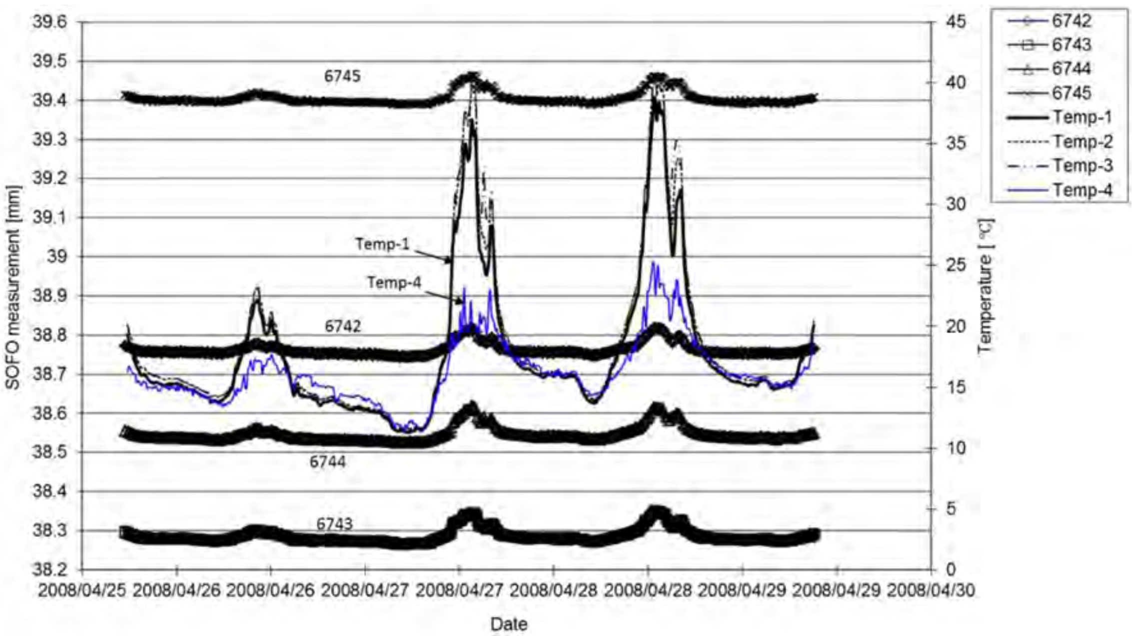

Figure 12. Result of thermal expansion test of a steel pipe.

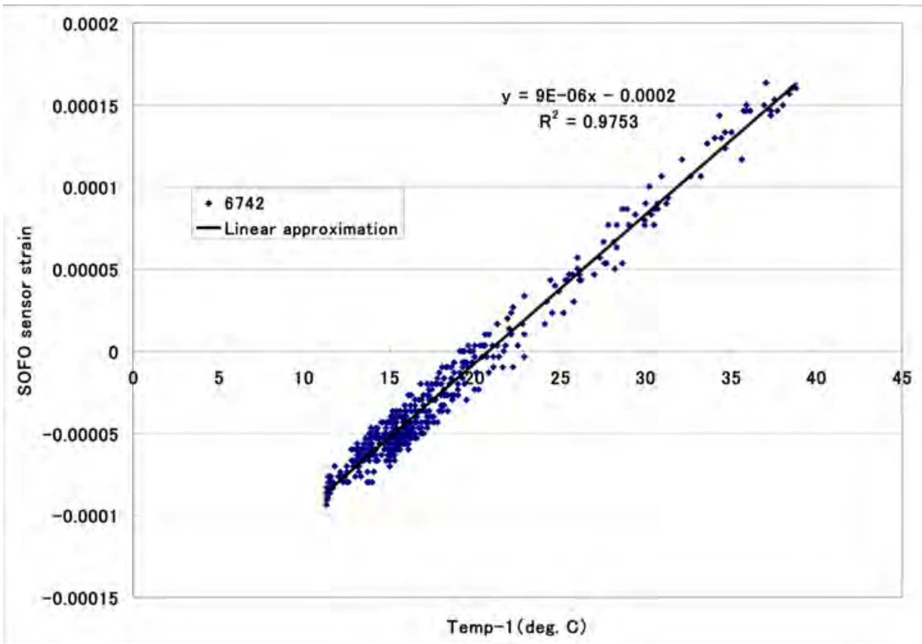

Figure 13. Thermal expansion coefficient of a steel pipe (sensor No. 6742).

the high-rise building, because the fixation method with glue for the sensor 6742 was applied, a regression analysis was conducted by applying Temp-1 data. The analysis result is shown in Fig. 13. As a result of a least square approximation, a coefficient of thermal expansion of 9.0× 10-6 was obtained.

