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Seismic Response Evaluation ofNew WoodenHouse by Collapsing Process Analysis

*Hayato Nishikawa[1)]and Tomiya Takatani[2)]

[1)] *Education and Research Supporting Center, MNCT, Maizuru 625-8511,Japan*
[1)] *nisikawa@maizuru-ct.ac.jp*
[2)] *Department of Civil Engineering& Architecture, MNCT, Maizuru 625-8511,Japan*
[2)] *takatani@maizuru-ct.ac.jp*

ABSTRACT

Vibration measurement using an oscillation system has been carried out to evaluate the seismic performanceagainst a strong earthquake ground motion for a lot of old existing wooden houses built by old seismic design codesin Japan, and the natural frequencyand damping factor ofan old wooden house can be obtained from this vibration measurement. In this paper, the seismic performance of a new two-story wooden house recently built bya traditional wood framed-based construction method was investigated by not only a collapsing process analysis but also a vibration measurement in order to discuss the seismic performance of the new two-story wooden house in comparison with the old two-story wooden house built in 1961. It was found that not only the analytical frame model of wooden house but also the seismic performance of wooden house using the collapsing process analysis may be valid and effective from a view point of the seismic retrofit of old wooden house.

1. INTRODUCTION

A great number wooden housesin Japan have suffered severe damage such as large deformation and collapsingagainst several earthquakes with Magnitude 7 to9, because most of the collapsed wooden houseswere built by some old earthquake design codes before 1981.Seismic retrofitting policyfora great number of old wooden houseshas become an urgent and important issue to solve as quickly as possible in Japan.In general, a seismic retrofitting work for the old existing wooden house can be schematically and statically decided by an upper structural index and some investigation dataof its house, and also does not need any seismic response of wooden house in the decision process of its seismic retrofit design. This upper structural index is a ratio of the possessiveseismic resistant force to the necessary one of the wooden house.

[1)]Technical Staff
[2)]Professor

Vibration measurement using an oscillation system has been carried out to evaluate the seismic performanceagainst a strong earthquake motion for a lot of existing wooden houses in Japan since 1981, and the natural frequencies and damping factors for both ridge and span directions in the existing wooden house can be obtained from this vibration measurement. Based on the vibration measurement result, seismic performance of an existing wooden house can be easily evaluated. The higher the natural frequency of the wooden house has,the higher seismic safety level the wooden house has against a strong earthquake motion. However, the vibration intensity and its oscillation amplitude used in vibration measurement are quite small not to cause any vibration damages in wooden house. Whether a severe damage in wooden house against a strong earthquake ground motion occurs or not cannot be judged from the vibration measurement with small vibration intensity and amplitude.

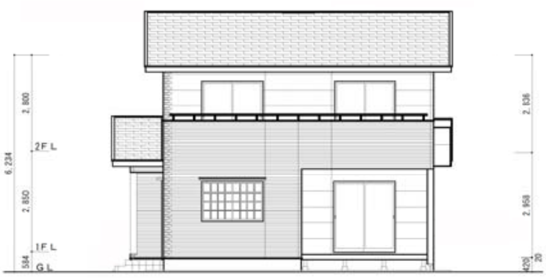
In order to investigate the seismic performance of a new wooden house recently built by a traditional framed-based construction method in Japan, a collapsing process analysis of the wooden houseduring a strong earthquake ground motionwas conducted in this paper. Aseismic response analysis of the wooden house can be carried out byusing astructural analysissoftware “Wallstat” (Nakagawa *et al.* 2010, Nakagawa 2011) based on the Distinct Element Method (Cundall*et al.* 1979). Seismic response behavior of an old wooden house built before 1981 wasinvestigated by Nishikawa *et al*. 2012. In this paper, four earthquake ground motion waves with the Japan Meteorological Agency (referred to as JMA hereafter) seismic intensity of “6 upper” level are used in the collapsing process analysisin order to compare the seismic performance of a new wooden house with that of an old house.

2. OUTLINE OF NEW WOODEN HOUSE AND ITS COLLAPSING MODEL

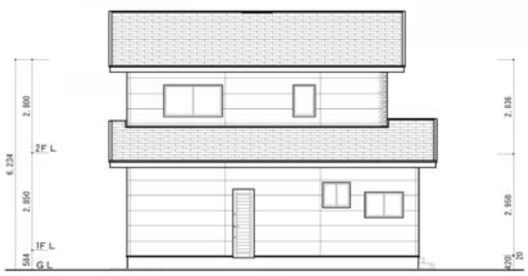
Target of the collapsing process analysis in this paper is a new two-story wooden

(a) First floor (b) Second floor

Fig.1 Floor plan of a new two-story wooden house, O-house (Unit: mm)



(a) East direction

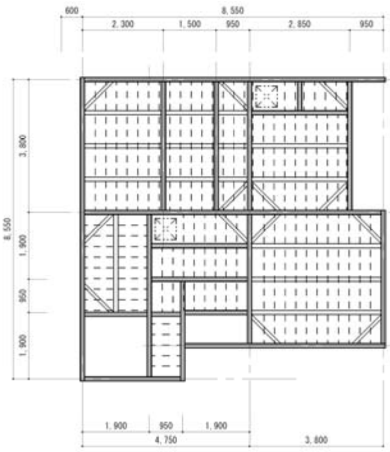


(b) West direction

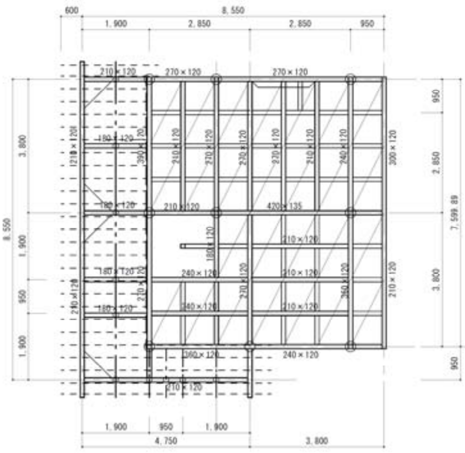
(c) South direction

(d) North direction

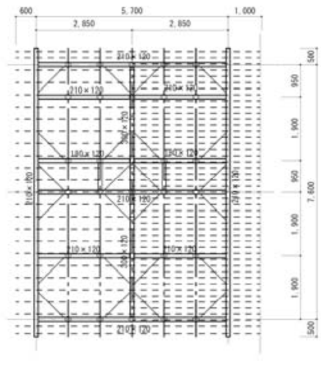
Fig.2 Elevation plan of anew two-story wooden house, O-house (Unit: mm)



