Long-term Structural Monitoring and Damage Detection of High-rise Buildings by use of Fiber Optic Sensors

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SUMMARY:
A new way of structural monitoring and damage detection procedure will be discussed, which employs fiber optic sensors for static and dynamic axial deformation of columns of steel high-rise buildings. The long-term monitoring is done for the E-defense specimen and actual high-rise buildings during their construction and demolition. Static deformation of columns was properly measured showing the change of building weight, which is effective data for the evaluation of structural stiffness through the natural period of the structure. Dynamic deformation measurement was also tried using the same sensors. It was observed that the dynamic axial deformation of columns shows natural frequency of the structure, and is possible information on structural damage as change of stress distribution in the structure. Log-term stability of the fiber-optic sensor is effective for structural monitoring, however, the correction of thermal strain is strictly required as shown in the paper.

Keywords: Steel structure, Structural health monitoring, Observation, Fiber optic sensor, E-defense,

1. INTRODUCTION

During the 2011 off the Pacific coast of Tohoku Earthquake, Japan, a number of high-rise buildings showed large responses in Tokyo metropolitan area and in other areas where several hundreds kilometres apart from the earthquake source. Responses were not extremely large as to cause severe structural damage, however interior equipments were damaged and some users have injured. The long-period component of seismic waves with period of several seconds will predominate especially within the large sedimentary basin. Most of high-rise buildings in Japan are located in large cities on sedimentary basins, however, the effect of long-period ground motion was not suitably considered in structural design in the past, and they have not yet experienced destructive earthquake ground motions with long-period component. In Japan, other large earthquakes are predicted to occur in the near future along the southwest coast of the Pacific Ocean. Structural retrofitting of existing high-rise buildings has just started in Japan using additional dampers.

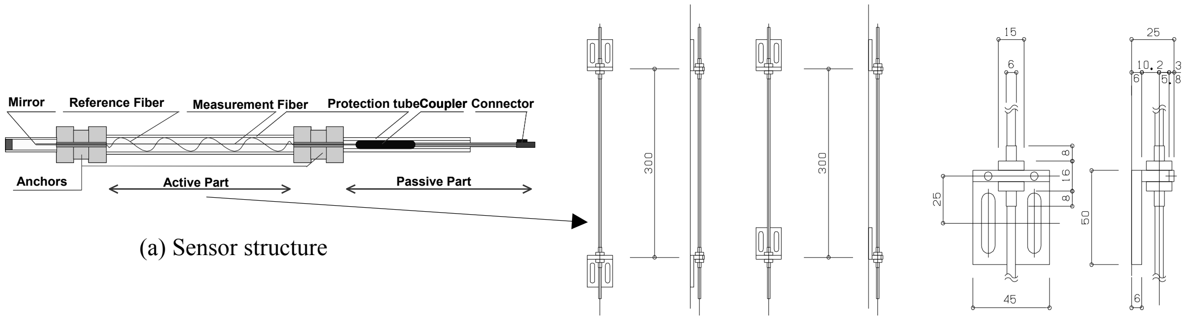
Considering such situations, a procedure for earthquake response monitoring and structural damage estimation of existing high-rise buildings are required to verify their necessity of seismic retrofit before earthquakes and to evaluate their safety and usability quickly after the earthquake. Many high-rise buildings will suffer severe shaking in the same time during coming large earthquakes in Japan, professional engineers for damage inspection will be seriously shorthanded. In the present paper, structural monitoring and damage detection procedure will be discussed, using fiber optic sensors for static and dynamic axial deformation of columns of steel high-rise buildings. The long-term monitoring is done for the E-defense specimen and an actual high-rise building during their construction and demolition. Static deformation of columns shows the change of building weight, and dynamic axial deformation of columns shows natural period of the structure. Thus the structural stiffness and its change are precisely evaluated through the observed results. Log-term stability of the fiber optic sensor is suitable for structural monitoring, however, the correction of thermal strain is strictly required as shown in the later section.

