

Seismic performance of Japanese traditional old wooden house against a strong earthquake ground motion

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ABSTRACT

It is very important for structural engineers to accurately make an evaluation of seismic response of a traditional old wooden house in the design process of seismic retrofit. In order to investigate the seismic behavior of a traditional old two-story wooden house, 3-D non-linear collapsing process analysis of this wooden house was conducted against a strong earthquake ground motion. The effect of seismic retrofitting countermeasure on the seismic behavior of an old wooden house was numerically investigated by 3-D non-linear seismic collapsing analysis in this paper.

1. INTRODUCTION

There are a lot of Japanese-style traditional old wooden houses in Japan. Especially, these Japanese-style traditional kind of old wooden houses attract so many foreigner tourists as well as Japanese people and also they have a lower seismic performance against a strong earthquake. Therefore, it is very important for structural engineers to accurately evaluate a seismic response of a traditional old wooden house in the design process of seismic retrofit, because the relationship between the seismic performance ratio and the seismic response of traditional old wooden house can play a key role to propose an effective countermeasure in the design process of seismic retrofit for the wooden house.

By 3-D non-linear collapsing process analysis of Japanese-style traditional wooden house, Takatani and Nishikawa (2015, 2016) have been reported seismic performance of Japanese-style wooden house against several strong earthquake ground motions observed by the national Institute for Earth Science and Disaster Resilience in Japan.

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In order to investigate the seismic performance and behavior of a Japanese-style traditional old two-story wooden house, the Ohkumo memorial house, 3-D non-linear collapsing process analysis (Nakagawa and Ohta, 2010) of this wooden house was conducted against a strong earthquake ground motion. A non-linear behavior of timber elements in the wooden structure during a strong earthquake ground motion can be simulated by this 3-D non-linear collapsing process analysis based on the Distinct Element Method (Cundall and Strack, 1979).

In this paper, seismic diagnosis of the Ohkumo memorial house is carried out by both a general seismic diagnosis and the limit strength capacity calculation method to evaluate its seismic performance. 3-D non-linear collapsing process analysis of the Ohkumo memorial house is conducted to investigate the effect of seismic retrofitting countermeasure on the seismic response behavior. Seismic retrofitting countermeasures by both the structural plywood and the rough-coated wall are analytically investigated in this paper.

2. OUTLINE OF A JAPANESE-STYLE TRADITIONAL TWO-STORY WOODEN HOUSE

Photo 1 shows the Ohkumo memorial house (former the Hirano house) built by the technique of Sukiya-zukuri in 1909, which is a modern Japanese-style two-story wooden house and has a king-post truss in the roof frame over a kitchen as shown in Photo 2. There are many reception rooms with tatami floor, a tea-ceremony room, and a beautiful garden in this wooden house as shown in Photo 3.

Fig.1 indicates the elevation views of the Ohkumo memorial house, and the floor plan of the Ohkumo memorial house is illustrated in Fig.2. It can be seen from Figs.1 and 2 that there are a lot of rooms on the first and second floors of the Ohkumo memorial house and it has especially less walls in the south-east area of the first floor in comparison with the second floor because of a two-story wooden structure built by the Japanese traditional frame construction method.



The 2019 World Congress on
Advances in Structural Engineering and Mechanics (ASEM19)
Jeju Island, Korea, September 17 - 21, 2019



Photo 1. The Ohkumo memorial house (Former Hirano house)



(a) King-post truss



(c) Reception room



(d) Tea-ceremony room

Photo 2. Roof frame and reception rooms in the Ohkumo memorial house



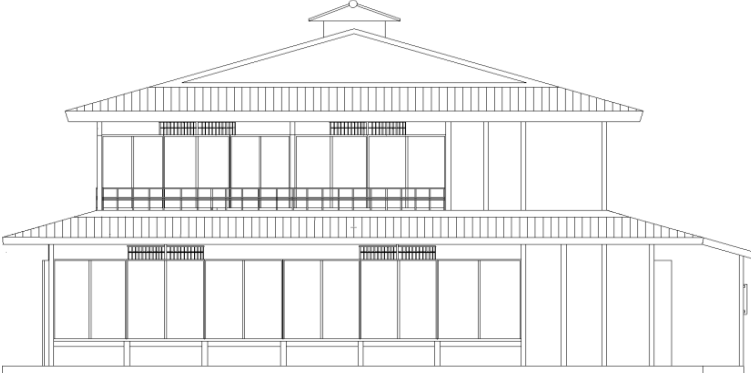
Photo 3. Garden view of the Ohkumo memorial house



