SEISMIC COLLAPSING BEHAVIOUR OF ONE-STORY WOODEN STRUCTURE WITH THATCHED ROOF UNDER STRONG EARTHQUAKE GROUND MOTION

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ABSTRACT

In Japan, there has existed a serious problem on seismic retrofit for a lot of one-story wooden structures such as temples and shrines in famous tourist resort areas, which were built by a Japanese traditional framed-construction method and have some types of thatched roof instead of tiles. In order to investigate the seismic behaviour of an old one-story thatched roof wooden structure, “Yakushi-doh”, 3-D non-linear collapsing process analysis of Yakushi-doh structure was conducted against a strong earthquake ground motion with the Japan Meteorological Agency seismic intensity of “6 upper” level. A non-linear behaviour 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 effect of the post fixing condition under wooden structure floor on seismic response of Yakushi-doh structure was numerically investigated in this paper.

KEYWORDS

One-story wooden structure with thatched roof, 3-D non-linear collapsing process analysis, seismic response.

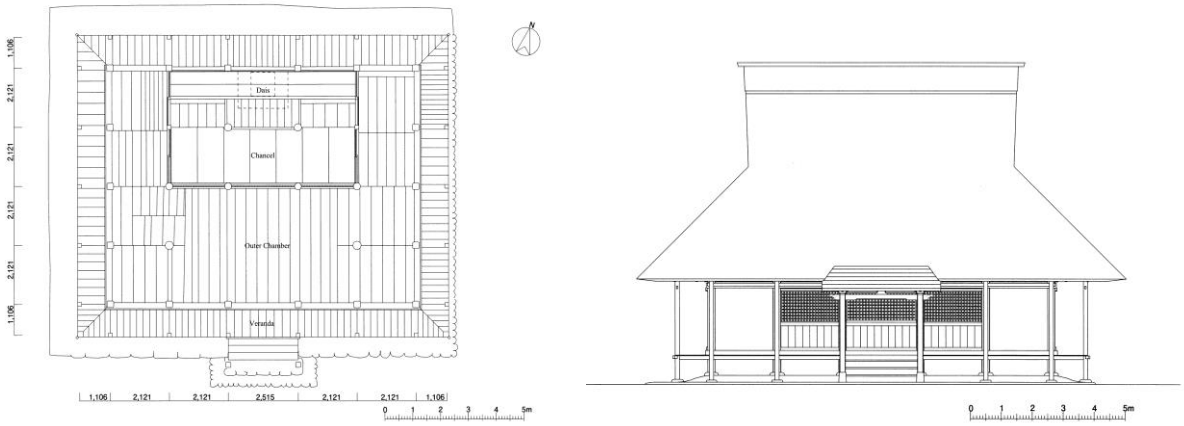
INTRODUCTION

It is well known that a great number of wooden houses collapsed in the 1995 Hyogo-ken Nanbu Earthquake. In order to investigate seismic performance of wooden house against a strong earthquake ground motion, seismic collapsing analyses (Nakagawa and Ohta 2010; Takatani 2013, 2014; Takatani and Nishikawa 2012, 2014) for many Japanese old wooden houses built by a Japanese traditional framed-construction method have been conducted by 3-D non-linear collapsing process analysis based on the Distinct Element Method (Cundall and Strack 1979). In Japan, there has existed a serious problem on seismic retrofit for a lot of one-story wooden structures such as temples and shrines in famous tourist resort areas, which were built by a Japanese traditional framed-construction method and have some types of thatched roof instead of tiles. Because they are important cultural assets in Japan, it may be so difficult and not a good plan from a view point of scenery preservation to reconstruct these thatched roof wooden structures to conduct their seismic retrofits. It is, therefore, very important for structural engineers to perform seismic retrofit for one-story thatched roof wooden structure without reconstruction. In order to investigate the seismic behaviour of an old one-story thatched roof wooden structure, “Yakushi-doh”, 3-D non-linear collapsing process analysis of Yakushi-doh structure was conducted against a strong earthquake ground motion with the Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level. In general, the posts under an old wooden structure floor of Yakushi-doh structure are erected on their foundation stones and are not fixed. In this paper, the effect of the post fixing condition under wooden structure floor on seismic response of Yakushi-doh structure was numerically investigated by using two earthquake ground motions measured in 1995 in the seismic collapsing analysis.