2. FIBER OPTIC SENSOR

Static and dynamic column axial deformation was monitored by SOFO system with fiber optic sensors (Mikami *et al*., 2006). Outline of the sensor and installation on the column of the specimen is shown in Figure 1. Sensors with gauge length of 300 mm, not a local strain gauge, were selected and installed at middle position of the columns to measure averaged axial deformation. The sensor consists of two optical fibers as shown in Figure 1(a) to cancel the effect of environmental temperature. As the result, the sensor has accuracy with a resolution of 2.0 micrometers in static displacement, and 0.01 micrometers in dynamic displacement within the frequency range under 1 kHz.

Thermal effect of sensors were corrected by the sensor itself, however the thermal strain of steel column should be properly corrected using observed temperature of the column. The sensors were mounted by bonding L-figure steel fixtures (brackets) supporting both ends to the surface of the column. These brackets at both ends of the sensors were fixed with the figure L facing the same direction because the effect of the thermal strain of these brackets on measurement results was not ignorable.

Static column axial deformation was measured during construction or demolition of the structure with the 10 minute intervals. Dynamic axial deformation is also measured by the same sensors and digital type data recorder was used with 100Hz sampling.



(a) Sensor structure

(b) Sensor installation on column (c) detailed shape of bracket

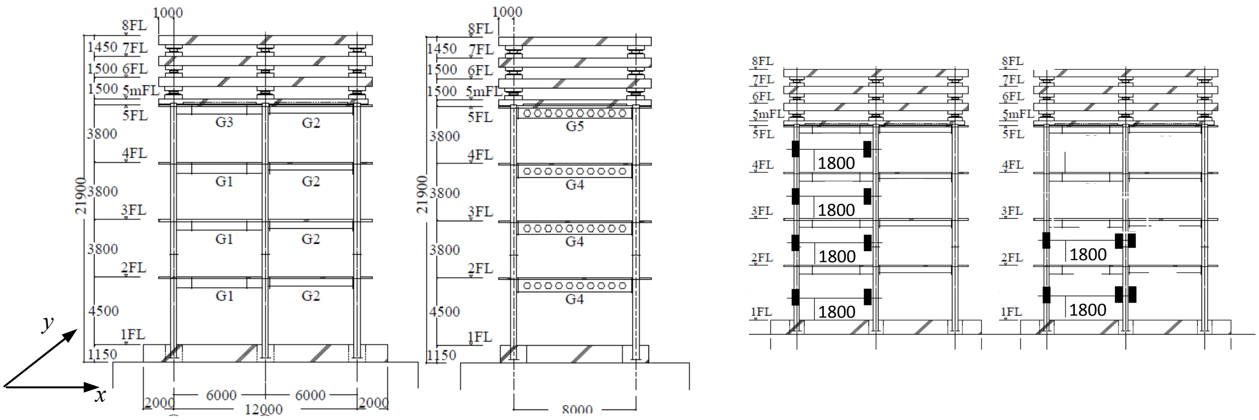
Figure 1. Fiber optic sensor and installation on the steel column

3. HIGH-RISE BUILDING SPECIMEN FOR E-DEFENSE SHAKING TABLE EXPERIMENT

3.1. Full-scaled high-rise building model for E-defense subjected to long-period ground shaking

Verification of the methods and sensors was done on a full-scaled steel framed high-rise building specimen for E-defense shaking table experiment, which was damaged by long-period predominant earthquake shaking. The objective of the shaking table experiment is to develop damage reduction measure of high-rise buildings in the 1970s for long-period ground motions. Figure 2 shows the outline of the test structure (Nagae et al., 2009). The structure is modeled after a high-rise building of 21 stories with height of 80 meters and is showing general feature of high-rise buildings in Japan in the 1970s. The 1st to 4th stories of the structure are actual size with realistic details, and upper floors are concentrated into three masses supported by rubber bearings. Averaged story stiffness and inelastic characteristics are modeled by steel dampers. Total weight of the structure is approximately 10,000 kN and the 1st natural period is designed as 2.4 s. As the structure has few non-structural members, it is suitable for investigating structural monitoring and damage detection procedure.

Figure 2 also shows the location of main acceleration sensors and fiber optic sensors. Static column axial deformation was measured at two columns of each story and dynamic deformation was measured using totally eight sensors at both sides of two columns at the 1st and 2nd stories as shown in Figure 2.



