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Study on Earthquake Damage Prediction by Considering Variations of Seismic Performance of Wooden Houses

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Synopsis

In order to promote aseismic retrofit and to mitigate earthquake damage, it is necessary for inhabitants to recognize the seismic risk of their own houses. This paper presents a method for damage prediction of a wooden house based on the results of seismic capacity evaluation and strong motion evaluation. The method is developed so as to simulate the wooden house damage in recent earthquakes in Japan. Finally, we confirm the effect of aseismic retrofit on seismic damage mitigation from predicting seismic damage of wooden houses by the proposed method.

Keywords: earthquake damage prediction, wooden houses, seismic performance, maximum drift angles, damage probability, strong ground motions

1. Introduction

To mitigate the earthquake damage of wooden houses that influences life safety during strong ground motions, promotion of aseismic retrofit is required. Therefore, it is important to let the inhabitants recognize earthquake risk of the area they live in and the effect of aseismic retrofit; and it is necessary to develop a method of earthquake damage prediction which not only evaluate the damage based on analysis results of strong ground motions but also take into consideration the difference of seismic performance, strength and deformation, of wooden houses.

In the promotion of aseismic retrofit of wooden houses, both the damage predictions for a group of houses and an individual one are necessary. The evaluation results for wooden houses in a local area are important data for making disaster prevention plan of the area. On the other hand, the evaluation results of an individual house make the owner understand earthquake hazard and the effect of aseismic retrofit concretely, and raise the incentive to conduct aseismic retrofit.

In this study, we present two methods for earthquake damage prediction of wooden houses based on the evaluation results of seismic capacity and strong ground motions. One is the method for individual wooden house, which predict damage probability of wooden house. Another is the method for wooden houses in an area, which predict the damage ratio of wooden houses. Both in the method, the earthquake damage of wooden house is predicted from estimated maximum drift angles by using the fragility functions, which are constructed based on seismic damage data in recent earthquakes. Then, the proposed methods are applied to wooden houses in Kyoto city, and the mitigation effects of retrofit are discussed.

2. Method of earthquake damage prediction for an individual wooden house

2.1 Outline of the method

The method of damage prediction for an individual wooden house is based on the results of seismic capacity and strong motions.

Figure 1(a) shows the flowchart. First, with the properties available from an investigation of the house, the analysis model of an individual wooden house is constructed by using the steps of seismic capacity evaluation used in the calculation method of response and limit strength (Suzuki et al., 2001). Second, the maximum drift angle of wooden houses is estimated from the response analysis of constructed model under the estimated ground motions (Hayashi, 2002). Finally, the probability of damage of a wooden house is predicted from estimated maximum drift angle by using the fragility functions. An example of a 2-storied wooden house is used to explain each step in detail, from 2.2 to 2.4.

2.2 Modeling of a wooden house

Modeling of a wooden house follows the method of seismic performance evaluation used in the calculation method of response and limit strength (Suzuki et al., 2001).

First, the main structural properties, such as plans, height, seismic performance elements, etc., of a wooden house are investigated, and the seismic performance elements, such as mud wall, handing wall, etc., are extracted (Fig.2(a)). Then the standard force-displacement curve is used each seismic performance element, and the force- displacement curve of the whole wooden house is calculated by adding the curve of each element (Fig. 2 (b)). Besides, with the investigated story height and mass of the 2-storied wooden house, an equivalent 1-storied one, which is a single-degree-of-freedom (SDOF) system, is obtained based on the steps in the calculation method of response and limit strength (Fig. 2 (c)).

2.3 Estimated maximum drift angle

Next, maximum drift angle of wooden house during strong ground motions is estimated by using equivalent-performance response spectrum developed by Hayashi (2002).

