Seismic Performance of One-storey Thatched Roof Wooden Structure Against a Strong Earthquake Ground Motion

Tomiya Takatani[1], Hayato Nishikawa[2]
1. Dept. of Civil Eng. & Archi., Nat'l Inst. of Tech., Maizuru College, Maizuru, Kyoto, Japan
2. National Institute of Technology, Maizuru College, Maizuru, Kyoto, Japan
E-mail:takatani@maizuru-ct.ac.jp[1], nisikawa@maizuru-ct.ac.jp[2]

Abstract: In order to investigate the seismic behaviour of an old one-storey thatched roof wooden structure, 3-D non-linear collapsing process analysis of this wooden 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 this wooden structure was numerically investigated in this paper.
Keywords: seismic collapsing analysis; seismic retrofit; post fixing condition.

1. Introduction

In Japan, there has existed a serious problem on seismic retrofit for a lot of one-storey 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. It is, therefore, very important for structural engineers to make seismic retrofit for one-storey thatched roof wooden structure without reconstruction. In order to investigate the seismic behaviour of an old one-storey thatched roof wooden structure, 3-D non-linear collapsing process analysis of this wooden structure was conducted against a strong earthquake ground motion with the Japan Meteorological Agency (JMA) 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 (Nakagawa and Ohta, 2010[1]) based on the Distinct Element Method proposed by Cundall and Strack 1979[2]. Takatani 2013[3], 2014[4], Takatani and Nishikawa 2014[5], 2015[6], 2016[7] reported seismic collapsing analyses for various Japanese-style wooden structures with a low seismic performance to verify an appropriateness of each seismic retrofitting countermeasure against a strong earth-quake ground motion. In general, the posts under an old Japanese-style wooden structure floor are erected on their foundation stones and are not fixed. The effect of the post fixing condition under wooden structure floor on seismic response of this wooden structure was numerically investigated in this paper.

2. Outline of one-storey thatched roof wooden structure

Photo 1 shows a one-storey Japanese-style wooden structure with thatched roof, which was built more than

(a) Panoramic view (b) Box stairs (c) Attic space floor

Photo 1. One-storey thatched roof wooden structure

150 years ago by an old Japanese traditional framed-construction method and have a thatched roof instead of tile. This wooden structure has been used as a regional museum. Using a box stairs makes good use of a limited space under stairs, and an attic space in the past was a storage area for grass or sedge used for thatching material. Figure 1 indicates floor plan, elevation one, and cross section ones of this wooden structure. The width, depth, and height of this wooden structure are 13.23m, 10.26m and 8.25m, respectively.

Photo 2 shows a post erected on a foundation stone under this wooden structure floor. There are many posts erected on their foundation stones with flat plane under this wooden 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 the seismic response of this wooden structure is numerically investigated through the seismic response behaviours at several points. However, the details of the collapsing process analysis were described by Takatani et al. (2015[6]), and they are indicated briefly in the next section.

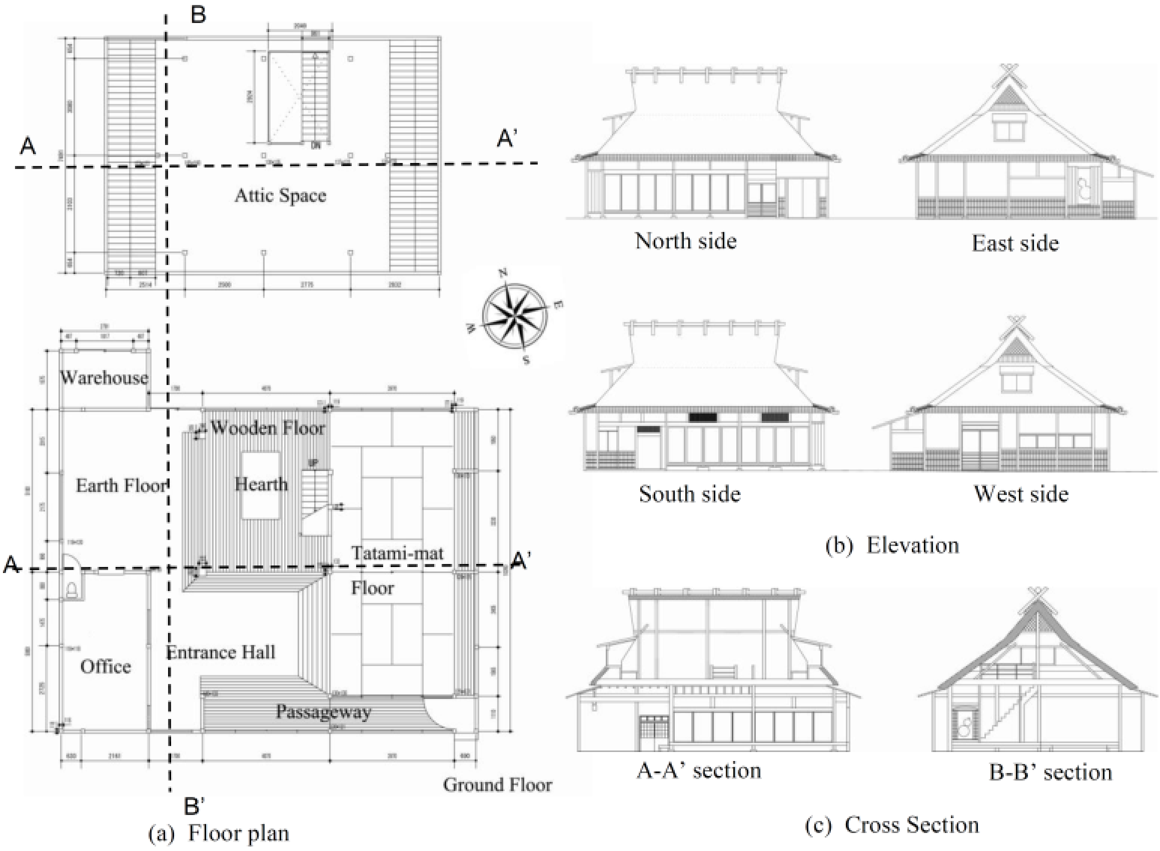


Figure 1. Sketch of one-storey thatched roof wooden house

Photo 2. Post erected on a foundation stone

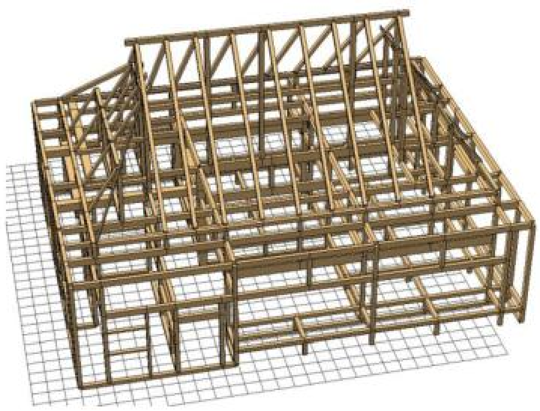


Figure 2. Analytical frame model part.