(a) South side



(b) North side

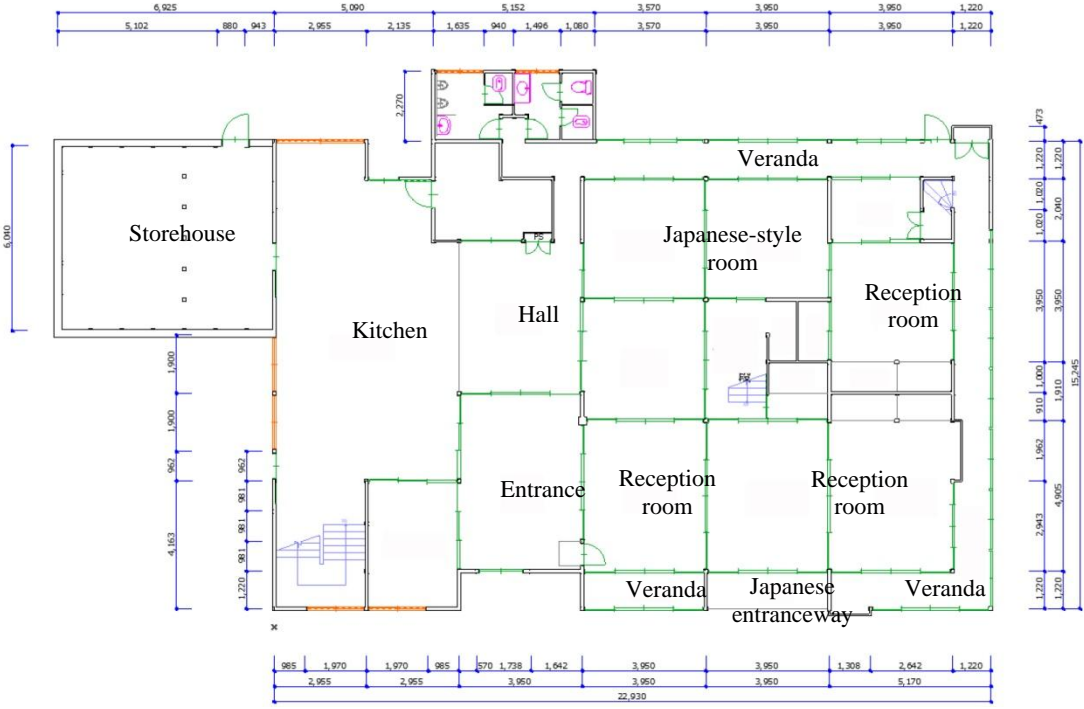


(c) East side

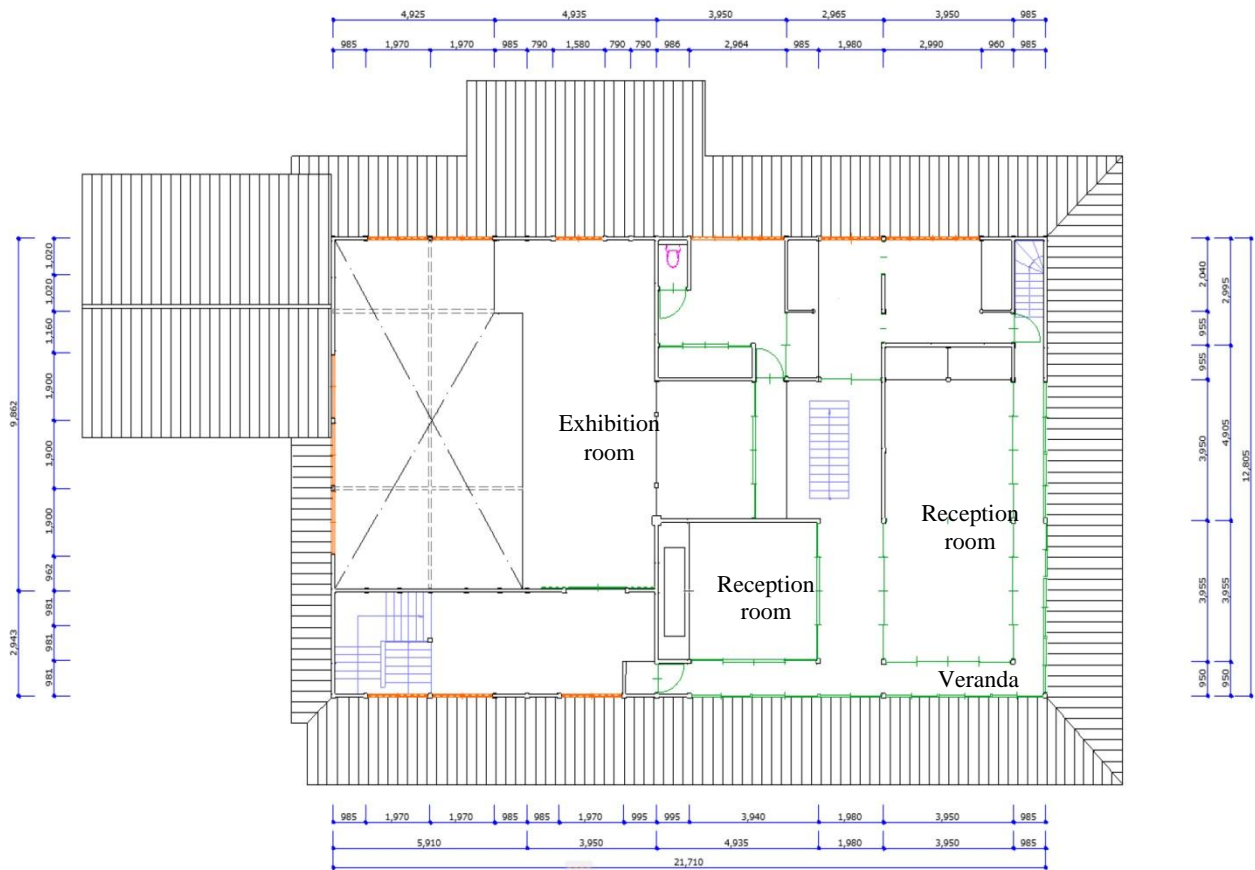


(d) West side

Fig.1 Elevation view of the Ohkumo memorial house



(a) First floor



(b) Second floor

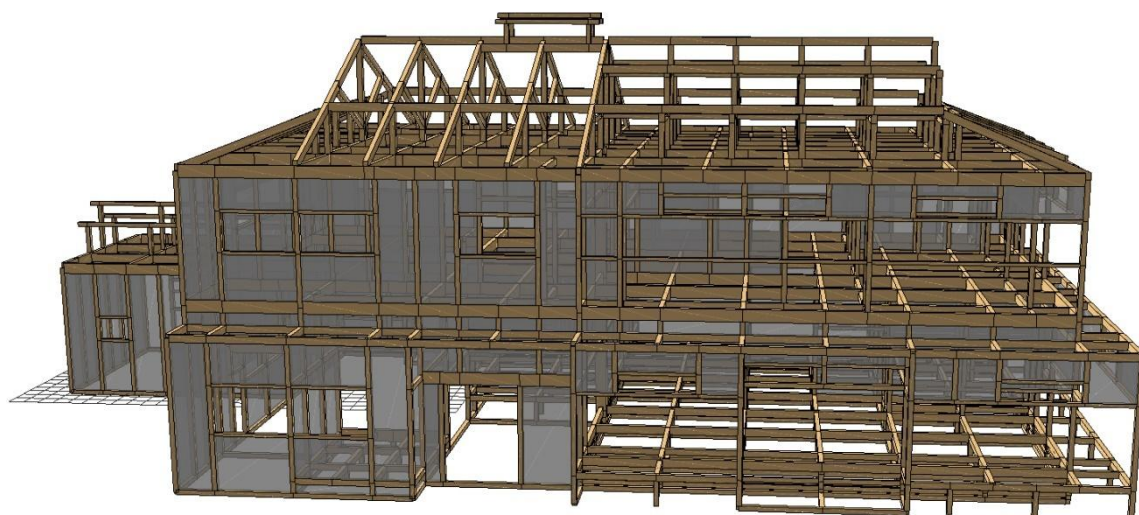
Fig.2 Floor plan of the Ohkumo memorial house (Unit: mm)

3. OUTLINE OF SEISMIC COLLAPSING WOODEN FRAME MODEL

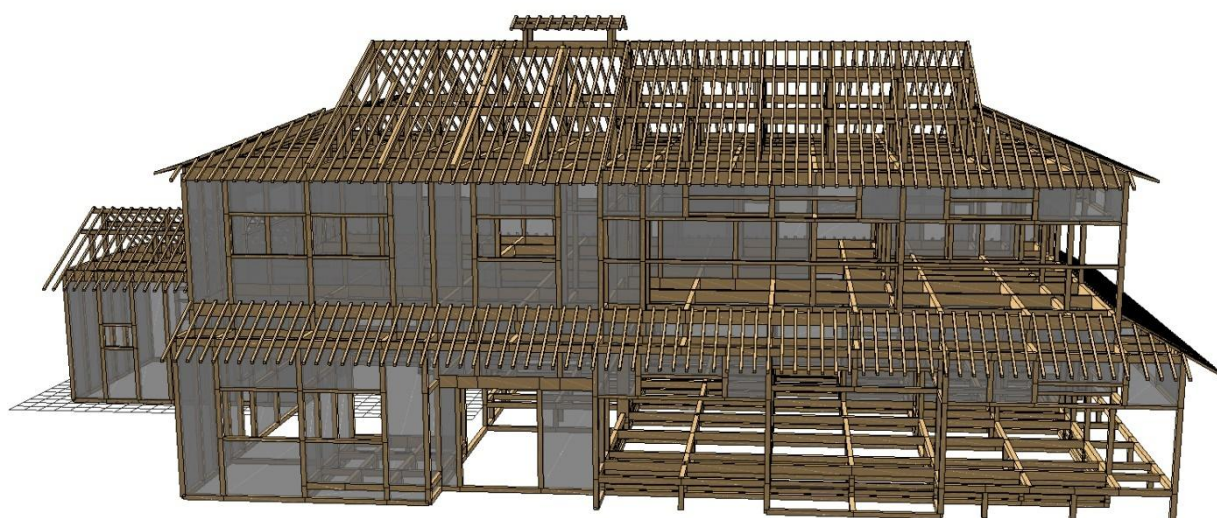
Target of the collapsing process analysis in this paper is a Japanese-style traditional two-story wooden house, the Ohkumo memorial house, which was built by a traditional wood framed-based construction method in 1909. A wooden frame model used in 3-D non-linear collapsing process analysis based on the Distinct Element Method is need in order to investigate seismic collapsing behavior of the Ohkumo memorial house.

