HEALTH MONITORING OF 4-STORY STEEL MOMENT FRAME BEFORE AND AFTER THE COLLAPSE TEST

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ABSTRACT :

Changes of modal parameters of a full scale 4-story steel building due to construction progress or seismic damage are evaluated in the shaking table test of the 2007 E-defense project, which are expected to employ as damage index of structural health monitoring. To evaluate the modal parameters, the continuous ambient vibration test has been conducted since the building was in bare steel frame state. After the ambient vibration test was started, the floor slabs are cast and non-structural components were installed. After the completion, various levels of seismic excitations were given to the building, and finally the building collapsed on the first floor. Through such process of the construction and the excitation test, a series of ambient vibration record in eighty days is obtained. The modal parameters in every five minutes are successively estimated by the cross-spectrum based modal identification. From the results, changes of the modal parameter are discussed on different states of construction as well as before and after the seismic excitations, which are very useful to develop the vibration-based damage detection. Change of the modal parameter due to different levels excitations is also investigated by using several small excitation records, which can be caused by changes of story-stiffness increment added by the non-structural components.

KEYWORDS: Structural Health Monitoring, Damage Detection, Natural Frequency, Steel Building

1. INTRODUCTION

For evaluating structural integrity of an aging structure or a suffering building in disaster area, research and development of structural heath monitoring (SHM) have intensely investigated in resent earthquake engineering field. Of SHM, vibration based-damage detection (VBDD) is expected to widely employ to find earthquake-induced damage of buildings, where changes of modal properties such as the changes of natural frequency and modal participation factors are detected before and after earthquake [1]. Numerous vibration records of buildings have been observed for strong earthquake motion or ambient vibration individually before. However, few set of both strong earthquake motion and ambient vibrations before and after the earthquake have been amassed completely, and no complete observation data of a building have been obtained during the all lifetime from early construction works to final collapse state, which are need to establish the VBDD. Especially, the modal properties of a steel building is strongly affected by non-structural components, such as exterior or partition walls, but it is very difficult to predict the modal properties of a steel building with considering the non-structural components. To establish the VBDD especially for a steel building, the accurate prediction scheme of modal properties must be developed, and to proceed on this development, the complete series of the modal properties are needed in the construction process as well as in the damage process due to several intensities of earthquakes.

In the study, a long-term ambient vibration test have been continuously conducted on a full-scale 4-story steel frame building specimen during the whole life, to utilize a collapse shaking table test of the E-Defense project on the Hyogo Earthquake Engineering Research Center, National Research Institute for Earth science and Disaster prevent (NIED), conducted on September, 2007 [2][3]. From the continuous ambient vibration records, transition of modal properties are evaluated in the whole lifetime, such as from the early construction in bare steel frame state, through the construction works on the non-structural components and the seismic experiences against small to middle levels of earthquakes, to the end of final collapse on the first story of the building. The