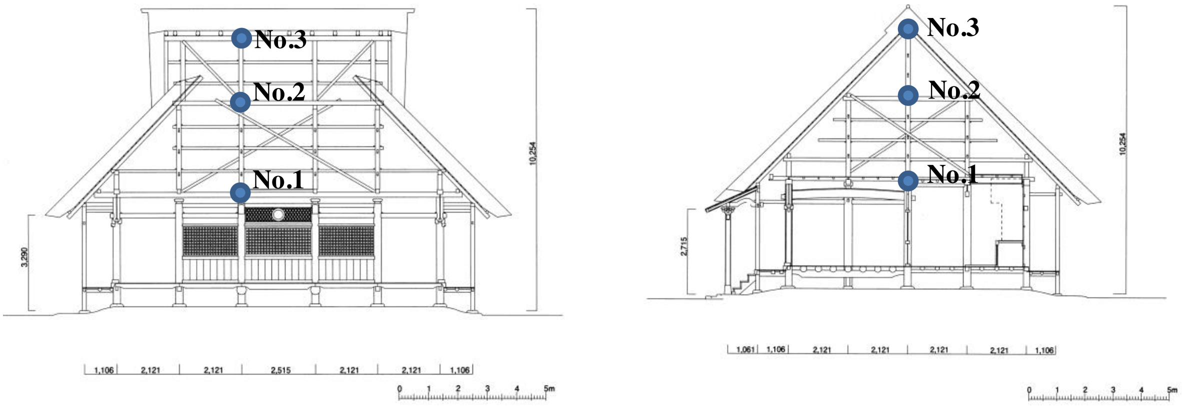
OUTLINE OF YAKUSHI-DOH STRUCTURE

Photo 1 shows one-story wooden structure with thatched roof, Yakushi-doh structure, which was built an old Japanese traditional framed-construction method and have a thatched roof instead of tile. Yakushi-doh structure was dedicated in 1617 to deify “Bhaisajyaguru”, who has been believed in a Buddha able to cure all ills, and has been an important cultural asset. Figure 1 indicates floor plan, elevation one, and cross section ones of Yakushi-doh structure. The width, depth, and height of Yakushi-doh structure are 13.211m, 11.756m and 10.254m, respectively. Photo 2 shows a post erected on a foundation stone under Yakushi-doh structure floor. There are many posts erected on their foundation stones with flat plane under Yakushi-doh structure floor, and they are not fixed on their foundation stones. Consequently, this system is likely to be a seismic base isolation. In this paper, the effect of the post fixing condition under wooden structure floor on seismic response of Yakushi-doh

Photo 1 One-story wooden structure with thatched roof, “Yakushi-doh”



(a) Floor Plan (b) Front Elevation



(c) Front Cross Section (d) Side Cross Section

Figure 1 Plan design and elevation plan of “Yakushi-doh” structure

Photo 2 Post erected on a foundation stone

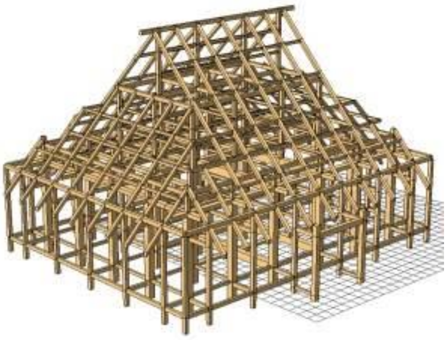


Figure 2 Collapsing wooden frame model

structure is numerically investigated through the seismic response behaviours at Nos.1 to 3, which are illustrated in Figure 1 and are three measuring points in the collapsing process analysis described below.

OUTLINE OF COLLAPSING ANALSYS

Seismic Collapsing Analysis

In this paper, a structural analysis software of “Wallstat” is employed in order to investigate seismic response behaviour and collapsing process of Yakushi-doh structure during a strong earthquake ground motion. This software has an original analysis technique (Nakagawa and Ohta 2010) using the basic theory of the 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, Yakushi-doh structure can be modelled by a lot of timber elements such as beam and pillar connected with non-linear spring as shown in Figure 2, and also can be modelled by lumped mass and the weight of each floor in Yakushi-doh structure model can be obtained from each structural element as illustrated in Figure 3. Timber characteristics of the compression and tensile elasto-plastic springs consist of an elastic part and slip-type part.

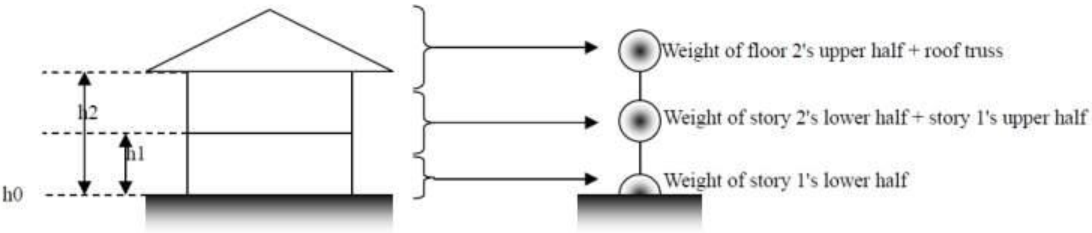


Figure 3 Weight of floor in the analytical model of wooden house (Nakagawa 2011)

Modelling of Structure Element

- Modelling of Frame

Timber frame is modelled by two elasto-plastic rotational springs (plastic hinge) and an elastic beam component as shown in the left-hand side of Figure 4. The spring can be defined by a relationship between bending moment M and angle of rotation θ with the skeleton curve indicated in the right-hand side of Figure 4. The bending moment starts to fall once if it is over the maximum bending moment, and the rotating spring changes to a pinned joint state at the point if the bending moment reaches 0, and then the beam component can be judged to have been broken.

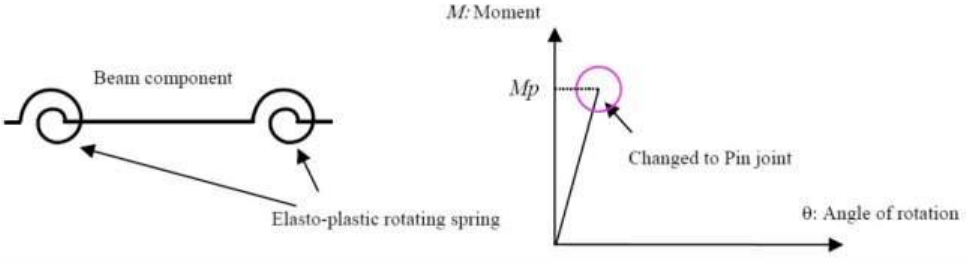
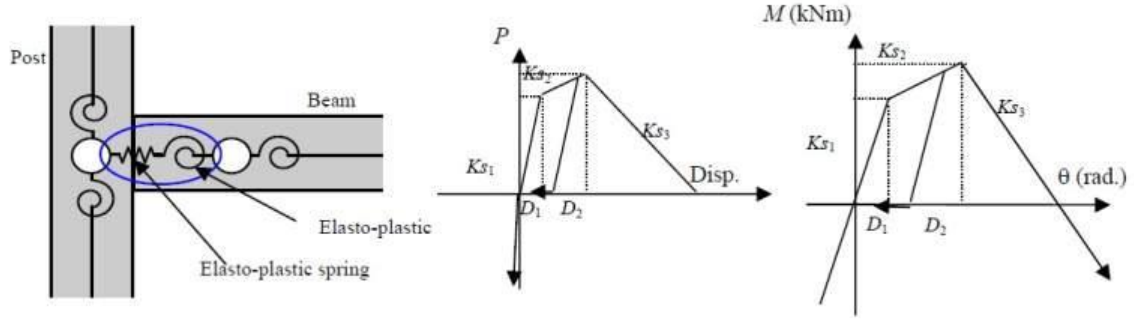