Fig.3 shows a wooden frame model of the Ohkumo memorial house, which consists of wooden beams and posts. Fig.3(a) indicates a frame model with walls and Fig.3(b) illustrates a frame model with roof joists. In this paper, a frame model shown in Fig.3(a) is employed in 3-D seismic collapsing analysis.

In this paper, a structural analysis software of “Wallstat” is employed in order to investigate seismic response behavior and collapsing process of one-story thatched roof wooden structure during a strong earthquake ground motion. This software has an original analysis technique (Nakagawa and Ohta, 2010) using the basic theory of the



(a) Frame model



(b) Frame model with roof joist

Fig. 3 Wooden frame model for 3-D collapsing process analysis

Distinct Element Method (Cundall and Strack, 1979), and can be taken into consideration the extremely non-linear properties of timber members breaking or being dispersed. In the collapsing process analytical calculation, two-story wooden house can be modelled by a lot of timber elements such as beam and pillar connected with Method (Cundall and Strack, 1979), and can be taken into consideration the extremely non-linear properties of timber members breaking or being dispersed. In the collapsing process analytical calculation, two-story wooden house can be modelled by a lot of timber elements such as beam and pillar connected with non-linear spring, and also can be modelled by lumped mass and the weight of each floor in two-story wooden house model can be obtained from each structural element. Timber characteristics of the compression and tensile elasto-plastic springs consist of an elastic part and slip-type part.

4. SEISMIC DIAGNOSIS OF THE OHKUMO MEMORIAL HOUSE

General seismic diagnosis can be defined as given by Eq.(1),

$$\text{Upper Structural Index} = \frac{\text{Possession Seismic Capacity (kN), } edQ_u}{\text{Required Seismic Capacity (kN), } Q_r} \quad (1)$$

where, the upper structural index is defined by a possession seismic capacity of wooden house to the required seismic capacity of the wooden house.

While, the seismic diagnosis due to the limit strength calculation method is defined as given by Eq.(2),

$$\text{Upper Structural Index} = \frac{\text{Safety Limit Seismic Capacity (kN), } Q_{si}}{\text{Operating Seismic Force (kN), } Q_{sni}} \quad (2)$$

where, the upper structural index is defined by a safety limited seismic capacity of wooden house to the operating seismic force of the wooden house.

This implies that if the upper structural index is less than 1.0, the wooden house will collapse against a strong earthquake motion with the JMA seismic intensity, "6+" or "7" level. Table 1 shows a judgement of the upper structural index.

Table 1 Judgement of the upper structural index

Value of Upper Structural Index	Judgement
More than 1.5	Not collapse
From 1.0 to 1.5	Roughly not collapse
From 0.7 to 1.0	Possibility of collapse
Less than 0.7	High possibility of collapse

Tables 2 and 3 show the upper structural index results obtained from both the general diagnosis and the limit strength calculation method for the Ohkumo memorial house before seismic retrofit, respectively. From these tables, it can be seen that the Ohkumo memorial house has a possibility or a high possibility of collapse against a strong earthquake motion with the JMA seismic intensity of "6+" or "7" level for either seismic diagnosis. This is because that the Ohkumo memorial house was built in 1909 by the Japanese traditional frame construction method and has especially less walls in the south-east area of the first floor in comparison with the second floor.

Therefore, seismic retrofitting countermeasure for the Ohkumo memorial house with a low seismic performance against a strong earthquake motion is investigated from a

Table 2 Seismic diagnosis result of the Ohkumo memorial house (Before seismic retrofit; the general diagnosis)

Floor	Direction	edQ_u	Q_r	edQ_u / Q_r	Judgment
2	X	104.42	155.62	0.67	Possibility of collapse
	Y	91.98		0.59	Possibility of collapse
1	X	109.13	298.48	0.36	High possibility of collapse
	Y	160.53		0.53	Possibility of collapse

Table 3 Seismic diagnosis result of the Ohkumo memorial house (Before seismic retrofit; the limit strength calculation method)

Floor	Direction	Q_{si}	Q_{sni}	Q_{si} / Q_{sni}	Judgment
2	X	148.42	159.73	0.92	Possibility of collapse
	Y	130.25	218.57	0.59	Possibility of collapse
1	X	174.42	306.73	0.56	Possibility of collapse
	Y	230.39	420.72	0.54	Possibility of collapse

Table 4 Seismic diagnosis result of the Ohkumo memorial house (After seismic retrofit by structural plywood; the general diagnosis)

Floor	Direction	${}_{ed}Q_u$	Q_r	${}_{ed}Q_u / Q_r$	Judgment
2	X	182.43	155.62	1.17	Roughly not collapse
	Y	160.89		1.03	Roughly not collapse
1	X	313.96	298.48	1.05	Roughly not collapse
	Y	400.49		1.34	Roughly not collapse

Table 5 Seismic diagnosis result of the Ohkumo memorial house (After seismic retrofit by structural plywood; the limit strength calculation method)

Floor	Direction	Q_{si}	Q_{sni}	Q_{si} / Q_{sni}	Judgment
2	X	219.97	294.33	0.74	Possibility of collapse
	Y	206.71	283.88	0.72	Possibility of collapse se
1	X	348.35	566.20	0.61	High possibility of collapse
	Y	387.51	544.75	0.71	Possibility of collapse

Table 6 Seismic diagnosis result of the Ohkumo memorial house (After seismic retrofit by rough-coated wall; the general diagnosis)

Floor	Direction	${}_{ed}Q_u$	Q_r	${}_{ed}Q_u / Q_r$	Judgment
2	X	97.27	155.62	0.62	Possibility of collapse
	Y	90.89		0.58	Possibility of collapse
1	X	198.34	298.48	0.66	Possibility of collapse
	Y	268.14		0.89	Possibility of collapse

Table 7 Seismic diagnosis result of the Ohkumo memorial house (After seismic retrofit by rough-coated wall; the limit strength calculation method)

Floor	Direction	Q_{si}	Q_{sni}	Q_{si} / Q_{sni}	Judgment
2	X	218.04	166.33	1.31	Roughly not collapse
	Y	204.02	200.40	1.01	Roughly not collapse
1	X	488.14	419.63	1.16	Roughly not collapse
	Y	627.96	505.05	1.20	Roughly not collapse

view point of the seismic diagnosis in order to satisfy the upper structural index of “more than 1.0”.

Tables 4 and 5 indicate the upper structural index results obtained from both the general diagnosis and the limit strength calculation method for the Ohkumo memorial house after seismic retrofit by the structural plywood (Photo 5), respectively. The characteristics of the structural plywood have a higher stiffness and less toughness than the rough-coated wall. While, the rough-coated wall has a higher toughness characteristics in spite of a lower stiffness than the structural plywood.

Tables 6 and 7 illustrate the upper structural index results obtained from both the general diagnosis and the limit strength calculation method for the Ohkumo memorial house after seismic retrofit by the rough-coated wall (Photo 6), respectively.



Photo 5. Structural plywood



Photo 6. Rough-coated wall

5. SEISMIC COLLAPSING RESULTS OF TWO-STORY WOODEN HOUSE

5.1 Input excitation

Seismic collapsing process analysis of a Japanese-style traditional two-story wooden house is carried out in this paper. Fig.4 shows the standard acceleration response spectra on the engineering rock base whose shear wave velocity is more than 400m/s. In this paper, an input earthquake motion wave is numerically evaluated from the standard acceleration spectrum of “Safety limit” state by the site amplification effect of the Ohkumo memorial house. Fig.5 indicates a site amplification, G_s , for each kind ground. The site amplification around the Ohkumo memorial house is the first kind ground (Board of education in Ohe town, 2000). Fig.6 illustrates an acceleration wave,

velocity one, and displacement one calculated from both the standard acceleration response spectrum of “Safety limit” state and the site amplification of the first kind ground. Table 8 shows the maximum values of acceleration, velocity, and displacement waves shown in Fig. 6.