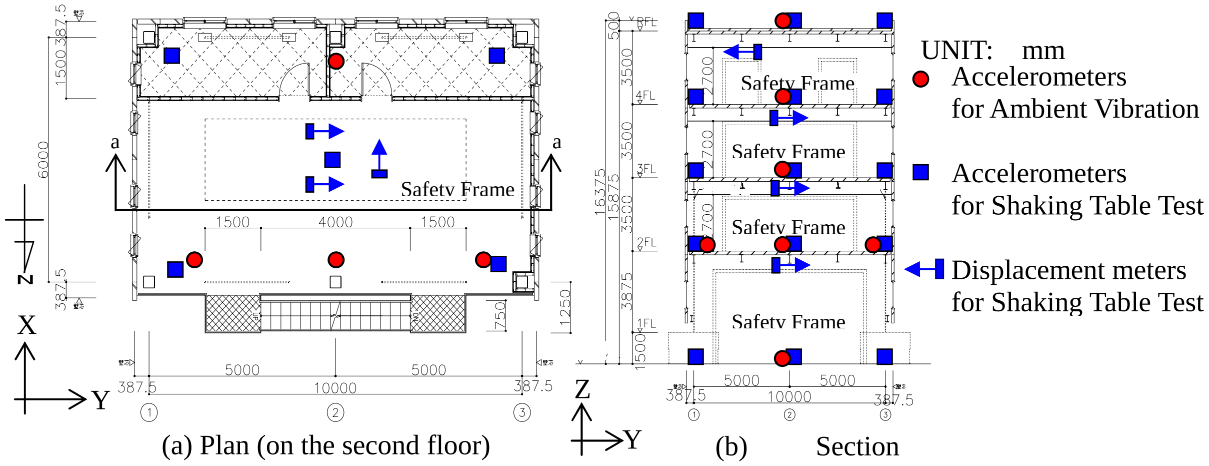


Figure 1: The full-scale 4story steel frame building specimen on the collapse experiment

amplitude dependency on the modal property is also investigated from the shaking table test records with four different levels of seismic excitations, which is largely affected by the stiffness of the non-structural components.

2. OUTLINE OF THE STEEL BUILDING[2][3]

The building treated in the paper is a full-scale 4-story steel building, which is a shaking table test specimen on the collapse experiment on the E-defense of NIED, shown in Figure 1. The aim of the shaking table test is to investigate the seismic performance of a steel building comprising the moment frame, and especially to simulate complete story collapse of a real steel building against ultimately huge earthquake. Thus, to simulate the real behavior, the building was constructed using real size structural steel members as well as assembling real exterior walls, real ceilings and real partition walls. Of the non-structural components, the exterior walls are installed on the all floors except on the north-side, and the ceiling and partition walls are installed on the second to the forth floors. As shown in Figure 1, the temporally stairs are installed on the north-side for construction and observation inside the building, which are removed during the shaking table test.

The construction and experiment works process are shown in Figure 2. The erection of the steel frame of the building was begun on the strong reaction floor inside the shaking table facility from July 2, 2007. After scaffolding erected around the steel frame, the concrete floor slabs were cast, and the non-structural components were installed. After the completion, the building was moved on the shaking table, and the shaking table tests were began on September 20. And various levels of seismic excitation were given to the building, and finally on September 27, the building was completely collapsed on the first story during the 100 percent excitation by the JR Takatori record of the 1995 great Hanshin-Awaji earthquake..

3. LONG-TERM AMBIENT VIBRATION TEST AND MEASUREMENT

The long-term ambient vibration test (LT-test) began on July 11, 2008, when the building was in bare steel frame state. The LT-test was continuously conducted until September 29, after the building collapsed. The measuring period of the LT-test are also shown in Figure 2. In the LT-test, eight sets of three-axial-accelerometers were installed at the center of each floor, and at the edges of the second floor, as plotted by red circle marks in Figure 1. These eight accelerometers were measured only for the ambient vibration from very quiet vibration in midnight to noisy vibration due to construction works, thus, whose measuring ranges, resolutions and sampling rate are set to 25 cm/s/s, 24 Bit and 200 Hz, respectively. Thus, the acceleration records of the LT-test can sometimes exceed over the measuring range during the shaking table tests, however, the ambient vibration focused on the study could be obtained accurately.

In addition to the above mentioned accelerometers for the LT-test, 25 three-axial accelerometers and 12 displacement-meters were installed for the shaking table test, as plotted by blue rectangular marks in Figure 1. These sensors were recorded only when the shaking table tests were conducted.

4. MODAL IDENFITICATION METHOD[4] [5] [6]

From the continuous records of the LT-test, natural frequencies, damping factors and modal vectors are identified by a cross spectrum based modal identification technique which is employed auto-regressive moving-average model (ARMA model) [4] [5] [6]. Here, the natural frequencies and damping factors are identified from the X- and the Y-components of acceleration records on the roof floor, and the complex modal vectors are identified from all components of the LT-test. In the modal identification, to obtain the modal property closely in time, all records on the LT-test are divided by every 3 minutes with two-thirds overlapping; therefore, the estimates of the modal properties are calculated by every one-minute.