Figure 4 Schematic diagram and skeleton curve of frame spring (Nakagawa 2011)



(a) Schematic diagram of joint element

(b) Characteristic of elasto-plastic spring

(c) Characteristic of rotational spring

Figure 5 Outline of joint modelling (Nakagawa 2011)

- Modelling of Joint Spring

Joint spring can be modelled by both an elasto-plastic spring and a rotational spring as shown in Figure 5(a). Timber characteristic of the compression and tensile elasto-plastic spring consist of an elastic part and slip-type part indicated in Figure 5(b), and also timber characteristics of the rotational spring is assumed to be a slip-type relationship between ending moment M and angle of rotation θ shown in Figure 5 (c). When the elasto-plastic spring or the rotational spring of the joint exceeds the maximum structural strength or moment and their strength values becomes 0, the joint will be adjudged to have been broken and then the spring will be annihilated.

- Modelling of Shear wall and Bracing

Vertical shear wall indicated in Figure 6 can be modelled by the replacement of truss component with a load-displacement non-linear relationship shown in Figure 8. Also, bracing shear wall illustrated in Figure 7 can be modelled by the replacement of compression and tensile truss components defined by a set of bi-linear and slip skeleton curve shown in Figure 8, too.

- Parameters of Structural Element

In general, Young's modulus and the maximum bending moment of timber component are assumed to be 2,000MN/m^2 and 10kNm, respectively. External and internal walls in a typical Japanese wooden house can be assumed to be lath mortal wall and clay wall, respectively. For seismic retrofit countermeasure for a wooden

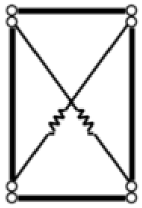


Figure 6 Shear wall spring (Nakagawa 2011)

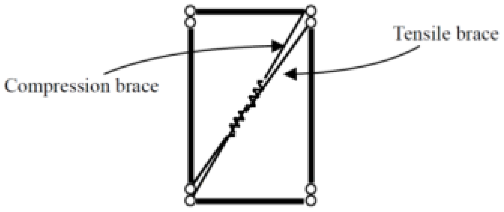


Figure 7 Outline of bracing shear wall (Nakagawa 2011)

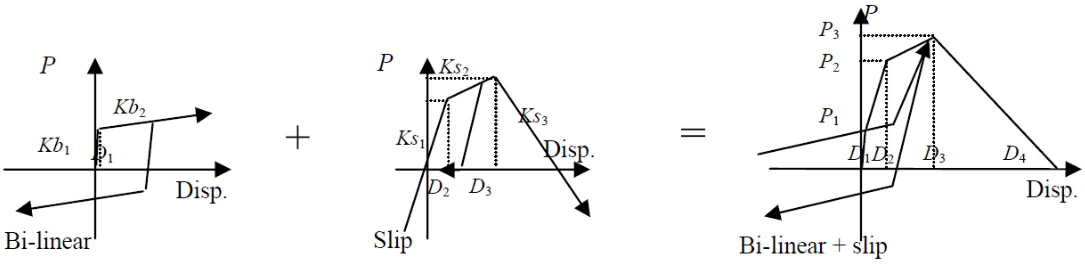


Figure 8 Hysteretic characteristics of shear wall and bracing (Nakagawa 2011)

Table 1 Parameters for hysteretic characteristics of vertical shear wall (Nakagawa 2011)

	P_1	P_2	P_3	P_4	D_1	D_2	D_3	D_4	h
	(kN)				(m)				(%)
Clay Wall	0.5	1.75	2.0	0.0	0.010	0.05	0.10	0.5	2
Lath Mortal Wall	1.0	3.50	4.3	0.0	0.002	0.01	0.05	0.2	2
Structural Plywood	3.0	9.50	10.5	0.0	0.010	0.06	0.12	0.3	2

h : viscous damping factor

Table 2 Parameters for hysteretic characteristics of elasto-plastic spring
(Tajima et al. 2000, Nakagawa 2011)

	Ks_1	Ks_2	Ks_3	D_1	D_2
	(kN/m)			(m)	
Stub Tenon	900	-18.919	-33.333	0.0015	0.02
Corner Bracing	5,128	651	-154	0.0027	0.015

Table 3 Parameters for hysteretic characteristics of bracing spring (Nakagawa 2011)

	P_1	P_2	P_3	P_4	D_1	D_2	D_3	D_4	h
	(kN)				(m)				(%)
Timber Brace1	0.500	2.500	2.800	0.000	0.001	0.015	0.050	0.250	2
Timber Brace2	1.500	4.500	6.700	0.000	0.002	0.053	0.110	0.200	2
Timber Brace3	4.500	8.500	9.200	0.000	0.003	0.061	0.150	0.200	2

house with lower seismic performance, a plywood is generally employed as internal wall. Parameters of hysteric characteristics of their walls are shown in Table 1. Parameters of stub tenon jointed at the interface between beam, column and corner bracing used for seismic retrofit work are described in Table 2. Table 3 shows the parameters of hysteretic characteristics of various timber braces used in a typical Japanese wooden house.