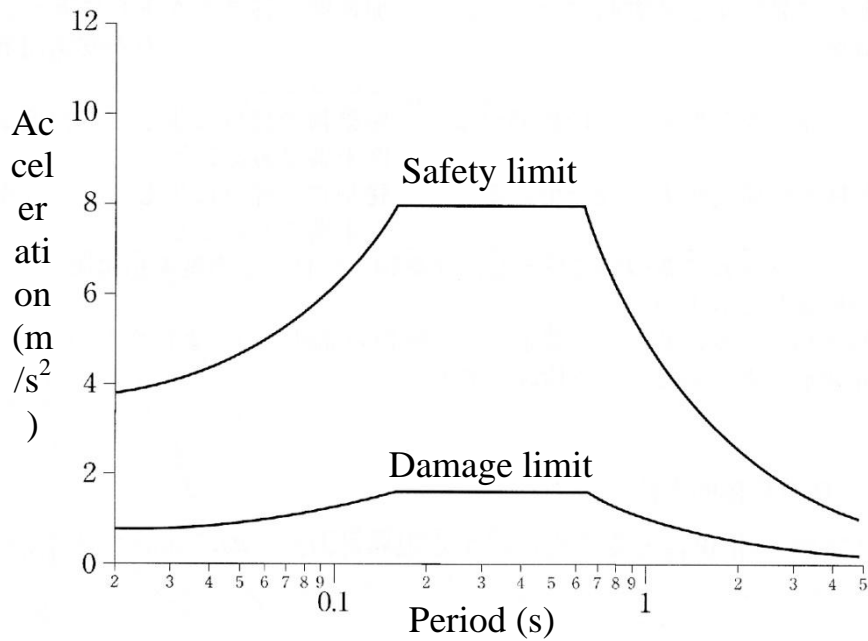


Fig.4 Standard acceleration response spectra on the engineering rock base

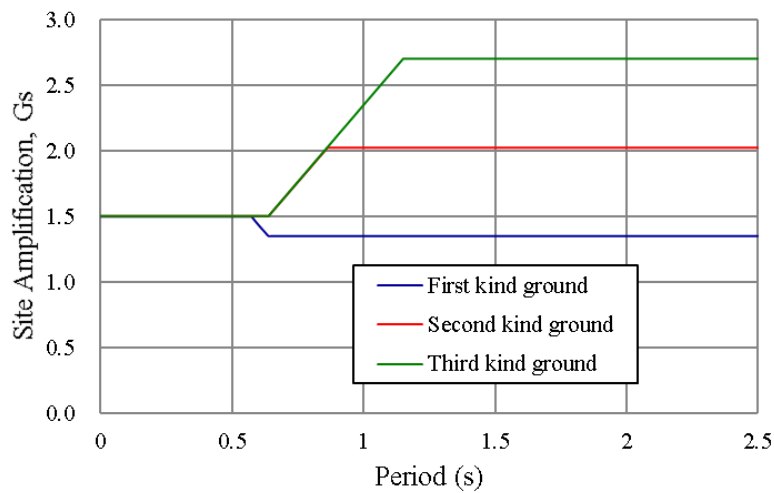


Fig.5 Site amplification, Gs

Table 8 Maximum values for earthquake ground motion waves

	Maximum value
Acceleration	533.5 (Gal)
Velocity	81.2 (kine)
Displacement	31.3 (cm)

5.2 Seismic Collapsing Results

Fig.7 shows the seismic collapsing results of the Ohkumo memorial house without seismic retrofit during an input earthquake ground motion wave shown in Fig.6. The post fixed condition is assumed to be unfixed.

Photo 7 shows a post erected on a foundation stone under a Japanese-style typical traditional wooden house floor. There are many posts erected on their foundation stones or wooden thresholds, and they are not fixed on their foundation stones or wooden thresholds. Consequently, this system is likely to be a seismic base isolation.

In this paper, 3-D seismic collapsing analysis was carried out under the unfixed condition for posts.

From Fig.7, the Ohkumo memorial house starts to suffer seismic damage on walls after 5 seconds and gradually the posts and walls of the wooden house destroy with the lapse of time, and completely collapses after 30

seconds. It is found that the Ohkumo memorial house trends to collapse the walls and posts on the first floor without a collapse of the second floor and the second floor part destroys after the collapse of the first floor. This implies that the Ohkumo memorial house collapses completely against a strong earthquake motion wave shown in Fig.6.

Seismic behavior of the Ohkumo memorial house with a seismic retrofit by structural plywood against an input earthquake motion wave shown in Fig.6 is indicated in Fig. 8. The Ohkumo memorial house starts to suffer seismic damage on walls and posts on the first floor after 10 seconds, and completely collapses after 40 seconds. In a similar manner to the collapsing behavior shown in Fig. 7, the Ohkumo memorial house collapses the walls and posts on the first floor without a collapse of the second floor and then the roof part destroys after a collapse of the first and second floors.

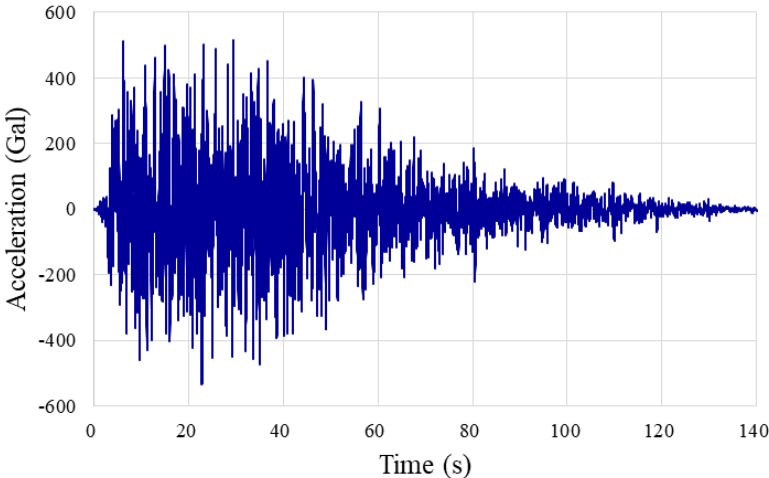
Fig.9 shows the seismic collapsing results of the Ohkumo memorial house with a seismic retrofit by rough-coated walls during an input earthquake ground motion wave shown in Fig.6. It can be seen from Fig.9 that the Ohkumo memorial house suffers seismic damage in the roof structure and on the walls and posts on the first floor, and does not lead to collapse completely regardless of a long duration time of 140 seconds. This is because the characteristics of the rough-coated wall has a higher toughness in spite of a lower stiffness than the structural plywood. It is found that the rough-coated wall may be the most suitable seismic retrofitting countermeasure for a Japanese-style traditional wooden house like the Ohkumo memorial house in comparison with the structural plywood.