In the method, a wooden house is simplified as a single-degree-of-freedom (SDOF) system. Analysis is conducted based on the simplified SDOF system, and results are applied to the original wooden house. The main results of the method are outlined below. An equivalent period T_{et} is related to the drift angle R_e as follows

$$T_{et}(R_e, C_{Be}) = 2\pi\sqrt{H_{et} \cdot R_e / (C_{Be} \cdot g)} \quad [1]$$

where M_e and T_{et} are the effective mass and effective height, respectively, M, C_{Be} and g are the total mass, the yield base shear coefficient, and the gravitational constant, respectively. The equivalent acceleration response spectrum corresponding to the specified drift angle R_e can be calculated from

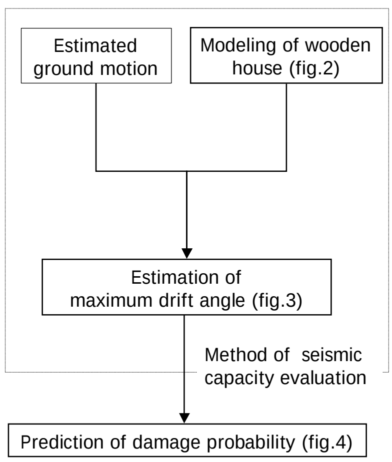
$$S_{aeS}(R_e, C_{Be}, h = 0.05) = C_{Be} \cdot g / F_h(h_{et}(R_e)) \quad [2]$$

where F_h is the reduction factor of acceleration spectrum. F_h depends on the damping ratio h, and in turn depends on the drift angle with the following relations

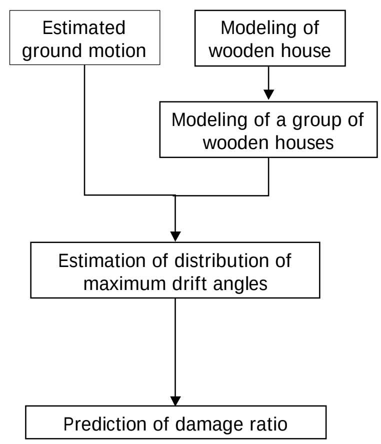
$$F_h(h_{et}(R_e)) = \frac{1.5}{1 + 10 \cdot h_{et}(R_e)} \quad [3]$$

$$h_{et}(R_e) = h_{eq}(R_e) + h_0 \quad [4]$$

$$\begin{cases} h_{et}(R_e) < 0.05 & h_0 = 0.05 - h_{et}(R_e) \\ h_{et}(R_e) \geqq 0.05 & h_0 = 0 \end{cases}$$



(a) An individual wooden house



(b) A group of wooden houses

Fig.1 Outline of the method of earthquake damage prediction

For a given drift angle R, both T_{et} and S_{aeS} can be calculated from [1] and [2]. A pair of T_{et} and S_{aeS} corresponds to a point in the response spectrum-period plane, as shown in Figure 3. For a fixed C_{Be}, an equivalent response spectrum curve can be drawn by varying the drift angle R_e.

2.4 Prediction of the damage probability

Finally, the damage probability of a wooden house is predicted from the maximum response drift angle R by using fragility functions.

It is assumed that the variation of damage by the maximum drift angle R could be expressed by lognormal distribution. The damage probability, $P_f(R)$, is calculated as

$$P_f(R) = \Phi\left(\left(\ln(R) - \ln(R_m)\right)/\zeta_R\right) \qquad [5]$$

where Φ is a standard normal distribution functions and R_m is the median value ; $(\ln(R_m)) = \lambda_R$, λ_R is the average of ln(R)) and ζ_R is the standard deviation of ln(R). Equations [5] is referred to as fragility functions here in.