(a) Foundation frame

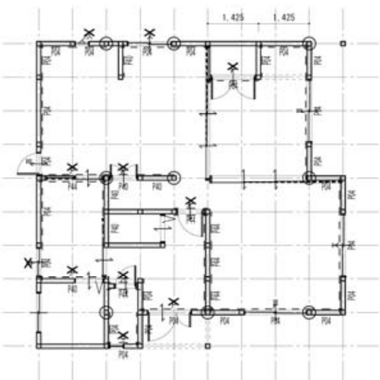


(b) Second floor frame

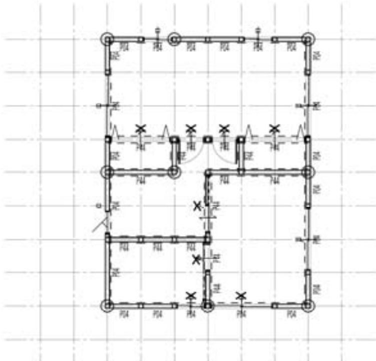


(c) Roof frame

Fig.3 Framing plan of a new two-story wooden house, O-house (Unit: mm)

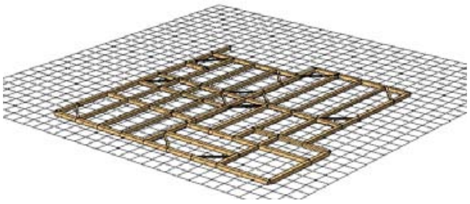


(a) Firstfloor

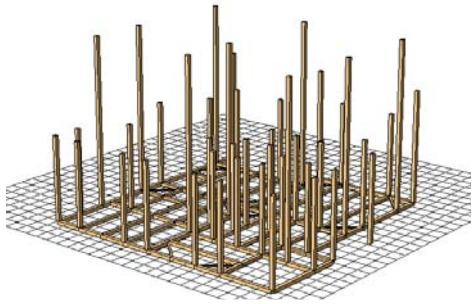


(b) Second floor

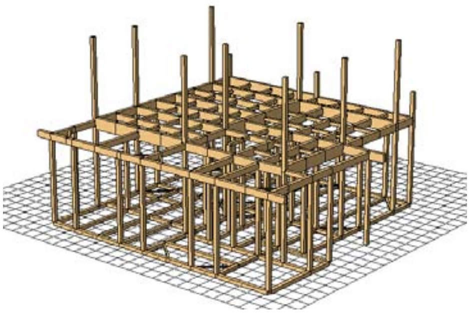
Fig.4 Framing plan of pillars and wallsin a new two-story wooden house, O-house