In a similar manner, a coefficient of thermal expansion of 10.0×10-6 was obtained for the sensors 6743~6745. This significant difference of the obtained thermal expansion coefficients is due to the difference of material and the installation direction of L-brackets.

Assuming that of the measured columns is 9.0×10-6, strains of SOFO sensors were analyzed from Eqs. (1) and (2). The results are shown in Fig. 14. Two big climbing cranes were set up on the top of the building at the early stage of construction of the building (see Fig. 9). One of them was removed in the period 1 (from Oct. 21, 2005 to Nov. 22, 2005) and the other one was removed in the period 2 (from Dec. 22, 2005 to Jan. 30, 2006). The loads acting on the columns should be decreased in accordance with these events. As shown in Fig. 14, compressive strains of all the columns were decreased remarkably in the period 1. It is supposed that not only the climbing crane but also other materials (heavy machinery, stocks of material, scaffoldings etc.) were removed. On the other hand, not all compressive strains were decreased in the period 2. It is considered that a load increase by inner side works (concrete floors, piping, concrete walls etc.) in the period 2

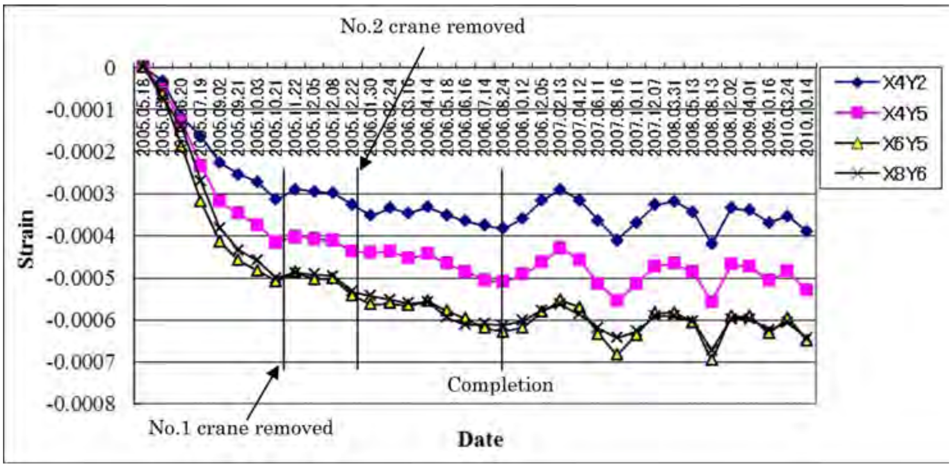

Figure 14. Static strain chages of the columns measured by SOFO sensors.

was very large comparing with those in the period 1. We had expected that because the dead load variation after the completion will be small and the strains of the columns will maintain almost the same values accordingly. The strains of the columns, however, have been changing remarkably after the completion as shown in Fig. 14. A strain gage was installed on each column as mentioned above. In order to confirm the effectiveness of the results with the SOFO sensors, we evaluated measurement results from the strain gages. Fig. 15 shows measurement results by the strain gages. Because the strain gages are self-compensated ones, the apparent strains due to temperature changes are negligible small over the measured temperature ranges and the measured strain changes are estimated to correspond to compressive axial force variations of the columns accordingly. Because gage lengths of the strain gages are only 3 mm, which is much smaller than those of 1 m-SOFO sensors, measurement precision of the strain gages may be lower than that of SOFO sensors. Nevertheless, measured axial force variations are considered to be effective in general. Although there are some irregular strain variations due to some measurement errors in the trend curves of X4Y2 and X6Y5 temporarily as shown in Fig. 15, overall strain changes are similar to those of SOFO sensors. Large strain fluctuations can be seen after the completion as well as SOFO sensors in Fig. 14.

From Figs. 14 and 15, it is obvious that axial forces of steel columns have been fluctuating even after the completion. The monitored columns are CFT (Concrete filled steel tube) ones and are filled with concrete inside and therefore inside concrete can also sustain dead load. After pouring concrete, concrete indicates complex behaviors such as thermal expansion, self-shrinkage, drying shrinkage, creep and etc. Since a total load acting on a column should be almost constant after the completion, it is estimated that axial forces in the opposite direction to steel columns have been acting on the inside concrete parts.

