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# Seismic damage prediction function for two-story wooden house based on structure damage in the 2016 Kumamoto earthquake

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## ABSTRACT

As main factors to the destruction of wooden houses in the 2016 Kumamoto Earthquake, strong earthquake motions due to fore-shock and main shock, the amplification effect of ground surface layer, and the pulse wave due to seismic fault rupture propagation have been indicated by many researchers and engineers. A seismic damage prediction function for wooden houses taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault is proposed in this paper.

## 1. INTRODUCTION

A tremendous seismic damage of collapse to wooden houses was caused by the 2016 Kumamoto Earthquake occurred on both April 14 and 16 (Building Research Institute, 2016). In particular, Mashiki town located at near the hypocenter of these earthquakes has twice earthquake ground motions with the Japan Meteorological Agency (hereafter referred as JMA) seismic intensity of “7” level successively. According to several seismic damage reports on 1,955 wooden structures in Mashiki town, wooden houses with no seismic damage were 414, ones with slight, small and medium seismic damage were 1,014, ones with large seismic damage were 230 and ones with collapse were 297. Especially, wooden houses built before 1981 were 214, ones built from 1981 to 2000 were 76, and ones built after 2000 were 7 from a view point of collapse (National Institute for Land and Infrastructure Management, 2016).

Takatani and Nishikawa (2014, 2015, 2016, 2017) have been reported the seismic performance of Japanese-style wooden house against several strong earthquake

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ground motions observed by the National Institute for Earth Science and Disaster Resilience in Japan. However, seismic performance of wooden house against twice strong earthquake ground motions with the JMA seismic intensity of “7” level like the 2016 Kumamoto Earthquake has not been analyzed before. In this paper, 3-D seismic collapsing process analysis (Nakagawa and Ohta, 2010) of the wooden house against the 2016 Kumamoto Earthquake ground motions with the JMA seismic intensity of “7” level was carried out in order to numerically investigate the seismic performance of Japanese-style two-story wooden house.

As main factors to the destruction of wooden houses in the 2016 Kumamoto Earthquake, strong earthquake motions due to fore-shock and main shock, the amplification effect of ground surface layer, and the pulse wave due to seismic fault rupture propagation have been indicated by many researchers and engineers. Also, Nozu (2017) reported that the effect of the rupture propagation of seismic fault in the main shock in the 2016 Kumamoto Earthquake affects seismic damage of bridge in the north-east area in its epicenter region (Building Research Institute, 2016; Goto et al., 2017). The purpose of this paper is to propose a seismic damage prediction function for two-story wooden house by taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault.

## 2. SEISMIC DAMAGE OF WOODEN STRUCTURE IN THE 2016 KUMAMOTO EARTHQUAKE

Fig.1 shows three epicenter locations of the 2016 Kumamoto Earthquake on April 14 - 16. The 2016 Kumamoto Earthquake caused severe damage to Kumamoto area.

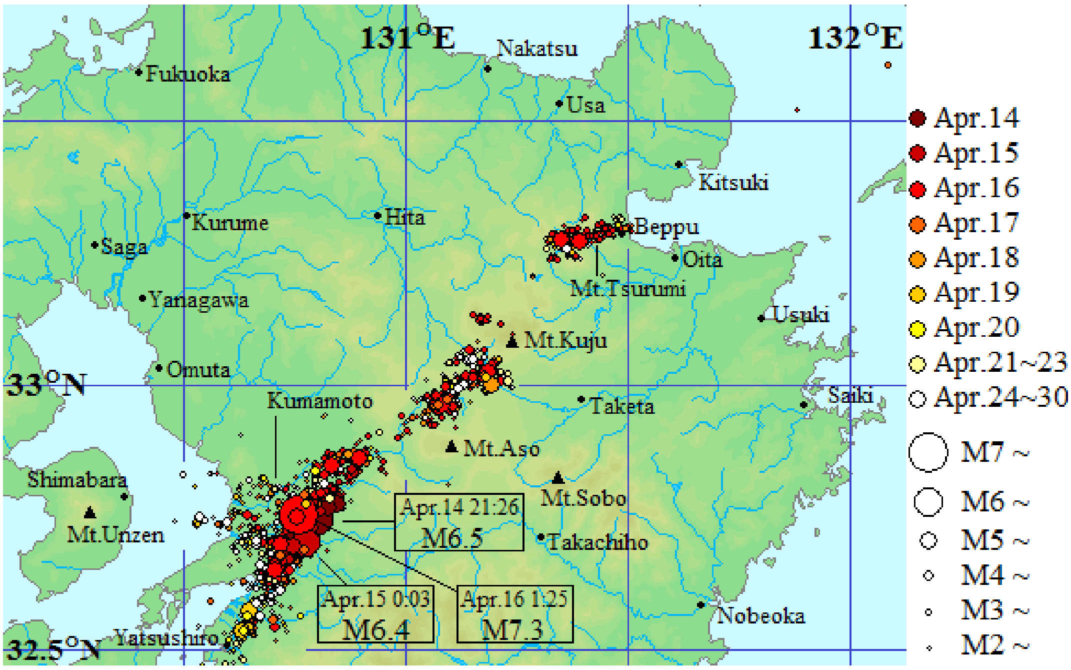


Fig.1 Epicenter locations of the 2016 Kumamoto Earthquake (Wikipedia, 2016).

Table 1 The 2016 Kumamoto Earthquake on both April 14 and April 16.

| | Magnitude M | JMA Seismic Intensity | Component | PGA (Gal) | PGV (kine) | PGD (cm) |
|---|---|---|---|---|---|---|
| Foreshock (April 14, 21:26) | 6.5 | 6.5 | EW | 922.9 | 90.7 | 14.9 |
| | | | NS | 759.4 | 74.6 | 12.2 |
| | | | UD | 1,399.4 | 56.1 | 2.7 |
| Main shock (April 16, 01:25) | 7.3 | 6.5 | EW | 1,155.8 | 137.9 | 38.7 |
| | | | NS | 651.8 | 84.2 | 14.4 |
| | | | UD | 873.4 | 40.2 | 12.9 |

Because of the shallow depth of hypocenter, the severe damage was caused in Mashiki town located 10km away from Kumamoto city. The earthquake consists of two strong earthquake ground motions on April 14 and 16 and a series of smaller foreshocks and aftershocks. The first earthquake with the magnitude 6.5 and the hypocenter depth 10km occurred in the Kumamoto area at 9:26pm, April 14. The acceleration waves measured at Mashiki town during this earthquake are shown in Table 1. Also, the earthquake with the magnitude 6.4 occurred again in the same area at 0:03am, April 15. The earthquake at 1:25am on April 16 was designated as the main shock of the 2016

Fig.2 indicates seismic damage of wooden structures in Mashiki town on each construction period by exhaustive survey conducted by the National Institute for Land and Infrastructure Management (2016). It is found that there is a significant damage rate of wooden house built before the New Seismic Design Standards Act in Japan amended after 1981 in comparison with that after 1981. Seismic damage of wooden