Using the identification scheme with the n-th order ARMA model, n estimates of eigenvalues are obtained at a time. Of the n estimates by the ARMA model, there are both substantial eigenvalues and spurious eigenvalues: i.e., the substantial eigenvalue is related to the modal properties of the building, whereas the spurious eigenvalue is related to obscure the physical meaning. From the substantial estimates, moreover, we must choose only one eigenvalue of our interest, such as the first translational mode, or the second bending mode. Thus, we must choose only one eigenvalue of our interest from all the estimates of the ARMA model obtained by every one minutes.

To extract the interest estimate related to the modal property with changing with the construction works or damage experiences, we develop a modal extraction scheme by using the Modal Assurance Criterion function (MAC function). The MAC function is to measure the similarity between two sets of modal vectors, which can given as follows

$$\mathrm{MAC}\{{}_j\boldsymbol{\varphi}_i, {}_j\boldsymbol{\psi}_{i-1}\} = \frac{|\,{}_j\boldsymbol{\varphi}_i^{\mathrm{T}}\;{}_j\boldsymbol{\psi}_{i-1}^{*}\,|^2}{{}_j\boldsymbol{\varphi}_i^{\mathrm{T}}\;{}_j\boldsymbol{\varphi}_i^{*}\cdot{}_j\boldsymbol{\psi}_{i-1}^{\mathrm{T}}\;{}_j\boldsymbol{\psi}_{i-1}^{*}} \tag{1}$$

where ${}_j\boldsymbol{\varphi}_i$ is the estimate of the j-th modal vectors at time i; ${}_j\boldsymbol{\psi}_{i-1}$ is the criteria modal vectors of the j-th mode; T is the transposed operator; $*$ is the complex conjugated operator. When the estimate ${}_j\boldsymbol{\varphi}_i$ is quite similar to the criteria modal vectors ${}_j\boldsymbol{\psi}_{i-1}$, the value of the MAC function is close to 1.0. On the other hand, when they are entirely different from each other, the value is close to 0.0. In the paper, the criteria modal vectors are proposed as

$${}_j\boldsymbol{\psi}_i = \frac{\sum_k \mathrm{MAC}_{i-k}\cdot{}_j\hat{\boldsymbol{\varphi}}_{i-k}}{\sum_k \mathrm{MAC}_{i-k}} \tag{2}$$

where MAC_{i-k} is the value of the MAC function at time $i-k$; ${}_j\hat{\boldsymbol{\varphi}}_{i-k}$ is the j-th modal vectors at time $i-k$, which are chosen as the estimate of the j-th mode vectors in the former time steps.

After the estimates of modal properties are calculated by the cross spectrum based modal identification technique for all measured records, the modal extraction scheme with Eqs.(2) and (3) is performed as follows. The first estimate of the modal property is selected from all the estimates at the initial time, calculated by the identification technique, which are evaluated as the modal property of interest and traced in the all measuring

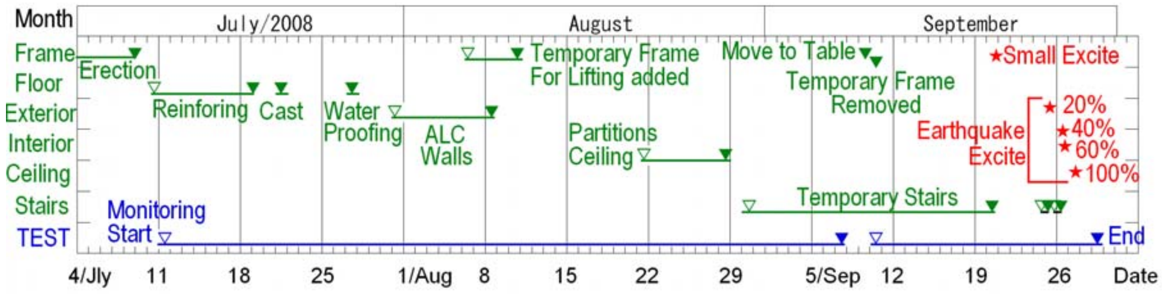


Figure 2: The construction work, the shaking table test, and the Long-term ambient vibration test