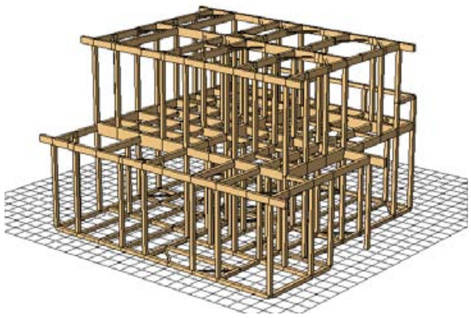
(a)Foundation frame model



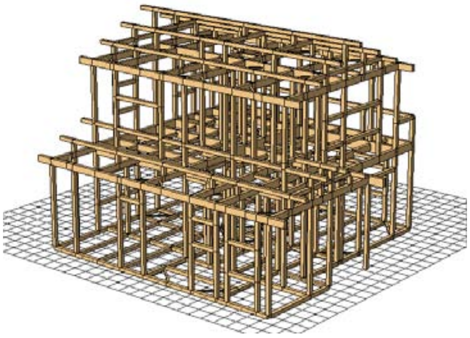
(b) Pillar model of first floor



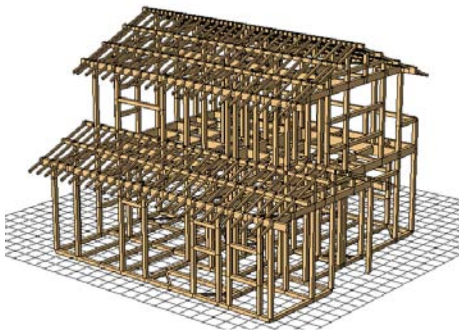
(c) Second floor model



(d) Ceiling frame of second floor



(e) Roof frame model



(f) Complete frame model with roof rafters

Fig.5 Wooden frame modelof a new two-story wooden house, O-house

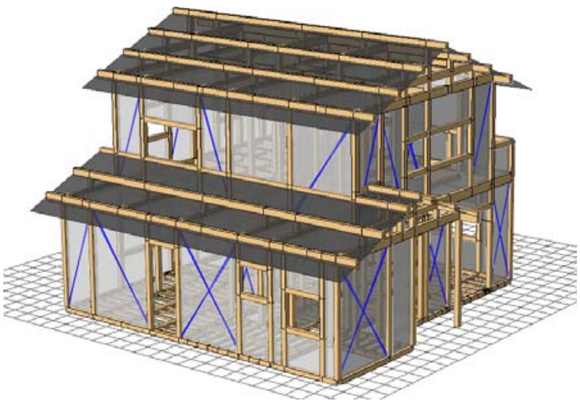


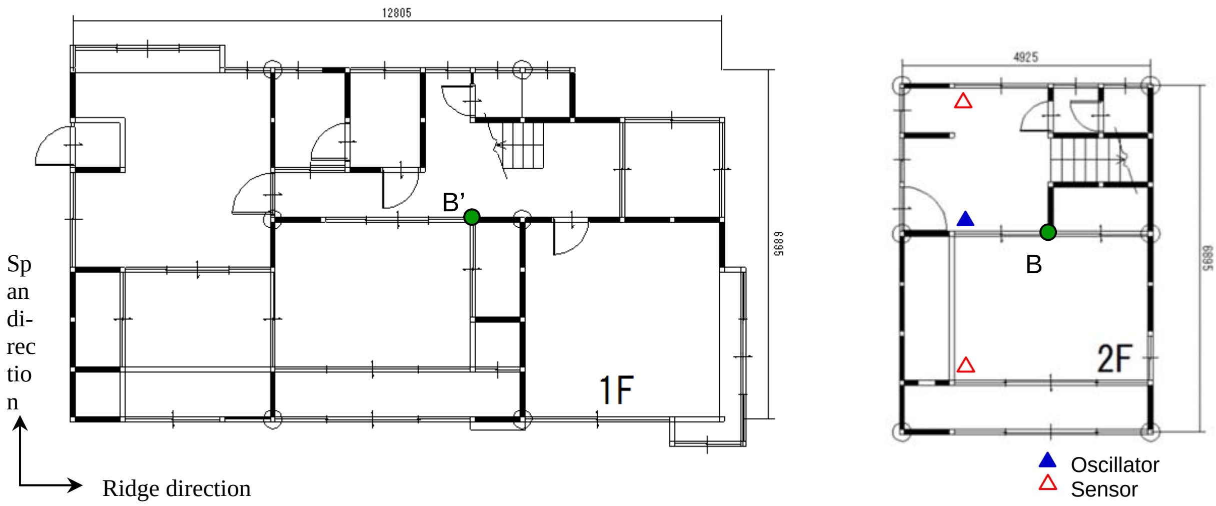
Fig.6 Analytical frame model for a new two-story wooden house, O-house

house, which was built by a traditional wood framed-based construction method in 2012. Fig.1 shows the new wooden house floor plans, and Fig.2 indicates the elevation views for four directions. The total floor area of this wooden house is 112.82m^2, and also the first floor area and the second one are 69.50m^{2}and 43.32m^2, respectively. The first floor height and the second one are 2.85m and 2.80m, respectively.

In the collapsing analysis of wooden house, the timber framework of the new wooden house shown in Figs.1 and 2 is modelled by a lot of elastic beam elements, based on the framing plan shown in Fig.3 and the framing plan of pillars and walls illustrated in Fig.4.

At first, the timber framework of first floor frame installed on the concrete foundation of wooden house shown inFig.5(a) is made referring to the foundation frame indicated in Fig.3(a). Referring to the first floor framing plan illustrated in Fig.4(a), the pillar framing model of ground floor shown in Fig.5(b) can be made by many pillars. Referring to the second floor framing plan shown in Fig.3(b), the beam framing model of second floor indicated in Fig.5(c) can be made by some girths and many floor beams. The ceiling frame model of second floor can be made by many pillars and beams, referring to the ceiling frame shown in Fig.3(c) and the second floor framing plan illustrated in Fig. 4(b). The roof frame model shown in Fig.5(e) can be made by vertical roof struts, tie beams and ridge ones, and finally the complete frame model with roof frames shown in Fig.5(f) can be made by a lot of rafters. In recent years, many joint metals such as holding metal, strap bolt, strip form metal, mountain-shaped metal and so on are used in the traditional wooden framed-based construction method in Japan since 1981. In the collapsing analysis of this new wooden house shown in Fig.1, the characteristics of these joint metals previously mentioned are modeled by some non-linear load-displacement relationships.

On the other hand, the walls and diagonal bracings of wooden house can be modeled by vertical structural planes using both truss element and elastic beam one, referring to the framing plan of pillar and walls shown in Fig.4. Fig.6 shows a collapsing analytical frame model with some roof elements of wooden house, which has walls and braces in the complete frame model with roof rafters shown in Fig.5(f). In this paper,



(a) First floor (b) Second floor

Fig.7 Floor plan of an old two-story wooden house, W-house

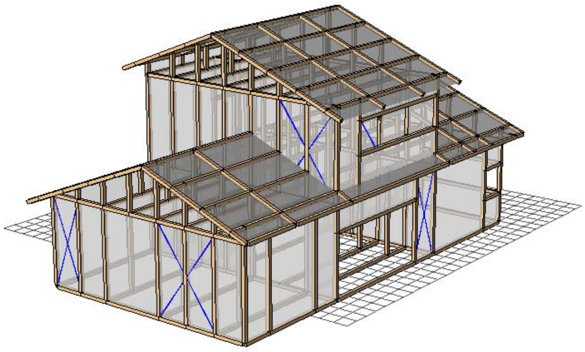


Fig. 8 Analytical frame model for an old wooden house, W-house, built in 1961

seismic performance of a new wooden house is numerically investigated by the collapsing analytical frame model shown in Fig. 6.

In order to compare with seismicbehavior of a new two-story wooden house during a strong earthquake ground motion with the JMA seismic intensity of “6 upper” level, the collapsing process analysisof an old two-story wooden house, W-house, built in 1961 shown in Fig.7 was conducted (Nishikawa *et al*. 2012).Fig.8 shows a collapsing process analytical model of the old two-story wooden housebuilt by an old seismic design code.