5.3 Seismic Collapsing Response Behavior

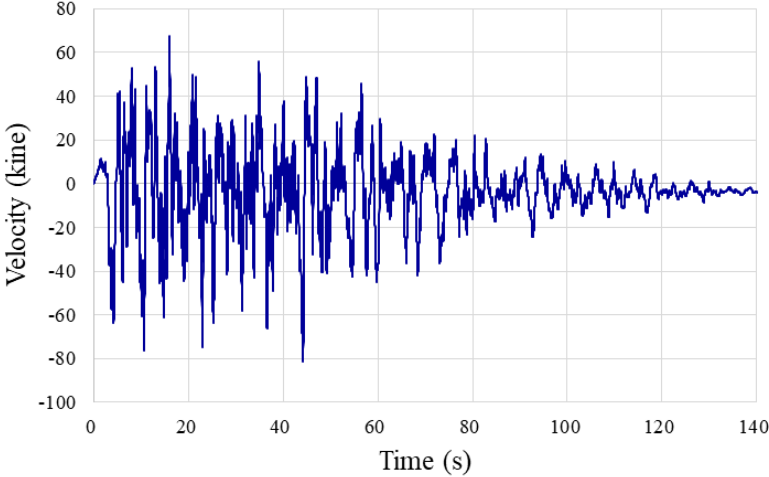
In this paper, some collapsing response spots shown in Fig.10 are investigated. Fig.11 shows seismic responses at 4 spots of A, B, C, and D of the Ohkumo memorial



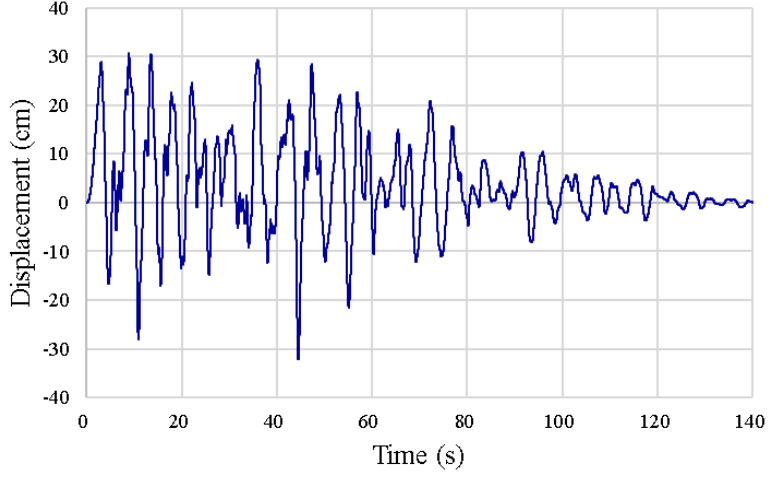
Photo 7. Post erected on a foundation stone



(a) Acceleration (Gal)

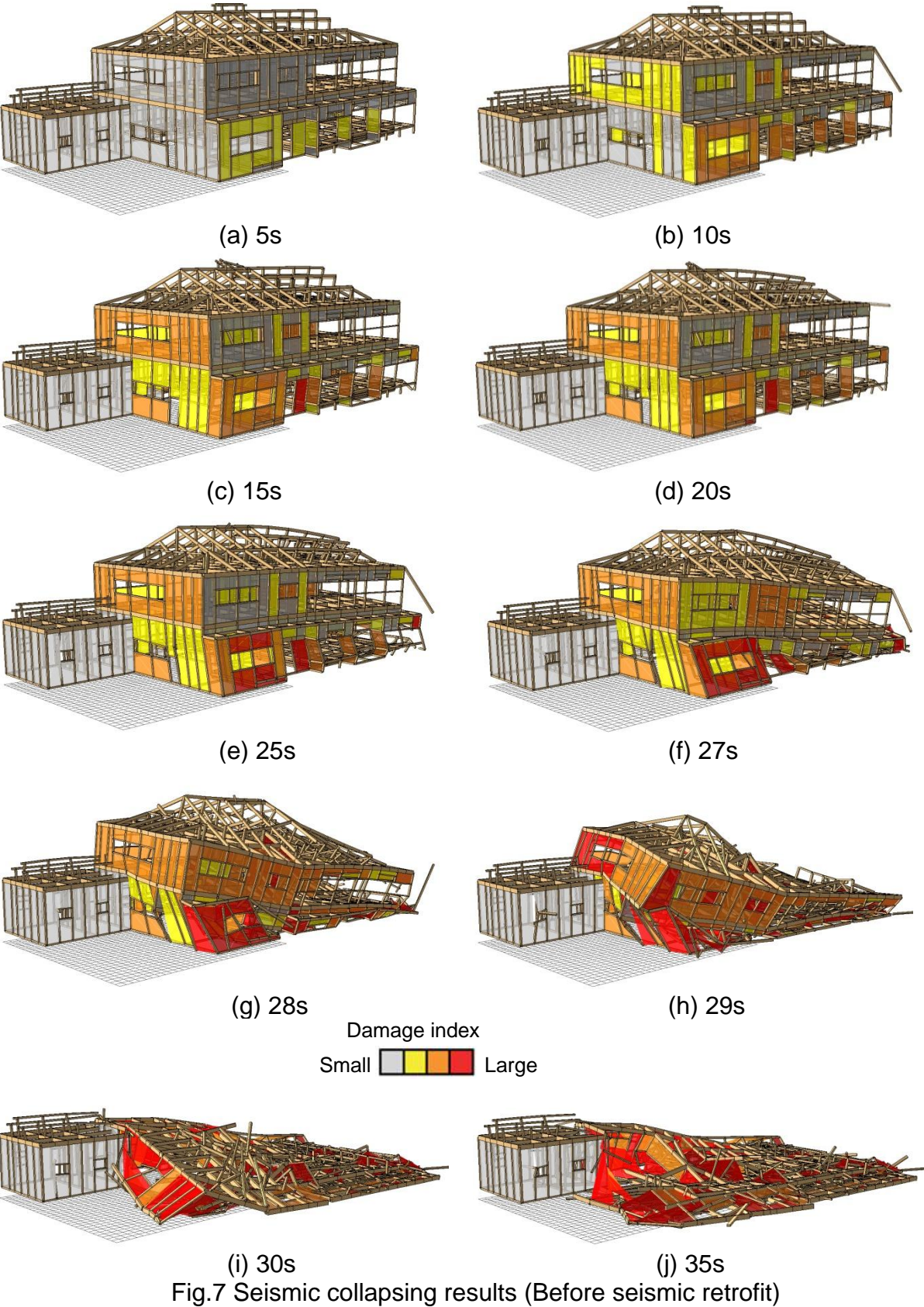


(b) Velocity (kine)



(c) Displacement (cm)

Fig. 6 Input earthquake ground motion (First kind ground)