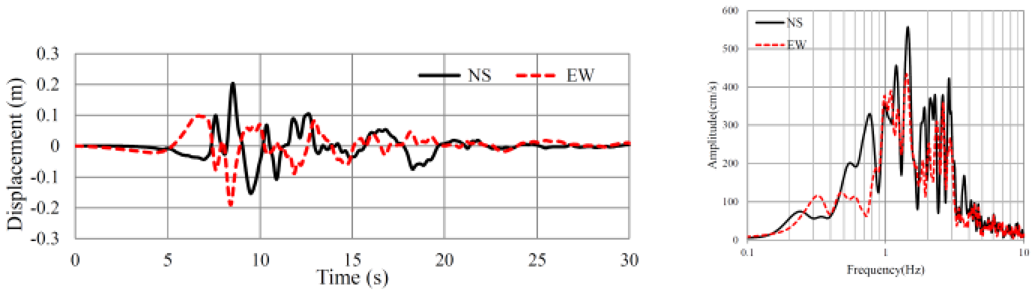
3. Outline of seismic collapsing analysis of wooden house

3.1 Seismic collapsing analysis

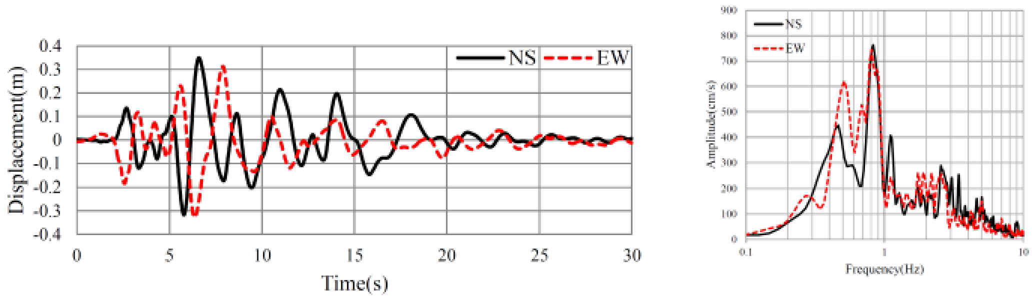
In this paper, a structural analysis software of "Wallstat" is employed in order to investigate seismic response behaviour and collapsing process of one-storey thatched roof wooden structure during a strong earthquake ground motion. This software has an original analysis technique (Nakagawa and Ohta, 2010[1]) using the basic theory of the Distinct Element Method (Cundall and Strack, 1979[2]), and can be taken into consideration the extremely non-linear properties of timber members breaking or being dispersed. In the collapsing process analytical calculation, one-storey thatched roof wooden 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 one-storey thatched roof wooden structure model can be obtained from each structural element. Timber frame shown in Figure 2 is modelled by two elasto-plastic rotational springs (plastic hinge) and an elastic beam component. The spring can be defined by a relationship between bending moment M and angle of rotation θ with the skeleton curve. 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

Table 1. Earthquake motion records with the JMA seismic intensity of "6 upper" level

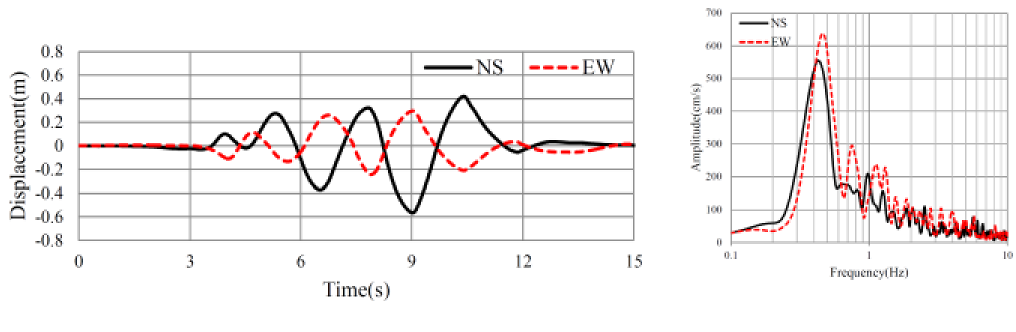
Earthquake Name	Seismic Intensity	Maximum Acceleration (Gal)	Maximum Velocity (kine)	Peak Frequency (Hz)	Duration Time (s)
JMA Kobe	6.4	818	91	1.43	30
JR Takatori	6.4	657	126	0.81	30
K-NET Kashiwazaki	6.3	638	113	0.45	15



(a) JMA Kobe



(b) JR Takatori



(c) K-NET Kashiwazaki

Figure 3. Input earthquake ground motions

bending moment reaches 0, and then the beam component can be judged to have been broken.

Joint spring can be modelled by both an elasto-plastic spring and a rotational spring. Timber characteristic of the compression and tensile elasto-plastic spring consist of an elastic part and slip-type part, 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. 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.

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

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 house with lower seismic performance, a plywood is generally employed as internal wall.

3.2 Input earthquake motion

Table 1 shows some parameters of three earthquake ground motion wave records used as an input excitation of the collapsing process analysis. Both JMA Kobe and JR Takatori waves were measured in the 1995 Hyogo-ken Nanbu Earthquake (M7.3), and K-NET Kashiwazaki wave was done in the 2007 Niigata Chuetsu-Oki Earthquake (M6.8).

Figure 3 indicates three displacement wave data and their Fourier acceleration spectra for both NS and EW components in each earthquake ground motion records shown in Table 4. In the JMA Kobe wave record indicated in Figure 3(a), 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 3(b) exists about 0.8Hz. While, a peak in each wave component of the K-NET Kashiwazaki wave record illustrated in Figure 3(c) is 0.45Hz. Because there are peak frequencies in three earthquake ground motion wave records in the frequency range of about 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[8].

4. Seismic performance results

Figure 4 shows seismic behaviour of one-storey thatched roof wooden structure without seismic retrofit countermeasure during the JMA Kobe wave. This wooden structure suffers seismic damage on walls after 5 seconds, and collapses after 9 seconds. It is found that thatched roof wooden structure trends to collapse the walls on first floor without collapse of the roof part of thatched roof wooden structure and the roof part destroys after the collapse of first floor.

Seismic behaviour of one-storey thatched roof wooden structure without seismic retrofit during the JR Takatori wave is indicated in Figure 5. This wooden structure starts to suffer seismic damage on walls after 3 seconds, and collapses after 8 seconds. In a similar manner to the JMA Kobe, one-storey thatched roof wooden structure collapses the walls on first floor without collapse of the roof part of thatched roof wooden structure and then the roof part destroys after the collapse of first floor.

Seismic behaviour of one-storey thatched roof wooden structure without seismic retrofit during the Kashiwazaki wave is illustrated in Figure 6. This wooden structure starts to suffer seismic damage on walls after 4.5 seconds, and collapses after 9 seconds. It is found that one-storey thatched roof wooden structure without seismic retrofit collapses against a strong earthquake ground motion with the JMA seismic intensity of "6 upper" level and the maximum velocity of over 90 kine.

Figure 7 shows seismic behaviour of one-storey thatched roof wooden structure with seismic retrofit countermeasure after three earthquake motions. Seismic retrofit for one-storey thatched roof wooden structure was conducted under the condition of the limit strength calculation method of 1.0 value. Even though one-storey thatched roof wooden structure with seismic retrofit under the limit strength calculation method of 1.0 value collapses against both the JMA Kobe and JR Takatori waves, it does not collapse for the Kashiwazaki wave although it has a slight damage on the walls.

Seismic behaviour of one-storey thatched roof wooden structure with seismic retrofit after three earthquake motions is indicated in Figure8. Seismic retrofit is done under the condition of the limit strength calculation method of 1.5 value. Although the roof part of one-storey thatched roof wooden structure does not completely collapse against the JMA Kobe wave, it completely collapses in spite of no collapse of the first floor against the JR Takatori wave.

The effect of the post fixing condition on seismic behaviour of one-storey thatched roof wooden structure is investigated in this paper.