3. VIBRATION EXPERIMENTAL RESULTS OF O-HOUSE AND W-HOUSE

Vibration experiment using an oscillator-measurement system was conducted for both anew wooden house, O-house, shown in Fig.1 and an old wooden house, W-house, indicated in Fig.7. An oscillator and sensor locations on the second floor of O-house are indicated in Fig. 1(b), and also an oscillator and sensor locations in W-house are done in Fig.7. Photo 1 shows a vibration measurement system, an oscillator with 50kg-mass and a sensor on the second floor. Fig.9 illustrates a sketch of vibration measurement system, which consists ofan oscillator part, a measurement one and a controlling analysis one. In the oscillator part, the amplitude of oscillator is controlled by an electric power amplifier, and the acceleration of oscillator ismonitored by an ICP-type acceleration detector. A sensor in the measurement part can be measured both acceleration and displacement values on the floor. There are a real-time vibration analysis deviceand a real-time vibration controlling system in the controlling analysis part. By the real-time vibration analysis device, acceleration valuesfrom sensors and oscilla-

(a) Measurement system (b) Oscillator (c) Sensor

Photo1Vibration measurement systemusing an oscillator

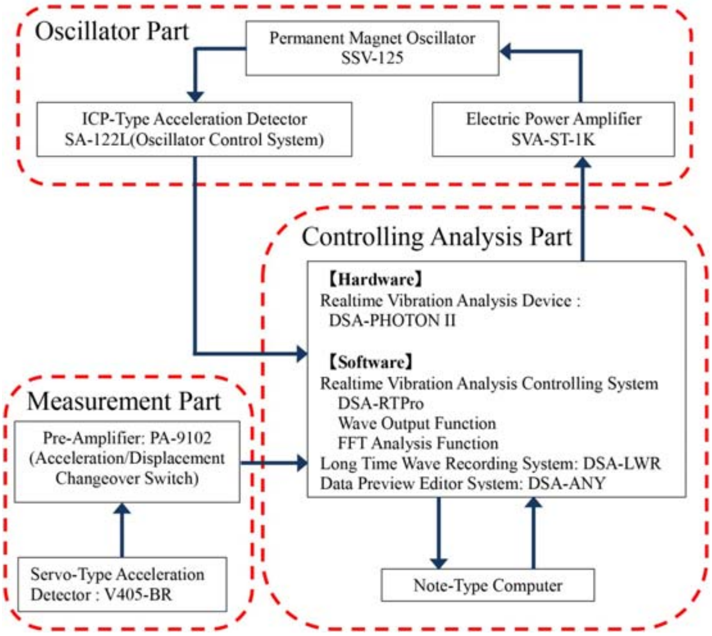


Fig. 9 A sketch of vibration measurement system

Table 1Naturalfrequenciesof O-house and W-house

	Ridge direction (Hz)	Span direction (Hz)
O-house (new house)	5.94	6.41
W-house (old house)	4.22	5.16

tor can be obtained, and the oscillator is controlled by the electric power amplifier and the real-time vibration controlling system. Sweep vibration of the wooden house can be controlled by the real-time vibration controlling system with some software.

Table 1 shows natural frequencies of transfer function obtained from vibration measurement system in both O-house and W-house. In general, the natural frequency range of an old wooden house built before 1981 is from 3.5Hz to 4.5Hz. While, the natural frequency range of a new wooden house built after 1981 is from 4.5Hz to 7Hz. Although W-house needs some seismic retrofit to secure seismic performance against a strong earthquake ground motion with the JMA seismic intensity of “6 upper” level, O-house has a high seismic performance against a strong earthquake ground motion.

4. SEISMIC COLLAPSING RESULTS OF NEW WOODEN HOUSE AND OLD HOUSE

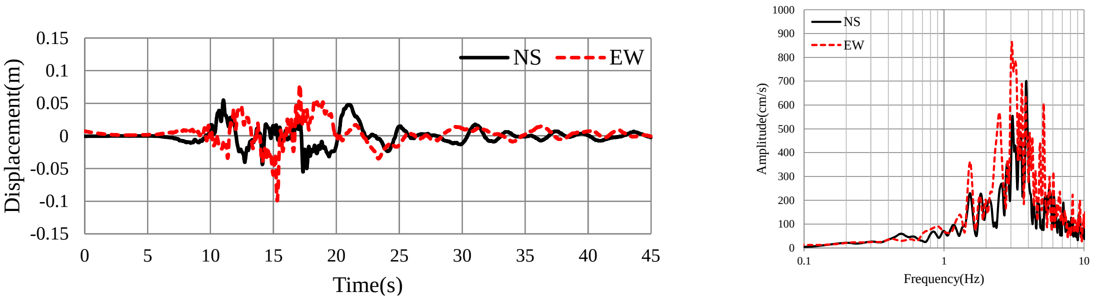
4.1 Input excitation

Collapsing process analysis of a new two-story wooden house, O-house, is carried out in thispaper. Four earthquake ground motion wave records with the JMA seismic intensity of “6 upper” level are employed as an input earthquake ground motion data in the collapsing analysis. The effect of the earthquake motion spectrum on the difference of seismic response can be investigated by using fourearthquake wave records with the same level intensity which has a different peak frequency in Fourier acceleration

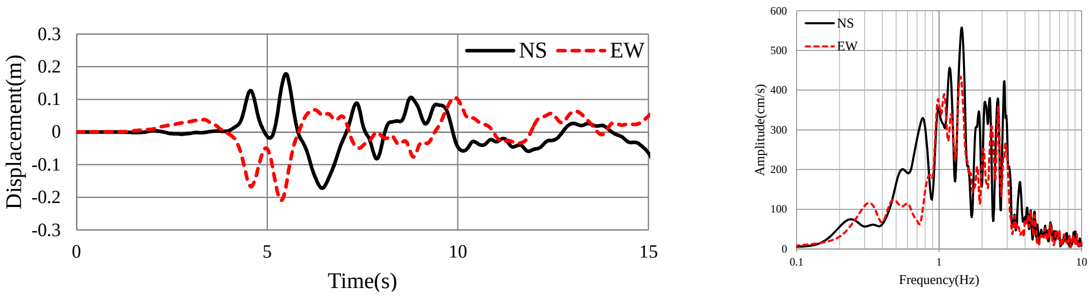
Table 2 Earthquake ground motion wave records

