Variation in vibration characteristics of retrofitted timber-framed house

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ABSTRACT: The objective of this study is to identify structural mechanisms and to grasp the variation in vibration characteristics of a timber-framed house, on which seismic retrofit and seismic observation are performed. We investigated the objective house in two ways. Firstly, the influence of structural members on vibration characteristics was evaluated by conducting ambient vibration measurements at five different retrofit construction stages. As results, doors and finishing, whose seismic performance is not expected very much in the structural design of timber-framed houses, have significant effect on natural frequency in small deformation range. Secondly, time variations of natural frequencies during an earthquake were evaluated from instantaneous frequencies calculated by the Hilbert Huang Transform (HHT) method. Natural frequencies decrease noticeably even under the small deformation range. They recover to the original values as the deformations decrease.

1 INTRODUCTION

To evaluate the seismic performance of a structure, it is important to grasp its seismic behavior under earthquake motions. We have been investigating vibration characteristics of timber-framed houses based on their seismic observation. According to our previous studies (Nii et al. 2004,2005), natural frequencies of them decrease noticeably even under relatively small ground motions.

The objective of this study is to grasp quantitatively the variation in vibration characteristics of a timber-framed house. We investigated the objective house, on which seismic retrofit and seismic observation are performed, in two ways. Firstly, the influence of structural members on the vibration characteristics was evaluated by conducting ambient vibration measurements at five different retrofit construction stages. Secondly, the time variations of the natural frequencies during an earthquake were evaluated from the instantaneous frequencies calculated by the Hilbert Huang Transform (HHT) (Huang et al. 1998) method.

2 VARIATION IN VIBRATION CHARACTERISTICS UNDER SEISMIC RETROFIT

2.1 *Description of the objective house*

The objective house, IR, is located in the north suburban area of Kyoto city in Japan. It is a two-storied

Figure 1. Exterior view of the house

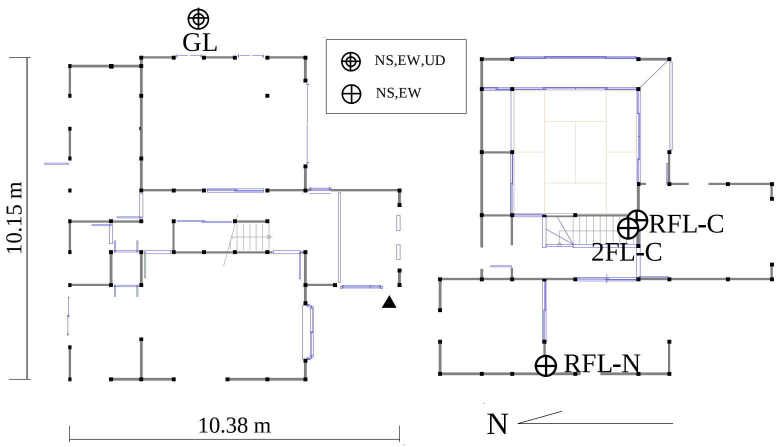


Figure 2. Plans and arrangement of seismometers

timber-framed house constructed in a traditional manner about 70 years ago. Seismic retrofit was conducted from February to June in 2004. Figures 1 and 2 show the exterior view and the plans of the house after the completion of the retrofit. The size of the house is 10.15m x 10.38m and the eave height is 5.8m. The seismic observation of the house has been carried out from September 2004. Symbols in the plans show the arrangement of seismometers. They are located at the ground level (GL), the second floor level (2FL-C), and the eave level (RFL-C, RFL-N).

To evaluate the influence of each structural element on the vibration characteristics, ambient vibration measurements were conducted at five different retrofit construction stages.

2.2 *Outline of seismic retrofit*

Figure 3 shows the process of the seismic retrofit works done between stages. Stage 1 corresponds to the original house before the retrofit. At first, extended parts of the house, roof tiles, decayed columns, floorboards, *tatami* (Japanese mat) and most of mud walls were removed and only original skeleton of the house remained. We call this stage as Stage 2. Decayed portions were repaired and new beams and columns were added before Stage 3. Most of the structural members such as mud walls, plywood walls, and braces were installed and main structure of the house was completed at Stage 4. Finally, interior and exterior finishing works were performed, and doors and windows were fitted before Stage 5. Stage 5 is the completion of the retrofit work.