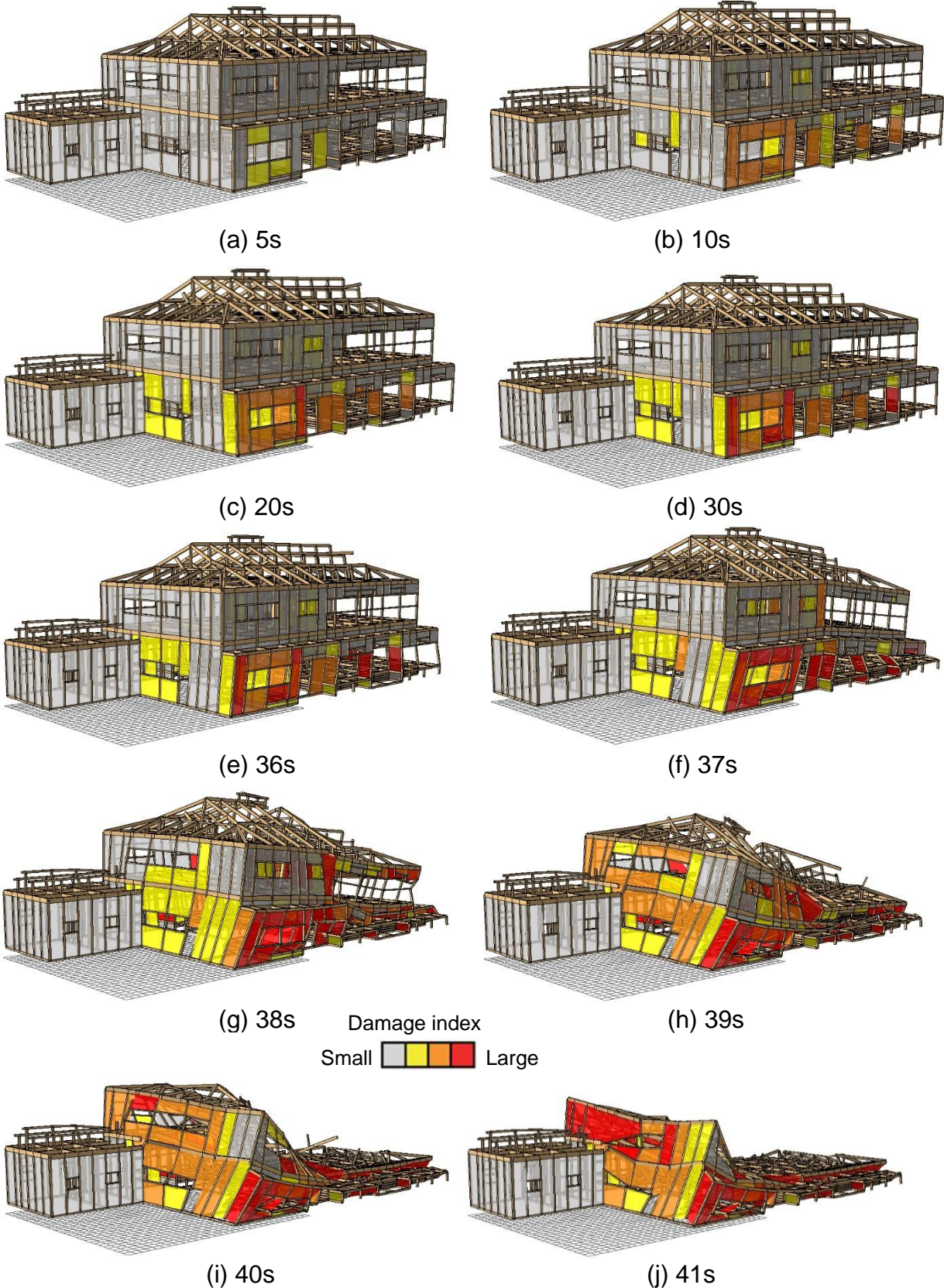


Fig.8 Seismic collapsing results (After seismic retrofit by structural plywood)

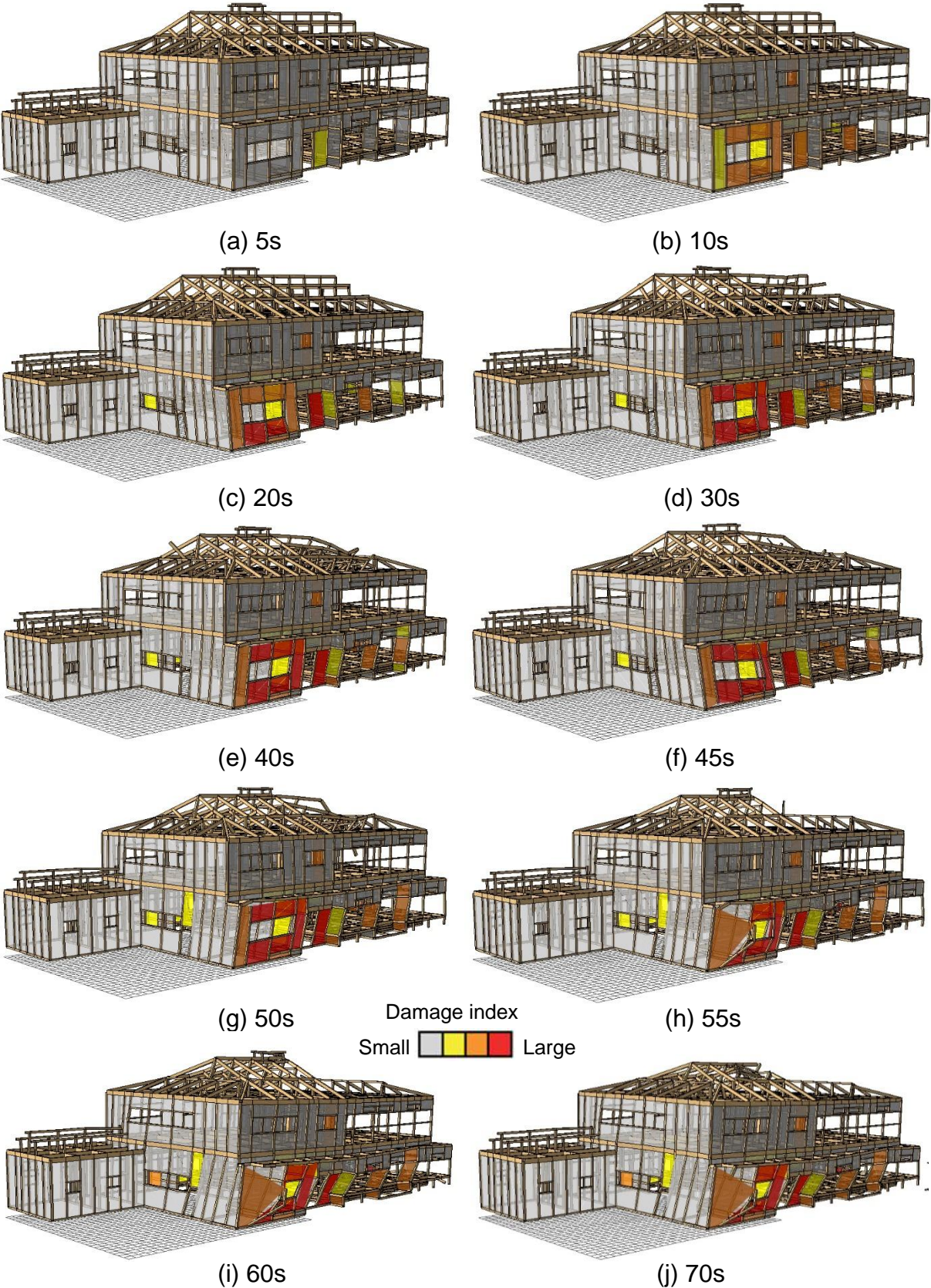


Fig.9 Seismic collapsing results (After seismic retrofit by rough-coated wall)