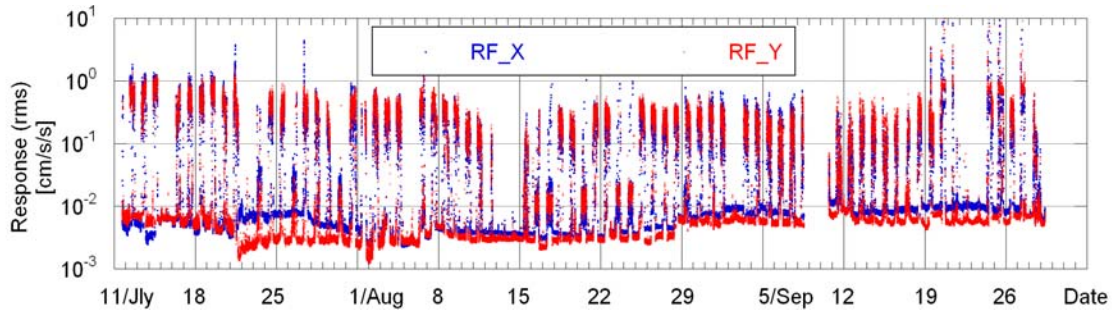


Figure 3: Acceleration amplitude on the roof of the building

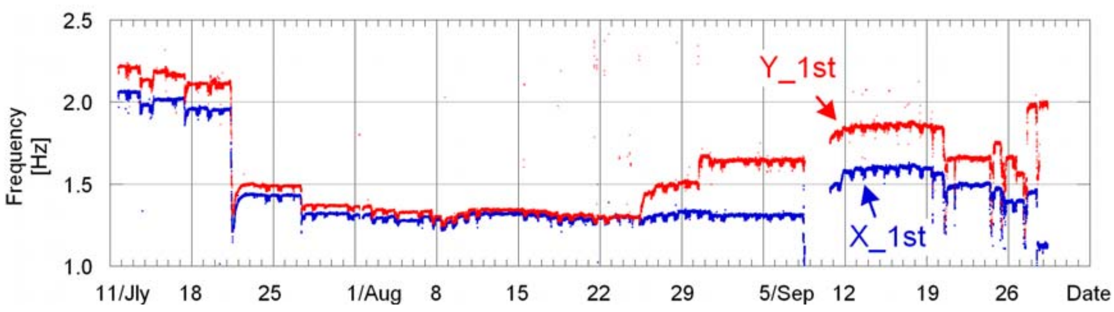


Figure 4: Transition of the first natural frequency

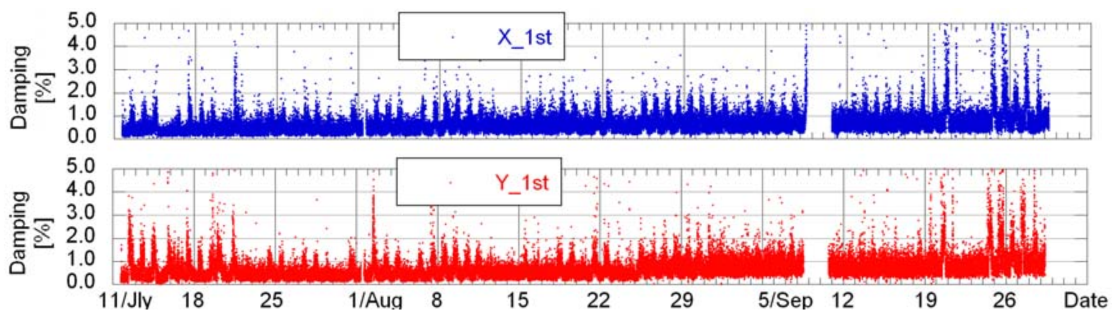


Figure 5: Transition of the first damping factor

period for the modal extraction. And the first criteria modal vectors are set to the modal vectors selected at the initial time. Proceeding the time increment to the next, the second estimate of the modal property is selected such that the MAC value in Eq.(1) is the largest of the estimates at the time step, by using the first criteria modal vectors. And, the second criteria modal vectors are calculated in Eq.(2) by using the first and second estimates and their MAC values. In such way, by using the former estimates of the modal vectors of interest and their MAC values, the calculation steps in Eqs.(1) and (2) are performed repetitively toward the order of time.