Figure 4 shows the process of installation of walls and finishing from Stage 3 to Stage 5. The middle and bottom figures show the condition of walls and finishing, which mainly affect the total lateral restoring force of the structure.

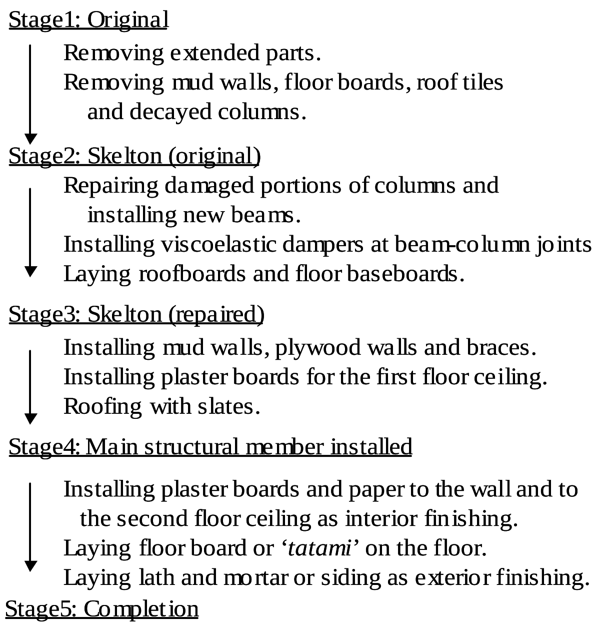


Figure 3. Process of seismic retrofit

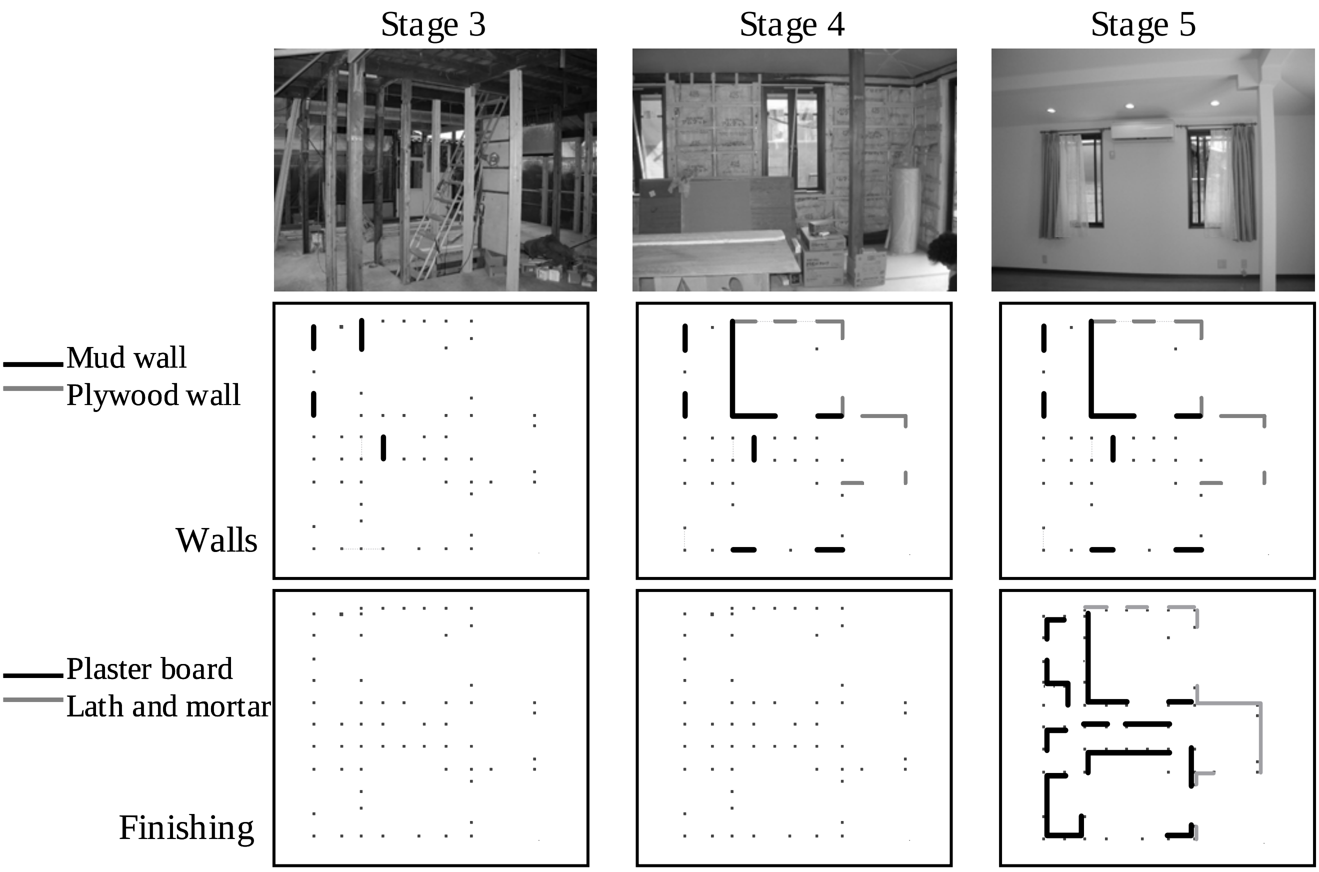


Figure 4. Process of installation of walls and finishing

2.3 *Ambient vibration measurement*

Ambient vibration measurement was conducted at each stage. At Stages 1 and 5, nine accelerometers were set at the second floor (3.1m above the ground) and one at the ground. At Stages 2 to 4, four accelerometers were set at the second floor and one at the ground. Each accelerometer has three channels and is able to measure vibration of one vertical