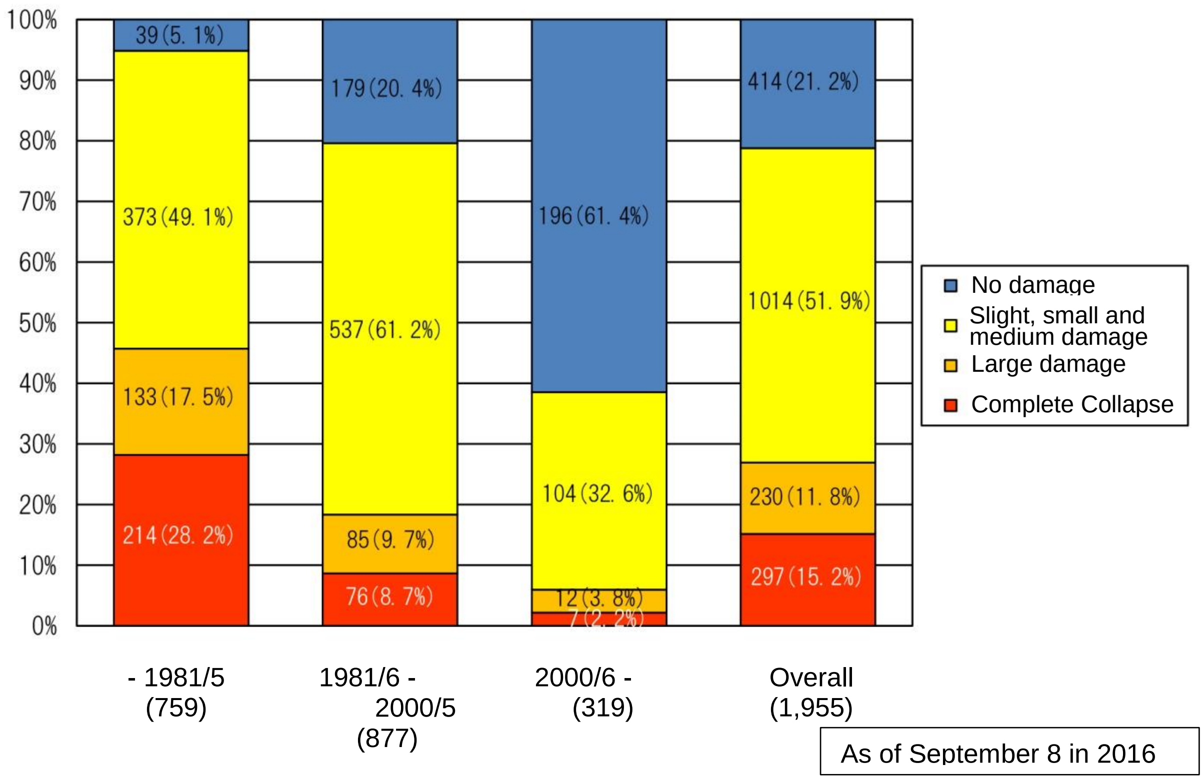



Fig.2 Seismic damage of wooden structures on each construction period by exhaustive survey (National Institute for Land and Infrastructure Management, 2016).

house built after 2000 is quite smaller than that after 1981 because of the specification of joint and connecting metals, balance calculation of seismic wall arrangement for wooden house. In 7 wooden houses built after 2000, 3 wooden houses collapsed because of the insufficient strength at the junction between timber pillar and beam due to some construction failures, and other wooden houses collapsed because of the collapse and inclination of their foundations.

On the other hand, the National Institute for Land and Infrastructure Management (2016) reported that the effect of the reginal seismic coefficient Z was not clearly identified in the seismic damage of wooden house in Mashiki town. The regional seismic coefficient Z in the Building Standards Act in Japan is defined to be a numerical value of 0.7 to 1.0 according to the past seismic damage, seismic fault activities and other seismic state in the area subjected to seismic evaluation. Therefore, the regional seismic coefficient Z in the Kumamoto prefecture has 0.8 to 0.9 because of past seismic damage and fault activities. Because a wooden house built in the Kumamoto prefecture has a lower seismic performance against a strong earthquake in comparison with other region in Japan with high potential for seismic damage and fault activities, they say that there was a tremendous seismic damage of collapse to wooden houses in the Kumamoto prefecture.

## 3. GENERATION OF INPUT EARTHQUAKE GROUND MOTION WAVE

In this paper, several earthquake motion waves are evaluated by an empirical Green's function method using seismic fault model considering a hypocenter location of the main shock and its asperity in the 2016 Kumamoto Earthquake. These earthquake motion waves have three seismic motion characteristics in this earthquake mentioned above. Difference between the rupture propagation effects on earthquake motion waves at 50 location points around a seismic fault is investigated. Earthquake ground motion waves observed at KiK-net Mashiki in the earthquake ($M_{JMA}$=4.2) occurred at 00:50 on April 15, 2016 are employed as Green's function in the empirical Green's function method. In order to investigate the site amplification characteristics, earthquake ground motion wave at each location is calculated using the site amplification characteristics with three different frequencies. In the calculation of earthquake motion wave on the ground surface, the non-linearization of ground due to a strong seismic motion can be considered by the multi non-linearity effect (Nozu et al., 2008).

Using earthquake motion waves calculated by the empirical Green's function method, seismic collapsing behavior of wooden house is numerically investigated by 3-D collapsing process analysis of "wallstat", which was developed by Nakagawa et al. (2010). To investigate the effect of consecutive earthquake motion wave on seismic performance of wooden house, earthquake motion waves in the foreshock, the main shock, and both the fore and main shocks are employed in this 3-D seismic collapsing process analysis of wooden house. Based on the maximum drift angle of wooden house obtained from collapsing analytical results, seismic damage state of wooden house is classified, and also seismic damage prediction map is made.

### 3.1 Empirical Green's Function Method

Empirical Green's Function Method can calculate an acceleration wave at the estimation point by some small to medium size earthquake motion waves occurring on a seismic fault of the target earthquake. In this paper, the empirical Green's function proposed by Nozu et al.(2008) was used to numerically calculate some acceleration waves. Propagation path characteristics were referred to a research paper by Kato (2001).

Fig.3 shows 61 location points in the analytical area in Kumamoto prefecture and the asperity locations of A1, A2, and A3. The fore-shock ($M_{JMA}$=6.5) in 2016 Kumamoto Earthquake occurred on 21:26 on April 14, 2016.

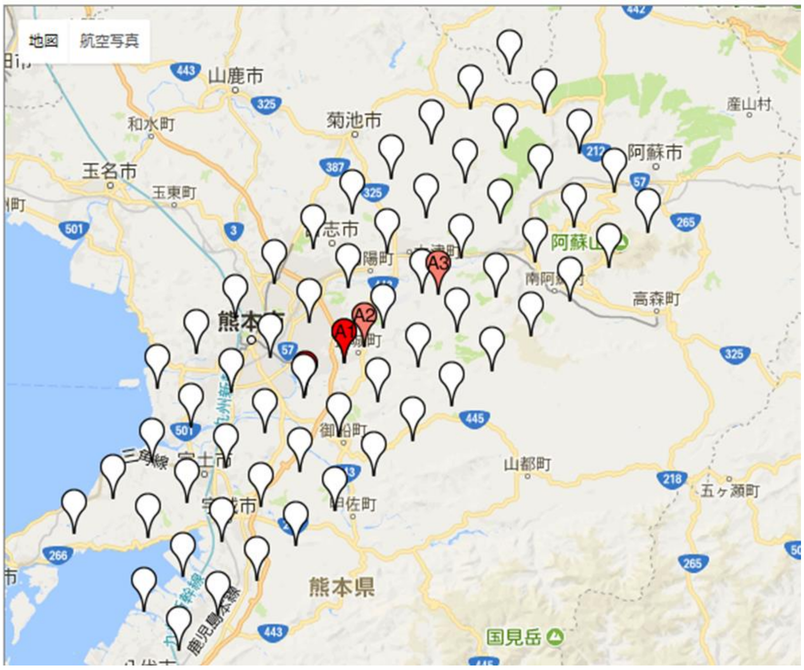


Fig. 3 Analytical location points and 3 asperities

### 3.2 Hypocenter Model

Hypocenter model employed in the empirical Green's function method is referred to a characterized hypocenter model of both the foreshock and main shock in the 2016 Kumamoto Earthquake proposed by Nozu (2016a, b). In this paper, characterized hypocenter model is described due to the limited space.