Figure 9 shows seismic behaviour of one-storey thatched roof wooden structure without seismic retrofit after

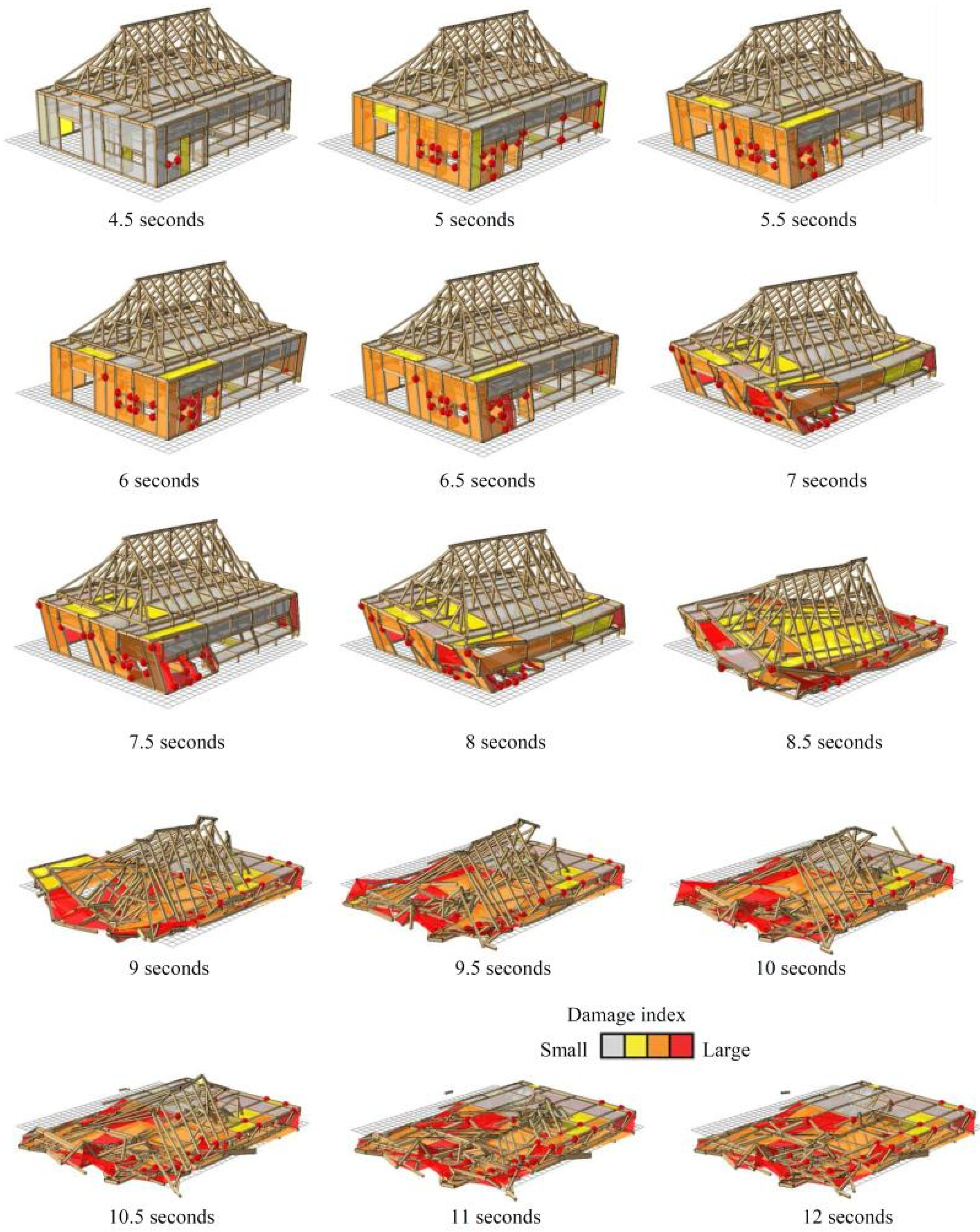


Figure 4. Seismic behaviour during earthquake motion (JMA Kobe, Without seismic retrofit, Post fixed condition)

three earthquake motions under unfixed post condition. Although one-storey thatched roof wooden structure without seismic retrofit against both the JMA Kobe and the Kashiwazaki waves does not collapse, it completely collapses against the JR Takatori wave.

Seismic behaviour of one-storey thatched roof wooden structure with seismic retrofit after three earthquake

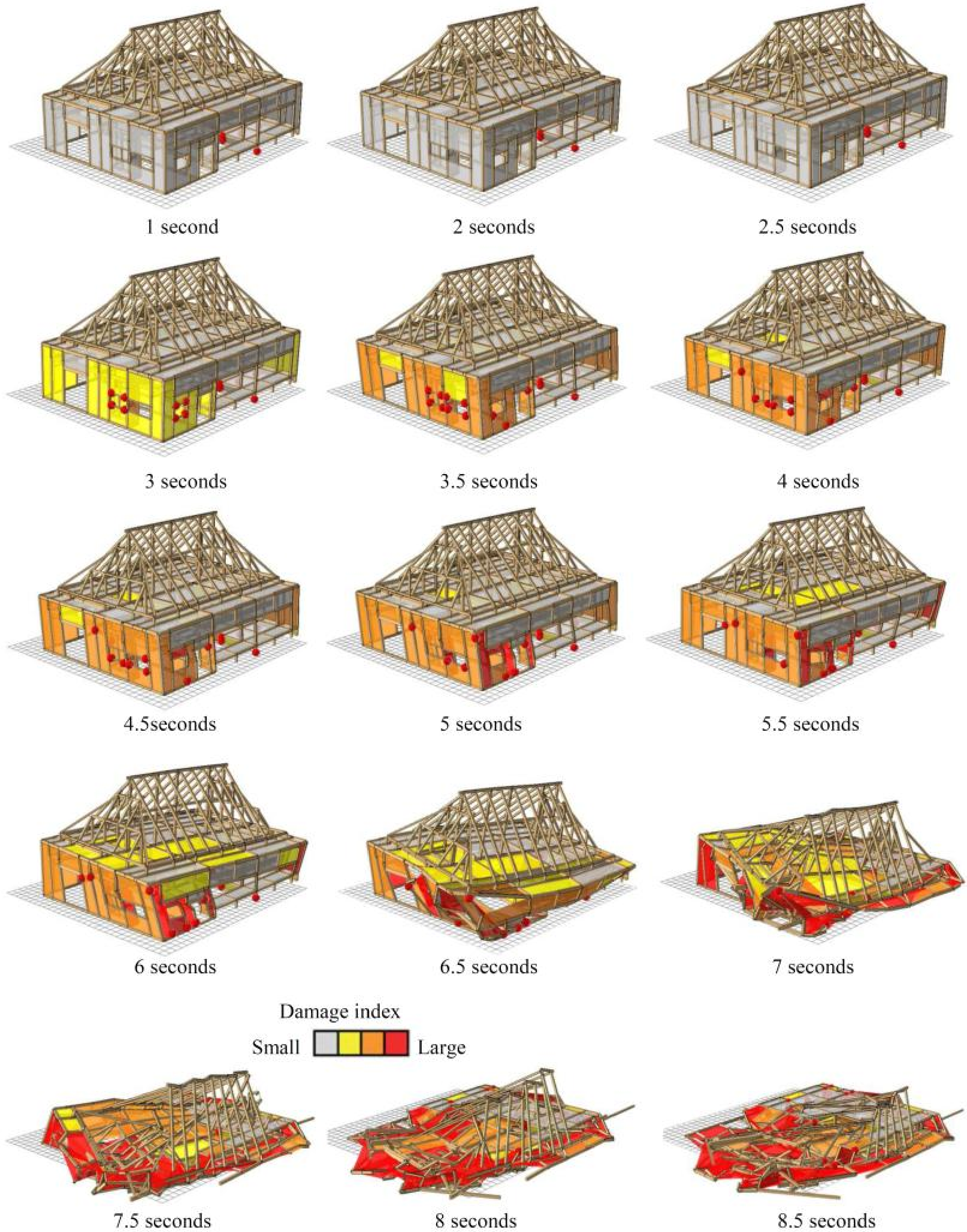


Figure 5. Seismic behaviour during earthquake motion (JR Takatori, Without seismic retrofit, Post fixed condition)