and two horizontal directions simultaneously. Figure 5 shows the representative locations of the accelerometers. Sampling frequency was 100 Hz. The duration time of each record was 600 seconds.

2.4 *Data Processing*

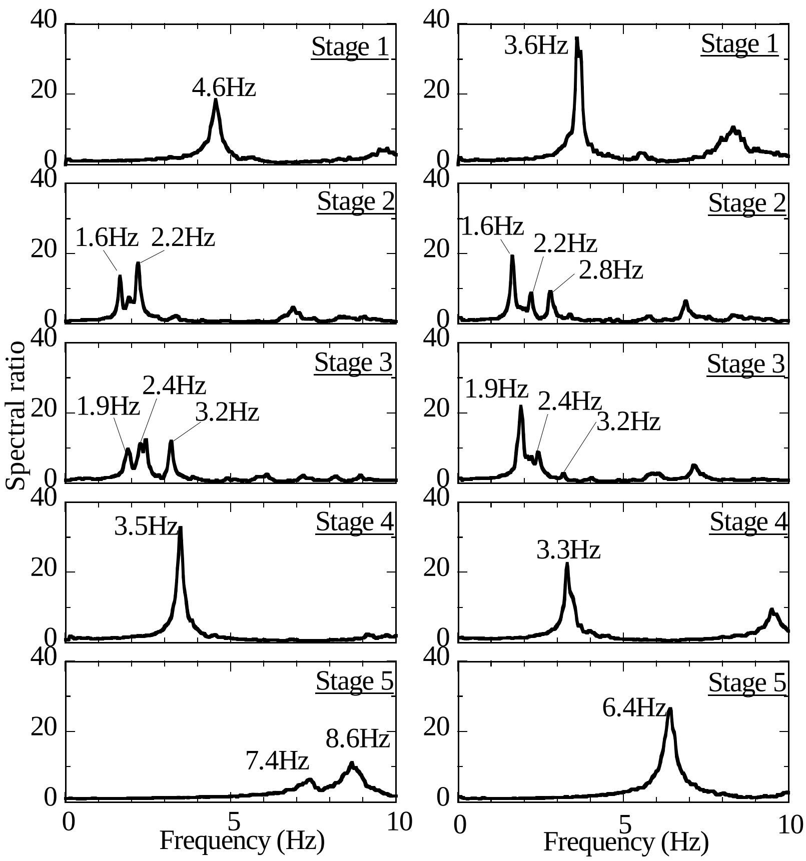
The measured data were processed in the frequency domain, as follows. Each time series data were divided into segments with duration times of 40.96s. To minimize errors of noise, the ensemble mean was calculated and the fast Fourier transform (FFT) was applied to the ensemble mean. The Fourier spectral ratio of the second floor to the ground level is calculated. Figure 6 shows the Fourier spectral ratios for the center measurement point ‘c’ shown in Fig. 5. Natural frequencies are identified by the peaks of the Fourier spectral ratios.