Fig.4 indicates an outline image around a hypocenter of the fore-shock mentioned above. A mark of ★ means a epicenter of the fore-shock, ★ means a epicenter of the main shock, □ means a epicenter of small to medium size earthquakes in making an evaluation of phase characteristics, ▲ means analytical location points.

Earthquake ground motion waves at 61 location points shown in Fig.3 nearby a seismic fault, which is supposed the foreshock and the main shock in the 2016 Kumamoto Earthquake, are created by the empirical Green's function method. In order to investigate the effect of the site amplification characteristics, these earthquake ground motion waves at 61 location points are evaluated by the site amplification characteristics with three different frequency characteristics. In this paper, earthquake motion waves at KMM008, KMM011 and KMM018 in the strong motion seismograph networks

(K-NET) are employed as three different frequency characteristics.

Fig.5 indicates a referred characterized hypocenter of the foreshock in the 2016 Kumamoto Earthquake. “Asperity 1” and “Asperity 2” are set in two location points of the seismic fault, where the maximum slip velocity value is estimated as a reference of earthquake motion wave inversion result. Table 2 shows some parameters regarding

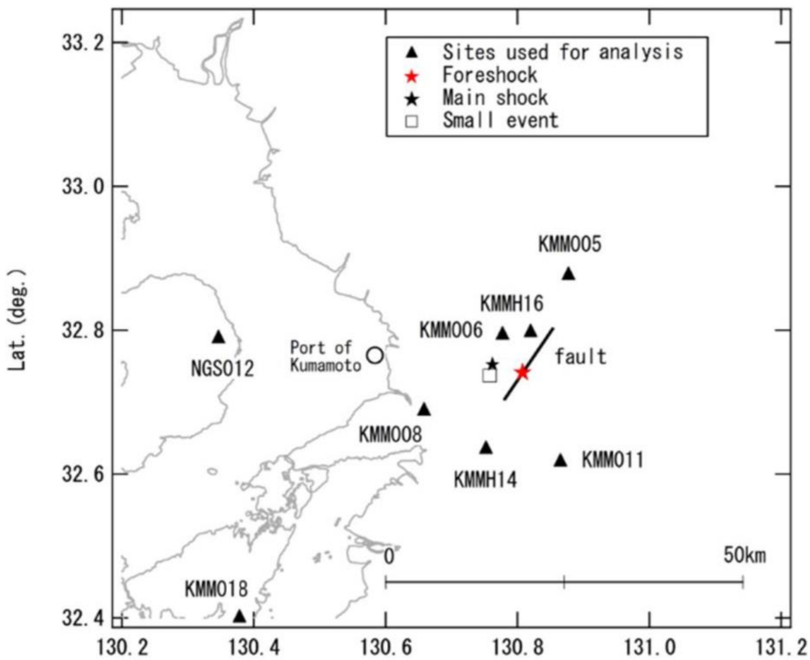



Fig.4 Information around a hypocenter of the foreshock in 2016 Kumamoto Earthquake

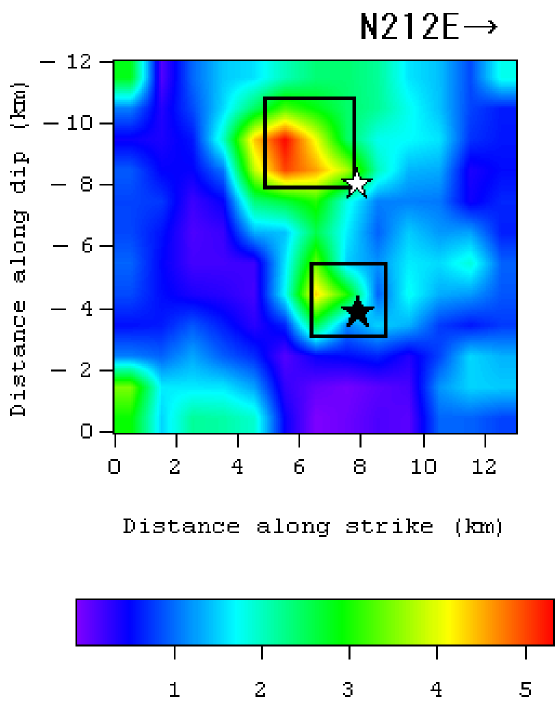



Fig.5 Characterized hypocenter of the foreshock in the 2016 Kumamoto Earthquake

Table 2 Parameters of characterized hypocenter model of foreshock in the 2016 Kumamoto Earthquake

| | Asperity 1 | Asperity 2 |
|---|---|---|
| East Longitude at Start Point (deg.) | 130.808 | 130.809 |
| North Latitude at Start Point (deg.) | 32.742 | 32.742 |
| Depth of Start Point (km) | 11 | 7 |
| Length (km) * Width (km) | 2.5 * 2.5 | 3 * 3 |
| Seismic Moment, Mo (N･m) | 1.50E+24 | 1.30E+24 |
| Relative Rupture Start Time (s) | 0 | 2.7 |
| Rupture Propagation Velocity (km/s) | 2.8 | 2.8 |
| Rise Time (s) | 0.33 | 0.4 |
| Division Number | 5 * 5 * 5 | 5 * 5 * 5 |

each asperity. Failure at each asperity is assumed to expand to the radical direction from a rupture start point of each asperity shown in Fig.5.

### 3.3 Site Amplification Characteristics

Site amplification characteristics are to display the surface soil layered ground amplification in the frequency domain, which is located on the earthquake engineering base rock (Approximately shear wave velocity 3km/s). In order to investigate the seismic intensity and the difference on seismic damage of structure, three different site amplification characteristics, KMM08, KMM011 and KMM018, are used in this paper. First natural frequencies at KMM08, KMM011 and KMM018 are 0.85Hz, 3.1Hz and 9,4Hz, respectively. Based on the ground classification of the Building Standards Act in Japan, KMM011 and KMM018 correspond to the second kind of ground, and KMM008 corresponds to the third kind of ground.

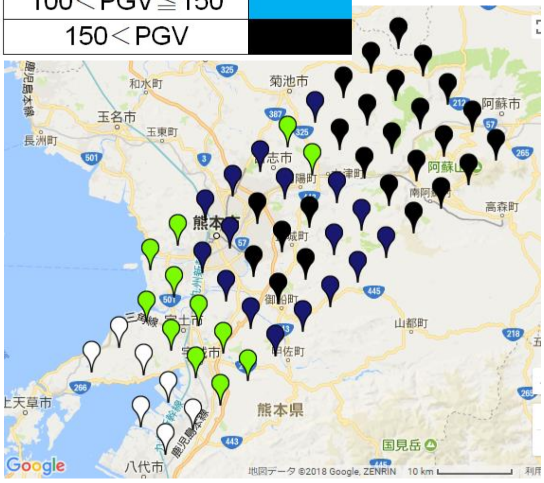
Fig.6 shows the maximum velocity, PGV (cm/s), distribution map and the maximum displacement, PGD (cm), distribution map, which are obtained by the empirical Green's function method using three site amplification characteristics mentioned above. It is found that PGV and PGD values trend to increase toward the north-east direction. Three seismic motions have a tendency to become larger in order of KMM008, KMM011 and KMM018.