motions under unfixed post condition is indicated in Figure 10. Seismic retrofit is conducted under the limit strength calculation method of 1.0 value. One-storey thatched roof wooden structure with seismic retrofit under the limit strength calculation method of 1.0 value collapses against only the JR Takatori wave. While, seismic behaviour of one-storey thatched roof wooden structure with seismic retrofit after the JR Takatori wave under unfixed post condition is illustrated in Figure 11. Seismic retrofit is conducted under the condition of the limit strength calculation method of 1.5 value. One-storey thatched roof wooden structure has some damages against

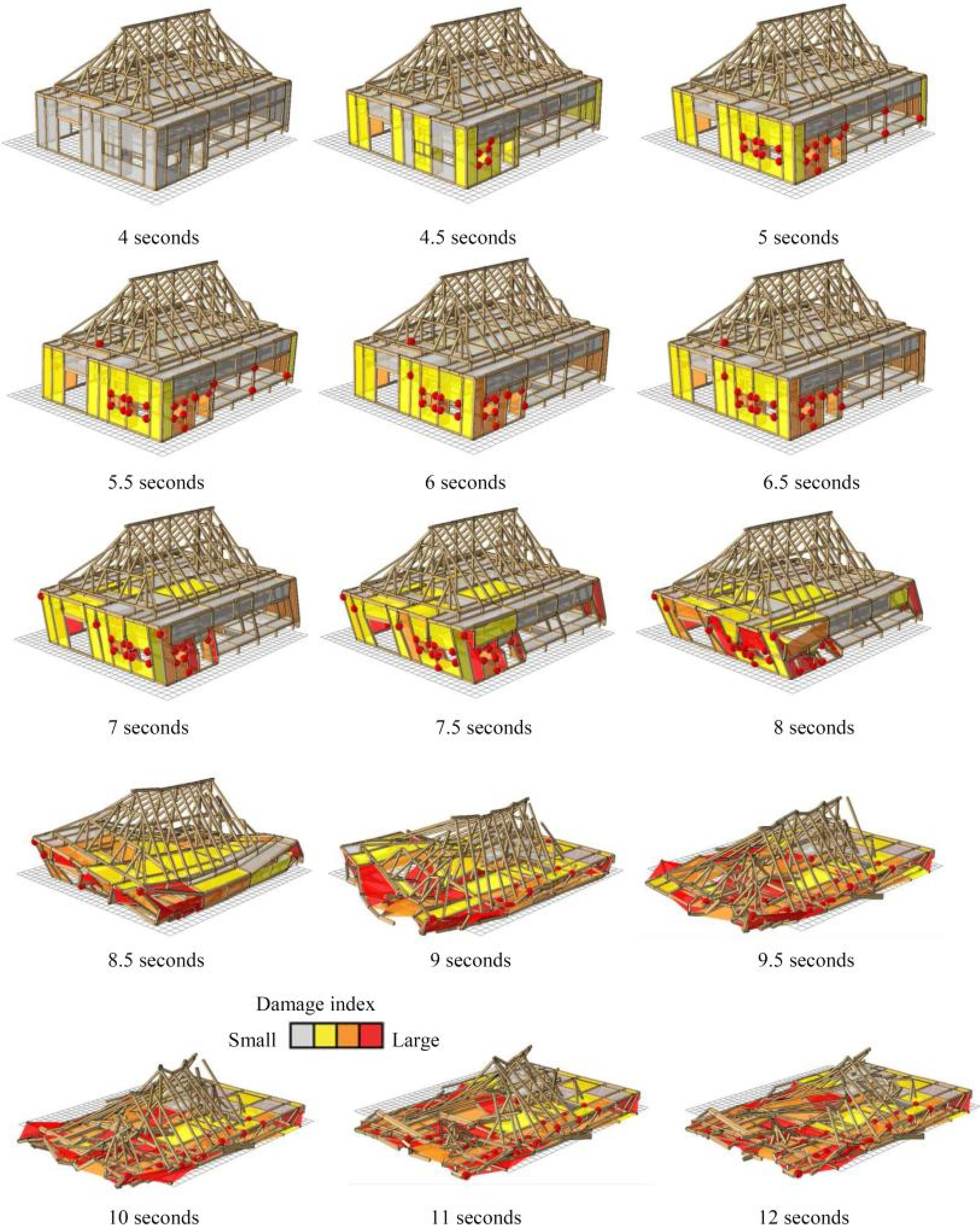


Figure 6. Seismic behaviour during earthquake motion (Kashiwazaki, Without seismic retrofit, Post fixed condition)

the JR Takatori wave and does not collapse because of the seismic retrofit condition of the limit strength calculation method of1.5 value. It was found form these figures that the unfixed post condition for one-storey thatched roof wooden structure seems to be similar to a seismic base isolation equipment.

Seismic response behaviour of one-storey thatched roof wooden structure during a strong earthquake motion is numerically investigated at four points set on the wooden frame model shown in Figure 12.

Figure 13 shows seismic response behaviour at each point of one-storey thatched roof wooden structure without seismic retrofit during the JMA Kobe wave. As is obvious from Figures 4 and 13, the timber element of

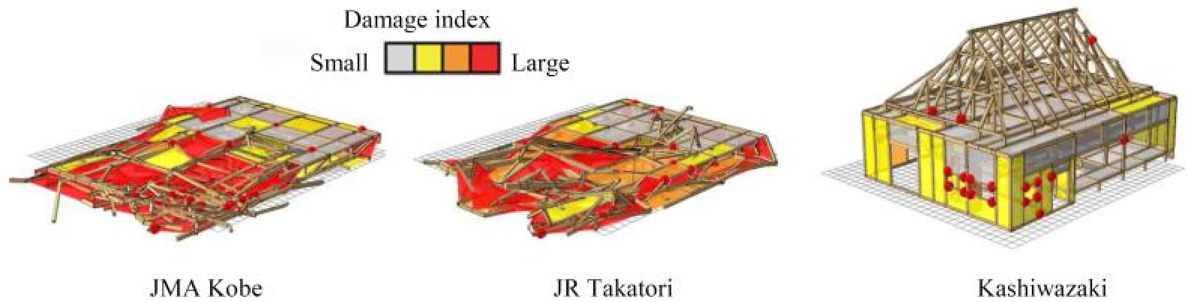


Figure 7. Seismic behaviour after earthquake motion
(With seismic retrofit, Limit strength calculation method 1.0, Post fixed condition)