Record Name	I_{JMA}	Peak Ground Acceleration (cm/s^2)	Peak Ground Velocity (cm/s)	f_p (Hz)	Duration (s)
KiK-net Higashi Naruse	6.4	2,449	76	3.06	50
JMA Kobe	6.4	818	91	1.43	15
JR Takatori	6.4	657	126	0.81	30
K-NET Kashiwazaki	6.3	638	113	0.45	15

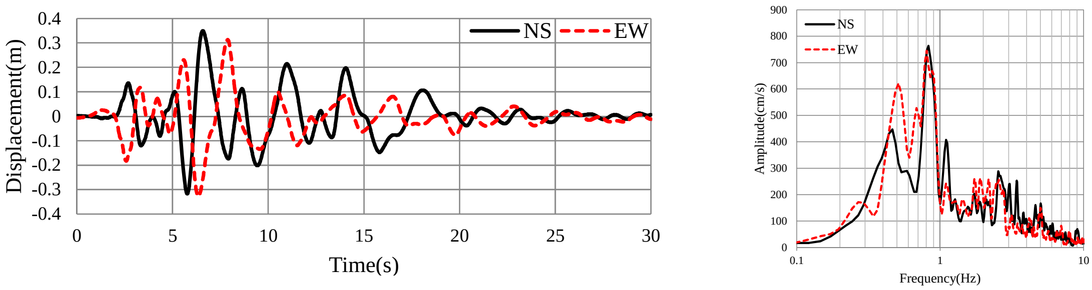
f_p : peak frequency of root mean square value of Fourier spectrum