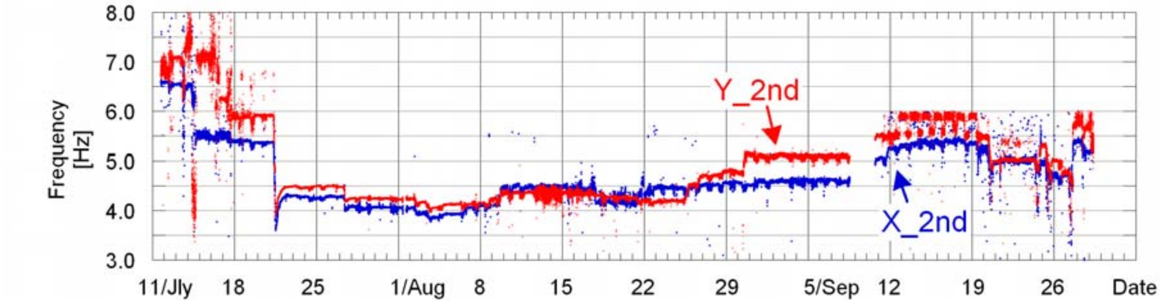


Figure 6: Transition of the second natural frequency

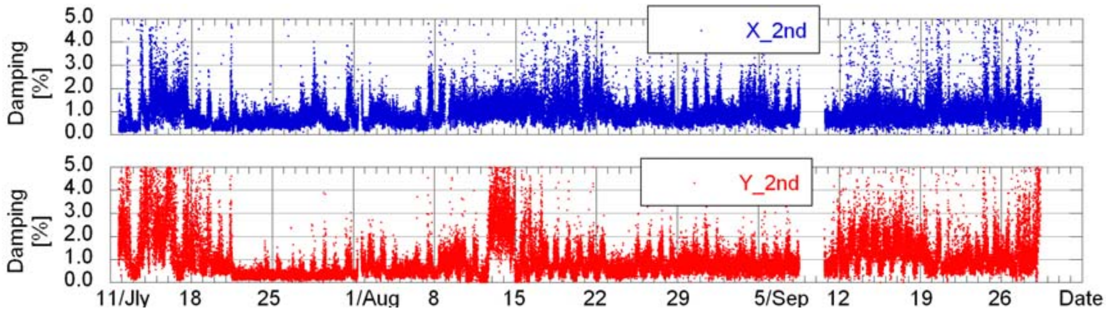


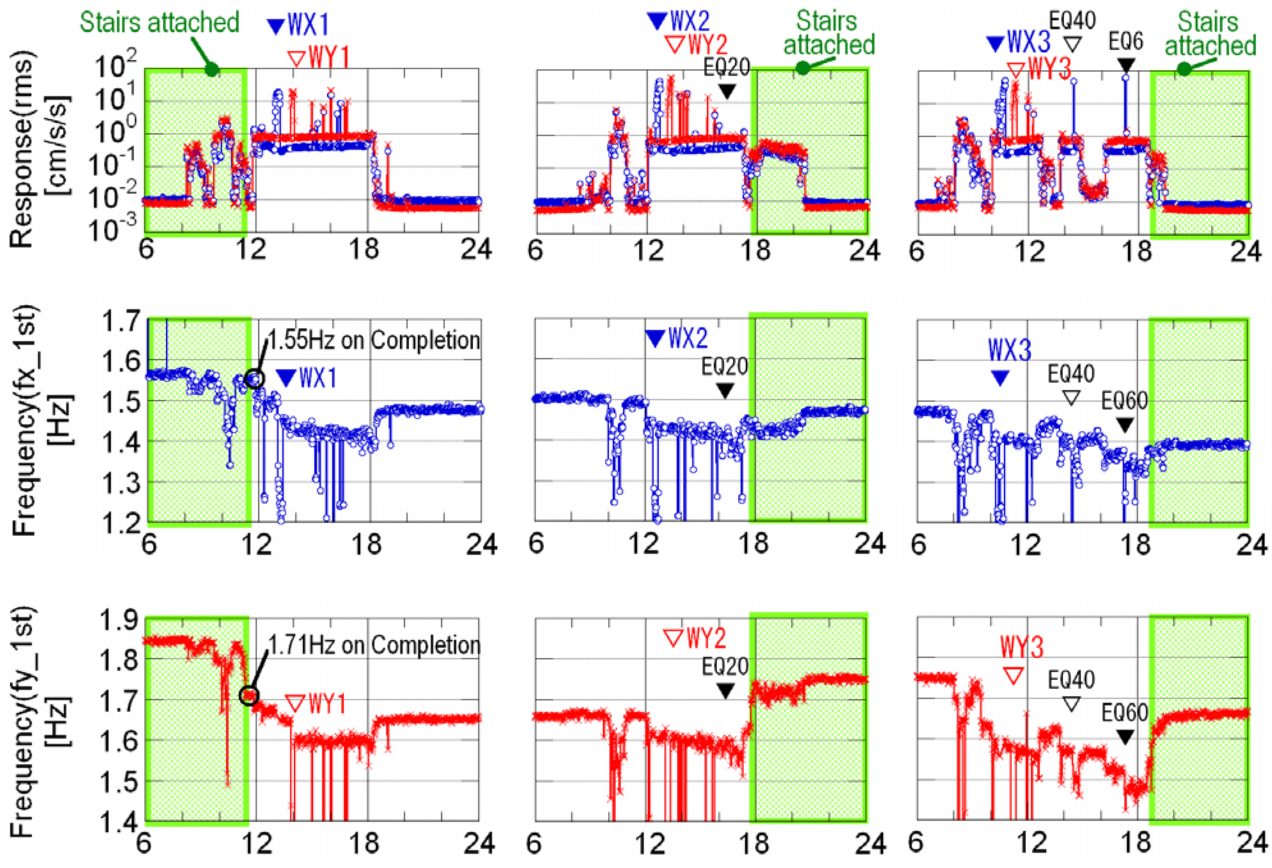
Figure 7: Transition of the second damping factor

As shown in Eq. (2), the criteria modal vectors ${}_j\boldsymbol{\psi}_i$ are calculated by weighted averaging the former estimates of the j-th modal vectors with its MAC values, therefore, the criteria modal vectors are affected by the estimates whose MAC values are large. Thus, the modal extraction are stably-performed when the modal vectors changes with the construction works and damages, or even when the modal property cannot be obtained in a short time because of the poor observation records, for example, contaminated by noise.

5. LONG-TERM TRANSITION OF MODAL PROPERTY

Modal properties of the building can be well-estimated in about 80 days from the early construction to the end after the complete collapsed. The amplitude of acceleration response on the roof floors, and the first and the second modal properties are shown in Figures 3 to 7, respectively.

As shown in Figure 4, the first natural frequencies on the X and Y directions were 2.1 Hz and 2.2 Hz in the bare steel frame state on July 11, and changed to 1.6Hz and 1.8 Hz in the almost completion just after moving the shaking table on September 12, and as removed the temporally stairs, they changed to 1.55Hz and 1.71 Hz just before the first seismic excitation on September 20. While the construction process, the first and second natural frequencies increased and decreased continuously. On the other hand, the damping factors are constantly about 1 percent, but the scattering width of the estimates is larger than those of the natural frequencies. Additionally, during the daytime of construction work performing, we found with the amplitude of acceleration response increasing, the natural frequencies decreased, whereas the damping factors increased; i.e., the vibration amplitude dependency of the modal property was detected. The detail changes of the natural frequencies are observed as follows.