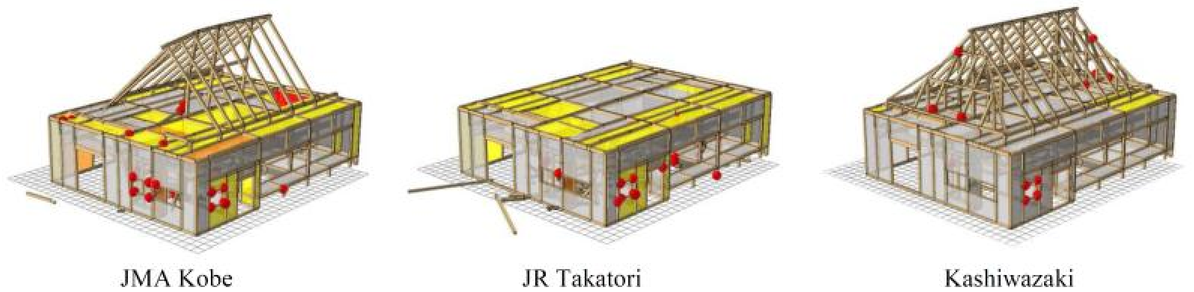


Figure 8. Seismic behaviour after earthquake motion
(With seismic retrofit, Limit strength calculation method 1.5, Post fixed condition)

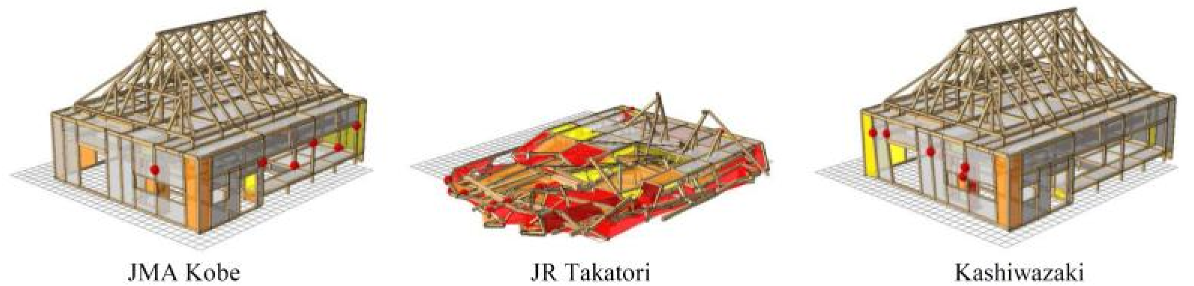


Figure 9. Seismic behaviour after earthquake motion
(Without seismic retrofit, Unfixed post under first floor, μ_s=0.3)

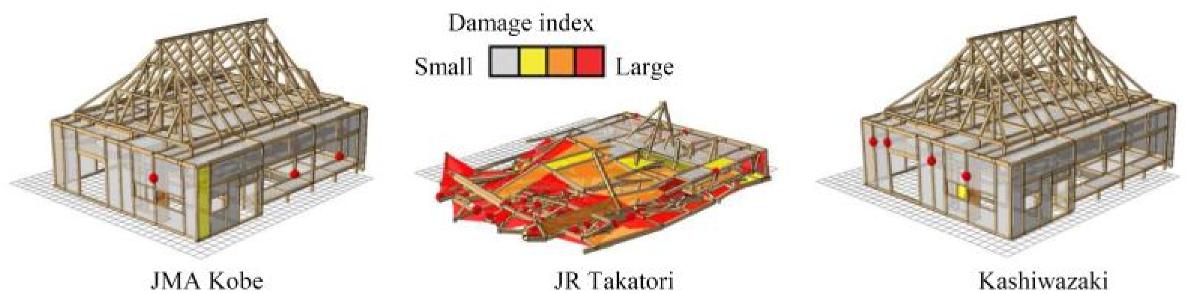


Figure 10. Seismic behaviour after earthquake motion (With seismic retrofit,
Limit strength calculation method 1.0, Unfixed post condition μ_s=0.3)

Figure 11. Seismic behaviour after earthquake motion (JR Takatori, With seismic retrofit, Limit strength calculation method 1.5, Unfixed post condition μ_s=0.3)

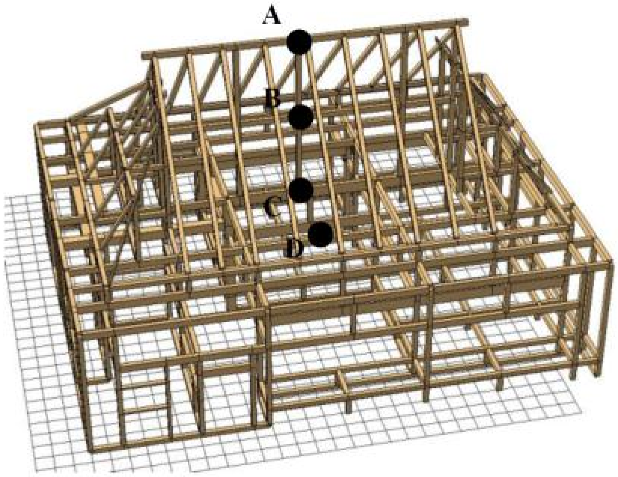


Figure 12. Analytical frame model with calculation points

each point falls down and the timber element of point A finally falls down after 11 seconds.

Seismic response behaviour at each point of one-storey thatched roof wooden structure without seismic retrofit during the JR Takatori wave is indicated in Figure 14. It is obvious from Figures 5 and 14 that the timber element of each point falls down and the timber element of point A finally falls down after 9 seconds.

Seismic response behaviour at each point of one-storey thatched roof wooden structure without seismic retrofit during the Kashiwazaki wave is illustrated in Figure 15. As can be seen from Figures 6 and 15, the timber element of each point falls down and the timber element of point A finally falls down after 13 seconds.

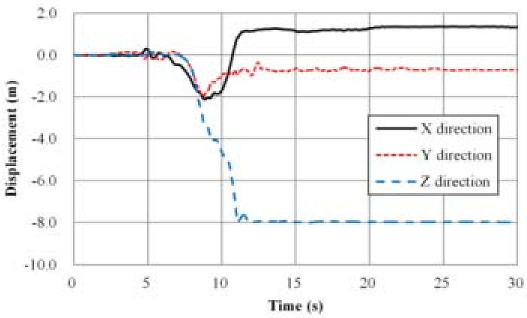
Although one-storey thatched roof wooden structure with seismic retrofit collapses against both the JMA Kobe and JR Takatori waves, it does not collapse against the Kashiwazaki wave. Seismic retrofit is conducted under the condition of the limit strength calculation method of 1.0 value. Seismic response behaviour at each point of one-storey thatched roof wooden structure with seismic retrofit during the Kashiwazaki wave is shown in Figure 16. Seismic response behaviour at each point has a displacement amplitude within 0.6 m because of the seismic retrofit.

Figure 17 illustrates seismic response behaviour at each point of one-storey thatched roof wooden structure with seismic retrofit during the JMA Kobe wave. Seismic retrofit is conducted under the condition of the limit strength calculation method of 1.5 value. As one-storey thatched roof wooden structure with seismic retrofit does not collapse as shown in Figure 8, seismic response behaviour at each point has a displacement amplitude within1.0 m and the displacements in X direction at points A and B are much larger than other ones at points C and D.

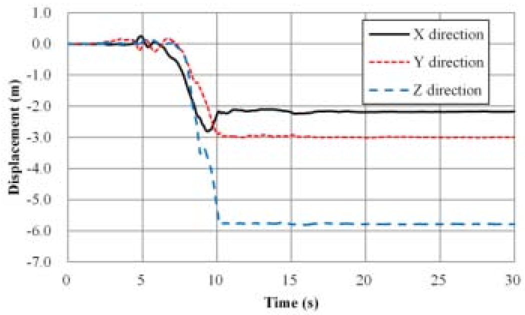
Seismic response behaviour at each point of one-storey thatched roof wooden structure without seismic retrofit under the unfixed post condition during the JMA Kobe wave is shown in Figure 16. As one-storey thatched roof wooden structure without seismic retrofit does not collapse because of the unfixed post condition as shown in Figure 9, seismic response behaviour at each point has a displacement amplitude within 0.2 m.