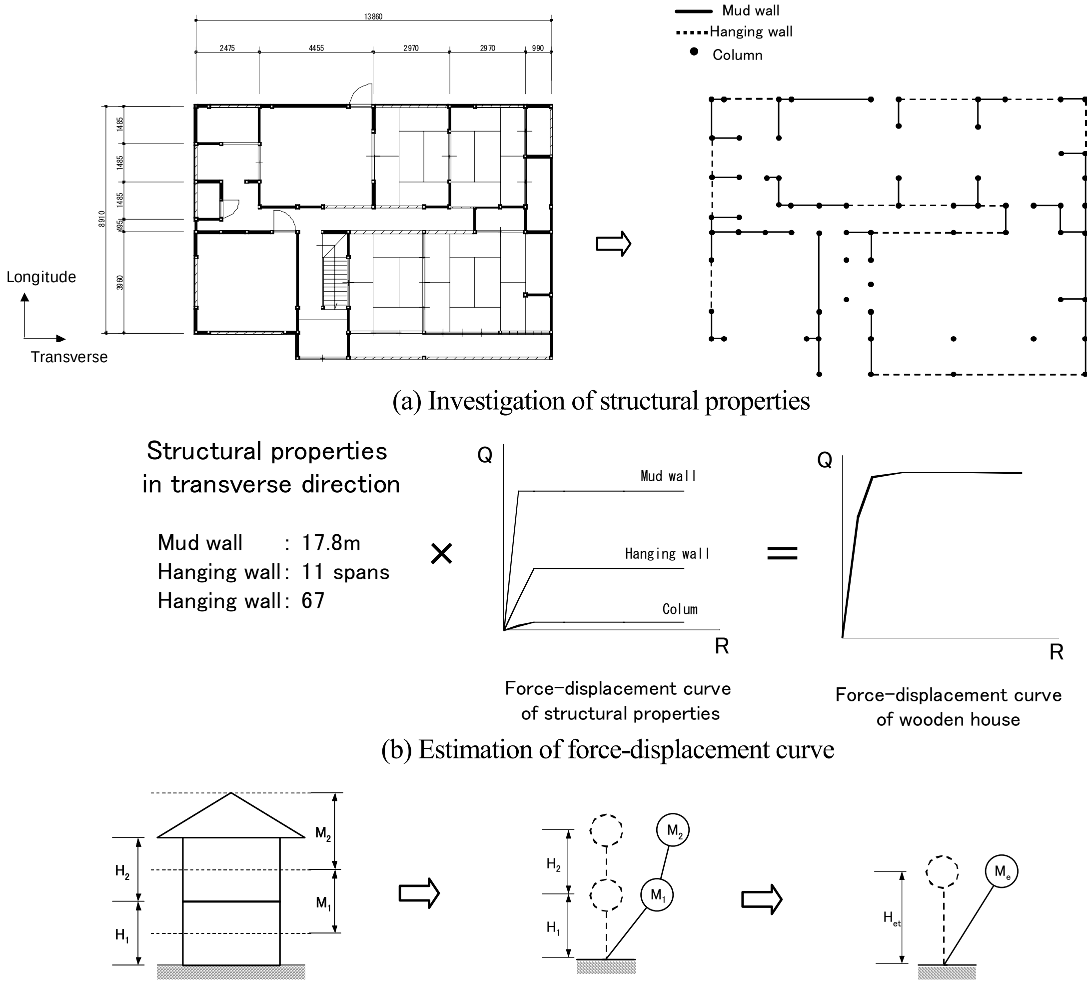
In this study, damage levels are categorized into 5 groups : No damage, Slight, Minor, Moderate, Sever (Hayashi et al., 2001). R_m and ζ_R are decided based on damage ratios of wooden houses at Hino-town in 2000 Western Tottori earthquake, as shown in Figure 4 (Morii et al., 2005).

3. Method of earthquake damage prediction for a group of wooden houses

3.1 Outline of the method

Figure 1(b) shows the flowchart of the method of earthquake damage prediction for a group of wooden house. Fundamentally, it is the same process as the method for individual wooden house.

First, modeling of the seismic performance of the group is expressed by lognormal distribution function based on the investigation results of individual wooden



(a) Investigation of structural properties

(b) Estimation of force-displacement curve

(c) Modeling of equivalent SDOF system

Fig.2 Evaluation of seismic performance of wooden house based on the calculation method of response and limit strength houses. Next, for given estimated strong ground motions, the maximum drift angle of an individual house is calculated by using the equivalent-performance response spectra, and then the distribution of the maximum drift angle for the group is obtained. Finally, with the damage probability of each house available by using the fragility functions, the damage ratios of the group is calculated as the average of the damage probabilities.

3.2 Simplification of modeling individual wooden house in group

When performing earthquake damage prediction for a group of wooden houses, the result of seismic capacity evaluation, based on the steps in the calculation method of response and limit strength, of an individual house is approximated by an elasto-plastic model, in which the yielding angle R_y, is 1/100rad and the angle of limit state is 1/30rad. Then it was converted to an equivalent-performance response spectrum by using equations [1] - [4].

3.3 Modeling of a group of wooden houses

A group of wooden houses model is modeled by lognormal distribution of the base shear coefficient, which is estimated from the result of seismic capacity evaluation of the individual ones modeled as a SDOF system. The parameters in the lognormal distribution function are the average base shear coefficient, C_{Be}, and the standard deviation, ζ_{CBe}.