(a)Test structure (b) Static measurement (c) Dynamic measurement

Figure 2. Outline of E-defense high-rise building specimen and location of fiber optic sensors

3.2. Static column deformation during construction of test building

Figure 3 shows change of axial deformation of the center column of the 2nd story during construction. Observation had been done on each 10 minutes and observed deformation is shown as a function of temperature. The sensor is designed to cancel out its own thermal effect, but the steel column and fixing brackets deform according to their temperature. Thus the observed results include the apparent linear coefficient of thermal expansion which are shown as slanted lines in Figure 3. Gradient of lines are approximately 0.6 x 10^{-5}/centi degree, which is roughly half of the coefficient of thermal expansion of general steel material. It is clearly observed in the figure 3 that the axial deformation of column is measured as degradation of the slanted lines. After correction of thermal strain using observed apparent coefficient of thermal expansion, Figure 4 shows clear and stable tendency of axial deformation by installation of the 6th and 7th floor of approximately 1,900 kN.

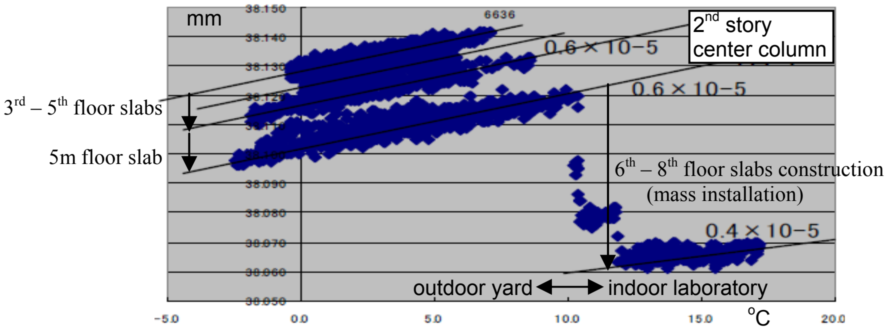


Figure 3. Static column axial deformation during construction

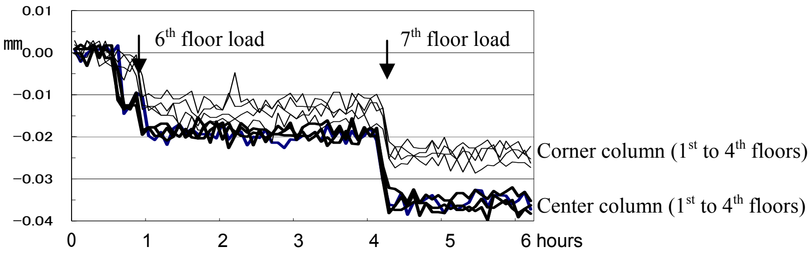
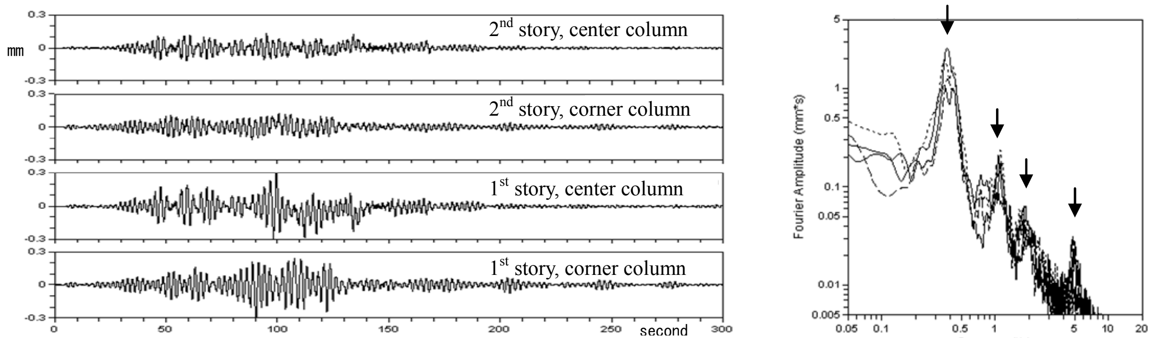


Figure 4. Static column axial deformation according to increasing weight of floor slabs