## 4. SEIMIC DAMAGE PREDICTION OF WOODEN HOUSE

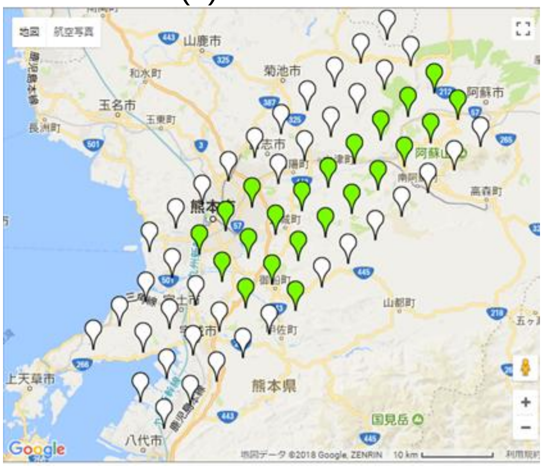
### 4.1 3-D Seismic Collapsing Process Analysis of Wooden House

In this paper, a structural analysis software of "Wallstat" is conducted in order to investigate the seismic response behavior and the collapsing process of wooden house during a large earthquake ground motion. This software has an original analysis technique (Nakagawa *et al.* 2010) using the basic theory of the Distinct Element Method proposed by Cundall *et al.* (1979), and can be taken into consideration the extremely non-linear properties of timber members breaking or being disperse. In the collapsing process analytical calculation, a wooden house can be modeled by a lot of timber ele-

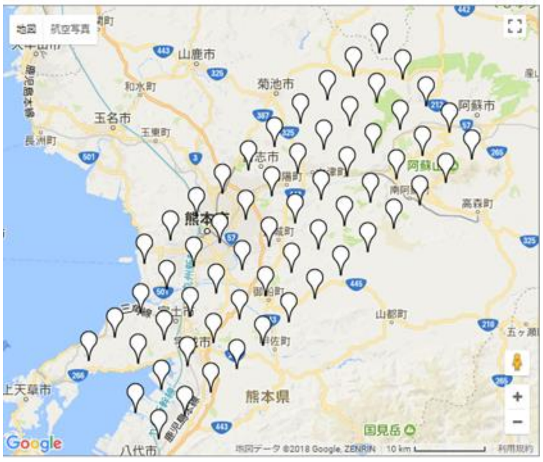
| PGV | color |
|---|---|
| 0＜PGV≦50 | |
| 50＜PGV≦100 | |
| 100＜PGV≦150 | |
| 150＜PGV | |




(a)KMM008




(b) KMM011

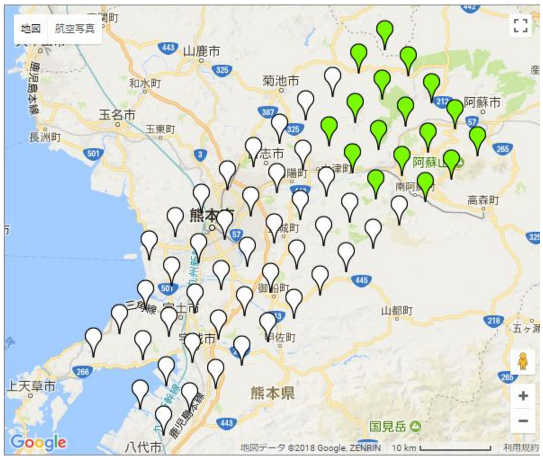



(c) KMM018

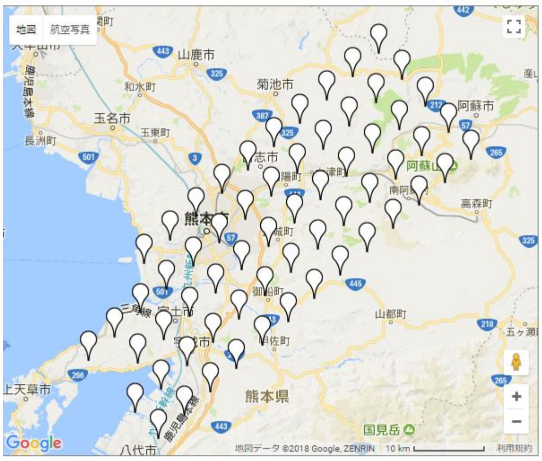
Maximum velocity (PGV)

| PGD | color |
|---|---|
| 0＜PGD≦10 | |
| 10＜PGD≦20 | |
| 20＜PGD≦30 | |
| 30＜PGD | |


(a)KMM008




(b) KMM011




(c) KMM018

Maximum displacement (PGD)

Fig.6 Maximum velocity and displacement distribution map ments such as beam and column connected with non-linear spring, and also can be modeled by lumped mass and the weight of each floor in wooden house model can be obtained from each structural element. In the collapsing analysis of this wooden house shown in Fig.5, the characteristics of these joint metals previously mentioned are modeled by some non-linear load-displacement relationships. However, these non-linear load-displacement relationships between timber pillar and beam elements and the seismic collapsing process analysis of "wallstat" software (Nakagawa and Ohta, 2010) based on the Discrete Element Method proposed by Cundall and Strack (1979) are not indicated due to the limited space. Details of "Wallstat" are referred to Takatani et al. (2012a, b).

In this paper, 3-D seismic collapsing process analysis for a two-story wooden house shown in Fig.7 is conducted and the maximum drift angle response can be evaluated from 3-D seismic collapsing process result against each earthquake motion wave and the seismic damage state of this wooden house is investigated.

3-D seismic collapsing frame model of wooden house built by the the Building Standards Act in Japan (2000) indicated in Fig.7 can be made by "wallstat" software. The junction part of wooden house is consist of stub tenon joint, and also is reinforced with a junction metallic material between timber pillar and beam. Concretely, Hold Down metallic material of 10kN (as referred to HD10kN) is used at pillar and hold down metallic material of 20kN (as referred to HD20kN) is used at beam. Wall is employed plasterboard and siding board. Relation between load and displacement for each member mentioned above is indicated in Fig.8.

The maximum drift angle is numerically evaluated form 3-D seismic collapsing process results against 61 earthquake motion waves.