Seismic response behaviour at each point of one-storey thatched roof wooden structure with seismic retrofit under the unfixed post condition during the JMA Kobe wave is indicated in Figure 19. Seismic retrofit is conducted under the condition of the limit strength calculation method of 1.0 value. Seismic response behaviour at each point is almost similar to that in Figure 18 and also has a displacement amplitude with a slight larger than that in Figure 18 because of seismic retrofit due to the limit strength calculation method of 1.0 value.

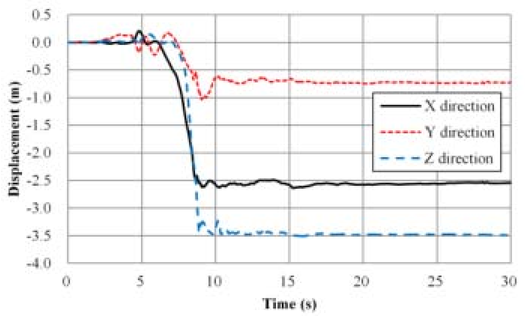
Seismic response behaviour at each point of one-storey thatched roof wooden structure with seismic retrofit under the unfixed post condition during the JR Takatori wave is illustrated in Figure 20. Seismic retrofit is con- ducted under the condition of the limit strength calculation method of 1.5 value. As one-storey thatched roof wooden structure without seismic



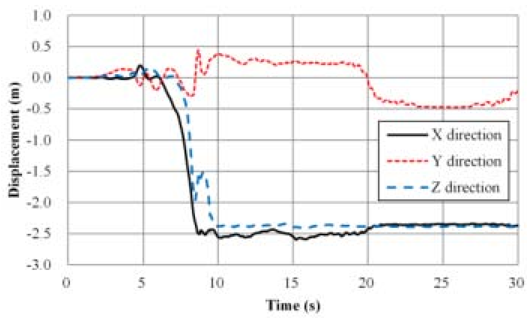
(a) Point A



(b) Point B

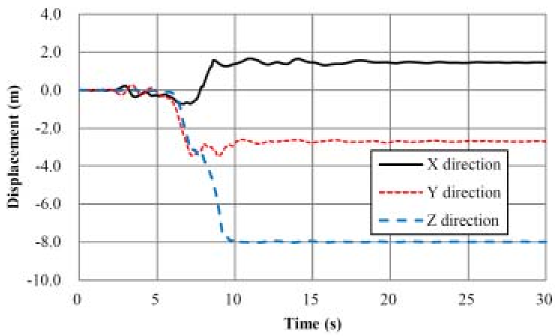


(c) Point C

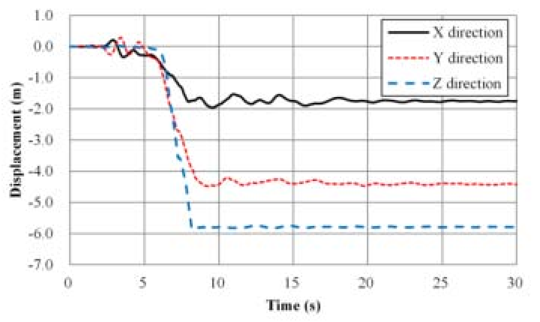


(d) Point D

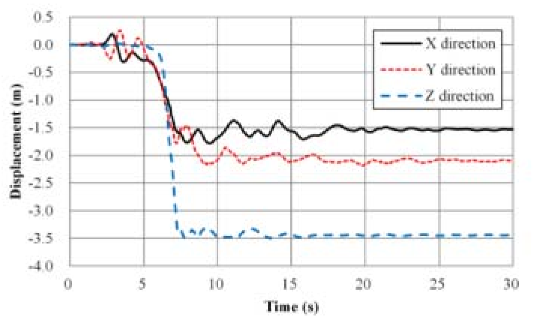
Figure 13. Seismic response behaviour (JMA Kobe, Without seismic retrofit)



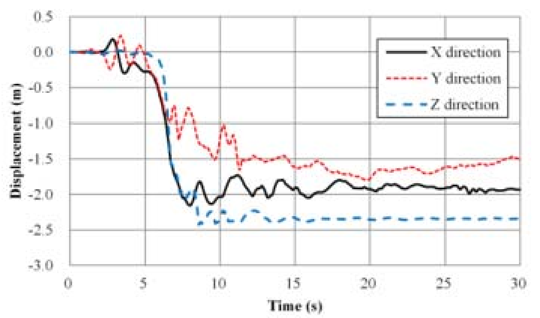
(a) Point A



(b) Point B



(c) Point C



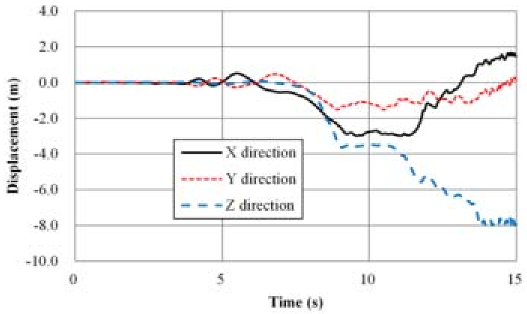
(d) Point D

Figure 14. Seismic response behaviour (JR Takatori, Without seismic retrofit)

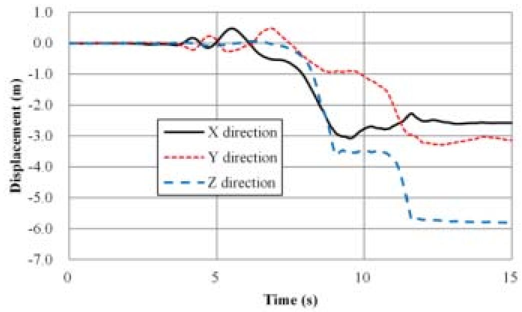
retrofit does not collapse as shown in Figure 11, seismic response behaviour at each point has a displacement amplitude within 0.8 m because of the seismic retrofit as well as the unfixed post condition.

5. Conclusions

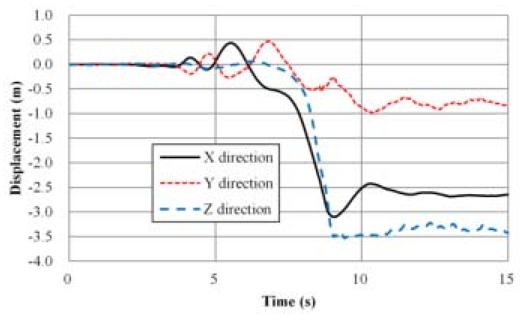
In order to investigate the seismic behaviour of an old one-storey thatched roof wooden structure, 3-D non-linear collapsing process analysis of this wooden structure was conducted against three strong earthquake ground mo-