2.5 *Variation in vibration characteristics*

The vibration characteristics were shifted as follows. Natural frequencies at Stage 1 are 4.6 Hz and 3.6 Hz in the NS and the EW direction respectively. At Stage 2, after most of the walls and floorboards are removed, vibration modes are coupled in the two directions. It can be seen from Fig. 7 that each frame vibrates inconsistently and the flexibility of the second floor becomes evident in the frequency range of 1.6 to 2.8 Hz. At Stage 3, the coupled frequency range increases slightly to the range of 1.9 to 3.2 Hz. This increase of the natural frequencies is considered as the influence of the repair of the skeleton. At Stage 4, vibration modes in the two directions become independent and the natural frequencies are 3.5 Hz in the NS direction and 3.3 Hz in the EW direction. Finally, at Stage 5, the natural frequencies increase drastically to 6.4 Hz in the EW direction and 8.6 Hz in the NS direction considering phase lag of its transfer function.

2.6 *Evaluation of weight and resisting capacity*

To evaluate quantitatively the influence of main structural elements and finishing shown in Fig. 4, the total weight of the house Mg and the lateral restoring force Q at Stages from 3 to 5 are calculated. The Mg was 117 kN at Stage 3, 183 kN at Stage 4, and 259 kN at Stage 5. Figure 8 shows the transition of Q. Rate of the increase of Q is larger than that of Mg especially at Stage 5.



(a) NS direction (b) EW direction

Figure 6. Fourier spectral ratio at each retrofit construction stage

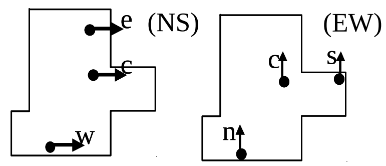
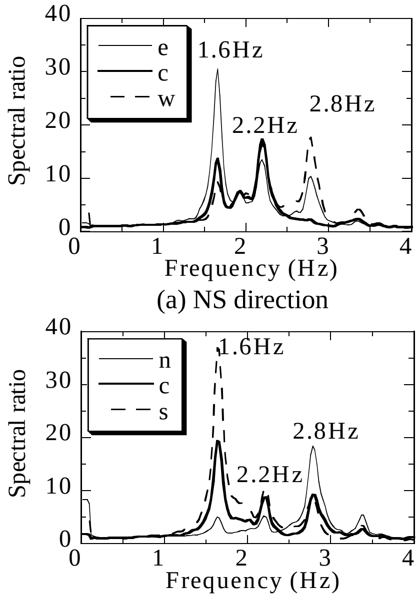


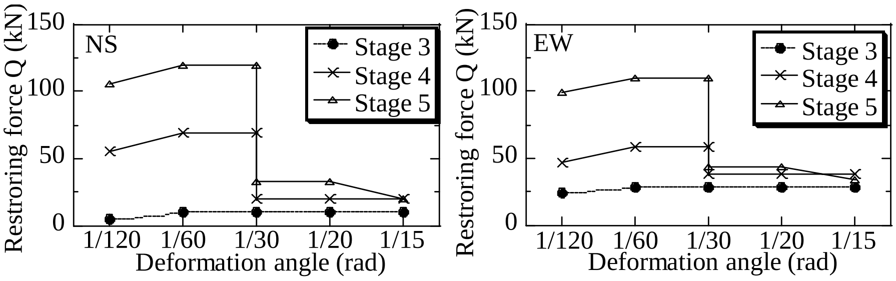
Figure 6. Representative locations of accelerometers in ambient vibration measurement