In this study, the standard deviation of equivalent height ζ_{Het} is added to ζ_{CBe}. Then, the new standard deviation of shear coefficient $\zeta_{CBe'}$ is calculated as

$$\zeta_{C_{Be'}} = \sqrt{\zeta^2_{C_{Be}} + \zeta^2_{H_{et}}} \qquad [6]$$

3.4 Evaluation of the distribution of the maximum drift angles

The Latin hypercube sampling method (the LHS method) (Howard et al., 1990) is used for calculating the distribution of the maximum drift angle. The LHS method is adopted because it could use smaller number of samples to obtain a stable solution. In this study, the number of samples of the LHS method is calculated as N=10.

4. Earthquake damage prediction in Kyoto city

Finally, the proposed methods are applied to wooden houses (*Kyo-machiya*) in Kyoto city, and the mitigation effects of retrofit are discussed.

4.1 Example of earthquake damage prediction for an individual wooden house

In Kyoto city, strong ground motions are estimated from eight active faults around Kyoto city, as shown in Figure 5 (Kyoto-city, 2003). The proposed methods are applied to KJ-house (*Kyo-machiya*) in Kyoto city by using the estimated strong ground motions of the *Biwako-Seigan* fault and *Hanaore* fault. One wave of estimated strong ground motions is created for each area without distinction of direction.

KJ-house is located the central of Kyoto city, as shown in Fig.5. Figure 6 shows the plans of KJ-house, which is long and slender in the longitudinal direction, seismic performance elements, such as mud wall, are mostly arranged in the longitudinal direction. In the results of seismic capacity evaluation, when the limit drift angle is 1/30rad, the shear coefficient $C_{Be(R30)}$ of equivalent SDOF model is 0.11 in transversal direction, 0.42 in longitudinal direction. The shear coefficient $C_{Be(R30)}$ in transversal direction is lower than that in longitudinal direction.

Figure 7 shows the result of earthquake damage prediction of KJ-house subjected to the estimated strong ground motions due to the *Biwako-Seigan* fault and *Hanaore* fault. In the case of the *Biwako-Seigan* fault,

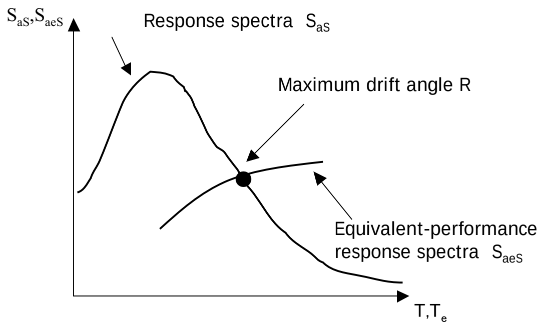


Fig.3 Estimation of maximum drift angel R

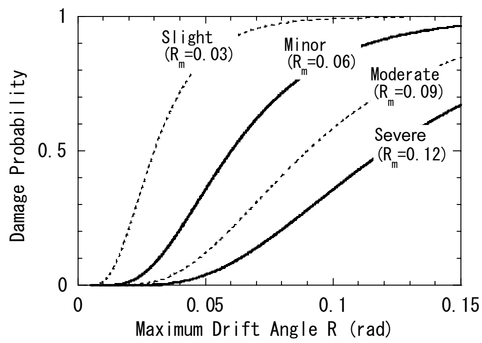


Fig.4 Estimated fragility functions (ζ_R=0.5)

the damage probability of KJ-house changes greatly due to differences in the strength. The damage probability is smaller as larger strength in longitudinal direction. On the other hand, in the case of the *Hanaore* fault, the difference in the damage probability due to the strength of wooden houses is not observed.

Figure 8 portrays the maximum drift angle in each estimated strong ground motions. In the case of the *Biwako-Seigan* fault, the estimated strong ground motions did not attain strong intensity and the predominant period is about 0.4 second, which means that the main components of the ground motions are short period ones. The maximum drift angle in the longitudinal direction, where the strength is larger, and transversal direction, where the strength is smaller, are 1/49 and 1/25rad, respectively. Therefore, the maximum drift angle decrease as the strength increase. On the other hand, in the estimated strong ground motions of *Hanaore* fault, the acceleration response spectrum shows predominant period of 1 to 3 seconds. Regardless of the strength, both in the longitudinal and transversal direction, the maximum drift angles are about 1/11 rad. Accordingly damage probability in the two directions are same.