Input Earthquake Motion in Seismic Collapsing Analysis

Seismic collapsing process analysis of Yakushi-doh structure is carried out in this paper. Two 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 two earthquake wave records with the same level intensity which has a different peak frequency in Fourier acceleration spectra. Table 4 shows some parameters of two earthquake ground motion wave records used as an input excitation of the collapsing process analysis.
Figures 9 and 10 indicate two displacement wave data and their Fourier acceleration spectra for both NS and EW components in each earthquake ground motion record shown in Table 4. In the JMA Kobe wave record indicated in Figure 9, a peak frequency in each wave component is from 1Hz to 1.5Hz, and also a peak in each wave component of the JR Takatori wave record illustrated in Figure 10 exists about 0.8Hz. Because there are peak frequencies in both the JMA Kobe and the JR Takatori wave records in 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 structure against a strong earthquake ground motion as reported by Sakai *et al*. (2002).

RESULTS AND DISCUSSIONS

Seismic Collapsing Behaviour

Figure 11 shows the seismic collapsing behaviour of Yakushi-doh structure under post fixed condition during the JMA Kobe earthquake ground motion wave shown in Figure 9. In seismic collapsing result of Yakushi-doh structure, the plastic deformation at the connection part between pillar and beam elements gradually increases during earthquake ground motion by means of the non-linearity characteristics. Yakushi-doh structure collapses after 16 seconds in the JMA Kobe wave record with a frequency range close to 0.5 to 1.0Hz. Figure 12 indicates the seismic collapsing behaviours of Yakushi-doh structure under post unfixed conditions of μ=0.2 and

Table 4 Earthquake ground motion wave records (the 1995 Hyogo-ken Nanbu Earthquake)

Record Name	I_{JMA}	Peak Ground Acceleration (cm/s^2)	Peak Ground Velocity (cm/s)	f_p (Hz)	Duration (s)
JMA Kobe	6.4	818	91	1.43	30
JR Takatori	6.4	657	126	0.81	30

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

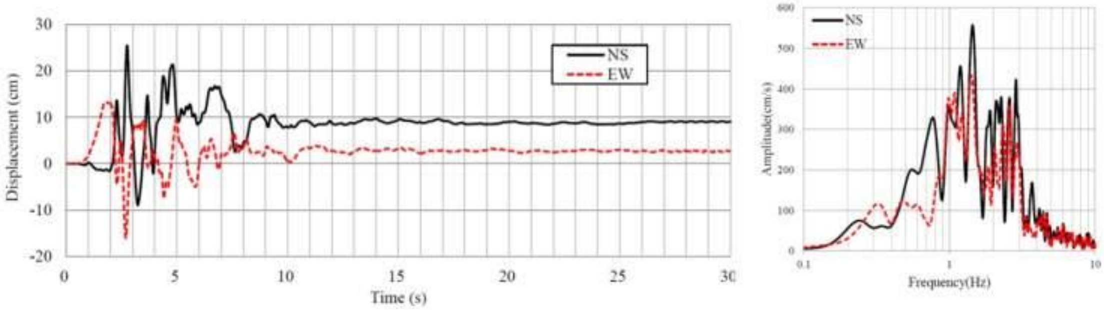


Figure 9 Displacement waves and Fourier acceleration spectra of the JMA Kobe wave

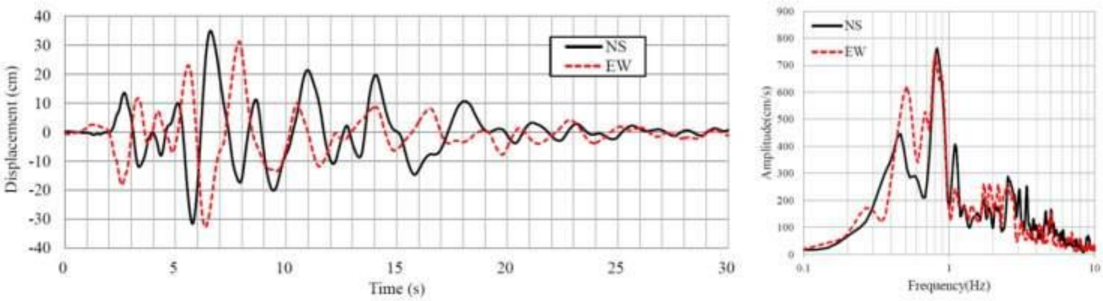


Figure 10 Displacement waves and Fourier acceleration spectra of the JR Takatori wave

0.4 during the JMA Kobe earthquake ground motion wave. The sign μ in this figure means a dynamic friction coefficient between a post element and its foundation stone under the floor of Yakushi-doh structure. It is found from Figure 12 that the collapsing elements of Yakushi-doh structure trends to increase with the friction coefficient μ, because the decrease of friction coefficient μ means to become a seismic base isolation.