(a) NS direction

(b) EW direction

Figure 7. Fourier spectral ratios at Stage 2



(a) NS direction (b) EW direction

Figure 8. Transition of lateral restoring force *Q*

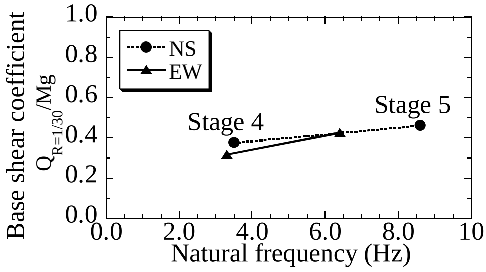


Figure 9. Relation between base shear coefficient and natural frequency

2.7 *Base shear coefficient and peak frequency*

Base shear coefficient ($Q_{R=1/30}$ / *Mg*, subscript *R* denotes the shear deformation angle) at Stage 4 is 0.38 in the NS direction and 0.32 in the EW direction. At Stage 5, it increases to 0.46 and 0.43 respectively. Although *Mg* increases, $Q_{R=1/30}$ increases much more due to the influence of the finishing such as plaster board and mortar with metal lath.

Figure 9 shows the relation between the base shear coefficients ($Q_{R=1/30}$ / *Mg*) and the natural frequencies at Stages 4 and 5. It indicates that doors and finishing, whose seismic performance is not expected very much in the structural design of timber-framed houses, have significant effect on natural frequency in the small deformation range.

3 VARIATION IN VIBRATION CHARACTERISTICS DURING EARTHQUAKE

3.1 *Seismic observation system*

Nine channels of the sensors are installed to observe the seismic response of the house. The location and orientation of the sensors are shown in Fig.2. Three channels are located at the ground level (GL), two channels are at the second floor level (2FL-C, 3.1m above the ground level), and four channels are at the eave level (RFL-C and RFL-N, 5.8m above the ground level).

All accelerometers are connected to the recorder set in the house. When the acceleration exceeds the specified trigger level, acceleration data are recorded. The sampling frequency is set at 100Hz. These data are gathered automatically from the laboratory in Disaster Prevention Research Institute, Kyoto University through telephone (ISDN) line once a day.

3.2 *Observed seismic record*

Seismic observation of the house started at the middle of September 2004. Several minor quakes have been observed.

Figure 10 shows the time history of the ground acceleration recorded at 23:30, 1st December 2004, which has the largest peak ground acceleration (PGA) before June 2005. The earthquake is occurred in the south of Kyoto prefecture and its JMA (Japan Meteorological Agency) magnitude is M=4.0. The PGA and the eave level accelerations were 0.296 m/s^2 and 0.796 m/s^2 in the NS direction and 0.266m/s^2 and 0.835 m/s^2 in the EW direction.

3.3 *Fourier spectral ratio*

Bold lines in Fig. 11 show the Fourier spectral ratio of 2FL-C to GL acceleration respectively for the NS (left) and the EW (right) direction, obtained from the two earthquakes occurred on December 1st, at 23:12 (top) and, above-referenced, 23:30 (bottom). The PGA recorded at 23:12 is 0.059 m/s^2 (NS) and 0.070 m/s^2 (EW). Thin lines in the same figures show the Fourier spectral ratio obtained from the ambient vibration measurement at Stage 5.

It can be seen from Fig. 11 that the peak frequencies decrease and become unclear as the ground motion level increases. The peak frequency in the EW direction drops from 6.4Hz to 4.8-5.3Hz during the earthquake of 23:30. The peak frequency in the NS direction is not identified from Fig. 11.

3.4 *Deformation dependency of natural frequency*

Natural frequency for each observed record is identified by the peaks of its Fourier spectral ratio. Figure 12 shows the relation between the natural frequencies and the maximum shear deformation angles for the observed earthquakes. The natural frequencies are normalized by the natural frequencies obtained from the ambient vibration measurement.

The KJ and KT are two other timber-framed houses located in Kyoto, whose seismic observation started prior to the objective house, IR. For some records, it was difficult to identify the natural frequency in the transverse direction because the peak of the Fourier spectral ratio doesn't appear clearly under relatively large ground motion.