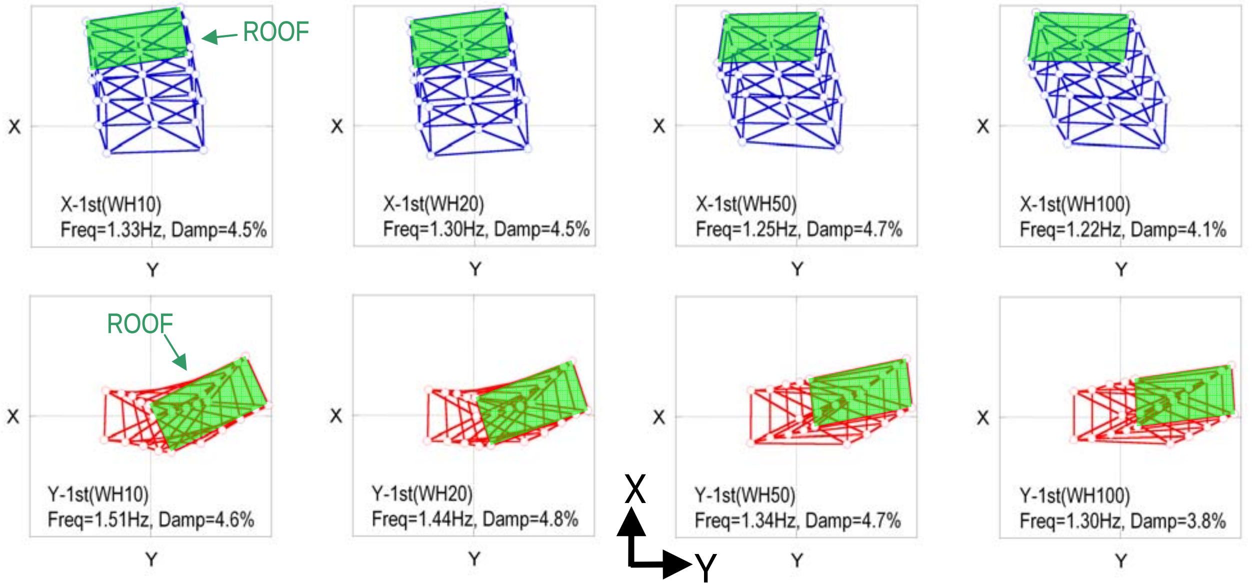
(a) September 20 (b) September 24 (c) September 25

Figure 8: Transition of the first natural frequencies during the days of shaking table test

WX,WY: small white noise excitation on X or Y direction only
EQ20: JR Takatori excitation with amplitude adjustment by 20 percent
EQ40: JR Takatori excitation with amplitude adjustment by 40 percent
EQ60: JR Takatori excitation with amplitude adjustment by 60 percent

Focusing on the construction process, on July 21, after casting concrete slab, the natural frequencies decreased at once by about 40 percent of the bare steel frame state. The change is caused by weight addition of the fresh concrete. Within the three days after the casting the natural frequencies gradually increased, when the concrete slabs were hardening. The similar change of the natural frequencies with casting the concrete was also observed on July 27, when the additional roof slab concrete was cast for water proofing. From September 30 to August 8 the exterior walls of aerated lightweight concrete (ALC) panels were installed, however, the natural frequencies did not change at all. In August 21-28, on the other hand, when the partitions walls were installed, the natural frequencies only on the Y direction increased rapidly by about 15 percent. As shown in Figure 1(a), the partition walls inside the building strongly act on the Y direction and the partition walls are light in weight, therefore, the natural frequencies only on this direction can increase. On August 30, when the temporally stairs were attached on Y direction, the natural frequency on the Y direction also increased, but the natural frequencies on the orthogonal direction did not change at all. The temporally stairs also affected the natural frequency only on the acting direction, as well as the partition walls did.

During the shaking table tests, the natural frequencies decreased gradually, which are discussed in the next section. Finally, after the building collapsed on the first story, the second floor was supported on rigid safety frames, therefore, the story stiffness increased on the first floor, and then the natural frequencies increased.



(a) PGA_X=0.10 m/s/s PGA_Y=0.09 m/s/s (b) PGA_X=0.17m/s/s PGA_Y=0.16m/s/s (c) PGA_X=0.34m/s/s PGA_Y=0.41m/s/s (d) PGA_X=0.79m/s/s PGA_Y=0.94m/s/s

Figure 9: The first modal properties identified from the six-axes simultaneously white-noise excitation

6. CHANGE OF NATURAL FREQUENCY DURING SHAKING TABLE TEST

To investigate the changes of natural frequency due to the seismic excitation in detail, one day transitions of the first natural frequencies and amplitude of the acceleration response on the top floor are shown in Figure 8. In the figures the transitions are shown from 6 to 24 o'clock on September 20, 24 and 25, and times of major seismic excitations are plotted by triangle marks. Since the natural frequencies are strongly affected by attaching the temporally stairs, the periods during the stairs attaching are filled with cross-hatching.