From these results, the following can be pointed out about damage mitigation for KJ-house. In the case of the estimated strong ground motions caused by the *Biwako-Seigan* fault, it is possible to reduce the damage by raising the strength of transversal direction. In contrast, in the case of the estimated strong ground motions caused by *Hanaore* fault, increasing strength of a wooden house will not decrease the damage, but raising the deformation capacity will mitigate the damage.

4.2 Example of earthquake damage prediction of a group of wooden houses

In this section, earthquake damage prediction of the 2-storied wooden houses group in Kyoto city subjected to the estimated ground motions of *Hanaore* fault is performed.

From the seismic capacity evaluation, based on

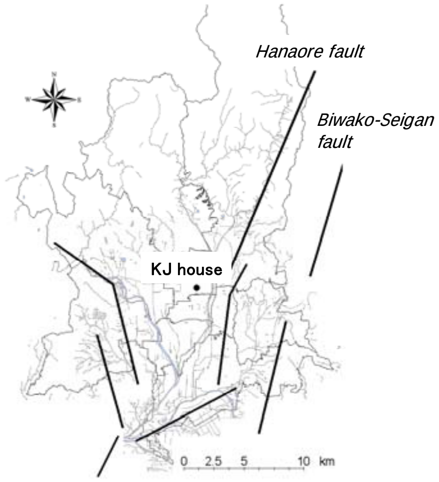
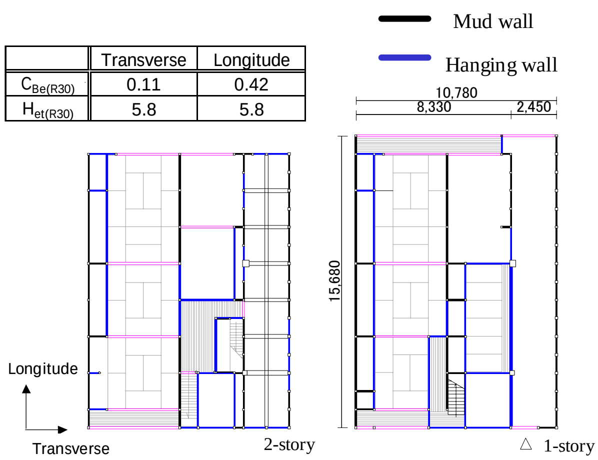


Fig.5 Location of faults around Kyoto city



	Transverse	Longitude
$C_{Be(R30)}$	0.11	0.42
$H_{et(R30)}$	5.8	5.8

Fig.6 Plans of KJ-house (*Kyomachiya*)

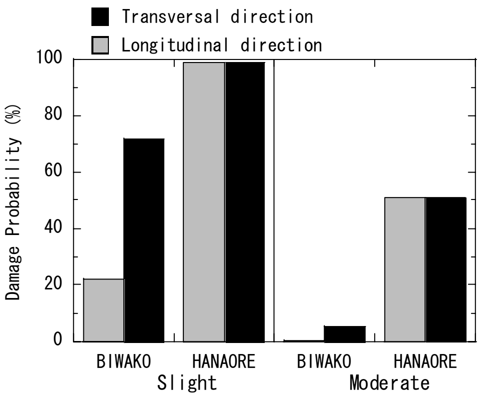


Fig. 7 Results of earthquake damage prediction in KJ-house

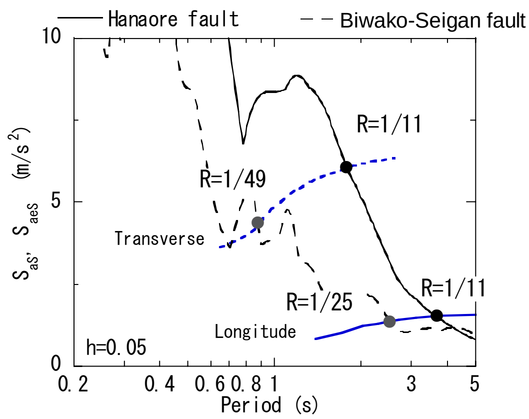


Fig.8 Maximum drift angles of KJ-house during estimated strong ground motions

calculation method of response and limit strength, of 30 wooden houses (*Kyo-machiya*). The wooden houses group model is constructed using the result 27 2-storied wooden houses, as shown in Figure 9 (Suda et al., 2005). The wooden houses group model is expressed by lognormal distribution of C_{Be} that the standard deviation of the equivalent height, H_{et} was added to the shear coefficient, $C_{Be'}$. The average of shear coefficient C_{Be} of wooden houses group model is about 0.43 for longitudinal direction, and about 0.15 for transversal direction. The average of the equivalent height H_{et} is about 4.4m for both directions.