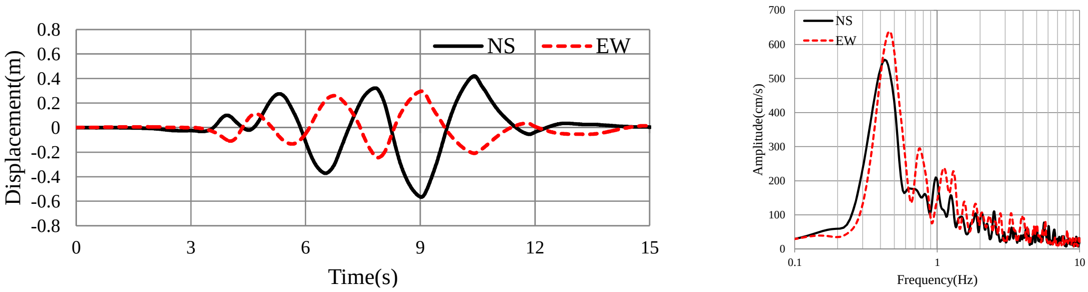
(a) KiK-net Higashi Naruse



(b) JMA Kobe

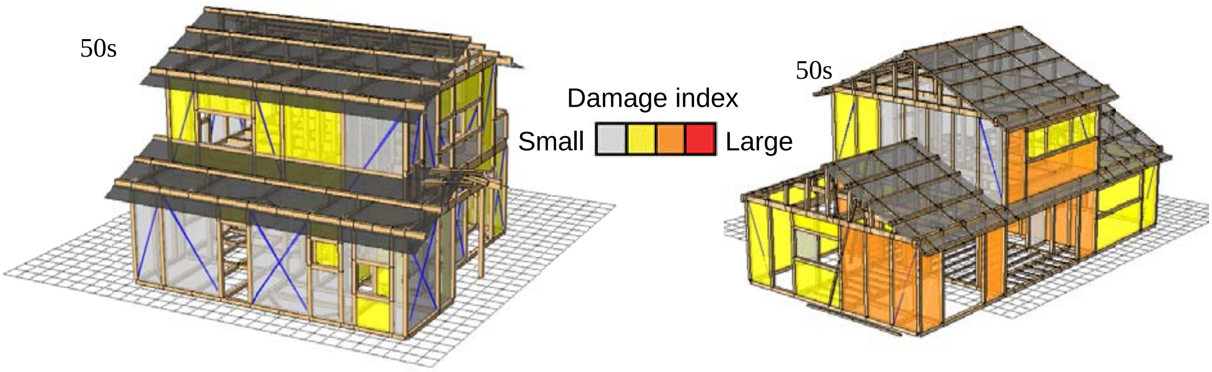


(c) JR Takatori

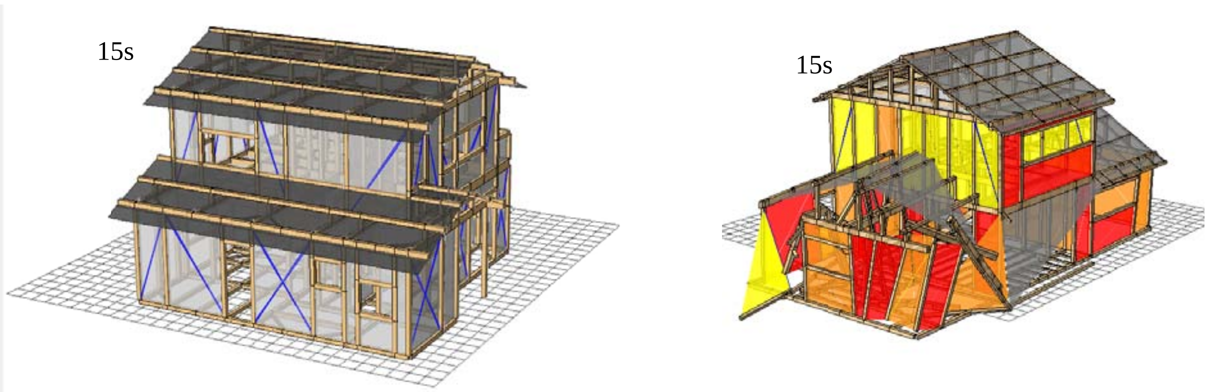


(d) K-NET Kashiwazaki

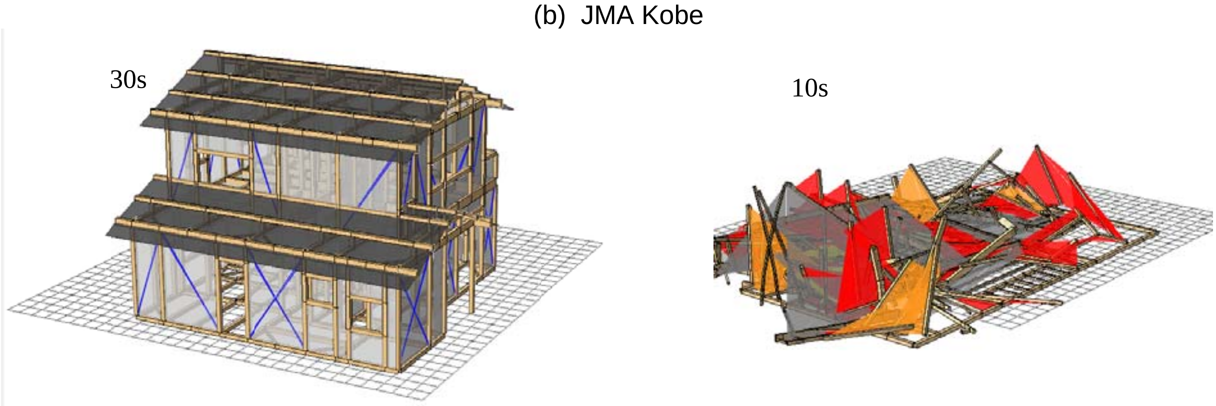
Fig.10 Displacement waves and Fourier acceleration spectra



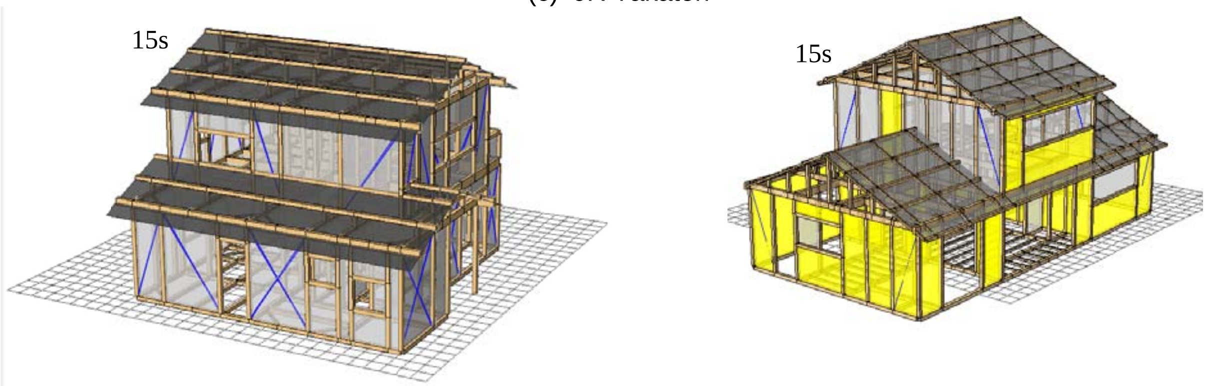
(a) KiK-net Higashi Naruse



(b) JMA Kobe



(c) JR Takatori



(d)K-NET Kashiwazaki

Fig.11 Collapsing Results for both O-house and W-house spectra. Table 2 shows some parameters of earthquake ground motion wave records used as an input excitation of the collapsing process analysis.

Fig.10 indicates four displacement wave data and their Fourier acceleration spectrafor both NS and EW components in each earthquake ground motion record shown in Table 2. The characteristics of their Fourier acceleration spectra are quite different from each other. In KiK-net Higashi Naruse wave record shown in Fig.10(a), the displacement amplitude in each wave component is smaller than other three waves and has a peak in high frequency range. In JMA Kobe wave record indicated in Fig.10(b), a peak frequency in each wave component is from 1Hz to 1.5Hz, and also a peak in each wave component of JR Takatori wave record illustrated in Fig.10(c) exists about 0.8Hz. On the other hand, there exists a peak in low frequency range in each wave component of K-NET Kashiwazaki wave record shown in Fig.10(d). Because there are peak frequencies in both JMA Kobeand JR Takatori wave recordsin the frequency range of 0.5 to 1.5Hz,their wave records seem to cause severe damage in the collapsing analysis of an old wooden house against a strong earthquake ground motion as reported by Sakai *et al.* (2002).

4.2 Collapsing Process and Seismic Response

Fig.11 shows the seismic collapsing results of both a new two-story wooden house, O-house, and a two-storyold wooden house, W-house, against four earthquake ground motion wave records shown in Fig.10. In seismic collapsing result of W-house, the plastic deformationat the connection part between pillar and beam elements gradually increases during earthquakeground motionby means of the non-linearity characteristics, because W-house has much lower seismic performance than O-house.W-house collapses after 15 seconds in JMA Kobe wave record with the frequency range close to 0.5 to 1.0Hz. In particular, W-house collapses after 10 seconds in JR Takatori wave record with the frequency range of 0.5 to 1.0Hz, and the frequency range has a significant relationship with the wooden house collapsing rate against a strong earthquake motion. Moreover, the maximum velocity of JR Takatori wave record is 126cm/s, and the wooden house collapsing rate greatly depends on the maximum velocity.

W-house does not collapse in KiK-net Higashi Naruse and K-NET Kashiwazaki wave records with the different frequency range to 0.5 to 1.0Hz. This is because the natural frequency of W-house is quite different from each peak frequency range of both KiK-net Higashi Naruse and K-NET Kashiwazaki wave records.