Figure 12 shows that the frequency-deformation relationship of IR is consistent with those of the other two houses.

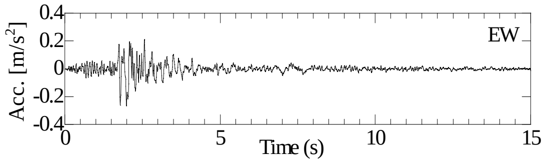
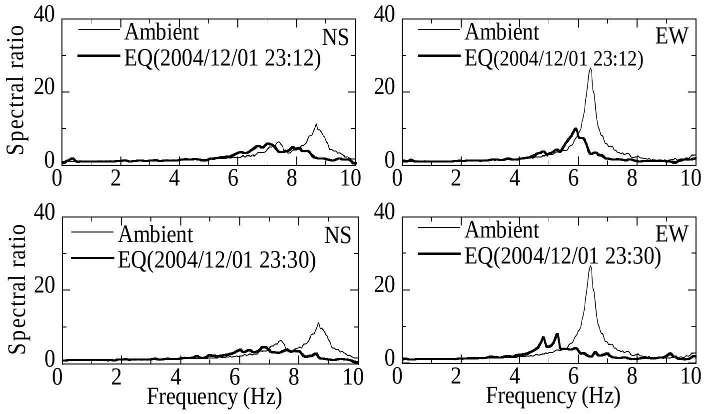
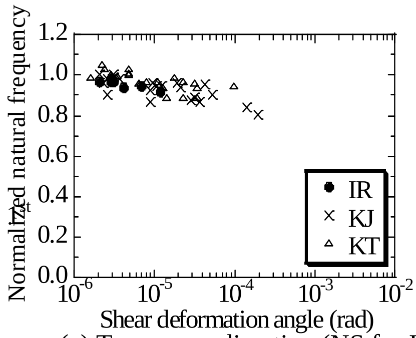


Figure 10. Ground acceleration (EW) observed at 23:30 1st December 2004

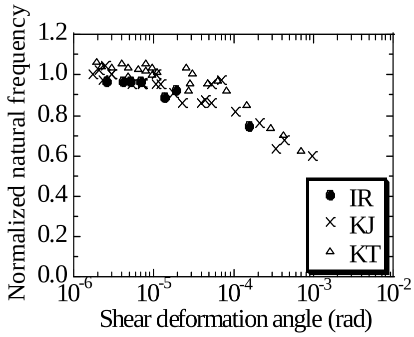


(a) NS direction (b) EW direction

Figure 11. Fourier spectral ratios

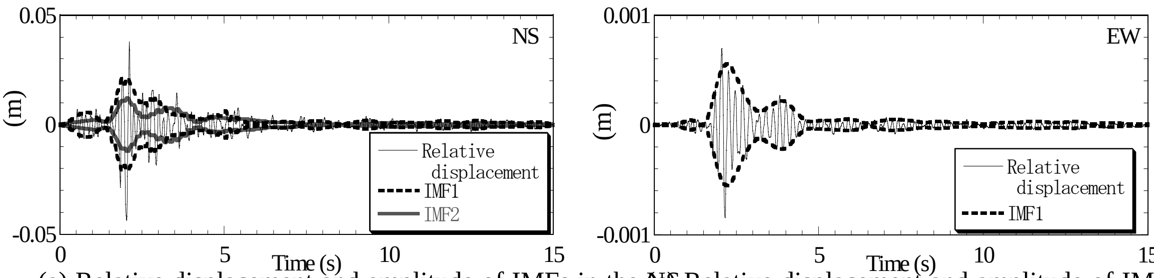


(a) Transverse direction (NS for IR)