During the shaking table running, the natural frequencies decreased with increasing the amplitude of acceleration response; the vibration amplitude dependency appeared clearly. On the transition of the natural frequencies, the rapid changes can be detected before and after seismic excitations in addition to the vibration amplitude dependency. On September 20, the natural frequencies suddenly decreased at the first shaking table test by two small white noise excitations on X and Y directions, denoted as "WX1" and "WY1" in Figure 8(a). On September 24, the natural frequencies did not change by the seismic excitation due to JR Takatori excitation with smaller amplitude adjustment by 20 percent, denoted as "EQ20"; the damage of the building did not progress because the vibration amplitude of the seismic excitation of the EQ20 might be lower than those by the WX1 or the WY1. On September 25, two steps of decrease of the natural frequencies are found at the two seismic excitations due to JR Takatori excitations with smaller amplitude adjustment by 40 and 60 percent, denoted as "EQ40" and "EQ60".

From the transition of the first natural frequencies, the changes due to the seismic excitation were detected clearly. The changes of the natural frequency might be caused by deteriorating stiffness of both main structural members as well as non-structural members. To clarify the relation between such changes and structural damage, further investigations will be needed to establish the VBDD.

7. CHANGE OF MODAL PROPERTY DUE TO VIBRATION AMPLITUDE

To investigate the vibration amplitude dependency of the modal property, the modal properties of the lower two modes are identified from the records observed by the six-axes simultaneously white-noise excitation test. In the excitation test, four different levels of a white-noise accelerations were give to the shaking table, whose peak ground acceleration (PGA) were set to 0.01G, 0.02G, 0.05G and 0.1G, respectively. The modal properties are estimated by the cross-spectrum based modal identification technique [4] [5] [6], where the natural frequencies and the damping factors are estimated from the acceleration record at the center of the roof as a referenced record, and the modal vectors are estimated from the cross-correlation functions between the referenced record and another all records at 24 observed points.

The modal properties against the four different excitations are shown in Figure 9, with the PGAs observed on the shaking table. With increasing the PGA, the orthogonal two natural frequencies decrease together, and they change to closely each other. Then, the shapes of mode vectors are also changing, especially on the Y-1st mode which is dominant on the Y direction. In the Y-1st mode shape the building deforms to translational on the Y direction with torsional motion within the small PGAs, however, in the large PGAs the torsional motion vanish and the shape change to two translational deformations on both X and Y directions. The torional motion within the small PGAs behaves such that the south-side of the building is stiffer than the north-side, where the south and north are on the upper and lower in the mode figures. As shown in the plan of Figure 1, the exterior walls of ALC panel were installed on the east-, west- and south-sides of the building, and in the north-size no exterior wall was installed for observation on the steel frames in bare state. Additionally, the temporary stairs were removed during the excitation test. Considering such situations, the stiffness of the whole building with the non-structural component in the north-side can be stiffer than that in the south-side. The fact the torional motion vanish in the large PGAs indicates that the additional stiffness disappeared in the large deformation state. This disappearance is also related to the decreasing tendencies of the natural frequencies observed above.

8. CONCLUSION

To investigate long-term transition of the modal property of a steel building for developing structural health monitoring, ambient vibration is continuously observed on a full-scale building for shaking table test. From the ambient vibration record, complete transition of the modal properties of the building can be obtained during all the lifetime when a steel building can generally experience the construction process or small to middle classes of earthquakes, and finally complete collapse. The transition of the modal properties are contained the several important facts as follows. (1) Natural frequencies increase and decrease with several construction works. (2) The natural frequencies suddenly decrease with every suffering the small to large excitations when the structural members behave in elastic or non-elastic range. It might be caused by deteriorating non-structural or structural members. (3) The modal property of a steel building is largely affected by the stiffness of non-structural members, especially in the ambient vibration state.

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