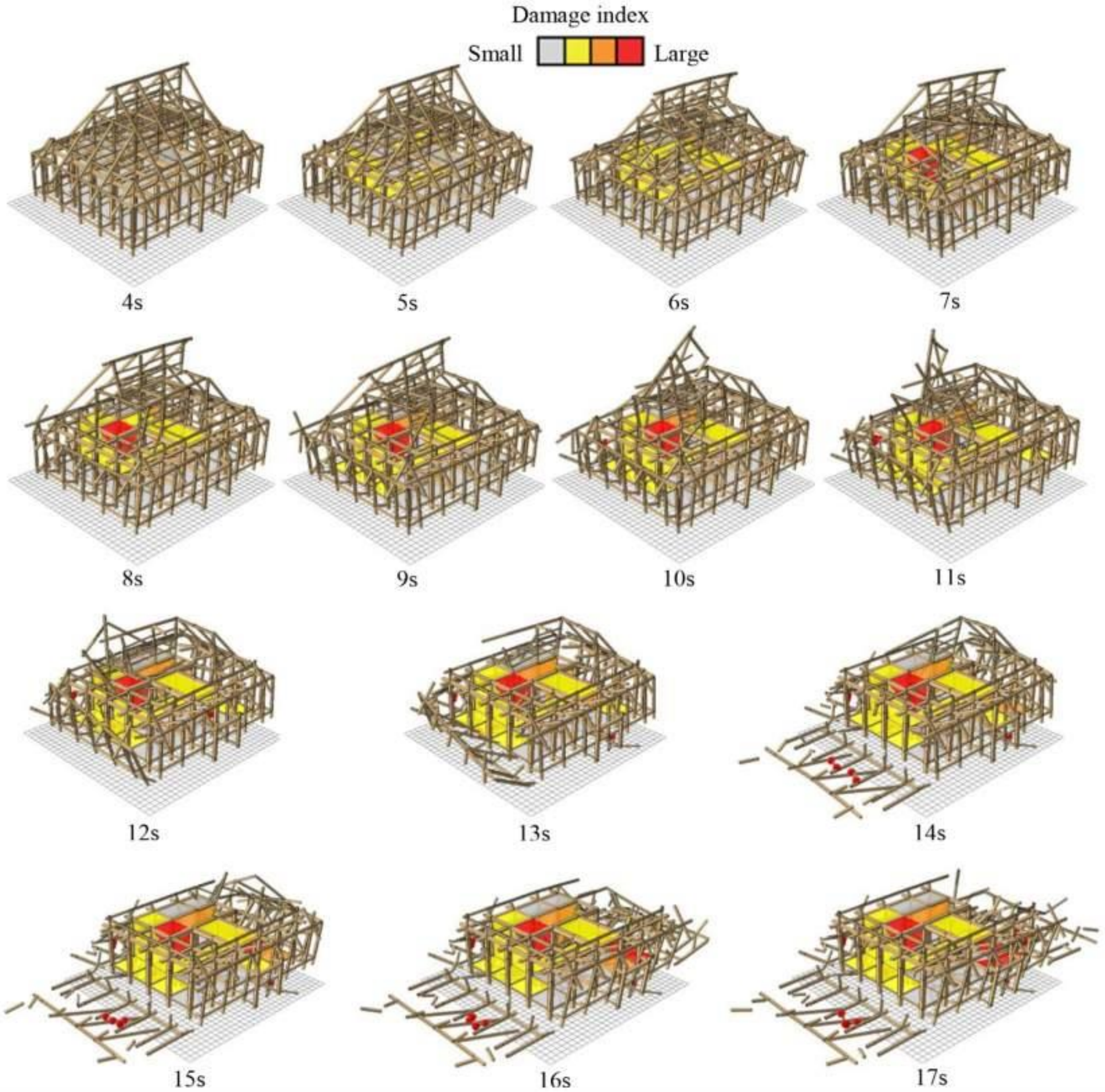
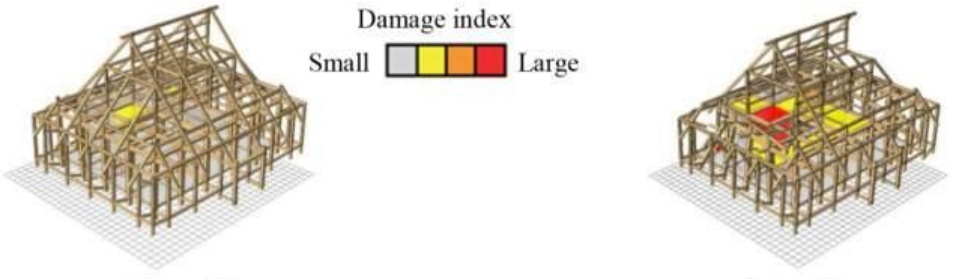


Figure 11 Seismic collapsing behaviour during the JMA Kobe wave under fixed post condition



(a) μ =0.2 (b) μ =0.4

Figure 12 Seismic collapsing state after the JMA Kobe wave under unfixed post condition

Figure 13 shows the seismic collapsing behaviour of Yakushi-doh structure under post fixed condition during the JR Takatori earthquake ground motion wave shown in Figure 10. In particular, Yakushi-doh structure collapses after 10 seconds in the JR Takatori wave record with a frequency range of 0.5 to 1.0Hz, and the frequency range has a significant relationship with an old wooden structure collapsing rate against a strong earthquake