On the other hand, there seems to cause a slight damage on O-house in KiK-net Higashi Naruse wave record. This is because that the natural frequency of O-house is near the predominantfrequency of KiK-net Higashi Naruse wave record because of a high stiffness at the connection part between pillar and beam elements.No damage in O-house during earthquake motion causes against other three wave records. This is because that the plasticphenomenon due to a non-linear behavior at the connection part between pillar and beam elements does not occur because of a high stiffness at the connection part.

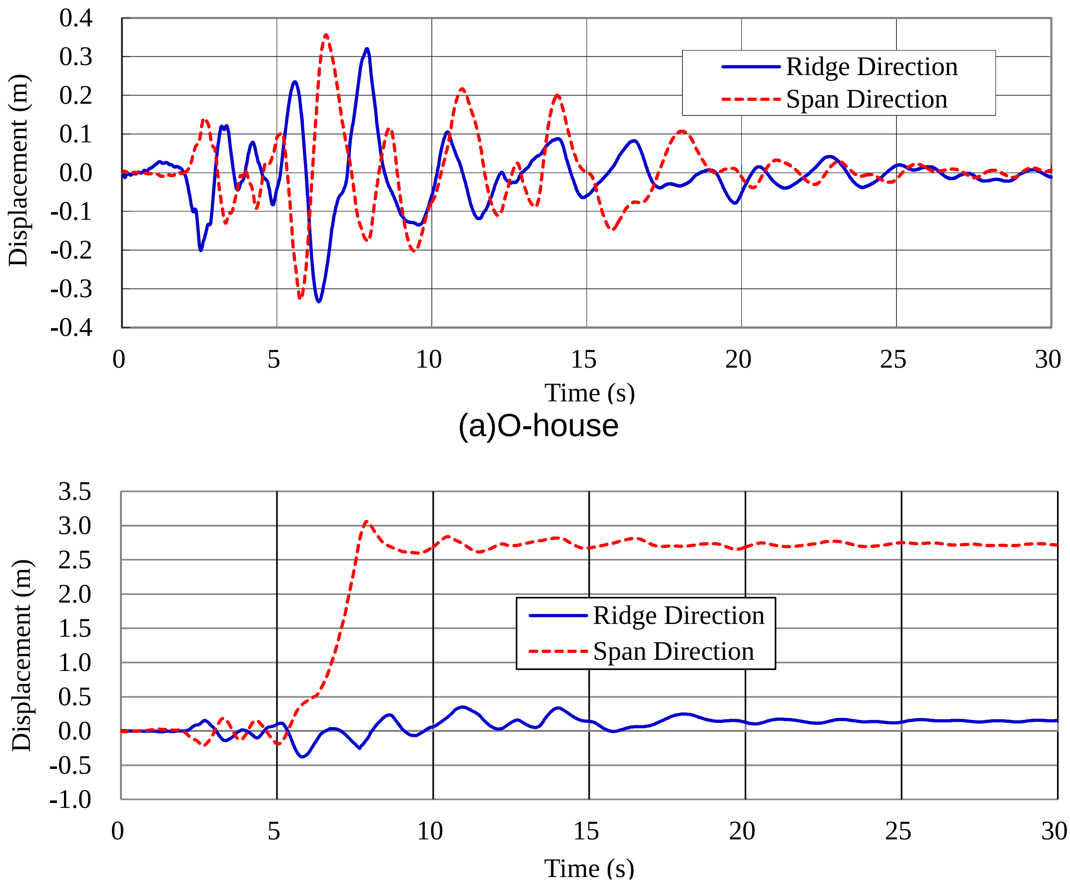
Fig.12 illustrates horizontal displacement response at the point A on the second floor in O-house shown in Fig.1 and horizontal displacement response at the point B on the second floor on W-house shown in Fig.7. JR Takatori wave record was used as an input earthquake ground motion in this collapsing analysis. Displacement response in the span direction in W-house is much larger than that in the ridge direction because of a complete collapse phenomenon of W-house, while both displacement responses in O-house are almost the same as the input earthquake ground motion wave shown in Fig.10(c) because of a high stiffness at the connection part between pillar and beam.

In this paper, the vibration characteristics of both O-house and W-house are evaluated by theirtransfer function curves, which can be numerically obtained from the response results due to an input motion of sinusoidal wave with a small amplitude and afrequency of 10Hz. The transfer function, $H(f)$, in this paper can be given by the following equation.

$$H(f)=\frac{F_2(f)}{F_1(f)} \tag{1}$$

where, $F_1(f)$ is Fourier spectrum of the displacement response at A'or B'point on the first floor just under the second floor shown in Figure 1(a) or Figure 7, and $F_2(f)$ is Fourier spectrum of the displacement response at A or B point on the second floor shown in Figure 1(b) or Figure 7.

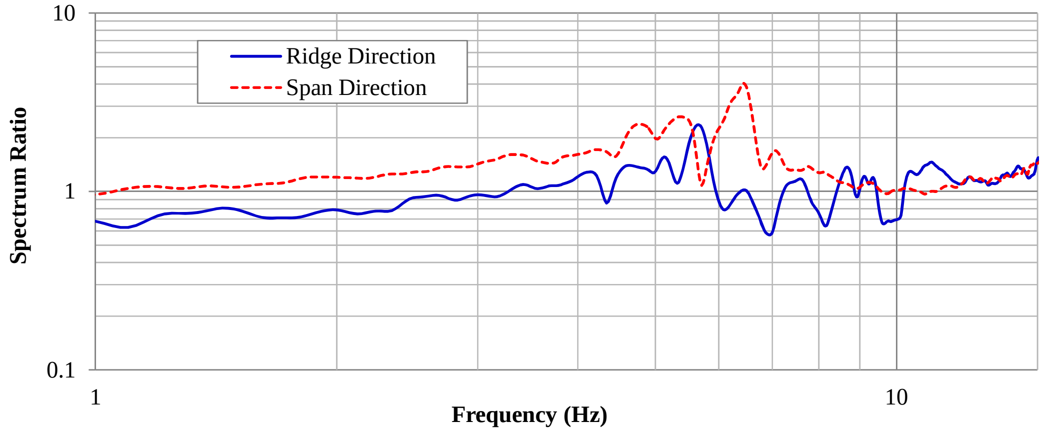
Fig.13 shows the transfer function curves of both O-house and W-house for both the ridge and span directions, which can be numerically evaluated by Eq. (1). It is found