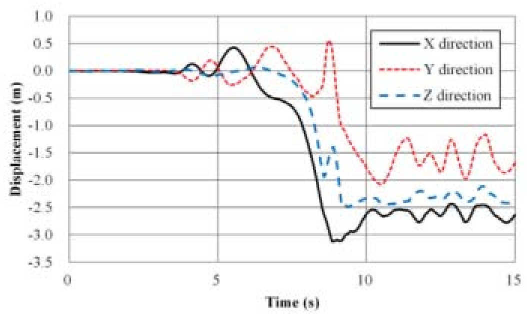
(a) Point A



(b) Point B

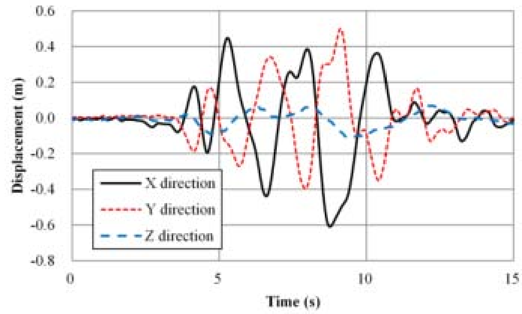


(c) Point C

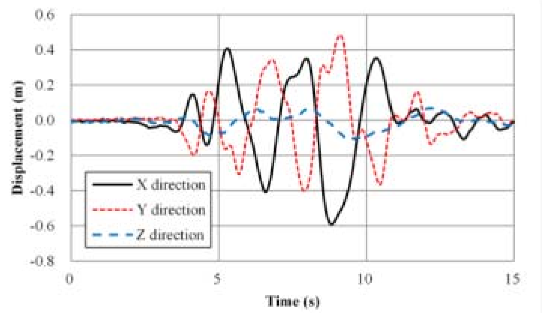


(d) Point D

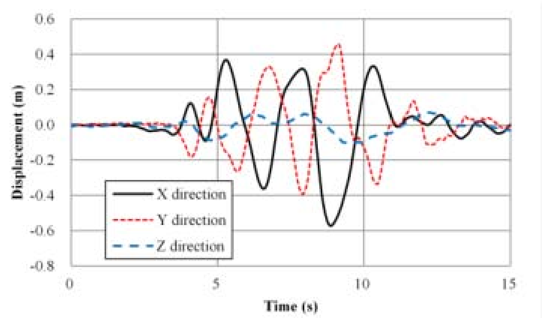
Figure 15 Seismic response behaviour (Kashiwazaki, Without seismic retrofit)



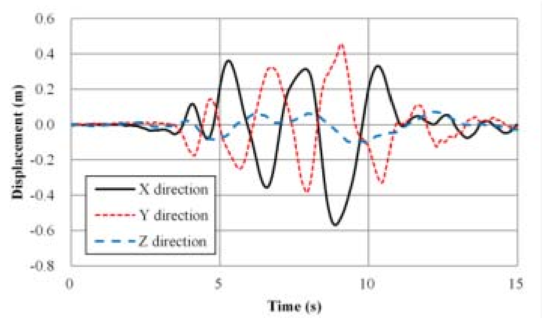
(a) Point A



(b) Point B



(c) Point C



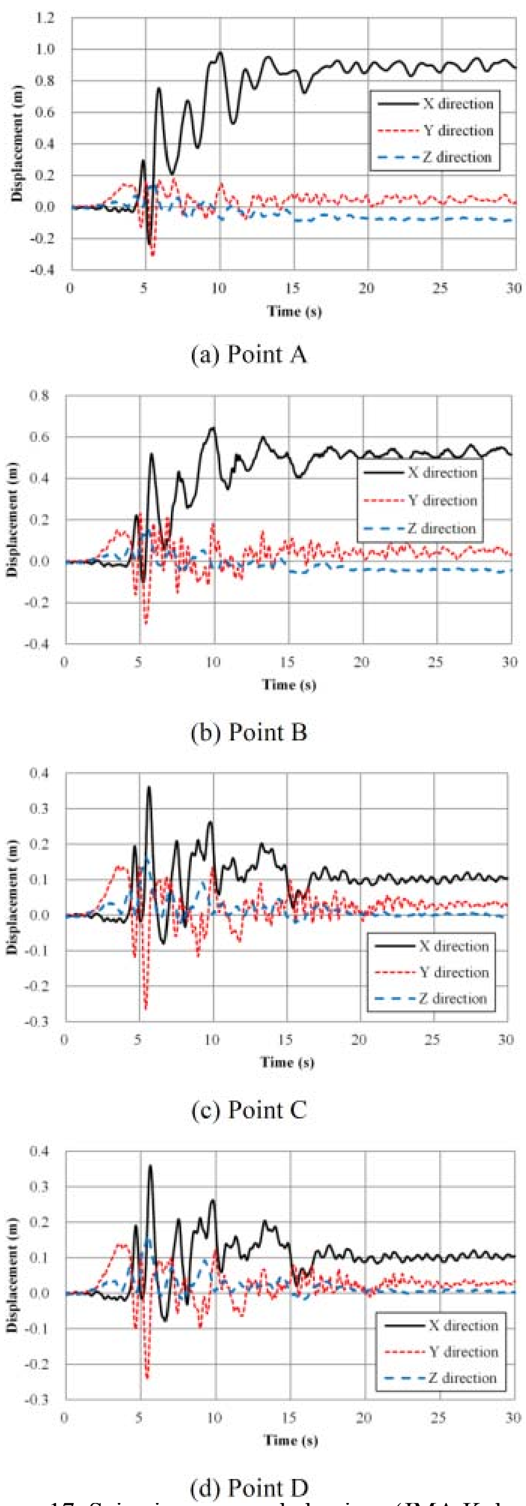
(d) Point D

Figure 16. Seismic response behaviour (Kashiwazaki, Limit strength calculation 1.0)

tions with the Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level. The posts under wooden structure floor are erected on their foundation stones and are not fixed. The effect of the post fixing condition under wooden structure floor on the seismic response of an old one-storey thatched roof wooden structure with/without seismic retrofit was numerically investigated in this paper.

The summary obtained in this paper is as follows.

(1) Seismic collapsing behaviour of a one-storey thatched roof wooden structure depends on the seismic intensity of the input earthquake ground motion in the collapsing analysis.



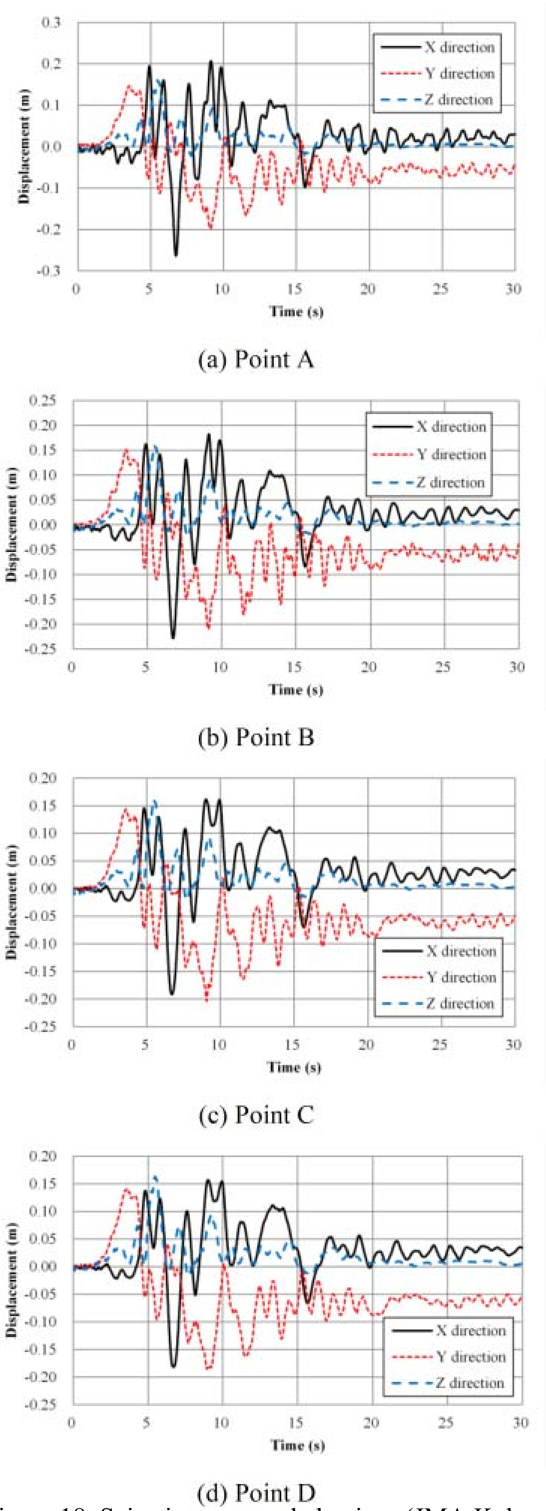
(a) Point A

(b) Point B

(c) Point C

(d) Point D

Figure 17. Seismic response behaviour (JMA Kobe, Limit strength calculation 1.5)