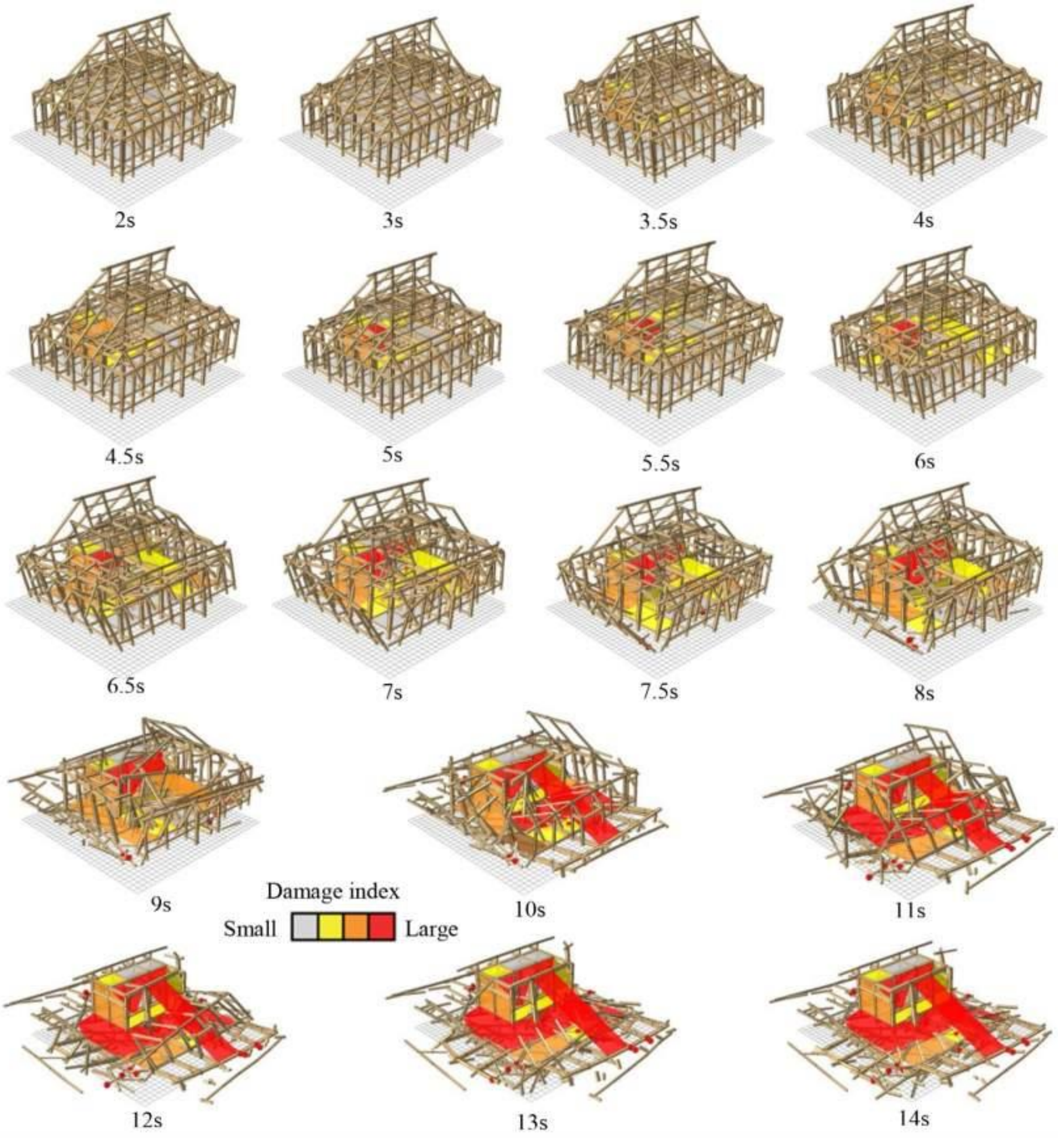
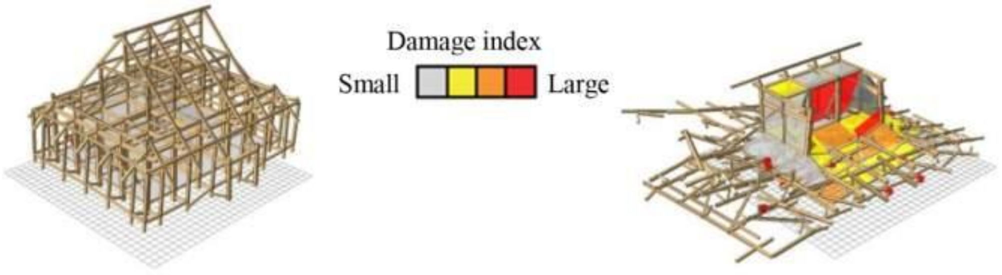
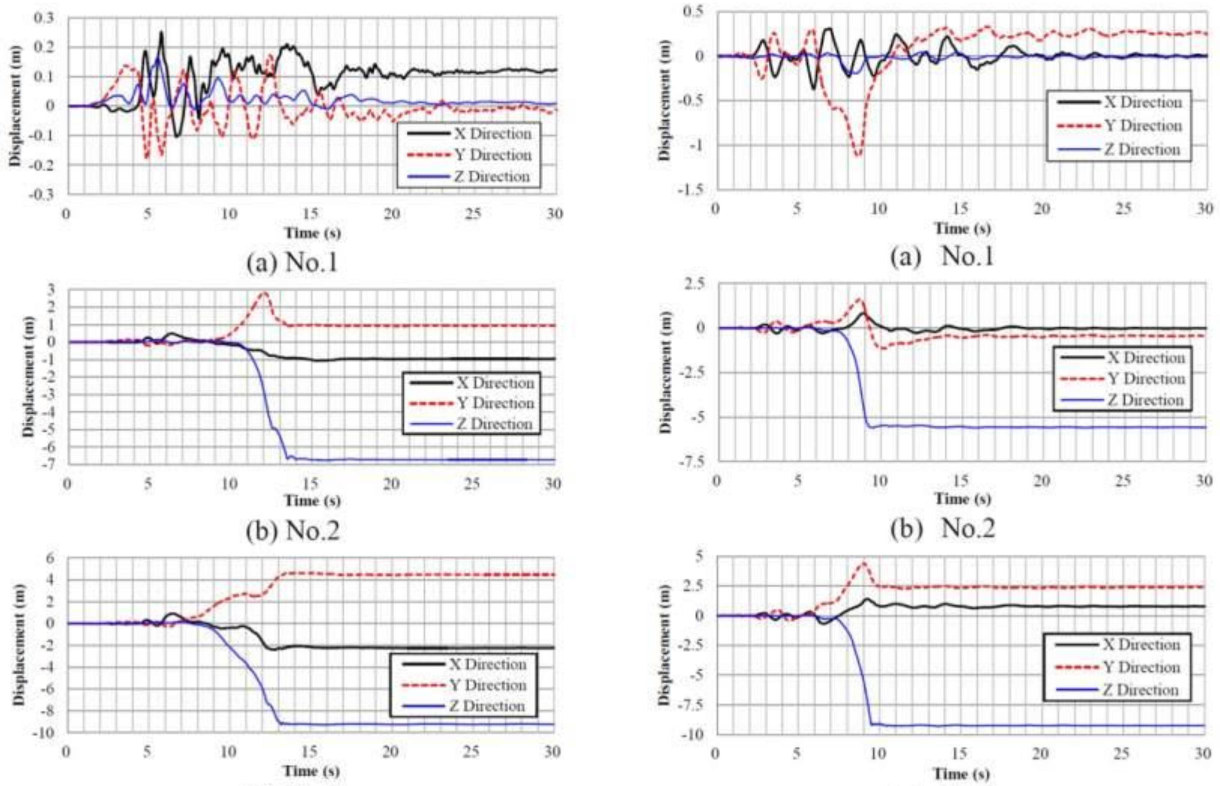