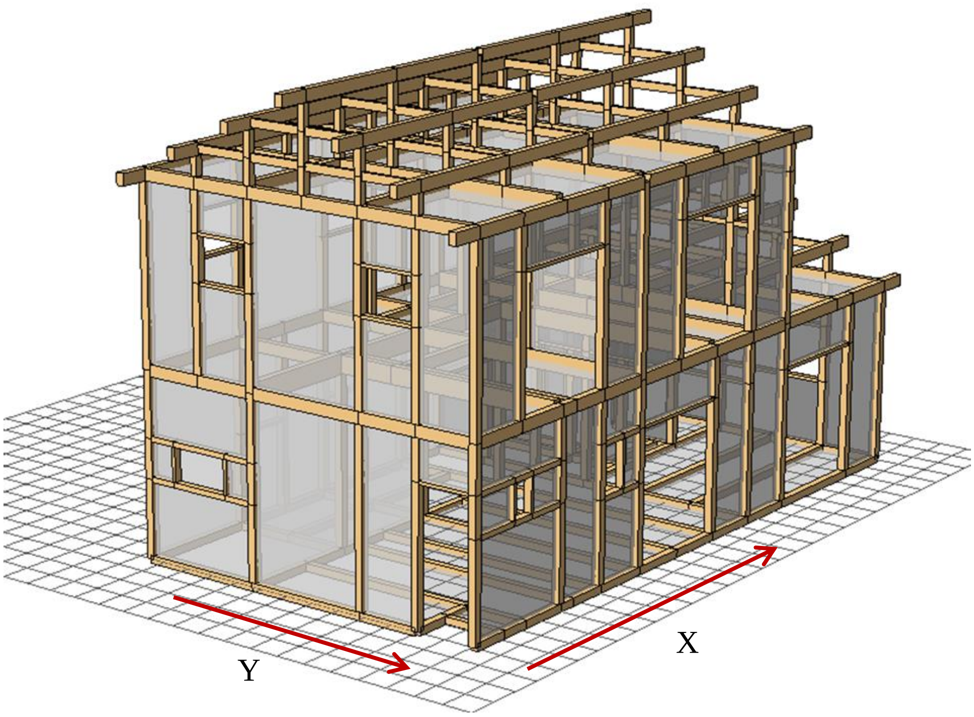
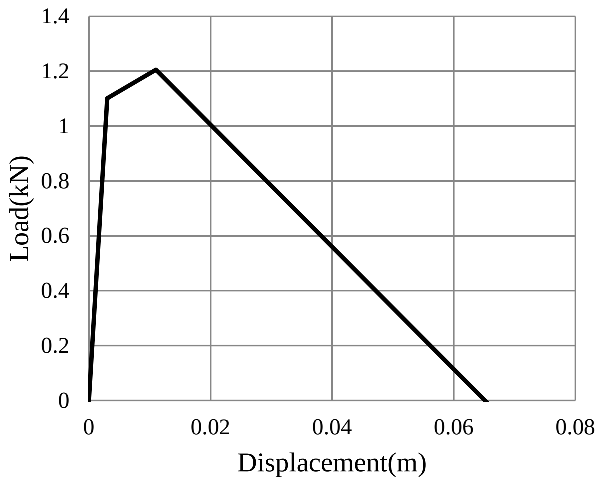
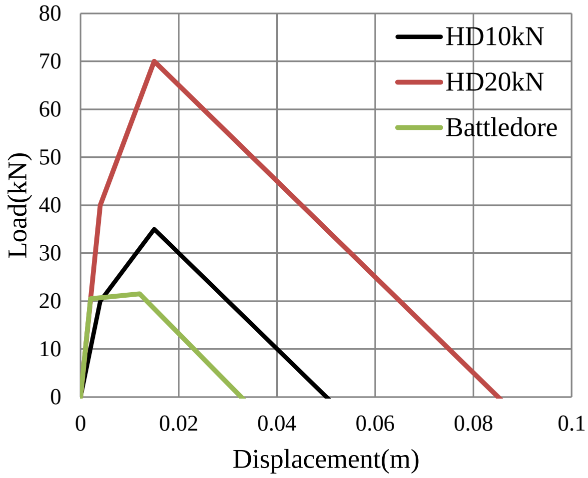


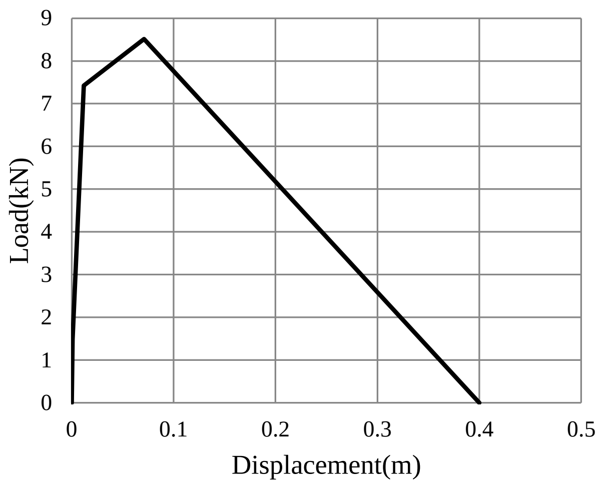

Fig.7 3-D seismic collapsing frame model




(a) Junction part




(b) Reinforcement of junction part



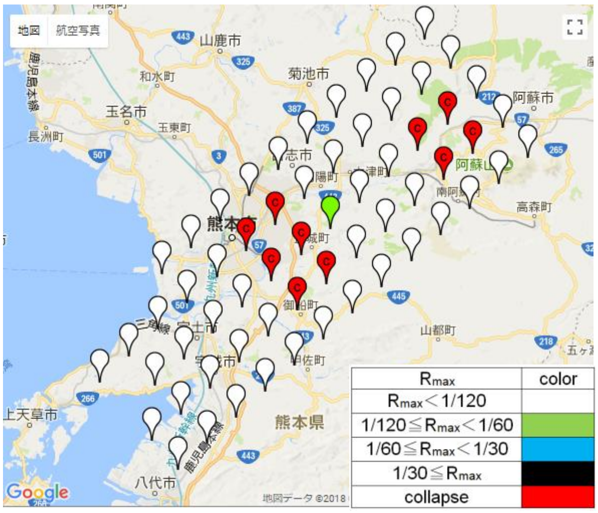

(c) Wall

Fig.8 Relation between load and displacement for each member

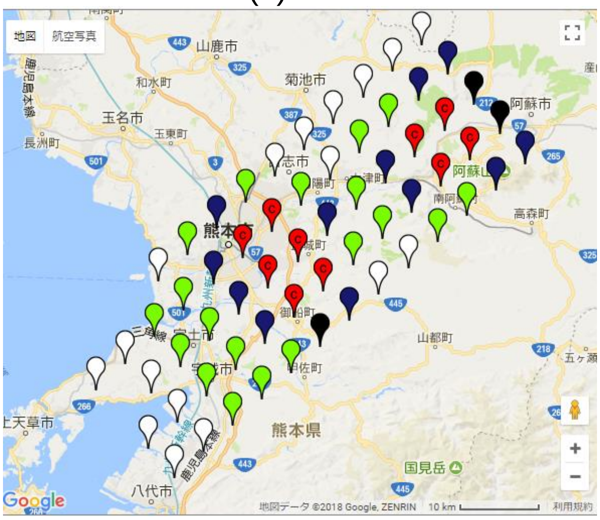
### 4.2 Evaluation of Maximum Drift Angle of Wooden House

The maximum drift angle is defined with the ratio of a horizontal displacement of each story layer to the height of each layer, and the maximum value in each direction is chosen from the maximum drift angles at four corners of wooden house.

Fig.9 shows the maximum drift angle distribution maps of Rx and Ry when EW and NS components of earthquake motion wave considering the site amplification characteristics of KMM008 were employed to X direction. Rx means the maximum drift angle chosen in four drift angles in X direction, and Ry means the maximum drift angle chosen in four drift angles in Y direction. Figs.10 and 11 indicate the maximum drift angle distribution maps of Rx and Ry in considering the site amplification characteristics of KMM011 and KMM018, respectively. It is found from Figs.9 to 11 that many wooden houses collapse against the earthquake motion wave of KMM008. This is because that PGV and PGD in KMM008 have the largest value in KMM008, KMM011 and KMM018.