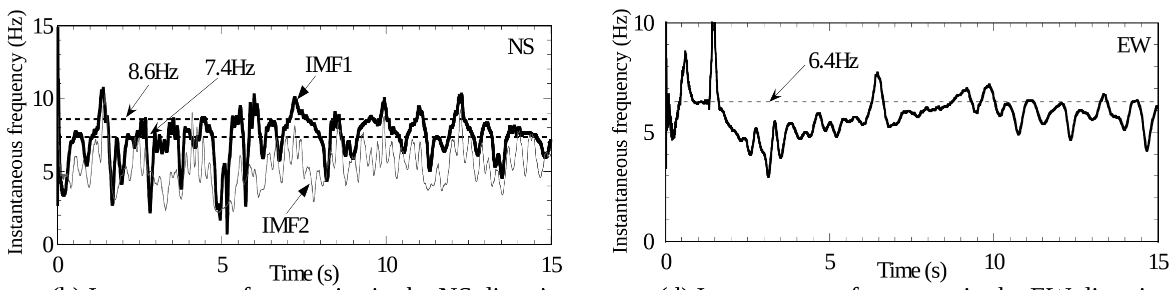
(b) Longitudinal direction (EW for IR)

Figure 12. Relation between natural frequency and shear deformation angle



(a) Relative displacement and amplitude of IMFs in the NS direction

(c) Relative displacement and amplitude of IMF in the EW direction



(b) Instantaneous frequencies in the NS direction

(d) Instantaneous frequency in the EW direction

Figure 13. Analysis results of the seismic response using the HHT

3.5 *Evaluation of instantaneous frequency using Hilbert Huang Transform*

To evaluate the time variation of the natural frequency during an earthquake, the Hilbert Huang Transform (HHT) is applied to the observed record. First in the HHT, the empirical mode decomposition (EMD) is applied to the record to decompose it into finite number of intrinsic mode function (IMF) in the order of high frequency. We call them IMF1, IMF2,…in the order of high frequency. Then, for each IMF, the Hilbert transform is applied to obtain the time-frequency result.

We used this method to the displacement at RFL-C relative to the ground level. Before the application of the method, low-pass filter was applied to cut off the high frequency components in order to identify the variation in natural frequency by the instantaneous frequency of IMF1. The filter was chosen in consideration of the natural frequency from the ambient data. Figure 13 shows the results of the NS and the EW direction. Figures 13a and 13c show relative displacement (solid line) and amplitude of the IMF (dashed line). Figures 13b and 13d show the instantaneous frequencies of IMFs (solid line). Natural frequencies from the ambient vibration measurement, 7.4Hz, 8.6Hz and 6.4Hz, are also depicted in the same figure (dashed lines).

3.5.1 *NS direction*

Figure 13a shows that the amplitude of IMF1 doesn't fit the relative displacement well as it does in the EW direction and amplitude of IMF2 is not negligible. Since instantaneous frequency of IMF2 is roughly below 7.4 Hz (Fig.13b), two modes at 7.4Hz and 8.6 Hz were not decomposed, which leads that both modes are in IMF1. Instantaneous frequency of IMF1 fluctuates too widely to identify the time variation.

3.5.2 *EW direction*

In Figure 13c, the dashed line approximately envelops the solid line, which means IMF1 is consistent with the relative displacement. Fluctuation of the instantaneous frequency is less than that of NS direction. It is possible to identify overall tendency of the variation in natural frequency. Decrease of instantaneous frequency lags the rise of displacement. It recovers gradually to the original natural frequency, 6.4Hz, as the deformation decrease.

The possible cause of this difference between the NS and the EW direction is that there is one prominent peak in the Fourier spectral ratio of the EW direction, while there are two close peaks in that of the NS direction.

4 CONCLUSIONS

The investigation of the variation in vibration characteristics of a timber-framed house, under retrofit construction and during earthquakes, leads following conclusions.

1) After installing fittings and finishing, the natural frequencies changes drastically, compared to the increase of the restoring force. It implies that the fittings and finishing have significant effect on natural frequencies especially in the small deformation range.
2) The natural frequency drops to 75% of the original value at the maximum shear deformation angle of 1/5000 rad. It recovers to the original value as the deformation decreases.
3) Applying the HHT method to the observed record, overall tendency of the variation in natural frequency can be successfully identified for the data whose Fourier spectral ratio has one prominent peak while some fluctuations in the instantaneous frequency are observed. On the contrary, it was not possible to identify the variation in natural frequency for the data whose Fourier spectral ratio has two close peak frequencies.

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