Figure 13 Seismic collapsing behaviour during the JR Takatori wave under fixed post condition



(a) μ =0.2 (b) μ =0.4

Figure 14 Seismic collapsing state after the JR Takatori wave under unfixed post condition



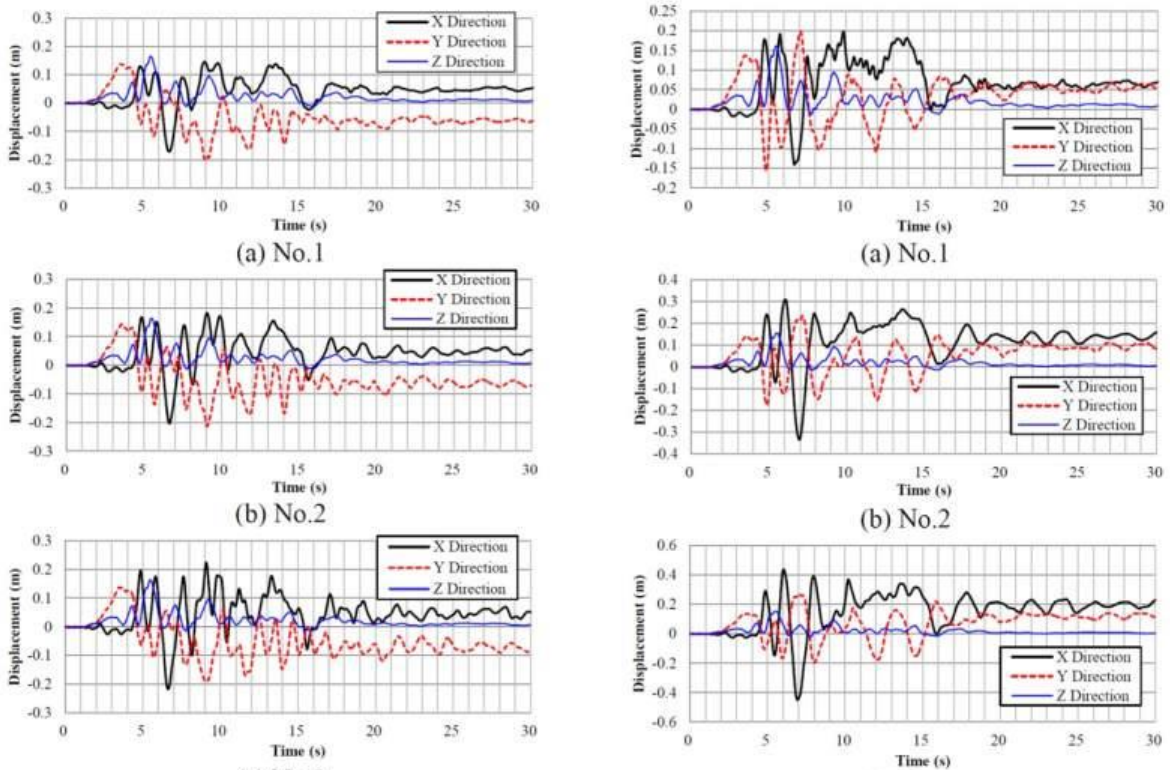
(a) No.1 (a) No.1

(b) No.2 (b) No.2

(c) No.3 (c) No.3

JMA Kobe wave JR Takatori wave

Figure 15 Displacement responses at Nos.1 to 3.