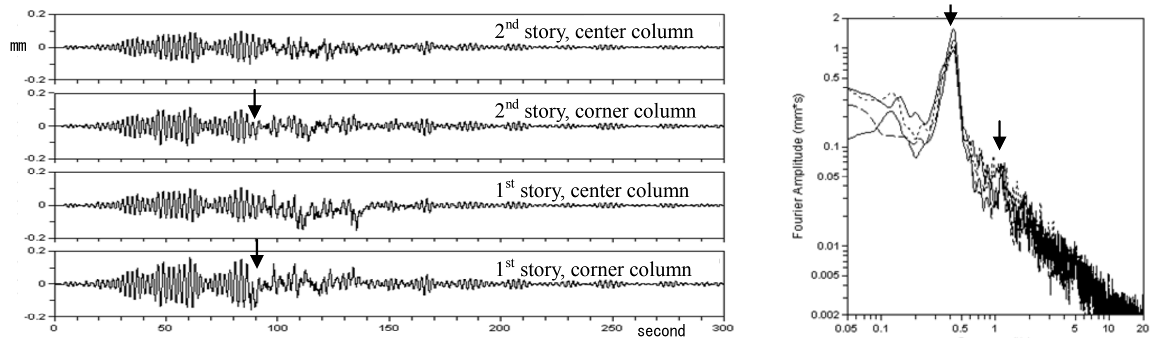
3.3. Dynamic column deformation during strong motion shaking

The sensors used for the research are capable of measuring dynamic displacement and expected to be available for evaluating the integrity of and damage to structures through the dynamic characteristics of buildings and their changes. During dynamic loading, totally eight sensors were installed at both sides of two columns at the 1st and 2nd stories as shown in Figure 2.

Figure 5 shows axial and bending deformation subjected to long-period predominant seismic shaking by calculating sum and difference of observed dynamic deformation respectively from two sensors attached on the both side of columns. The sum waveforms of corner columns of the 1st and 2nd story show clear change at the time of damage occurred (approx. 90 – 100 seconds from the start of shaking). Fourier spectra of the difference waveform show natural frequency peaks up to higher modes, however the spectra of the sum waveform only have the 1st natural frequency peak. This character may be caused that the axial stress of columns in lower story is influenced by the overturning moment of the 1st mode, and influenced by the change of stress distribution of the damaged structure. Detailed investigation will be required with dynamic response analysis of the frame.



(a) Column bending deformation by difference of both side sensors



(b) Column axial deformation by sum of both side sensors

Figure 5. Dynamic column bending deformation and axial deformation during shaking

4. ACTUAL HIGH-RISE BUILDING DURING DEMOLITION

4.1. Outline of building and demolition process

Column axial deformation of a high-rise steel building was continuously observed during demolition by use of fiber optic sensors to evaluate removed weight of upper floors. Installation, observation and data processing method of SOFO type fiber optic sensor were verified especially focused on correction of temperature-dependent effect on strain of steel structure. Figure 6 shows outline of the building, which was located in Nagoya city, 25 floors steel structure with 90m high, constructed in 1973. The 1st natural periods are evaluated as 2.47s (span direction) and 2.44s (longitudinal) in structural design process. Observed natural periods after removal of interior were 0.43Hz (2.3s) and 0.46Hz (2.2s). Vibration observation was continuously performed by use of strong motion accelerographs.

Figure 6 also shows the demolition process in approximately ten months. First the interior walls and materials were removed and then the structure was demolished in four months, which corresponds one floor per 4.4 days. Static measurement was done from February to July, and dynamic measurements were performed in eight times.

Totally nine fiber optic sensors were installed at steel column in the fourth floor of the building as shown in Figure 7. The fourth floor was the bottom of the steel framed superstructure, and evaluation of static and dynamic deformation of the structure was considered for sensor location in the floor.