3.4. Dynamic measurement with SOFO dynamic

We had considered that a strong exciting force will be necessary in order to observe vibrations of the columns and therefore decided to measure on a strong windy day. As a result, we conducted a dynamic measurement on March 17th 2006. It was a strong windy day and the maximum wind velocity was 15 m/s.

The measured column was X6Y5 which is near the center of the building. Fig. 16 shows a measurement result for about 1 minute between a.m.10:50 to 10:51 when the wind velocity was peak. A measurement result with a strain type accelerometer is also shown in Fig. 16. Small vibration amplitude of below 1 is detected clearly by SOFO sensor. FFT analysis result of this vibration is shown in Fig. 17 and the 1st bending mode of the building with a natural frequency of 0.375 Hz is clearly detected. On the other hand, the accelerometer was unable to detect the vibration because of the low acceleration of the column as shown in Fig. 16. In addition, the strain gage on the column was also unable to detect the vibration because of the low strain amplitude. We tried dynamic measurement on May 19th 2006. Although it was a light wind day, the 1st natural frequency of 0.375Hz was definitely detected. It was verified that SOFO Dynamic is capable of detecting the vibration of the column in the condition of low excitation force by a light wind, which ability stems from

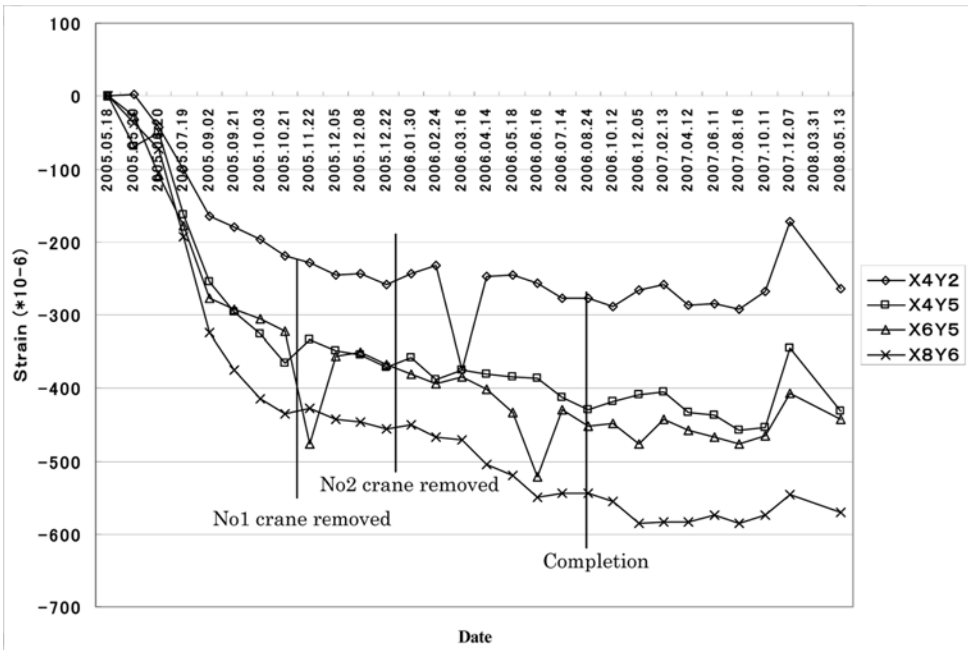

Figure 15. Static strain changes of the columns measured by conventional strain gages.

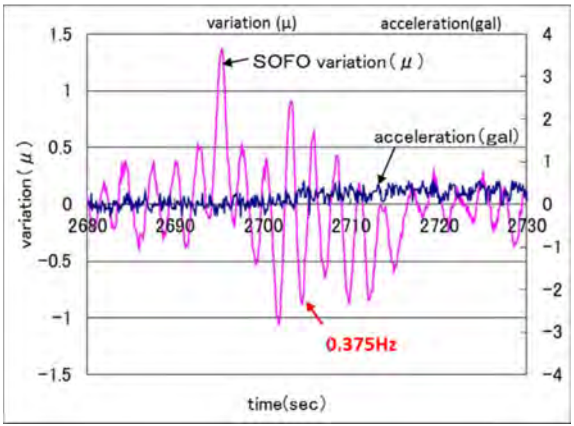

Figure 16. Result of dynamic strain measurement for the column X6Y5.