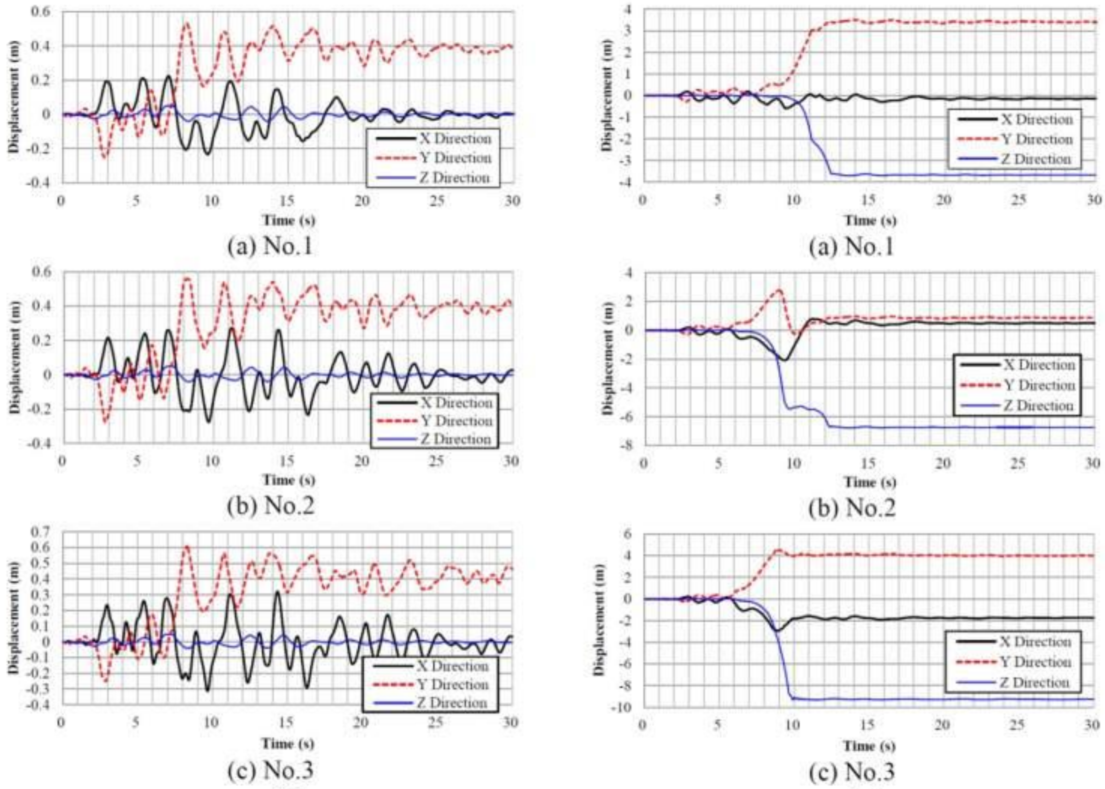
(a) No.1 (a) No.1

(b) No.2 (b) No.2

(c) No.3 (c) No.3

$\mu = 0.2$ $\mu = 0.4$

Figure 16 Displacement responses at Nos.1 to 3, the JMA Kobe wave



(a) No.1 (a) No.1

(b) No.2 (b) No.2

(c) No.3 (c) No.3

$\mu=0.2$ $\mu=0.4$

Figure 17 Displacement responses at Nos.1 to 3, the JR Takatori wave

motion. Moreover, the maximum velocity of the JR Takatori wave record is 126cm/s, and the wooden structure collapsing rate greatly depends on the maximum velocity. Yakushi-doh structure collapses after 10 seconds in the JR Takatori wave record with the frequency range close to 0.5 to 1.0Hz. Figure 14 indicates the seismic collapsing behaviours of Yakushi-doh structure under post unfixed conditions of μ =0.2 and 0.4 during the JR Takatori earthquake ground motion wave. Yakushi-doh structure does not collapse under post unfixed condition of μ =0.2, while it collapses after 10 seconds under post unfixed conditions of μ =0.4. There exists a significant difference between μ =0.2 and 0.4 in seismic collapsing response. It is, also, found from these figures that the collapsing elements of Yakushi-doh structure trends to increase with the dynamic friction coefficient μ , because the decrease of friction coefficient μ means to become a seismic base isolation.

Seismic Collapsing Response

Figure 15 shows seismic collapsing responses at Nos.1 to 3 under post fixed condition during the JMA Kobe and the JR Takatori waves. The heights of three measuring points of Nos.1 to 3 indicated in Figure 1 are 3.8m,6.2m, and 9.3m, respectively. Although the timber element of No.1 does not fall down for each earthquake ground motion, the timber elements of Nos.2 and 3 falls down after 13 seconds for the JMA Kobe wave and they does after 10 seconds for the JR Takatori wave. On the other hands, seismic collapsing responses at Nos.1 to 3 under post unfixed conditions of μ =0.2 and 0.4 during the JMA Kobe wave are indicated in Figure 16. It is found from Figure 12 that three timber elements of Nos.1 to 3 have slightly horizontal deformation after earthquake wave and does not fall down because of post unfixed condition. Figure 17 shows seismic collapsing responses at Nos.1 to 3 under post unfixed conditions of μ =0.2 and 0.4 during JR Takatori wave. Three timber elements of Nos.1 to 3 under post unfixed condition of μ =0.2 have some horizontal deformation of Y direction after earthquake wave and does not fall down because of post unfixed condition. While, three timber elements of Nos.1 to 3 under post unfixed condition of μ =0.4 fall down after 10 seconds.

CONCLUSIONS

In order to investigate the seismic behaviour of an old one-story thatched roof wooden structure, “Yakushi-doh”, 3-D non-linear collapsing process analysis of Yakushi-doh structure was conducted against two strong earthquake ground motions with the Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level. The posts under Yakushi-doh structure floor are erected on their foundation stones and are not fixed. The effect of the post fixing condition under Yakushi-doh structure floor on seismic response was numerically investigated in this paper.

The summary obtained in this paper is as follows.

(1) Seismic collapsing behaviour of a one-story thatched roof wooden structure depends on the seismic intensity of the input earthquake motion in the collapsing analysis.
(2) A one-story thatched roof wooden structure may be collapsed by a strong earthquake ground motion with the JMA seismic intensity of “6 upper” level.
(3) Seismic collapsing behaviour of wooden structure strongly depends on the post fixing condition under the floor of one-story thatched roof wooden structure.
(4) The collapsing elements of Yakushi-doh structure trends to increase with the dynamic friction coefficient μ, because the decrease of dynamic friction coefficient μ means to become a seismic base isolation.

In this paper, two earthquake ground motions measured in the 1995 Hyogo-ken Nanbu Earthquake are employed in this collapsing analysis of Yakushi-doh structure as a strong earthquake ground motions with the JMA seismic intensity of “6 upper” level, because these earthquake ground motions have been used in a lot of seismic collapsing analyses of various structures to investigate the seismic behaviour during a strong earthquake ground motion. If a wooden structure does not collapse against these earthquake ground motions, it may have a high seismic performance against a strong earthquake ground motions with the JMA seismic intensity of “6 upper” level.

3-D non-linear collapsing process analysis may be an effective tool to evaluate a seismic performance of wooden structure. Also, this collapsing process analysis has a significant potential to find when and where begin to break first in an old one-story thatched roof wooden structure during a strong earthquake ground motion. An optimum seismic retrofit of the one-story thatched roof wooden structure can be made by using the collapsing analysis. In addition, further investigation may be needed to simulate the collapsing process phenomenon of a one-story thatched roof wooden structure with or without seismic retrofit and make some concrete conclusions.

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