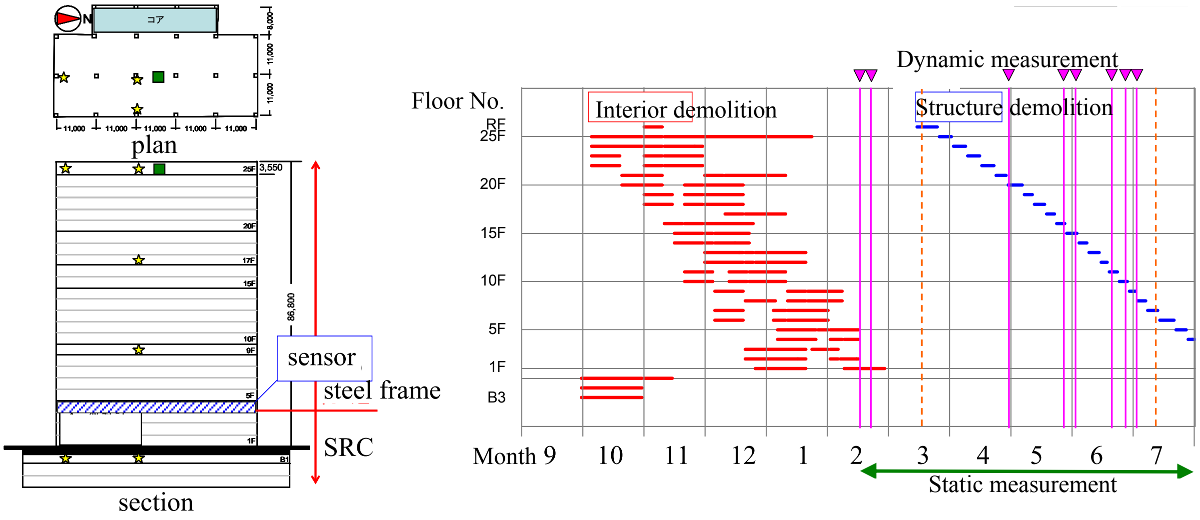
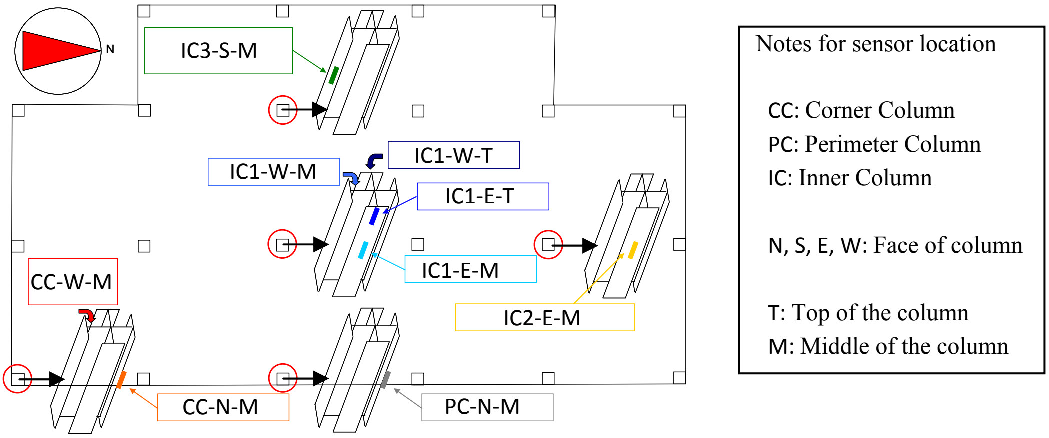


Figure 6. Otline of building and demolition schedule



Notes for sensor location

CC: Corner Column
PC: Perimeter Column
IC: Inner Column

N, S, E, W: Face of column

T: Top of the column
M: Middle of the column

Figure 7. Setup of fiber optic sensors on steel columns of the fourth floor

4.2. Static column deformation during demolition of the building

Demolition of the building was done from February to July, thus the effect of thermal strain was observed in daily fluctuation and increasing temperature with the season. Figure 8 shows change of axial deformation of IC-W-M sensor (inner column of the 4th story, facing west and middle height of the column) during demolition. Observation had been done in each 10 minutes and observed deformation is shown as a function of temperature. As the apparent linear coefficients of thermal expansion are different in each demolition stage, the thermal strain correction was done using observed coefficient. Observed results before demolition give the most stable and reliable coefficient.