The earthquake damage prediction results of transversal direction and longitudinal direction respectively are shown in Figure 10. On the whole, the damage ratio of longitudinal direction with larger strength is smaller than that of transversal direction. It is confirmed that performing the aseismic retrofit to raise the strength, the damage ratio fell. For example, although the damage ratio of transversal direction is over 40% at B point, in longitudinal direction with larger strength, the ratio is less than 10%.

From Figure 11, when the acceleration response spectrum shows predominant period of about 3 seconds and the strength is smaller than 0.2, the maximum response drift angle becomes large. That is to say, by increasing the strength to be larger than 0.2, resulting the maximum drift angle of about 1/15rad, so that the damage ratio decreases. On the other hand, at A point, no apparent difference of damage ratio is observed in both directions, and both the ratios are larger than 40%. As shown in Fig.11, the strength is less than 0.9, the maximum drift angle and the damage ratio will not decrease.

Therefore, in the region near active faults, only by increasing strength of a wooden house, it may be difficult to reduce the earthquake damage ratio. That is mitigating the deformation capacity of a wooden houses is necessary.

5. Conclusions

In order to promote aseismic retrofit and to mitigate earthquake damage, it is necessary for inhabitants to recognize the seismic risk of their own houses. This papers presents a method for damage prediction of a wooden house based on the results of seismic capacity evaluation and strong motion evaluation. The method of earthquake damage prediction of wooden houses is based on the results of response analysis under the estimated ground motion. Then, the probability of damage of wooden house is predicted from estimated maximum drift angle by using the fragility functions, which are constructed based on seismic damage data, we confirmed that the effect of variation of seismic performance on seismic damage mitigation from the results of analysis, the following conclusions can be drawn.

1) The proposed method of earthquake damage prediction can evaluate the seismic performance as probability of damage of wooden house.
2) It is confirmed that wooden houses damage is mitigated in large area by increasing the strength of wooden houses from the analysis results in the case of Hanaore-Fault in Kyoto city.
3) However, in the case of strong ground motions with predominant period in the range of 1 to 3 seconds, damage of wooden houses is not mitigated by increasing the strength of wooden houses. Therefore, it is important to consider not only the strength of wooden houses but also capacity of deformation to mitigate earthquake damage of wooden houses.

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References

Suzuki,Y., Saito,Y., Katagihara,K., Ikago,K. and Nojima,C. (2001) : Method of evaluation seismic performance of wooden frames - Limit bearing capacity analysis in wide range of deformation, Proceedings of the 11th Japan Earthquake Engineering Symposium, pp.1523-1528. (in Japanese).

Hayashi,Y. (2002) : Evaluation of Seismic Design Load based on Equivalent-Performance Response Spectra, The eleventh Japan earthquake engineering symposium,

pp.651-656. (in Japanese).
Hayashi,Y., Kitahara,A., Hirayama,T. and Ssuzuki,Y. (2001) : Evaluation of peak ground velocities in western Tottori earthquake of 2000, Journal of structural and construction engineering (transactions of architectural institute of Japan), No.548, pp.35-41. (in Japanese)
Morii,T., Hayashi,Y. and Saratani,A. (2005) : Semiempirical method for predicting seismic damage of wood houses based on seismic performance, Jounal of social safety science, No.7, pp.281-289.
Howard H.M , Hwang and Jing-Wen Jaw(1990): Probabilistic Damage Analysis of Structures, Journal of structural Engineering, Vol.116, No.7, ASCE, pp.1992-2007.
Kyoto-city (2003): Report on the third earthquake damage prediction in kyoto city. (in Japanese).
Suda,T., Suzuki,Y., Okuda,T. and Ogasawara,M. (2005) : Evaluation of structural characteristics of traditional wood houses in Kyoto bases on detail investigation, Journal of social safety science, No.7, pp.15-21. (in Japanese).