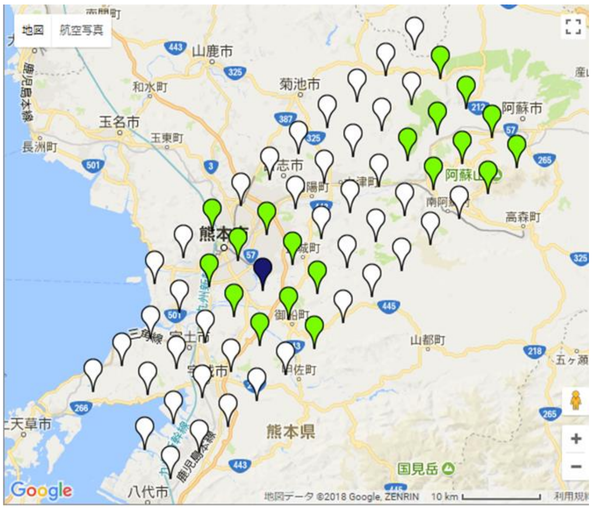



(a) Rx

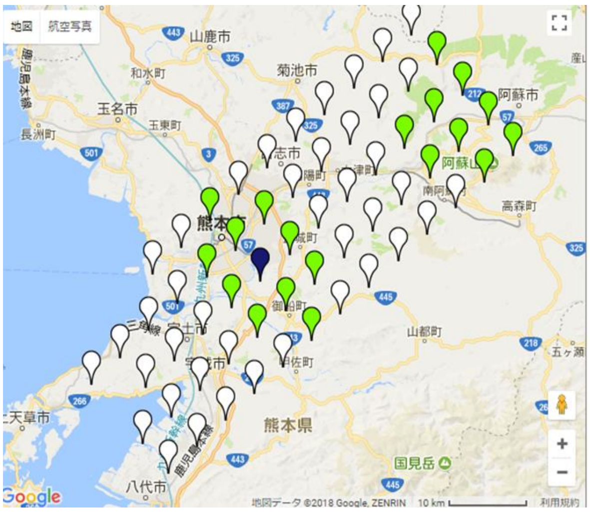


(b) Ry

X-EW component



(a) Rx



(b) Ry

X-NS component

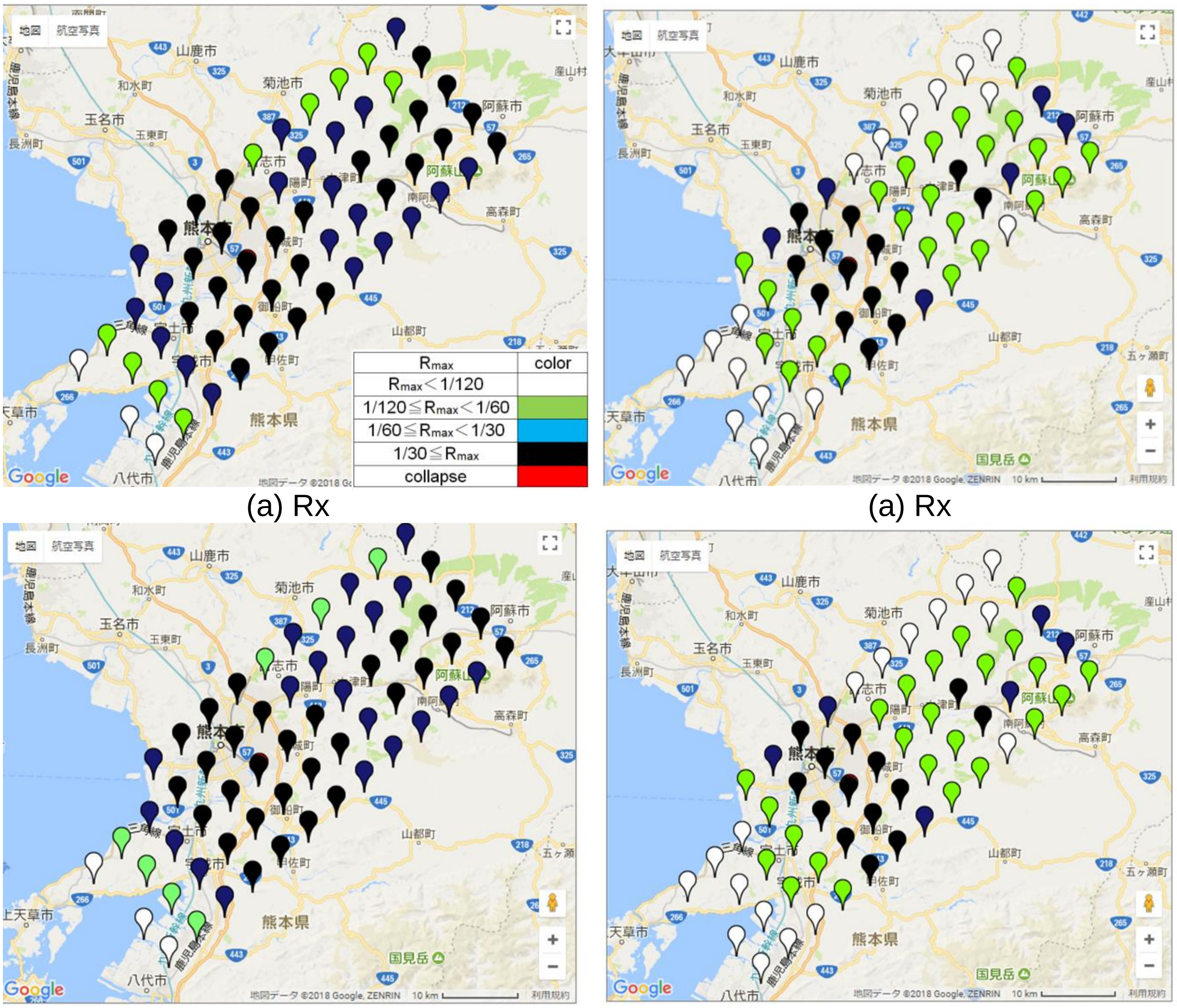
Fig.9 Maximum drift angle distribution maps (KMM008)

However, overall seismic damage of wooden house is the largest one in KMM011. Because the natural frequency of wooden house is almost 3.9Hz in both X and Y directions and the predominant frequency of the site amplification characteristics of KMM011 is 3.1Hz, it may be possible that the wooden house and the surface ground resonate each other. A reason for the collapse of wooden house in KMM008 may be considered to be the largest value from a view point of the seismic energy in KMM008.