Figure 9 shows change of loads of superstructure evaluated by corrected column deformation of the IC-W-M column. Difference is observed as evaluation method of correction coefficient, however the deformation (extension) of columns in the real structure is clearly shown.

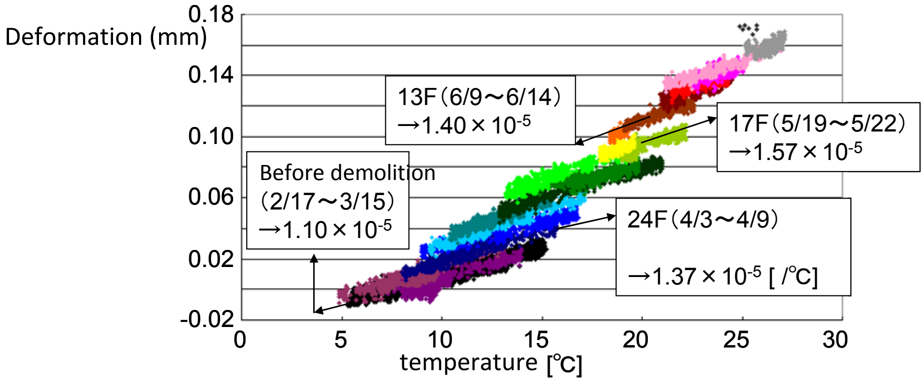


Figure 8. Evaluation of correction coefficient considering thermal strain of column IC-W-M during demolition

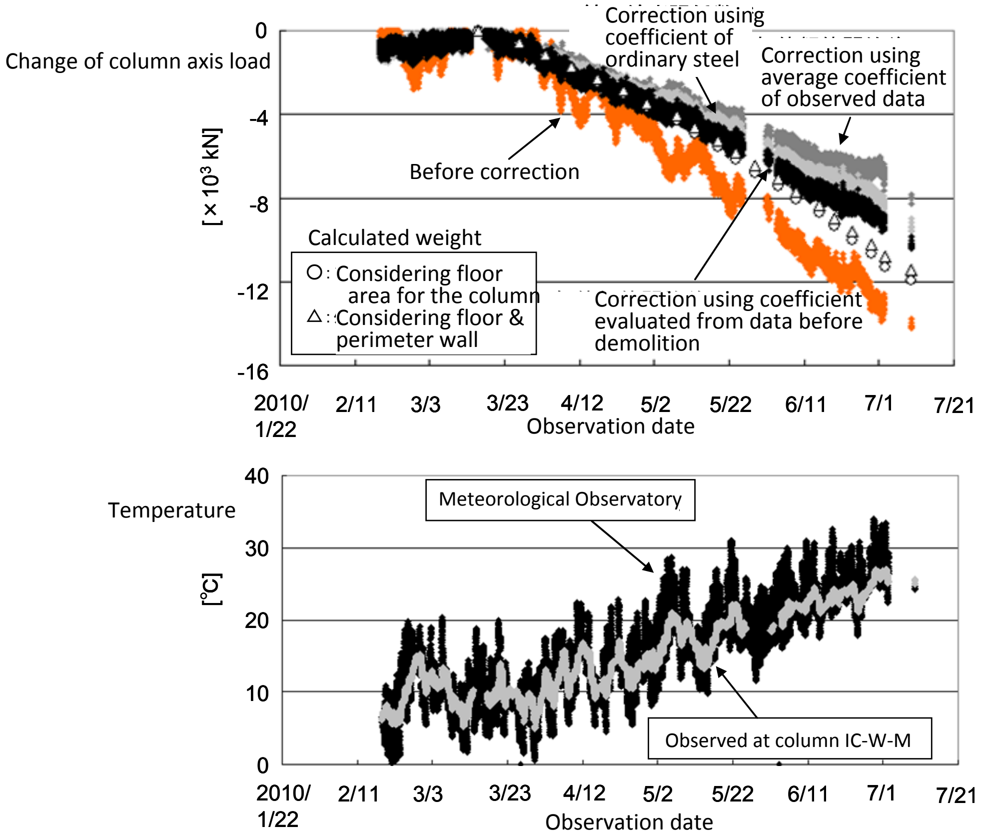


Figure 9. Corrected axial deformation of column IC-W-M during demolition by decreasing axial force