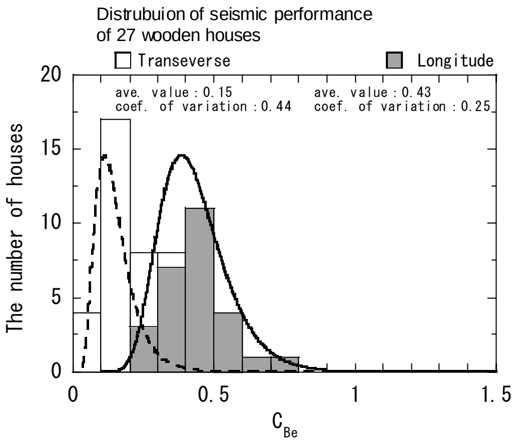


Fig.9 Model of a group of wooden houses

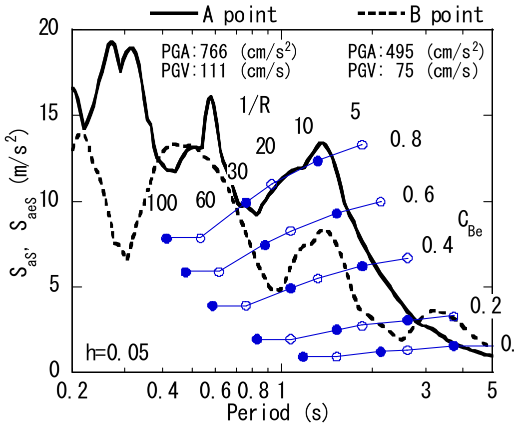
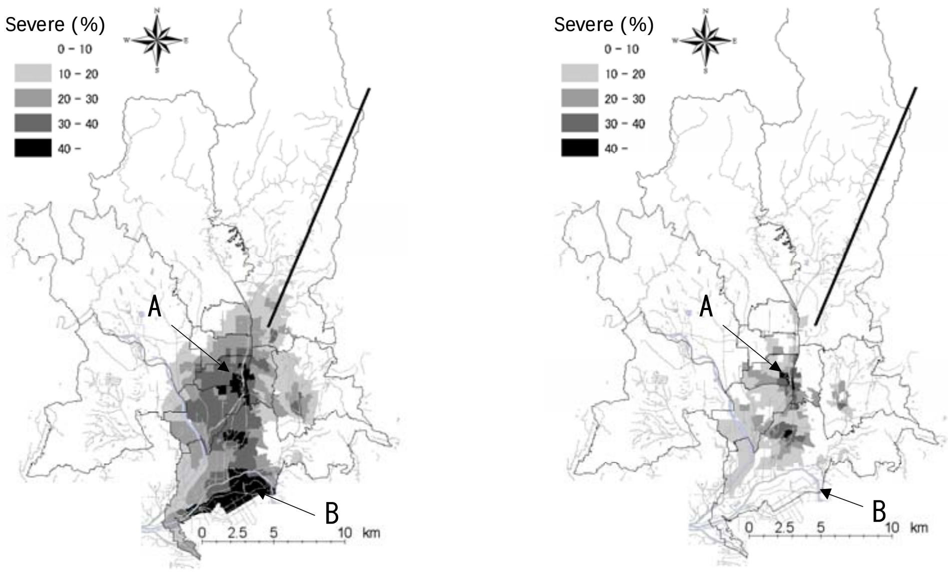


Fig.11 Estimated maximum drift angles R



(a) Transverse (λ_{CBe}=0.15) (b) Longitude (λ_{CBe}=0.43)

Fig.10 Results of earthquake damage prediction of the wooden houses in Kyoto city during estimated Hanaore fault

木造建物の耐震性能の変化を考慮した地震被害予測に関する研究

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要旨

本研究では，耐震診断結果に基づいて，木造住宅の耐震性能の変化を考慮できる木造住宅群の地震被害予測手法の提案を行い，地震被害の低減について分析した。1）提案した地震被害予測手法では，地域的な地震被害の低減に有効に作用する木造住宅の耐震性能を建物被害の被害率として確認することができる。2）耐力上昇が必ずしも建物被害の低減に繋がらず，耐力上昇とともに変形性能を確保していくことが重要である。

キーワード: 地震被害予測, 木造住宅, 耐震性能, 最大応答変形角, 損傷確率曲線, 強震動