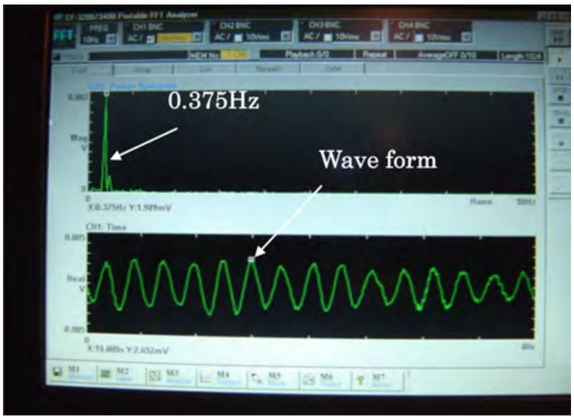

Figure 17. FFT analysis result of the dynamic strain data.

its ultra-high resolution of 0.01 μm.

The natural frequency of the building can be decreased if serious failures occur in the building by an event such as a great earthquake. Although we have not experienced any catastrophic earthquake with a seismic intensity of over 6 in Tokyo after the completion, we conducted a dynamic measurement temporarily on October 14th 2010. As expected, the measured 1st natural frequency had not been changed and was 0.375Hz. It is, therefore, considered that the structural integrity of the building had been demonstrated until that day.

4. Conclusions

A structural health monitoring technology based on the use of long-gage fiber optic deformation sensor: SOFO is being applied to a 33-floors tall building in Tokyo from May 2005.

The followings have been revealed as a result.

(1) Changes of normal forces acting on steel columns can be monitored with SOFO sensors.

(2) The monitoring was initiated on May 2005 and the latest measurement was performed on 14^{th} 2010. SOFO sensors had been stable during this period of more than five years. The long-term stability of SOFO system was confirmed consequently.

(3) The normal force acting on a column having CFT structure fluctuates even after completion of the building. We consider that this is because the filled concrete in the column also sustains dead load and the normal force of the concrete fluctuates in accordance with thermal expansion, drying shrinkage, creep, etc. of the concrete.

(4) In order to evaluate the fluctuation of the normal force acting on a column having CFT structure, it is necessary to monitor both normal forces acting on the steel column and the inner concrete. On the basis of this knowledge, a long-term monitoring of both normal forces acting on steel columns and the inner concrete by using SOFO sensors is being continued at Nagoya Mode Gakuen (Spiral Tower) from its construction stage in Feb. 2007 for the first time in the world (Nishizawa et al., 2007; Nishizawa et al., 2010).

(5) Column vibrating strain due to micro movement of the building can be detected by SOFO Dynamic which has a remarkable measurement resolution.

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References

Glisic, B., Inaudi, D., and et al. (2003). “Monitoring of building columns during construction”, 5th Asia Pacific Structural Engineering & Construction Conference (APSEC), Johor Bahru, Malaysia, pp. 593~606.

Inaudi, D., et al. (1996). “Bridge Monitoring by Interferometric Deformation Sensors”, SPIE International Photonics China Symposium on Laser Optoelectronics and Microphotonics: Fiber Optic Sensors, China.

Inaudi, D., et al. (2000). “Geo-structural Monitoring with Long-gage Interferometric Sensors”, SPIE Conference on Nondestructive Evaluation and Health Monitoring of Aging Infrastructure, USA.

Inaudi, D. and Glisic, B. (2004) “Combining Static and Dynamic deformation monitoring with long-gauge fiber optic sensors”, IABMAS’04, International Association for Bridge Maintenance and Safety, October 19-22, Kyoto, Japan.

Mikami, T., et al. (2009). “Health Monitoring of High-Rise Building with Fiber Optic Deformation Sensor”, *Transactions of the Japan Society of Mechanical Engineers*, *Series C*, 75(750), pp. 249~255. (in Japanese).

Mikami, T., et al. (2006). “High-rise Building Monitoring by Fiber Optic Sensors”, IABSE Symposium, Budapest, pp. 1~6.

Mikami, T., et al. (2002). “Structural Health Monitoring with

Fiber Optic Sensors", SEWC2002, Yokohama, Japan, T9-1-d-1, pp. 1~6.

Nishizawa, T., et al. (2010). "Measurement Using Optical Fiber Sensors in order to Ensure and Keep Track of the Quality and Performance of Buildings from the Design to Post-completion Stages", 5th World Conference on Structural Control and Monitoring, E-5:213.

Nishizawa, T., et al. (2007). "The Report of the Monitoring of High-rise Building with irregular shape", The Aim and Abstract of the Monitoring, Proceedings of Kyusyu Conference of Architectural Institute of Japan, pp. 83~84. (in Japanese).