4.3. Dynamic column deformation

Dynamic observation of column axial deformation were tried to verify that the observation is effective for evaluation of natural period and vibration characteristics of the structure. The observed time histories of column axial deformation are shown in Figure 10, comparing with Fourier spectra and vibration response of the building. Figure 11 shows spectral characteristics of observed data in two different stage of demolition. These figures show that the observed column axial deformation is sufficiently effective for evaluating dynamic properties of the building, and is not fully disturbed under construction noise. Figure 12 shows the change of evaluated natural frequency during demolition of the building. It is clearly shown that the dynamic observation by fiber optic sensor corresponds to the spectral results of seismometers.

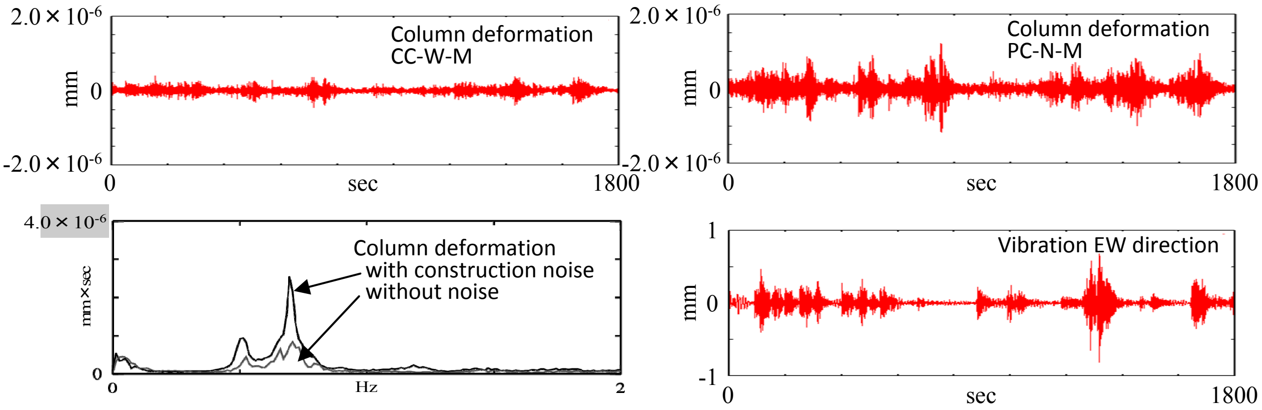
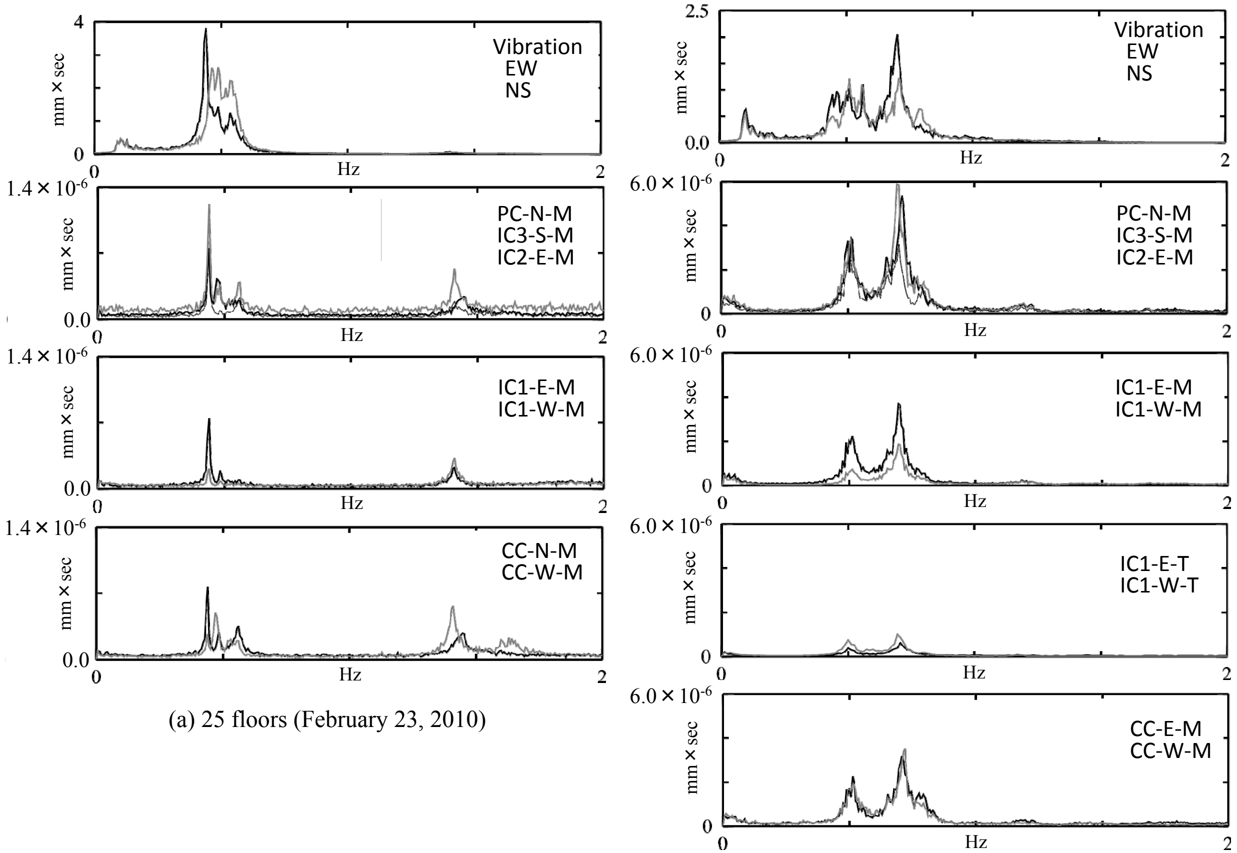