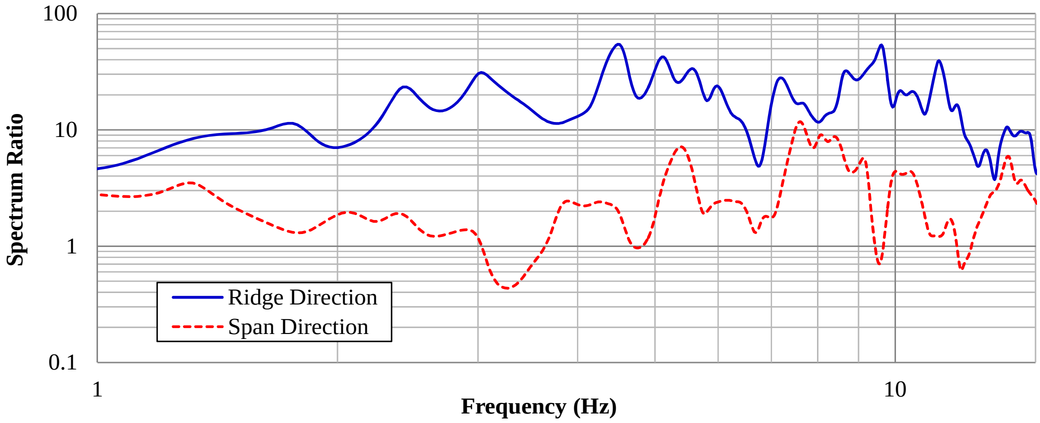
(a)O-house

(b)W-house

Fig.12Displacement response during JR Takatori wave record



(a) O-house



(b) W-house

Fig.13Transfer function curves of O-house and W-house

from the transfer function curves of O-house shown in Fig.13(a) that a peak frequency inthe ridge direction is about 5.66Hz and a peak in the span direction is 6.45Hz. A peak-frequency in the ridge direction is 5.94Hz and a peak in the span direction is 6.41Hz from Table 1 indicated natural frequencies obtained in the vibration measurement of O-house.

On the other hand, a peak frequency in the ridge direction is about 4.49Hz and a peak in the span direction is 5.40Hz from the transfer function curves of W-house.While, a peak frequency in the ridge direction is 4.22Hz and a peak in the span direction is 5.16Hz from Table 1 indicated natural frequencies obtained in vibration measurement of W-house. It should be noted from Fig.13 that peak frequencies obtained bythe collapsing analysis may be almost agree with the vibration measurement results. This implies that not only the analytical frame model of wooden house but also the seismic performance of wooden house using the collapsing process analysis may be valid and effective.

5. CONCLUSIONS

In this paper, the seismic performance of a new two-storywooden house recently built bya traditional wood framed-based construction method was confirmed by not only a collapsing analysis but also a vibration measurement in order to compare the seismic performance of a new wooden house with that of an old house. A collapsing process analysis of the wooden house was conducted using four earthquake ground motion waves with the JMA seismic intensity of “6 upper” level, in order to investigate the feasibility of the application of the collapsing analysis to the seismic performance evaluation of wooden house.The seismic performance of a new two-story wooden house was compared with that of an old two-story wooden house built by old seismic design code before 1981.

In summary, the following conclusions can be made based on the results presented in this paper.

(1) Peak frequencies in the transfer function curves of both a new two-story wooden house and an old wooden one obtained by the collapsing analysis are almost agree with the vibration measurement results. It should be found that not only the analytical frame model of wooden house but also the seismic performance of wooden house using the collapsing process analysis may be valid and effective from a view point of the seismic retrofit of old wooden house.

(2) An old two-story wooden house, which was built by a traditional wood framed-based construction method before 1981,may collapse by a strong earthquake ground motion with the JMA seismic intensity of “6 upper” level and the predominant frequency range of 0.5 to 1.5Hz. This is because that this predominant frequency range has a significant relationship with the existing old wooden house collapsing phenomenon during a strong earthquake motion.

(3)Because the stiffness at the connection part between pillar and beam elements in a new wooden house is much higher than an old wooden house built before 1981, a plastic deformation due to the non-linear characteristics at the pillar and beam joint part does not occur during a strong earthquake ground motion.

(4)The collapsing process analysis of a new two-storywooden house indicates that earthquake damage may occur in the new wooden house against a strong earthquake ground motion with the predominant frequency range close to its natural frequency. There seems to be a need for an intensive study on the actual practice of the wooden house because it is the most important term in the seismic performance evaluation of a traditional framed-based wooden house built after 1981.

Althoughthe effect of earthquake ground motion spectrum on the seismic response of wooden house is not presented in detail in this paper, it is necessary for an intensive study on the effect of earthquake ground motion spectrum on the seismic response of the wooden house during some earthquake ground motion wave data.In particular, the collapsing process behavior of an old wooden house during a strong earthquake ground motion can be accurately evaluated by this collapsing analysis presented in this paper.

This collapsing process analysis has a significant potential to find when and where begin to break first in an old wooden house during a strong earthquake motion. An optimum seismic retrofit of old wooden house can be made by using the collapsing analysis.

In order to make some concrete conclusions on the seismic performance of a traditional framed-based wooden house, further investigation ofcollapsing process phenomenonof several wooden houses may be needed.

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