(a) Point A

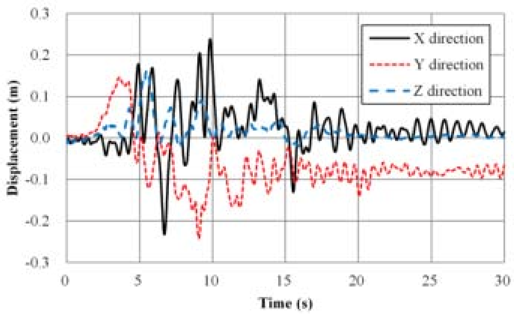
(b) Point B

(c) Point C

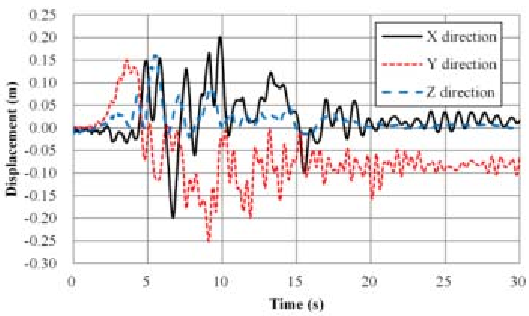
(d) Point D

Figure 18. Seismic response behaviour (JMA Kobe, Unfixed post condition, μ_s=0.3)

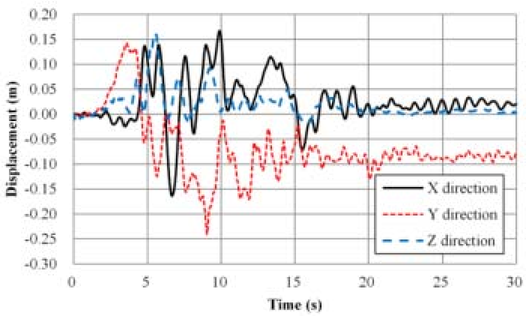
(2) Seismic collapsing behaviour strongly depends on the post fixing condition under the floor of one-storey thatched roof wooden structure.
(3) 3-D seismic collapsing analysis may be an effective method to numerically investigate the seismic performance of a one-storey thatched roof wooden structure with seismic retrofit under both fixed and unfixed post conditions.



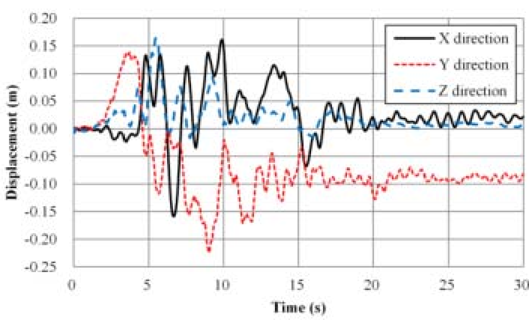
(a) Point A



(b) Point B

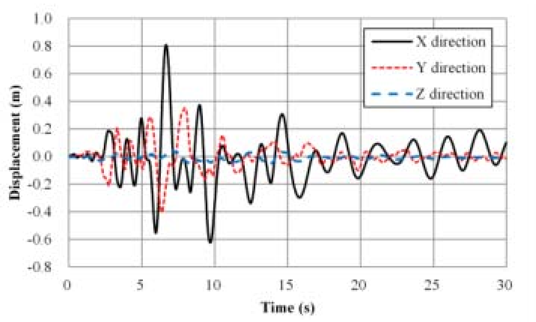


(c) Point C

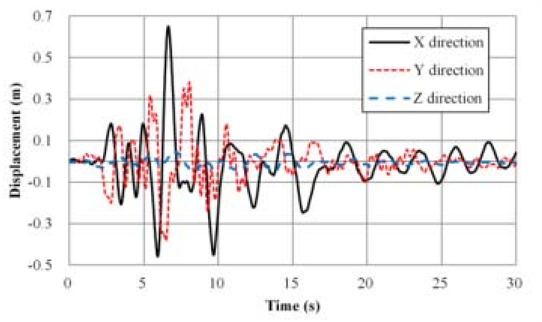


(d) Point D

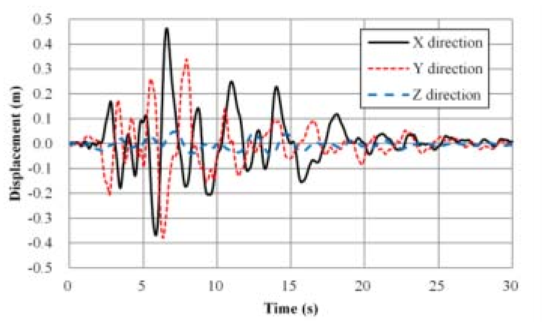
Figure 19. Seismic response behaviour (JMA Kobe, Unfixed post condition μ_s=0.3, Limit strength calculation 1.0)



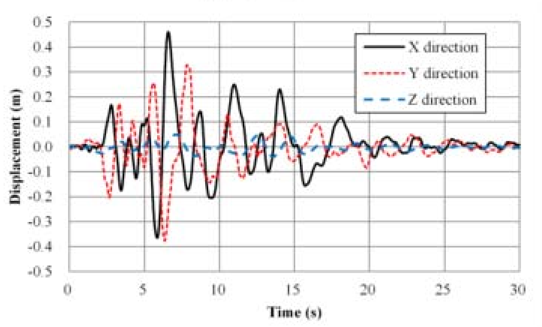
(a) Point A



(b) Point B



(c) Point C



(d) Point D

Figure 20. Seismic response behaviour (JR Takatori, Unfixed post condition μ_s=0.3, Limit strength calculation 1.5)

(4) 3-D seismic collapsing analysis of a one-storey thatched roof wooden structure under unfixed post condition may be a significant possibility to make a simulation of “seismic base isolation state”.
(5) Based on the seismic performance of one-storey thatched roof wooden structure without seismic retrofit under unfixed post condition, there may be a possibility of no collapse of this wooden structure from a view point of a peak frequency of the input earthquake ground motion wave.

The challenge of the future is to make an accurate evaluation of seismic response behaviour of one-storey thatched roof wooden structure during a strong earthquake ground motion. In addition to the evaluation of seismic response behaviour of the wooden structure, it is very important to accurately investigate a seismic performance of one-storey thatched roof wooden structure under unfixed post condition. This 3-D seismic collapsing process analysis verified a seismic base isolation effect by the friction coefficient between a post and its foundation stone, which plays a key role in seismic behaviour of one-storey thatched roof wooden structure concerning a seismic base isolation effect.

Therefore, further investigation on the seismic performance of one-storey thatched roof wooden structure under unfixed post condition against a strong earthquake may be needed to make some concrete conclusions.

6. References

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