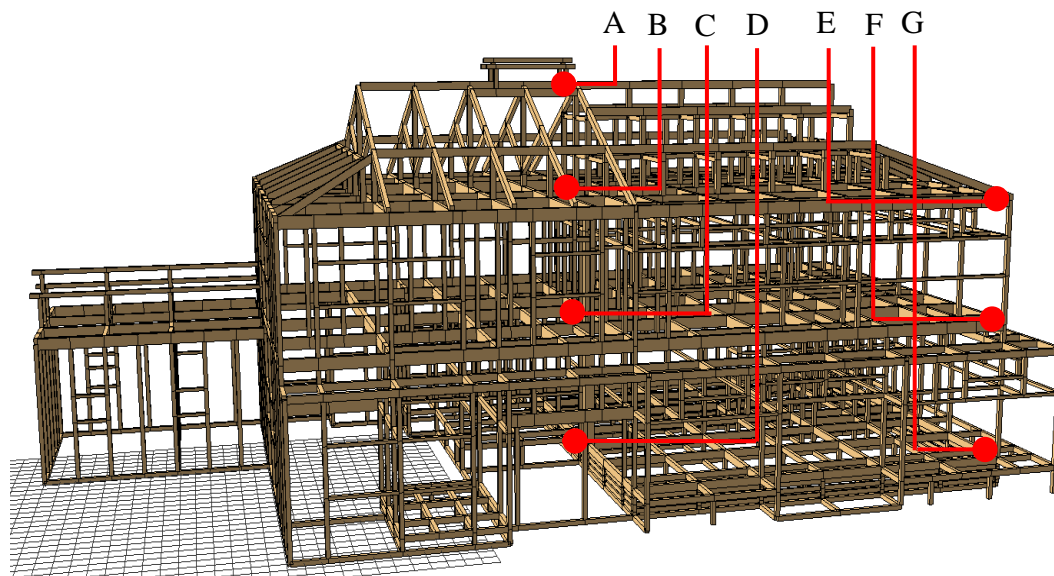


Fig.10 Seismic response spots during seismic collapsing behavior

house before seismic retrofit during an input earthquake motion wave shown in Fig.6. Seismic responses at 3 spots of E, F, and G during an input earthquake motion wave are indicated in Fig.12. 4 spots of A, B, C, and D are located almost at a center part of the Ohkumo memorial house, and is on the ridgepole, the roof frame, the beam of the second floor, and the beam of the first floor, respectively. 3 spots of E, F, and G are located at the roof frame, the beam of the second floor, and the beam of the first floor of the Ohkumo memorial house, respectively. It can be seen from Figs.11 and 12 that the Ohkumo memorial house without seismic retrofit starts to collapse after almost 25 seconds and completely collapse after 30 seconds.

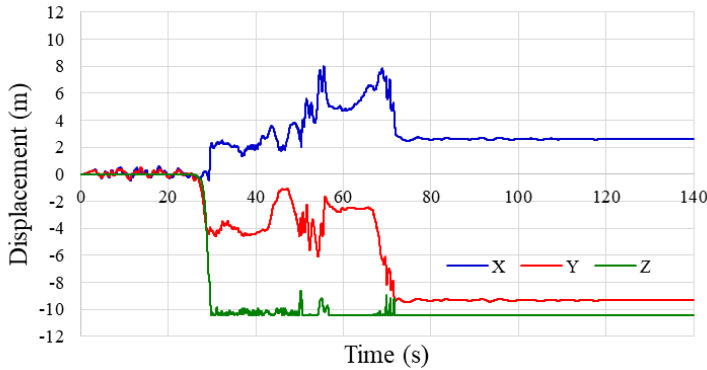
Fig.13 illustrates seismic responses at 3 spots of E, F, and G of the Ohkumo memorial house after seismic retrofit by structural plywood during an input earthquake motion wave. The Ohkumo memorial house with seismic retrofit by structural plywood starts to collapse after almost 36 seconds and completely collapse after 40 seconds.

Fig.14 shows seismic responses at 3 spots of E, F, and G of the Ohkumo memorial house after seismic retrofit by rough-coated wall during an input earthquake motion wave. The Ohkumo memorial house with seismic retrofit by rough-coated wall starts to collapse after almost 55 seconds and does not collapse after 60 seconds.

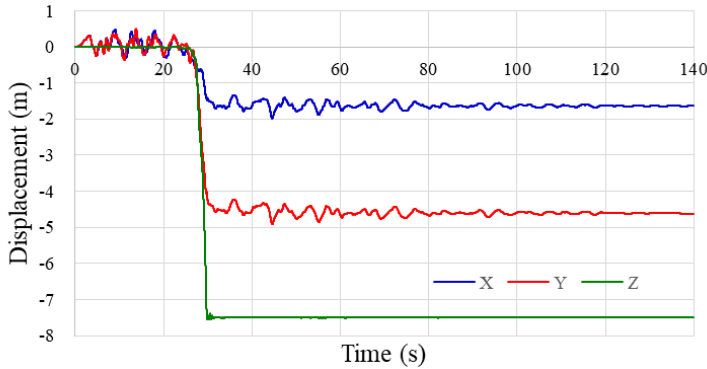
6. CONCLUSIONS

It is very important for structural engineers to accurately evaluate a seismic response of a traditional old wooden house in the design process of seismic retrofit, because the relationship between the seismic performance ratio and the seismic response of traditional old wooden house can play a key role to propose an effective countermeasure in the design process of seismic retrofit for the wooden house.

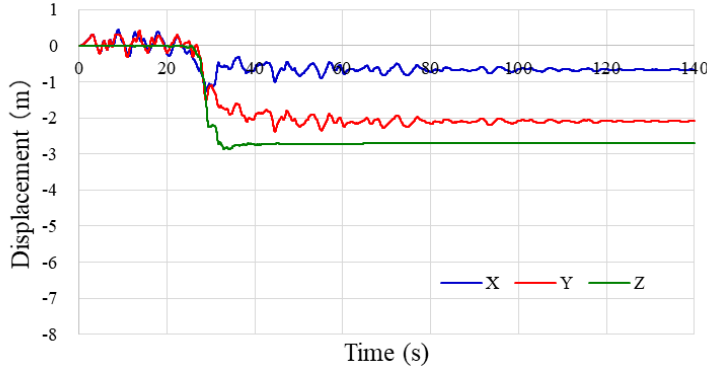
In order to investigate the seismic behavior of a Japanese-style traditional old two-story wooden house, 3-D non-linear collapsing process analysis of the wooden house



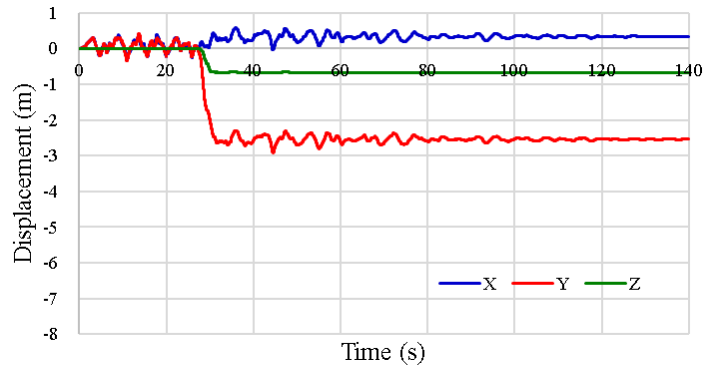
(a) A point



(b) B point



(c) C point

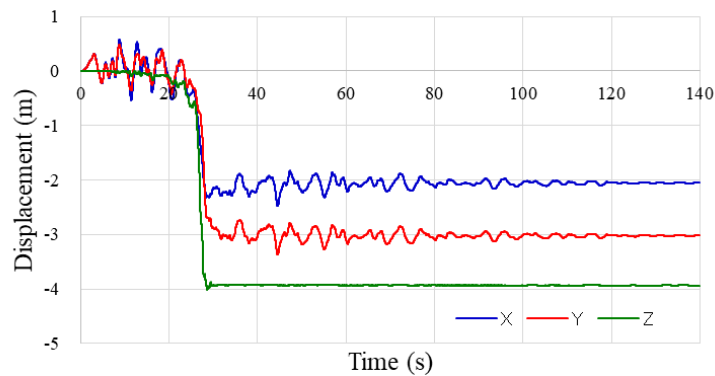


(d) D point

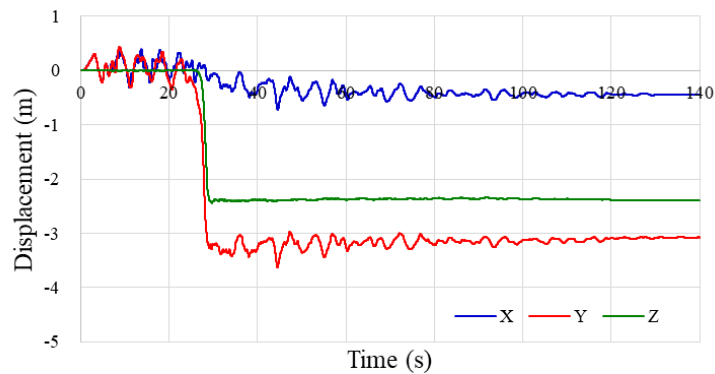
Fig.11 Seismic response (Before seismic retrofit)

was conducted against a strong earthquake ground motion. A non-linear behavior of timber elements in the wooden structure during a strong earthquake ground motion can be simulated by this 3-D non-linear collapsing process analysis based on the Distinct Element Method. The summary obtained in this paper is as follows.