Figure 10. Observed dynamic column deformation time histories and their Fourier Spectra



(a) 25 floors (February 23, 2010)

(b) 20 floors (April 30, 2010)

Figure 11. Observed dynamic column deformation

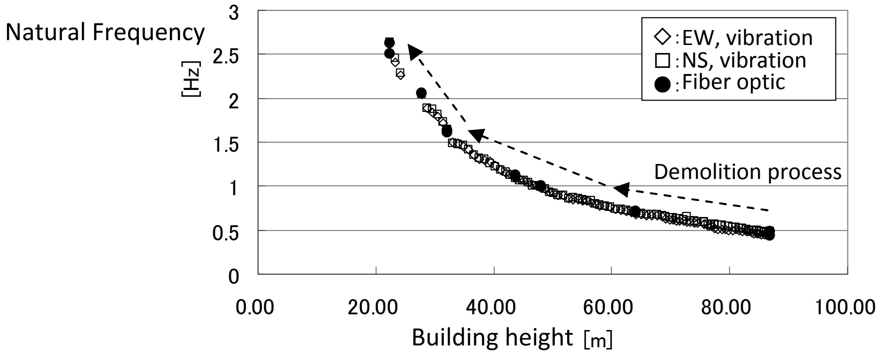


Figure 12. Change of natural frequency detected by fiber optic sensors comparing with those by acc. sensors

5. CONCLUSION

In this paper, fiber optic sensors were used for detection of static and dynamic column axial deformation. For the E-defense specimen, static deformation of columns was properly measured showing the change of building weight, which is effective data for the evaluation of structural stiffness. Dynamic deformation measurement was also tried during earthquake shaking considering axial and bending deformation. It was observed that the dynamic axial deformation of columns shows possible information on structural damage as change of stress distribution in the structure.

Column axial deformation of a high-rise steel building was continuously observed during demolition by use of fiber optic sensors to evaluate removed weight of upper floors. Installation, observation and data processing method of fiber optic sensors were verified in an actual building especially focused on correction of temperature-dependent effect on strain of steel structure. Accuracy of observed axis deformation was improved by evaluation of the apparent coefficient of thermal expansion which includes thermal deformation of sensor mounts. Evaluated weight of structures was verified by the actual weight of removed structures and detailed estimation by structural data. Accurate observation of weight of actual structure is important for structural health monitoring with natural frequency of the building.

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