### 4.3 Maximum Drift Angle of Wooden House

Based on the seismic collapsing process simulation results of wooden house described in the previous chapter, a prediction equation of the maximum drift angle of two-story wooden house can be written by

$$\log R_{\max} = c_1 + c_2 \log D + c_3 \left( X^2 + S \right) + c_4 X + c_5 \log f_g + c_6 f_g \tag{1}$$




(a) Rx (a) Rx

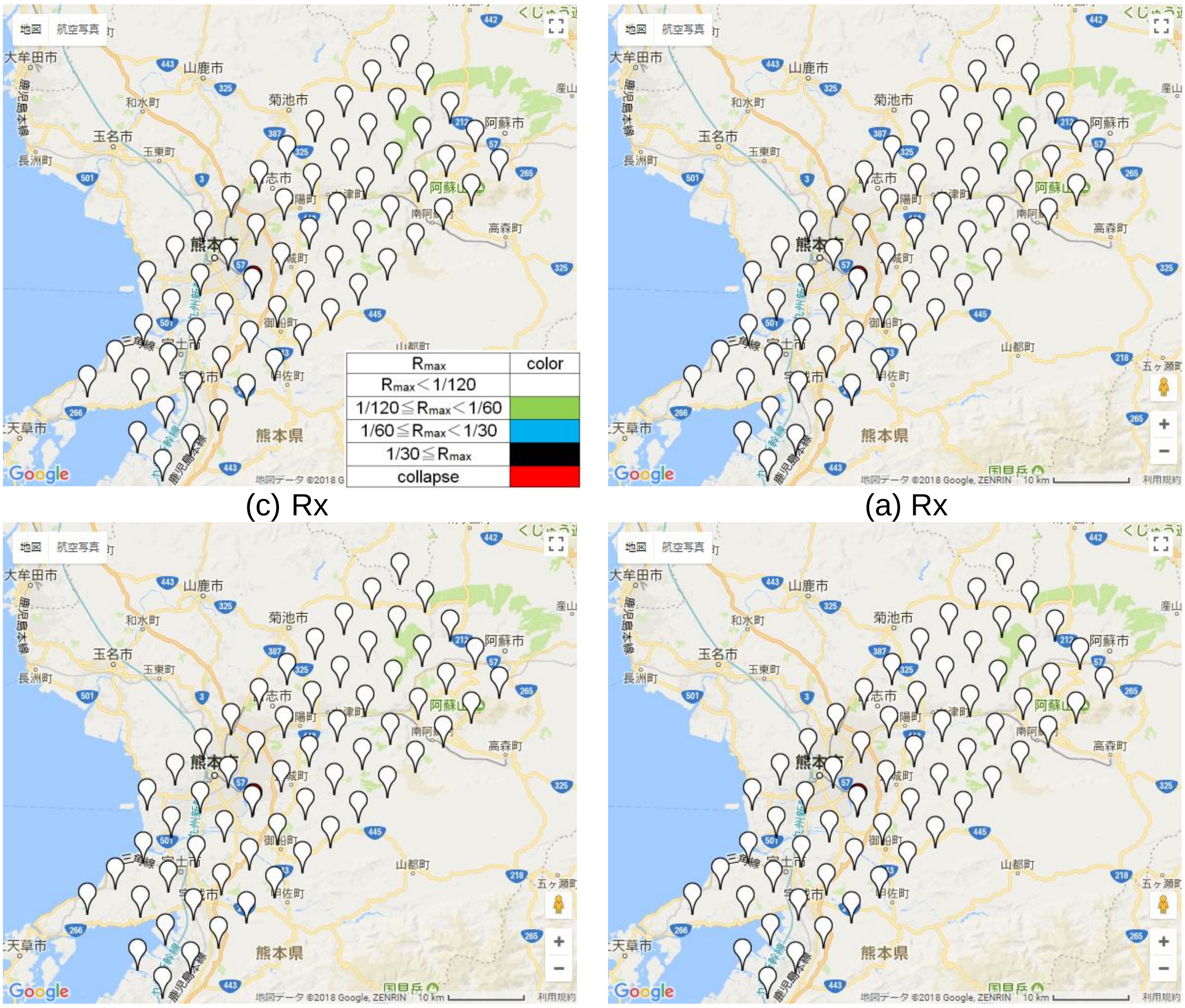
(b) Ry (b) Ry

X-EW component X-NS component

Fig.10 Maximum drift angle distribution maps (KMM011)

where, $D$ is directivity coefficient, $X$ is the minimum distance (km) of seismic fault, $f_g$ is the first natural frequency (Hz) of the site amplification characteristics, $c_1$ to $c_6$ are recurrence coefficients, and $S$ is the constant coefficient regarding the peak of seismic motion around a hypocenter. Eq.1 can be obtained by the recurrence analysis changing $S$ value. Table 3 shows each recurrence coefficients used in Eq.1.

Seismic damage prediction of wooden house around Kumamoto region may be possible by Eq.1 proposed in this paper. This seismic damage prediction of wooden house was obtained from the recurrence analysis based on some earthquake ground motion waves in the 2016 Kumamoto Earthquake, and also is used in estimating seismic damage prediction of two-story wooden house with high seismic performance and satisfying the seismic standard in the Building Standards Act in Japan amended in 2010. Therefore, a recurrence analysis considering the site amplification characteristics in other region may be needed in order to evaluate seismic damage prediction of wooden house in other region. Moreover, the seismic damage prediction of old wooden




(c) Rx (a) Rx

(d) Ry (b) Ry

EW component in X direction NS component in X direction

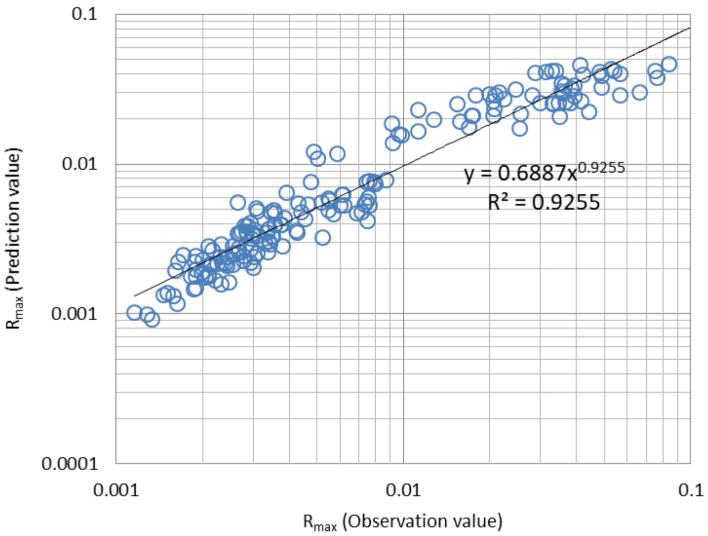
Fig.11 Maximum drift angle distribution maps (KMM018)

Table 3 Recurrence coefficients in Eq.1 (Input motion wave used in X direction)

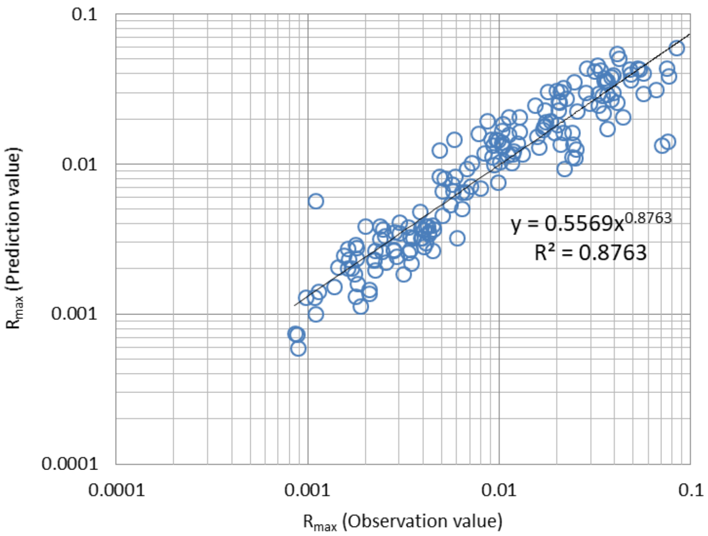
| | $R_{max}$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ |
|---|---|---|---|---|---|---|---|
| NS component | X | -1.769 | -3.147 | -0.287 | -0.17 | 2.147 | -0.375 |
| | Y | -1.119 | -0.292 | -0.221 | -0.009 | 1.892 | -0.338 |
| EW component | X | -1.246 | -0.511 | -0.146 | -0.018 | 3.273 | -0.492 |
| | Y | -1.378 | -0.069 | -0.025 | -0.027 | 0.608 | -0.207 |

house built before 2010 can be easily obtained from the recurrence analysis using seismic collapsing process results of this kind of wooden house.