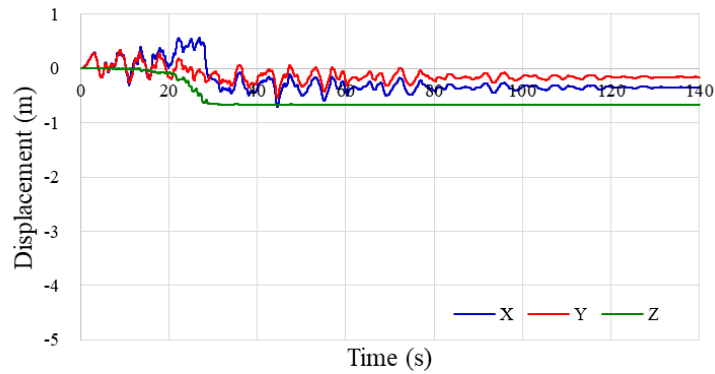
- (1) Seismic behavior of a Japanese-style traditional two-story wooden house under a strong earthquake ground motion can be numerically simulated by 3-D collapsing process analysis.
- (2) The application of 3-D collapsing analysis to a Japanese-style traditional two-story wooden house may play an important key role in seismic retrofit design process of this wooden house.



(a) E point



(b) F point

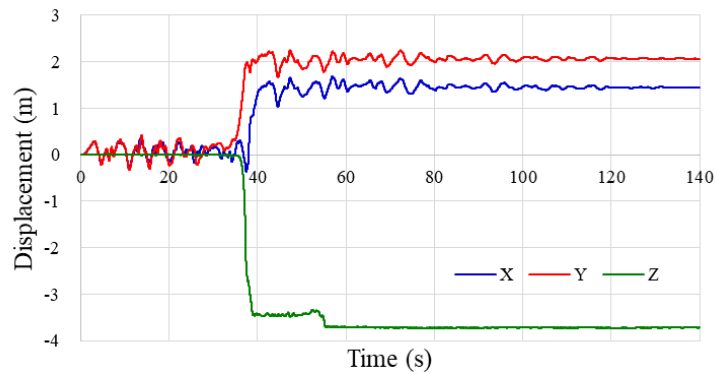


(c) G point

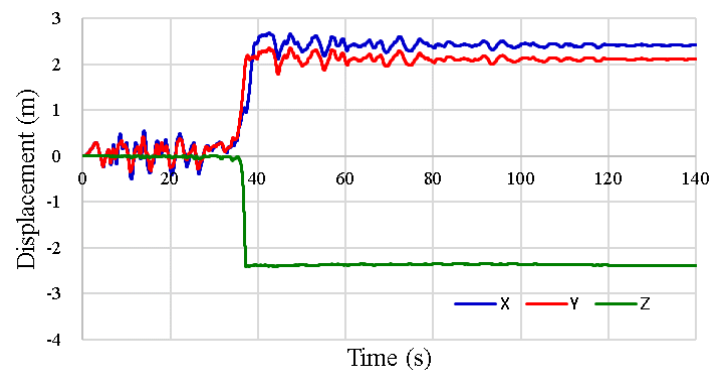
Fig.12 Seismic response (Before seismic retrofit)

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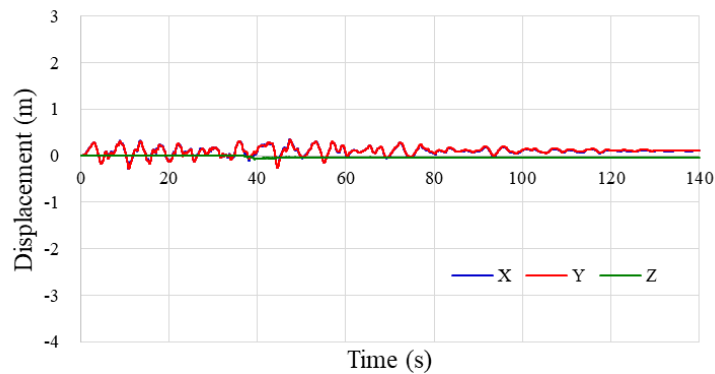
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(a) E point



(b) F point

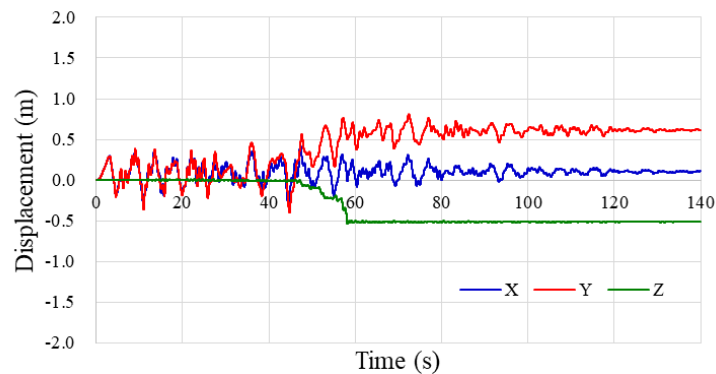


(c) G point

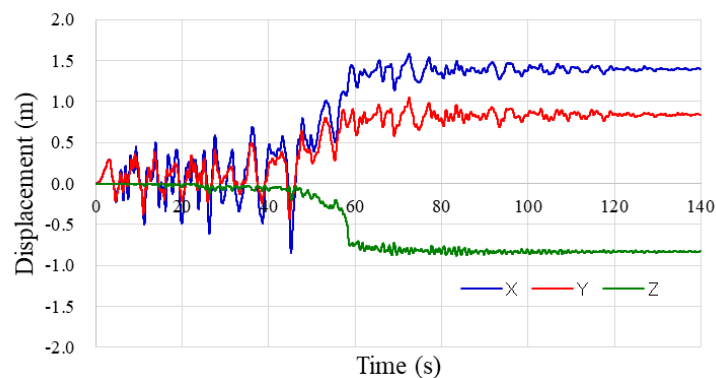
Fig.13 Seismic response (After seismic retrofit by structural plywood)

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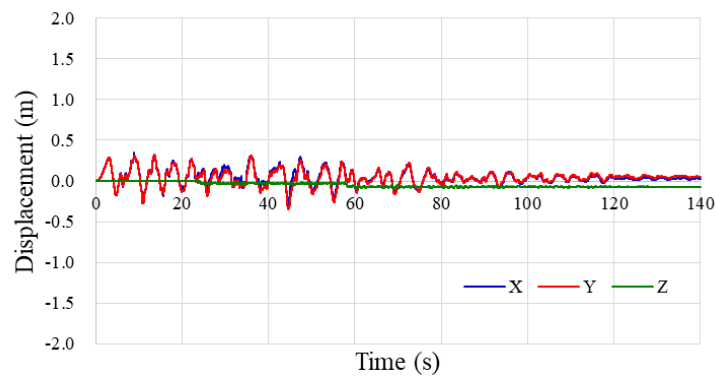
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(a) E point



(b) F point



(c) G point

Fig.14 Seismic response (After seismic retrofit by rough-coated wall)