## 4.4 Analytical Results




(a) Rx

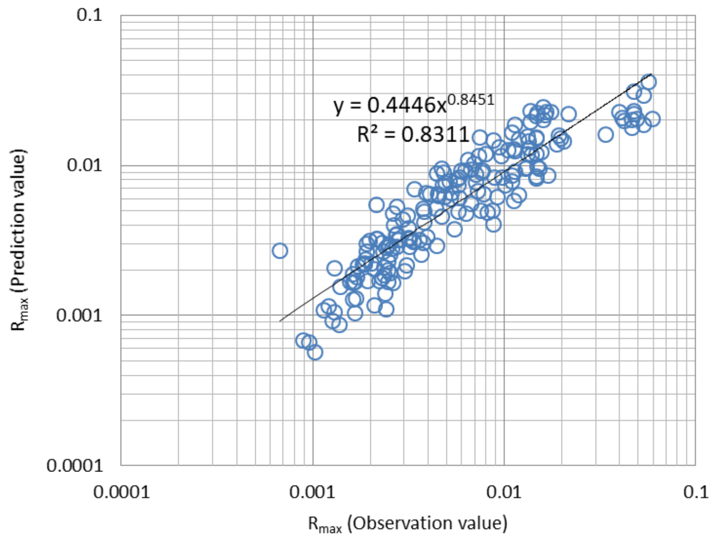



(b) Ry

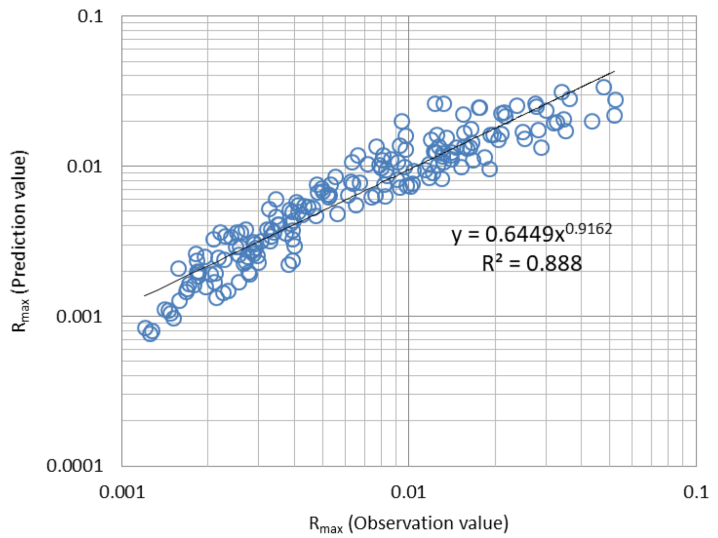
Fig.12 Comparison between $R_{max}$(Prediction value) and $R_{max}$(Observation value) (EW component in X direction)

A seismic damage prediction equation of the maximum drift angle of wooden house proposed in the previous session is investigated in this session. Comparison the maximum drift angle, $R_{max}$(Observation value), obtained from 3-D seismic collapsing process analysis with the maximum drift angle, $R_{max}$(Prediction value), calculated from Eq.(1) is conducted. $R_{max}$ in X direction describes Rx, and $R_{max}$ in Y direction describes Ry.

Coefficient of determination, $R^2$, of Rx is 0.93, and that of Ry is 0.88 as shown in Fig.12. Also, coefficient of determination, $R^2$, of Rx is 0.83, and that of Ry is 0.89 as shown in Fig.13. Any coefficient of determination is very close to 1.0. This implies that the prediction equation of the maximum drift angle, $R_{max}$, written in Eq.1 has an accu-




(a) Rx




(b) Ry

Fig.13 Comparison between $R_{max}$(Prediction value) and $R_{max}$(Observation value) (NS component in X direction) rate precision to seismic damage of wooden house and can utilize seismic damage of wooden house in Kumamoto region in future.

## 5. CONCLUSIONS

Thousands of wooden houses was destroyed by the 2016 Kumamoto Earthquake. As main factors to the destruction of wooden houses, strong earthquake motions due to fore-shock and main shock, the amplification effect of ground surface layer, and the pulse wave due to seismic fault rupture propagation have been indicated by many researchers and engineers. A seismic damage prediction function for wooden houses taking into consideration the consecutive strong earthquake motions, the amplification effect of ground surface layer, and the rupture propagation effect of seismic fault is proposed in this paper. Relationship between three ground characteristics above mentioned and the seismic damage for wooden house in the 2016 Kumamoto earthquake is analytically investigated by 3-D collapsing process analysis. In this collapsing analysis of two-story wooden house, the maximum drift angle is evaluated from the viewpoint of three ground characteristics above mentioned, and is a seismic damage prediction function for two-story wooden house. Earthquake ground motion waves of 61 locations nearby seismic faults were obtained from the empirical Green's function using seismic fault model based on the asperity locations and the hypocenters of both fore-shock and main one, and also the non-linearity of ground surface layer due to strong earthquake motion was numerically evaluated by the multi non-linearity effect.

The summary of this paper is as follows,

1) The maximum drift angle of wooden house considering the amplification effect of ground surface layer and the rupture propagation effect of seismic fault can be obtained from 3-D seismic collapsing process analysis.
2) When the natural frequency of wooden house is close to the natural frequency of amplification characteristics of ground surface layer, seismic damage of wooden house is larger regardless of the intensity of earthquake ground motion.
3) The effect of consecutive strong earthquake motions with both the fore-shock and main shock in the 2016 Kumamoto earthquake on the seismic performance of wooden house was analytically revealed. There may be a possibility to clearly occur the effect of consecutive strong earthquake motions in the wooden house with low seismic performance.
4) Seismic damage prediction of wooden house around Kumamoto region may be possible by the maximum drift angle prediction equation proposed in this paper. This seismic damage prediction of wooden house can be obtained from the recurrence analysis based on some earthquake ground motion waves in the 2016 Kumamoto Earthquake.

By the way, seismic damage prediction of wooden house proposed in this paper is used in estimating seismic damage prediction of two-story wooden house with high seismic performance and satisfying the seismic standard in the Building Standards Act in Japan amended in 2010. Therefore, a recurrence analysis considering the site amplification characteristics in other region may be needed in order to evaluate seismic damage prediction of wooden house in other region. Moreover, the seismic damage prediction of old wooden house built before 2010 can be easily obtained from the recurrence analysis using seismic collapsing process results of this kind of wooden house.

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