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A STUDY ON EARTHQUAKE RESPONSE CHARACTERISTICS AND DAMAGE PREDICTIONS OF ONE-STORIED WOODEN-FRAMED HOUSE MODELS WITH UNI-AXIAL AND BI-AXIAL ECCENTRICITIES

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SUMMARY

We present the relationships between the eccentric ratio and the earthquake responses of one-storied wooden-framed house models which have shear walls arranged irregularly. We introduce some uni- and bi-axial eccentric models to this earthquake response analysis under the assumption that the floor is rigid. With regards to the uni-axial eccentric models, we especially examine the effect that an increase in the wall quantity has on the vibration control of torsion, of which walls are perpendicular to the eccentric direction. We also predict the earthquake damage of wooden-framed houses taking into account the eccentric ratio and the wall quantity.

INTRODUCTION

As for the reasons why wooden-framed houses are damaged when subjected to earthquake motions, it is said that number of shear walls is very few, some problems exist regarding their construction, vibrations of torsion are generated due to the irregularity of shear walls and so on. The maximum eccentric ratio is specified as being 0.15 in Building Standard Law of Japan (BSLJ). However, this was not applicable to general or typical wooden-framed houses. On the other hand, according to the investigations of the present wooden-framed houses, it is understood that many houses have larger eccentric ratios than 0.15 [1]. It is proven that almost all the damaged houses had irregular shear walls on the first floor that created open spaces during the Hyogo-ken Nanbu earthquake, 1995. BSLJ says that shear walls must be balanced, but it does not specify how to arrange shear walls. In 2000, BSLJ was improved. At the same time, it was regulated on how to arrange the shear walls and the eccentric value was regulated less than 0.3 in the case of wooden-framed houses.

In the present structural seismic design of wooden-framed houses, where the wall quantity is regulated, it is premised that the walls' arrangement should be well-balanced. Many analytical and experimental researches have been carried out to make the characteristics of wooden-framed houses clear [2]-[8]. Although the influence of irregularly arranged shear walls on the dynamic characteristics of wooden-framed houses has been made clear from the elastic theory and many experiments, there have been few

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discussions based on the earthquake response characteristics from analytical viewpoints and quantitative researches of the influences of the change of the shear wall stiffness. The effect of the number of shear walls perpendicular to the eccentric plane of structures has rarely been examined on earthquake responses. In this paper, we present the earthquake response characteristics using one-story uni- and bi-axial eccentric models and a simple damped mass system model. We examine the effect increasing wall quantity has on the orthogonal directional vibration control of torsion for the uni-axial eccentric model. We also predict the earthquake damage of wooden-framed houses using the parameters of the eccentric ratios and the wall quantities.

ANALYTICAL MODEL

In order to carry out the earthquake response analysis of wooden-framed houses which have irregular arrangements of shear walls, we introduce a simple model where the floor is assumed to be rigid as shown in Fig.1. The model has m and n planes to x and y directions, respectively. The equation of motion of this model is expressed with x and y displacements and the rotational angle, θ, of the center-of-gravity of the floor, subjected to earthquake motions as follows:

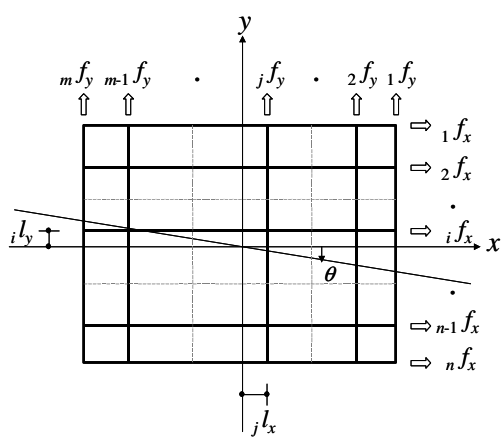
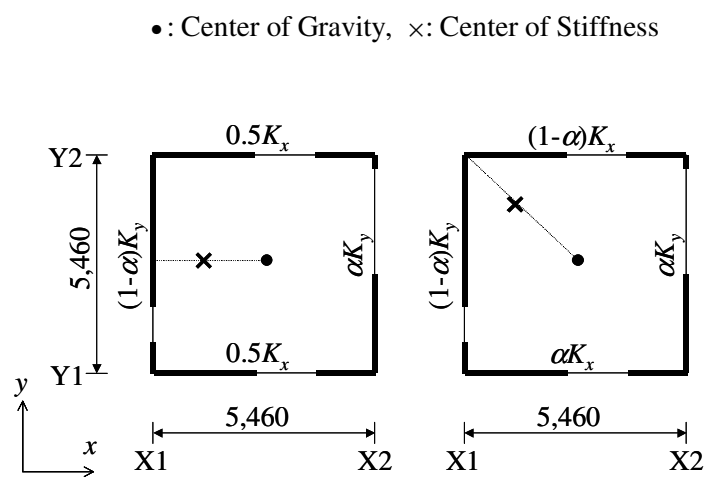
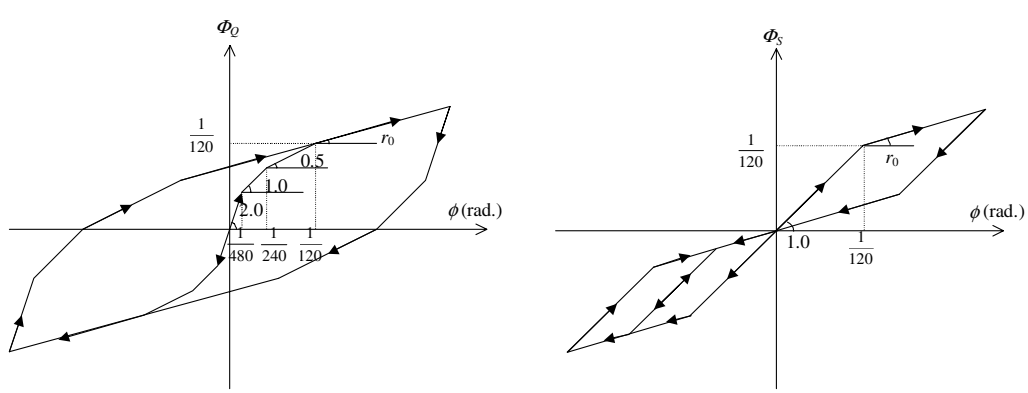


Fig.1 Analytical model with rigid floor



(a) Model 1 (b) Model 2

Fig.2 Plan of two analytical models



(a) Quadri-linear type (b) Slip type

Fig.3 Two restoring force models and yield rotational angles

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{Bmatrix}+\begin{bmatrix} C_x & 0 & 0 \\ 0 & C_y & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{Bmatrix}+\begin{Bmatrix} F_x \\ F_y \\ F_\theta \end{Bmatrix}=-\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix}\begin{Bmatrix} \ddot{x}_G \\ \ddot{y}_G \\ 0 \end{Bmatrix} \tag{1}$$

in which,

$$\left.\begin{aligned} C_x &= 2h_x\sqrt{K_x M} \quad \left(K_x=\sum_{i=1}^{n} {}_i k_x\right) \\ C_y &= 2h_y\sqrt{K_y M} \quad \left(K_y=\sum_{j=1}^{m} {}_j k_y\right) \end{aligned}\right\} \tag{2}$$

$$\left.\begin{aligned} F_x &= \sum_{i=1}^{n} {}_i f_x = \sum_{i=1}^{n} {}_i k_x\, {}_i\Phi_x\left({}_i u_x, {}_i\dot{u}_x\right) \\ F_y &= \sum_{j=1}^{m} {}_j f_y = \sum_{j=1}^{m} {}_j k_y\, {}_j\Phi_y\left({}_j u_y, {}_j\dot{u}_y\right) \\ F_\theta &= \sum_{i=1}^{n} {}_i f_x\, {}_i l_y - \sum_{j=1}^{m} {}_j f_y\, {}_j l_x \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} {}_i u_x &= x + {}_i l_y \theta \\ {}_j u_y &= x - {}_j l_x \theta \end{aligned}\right\} \tag{4}$$

In equations (1)-(4), M, I, C and F respectively are the mass, the rotational inertia, the viscous damping and the restoring force of the model, x_G and y_G the two directional displacements on ground due to the earthquake motions, f, k and Φ are the restoring force, the stiffness and the restoring force characteristics normalized by the horizontal stiffness at 1/120rad., and u the distance from the center-of-gravity to each plane. h is the critical damping ratio.

We simplify the model to two models; i.e. (a) uni-axial model (Model 1) and (b) bi-axial model (Model 2) as shown in Fig.2. The height is H=300cm for each. The unit weight is 1.8kN/m^2, considering a typical wooden-framed house. The ratio of the wall quantity of Y_1 and Y_2 planes for Model 1 is 0.5:0.5, and that of X_1 and X_2 planes is $(1-\alpha):\alpha$ for Model 1. The ratios of the wall quantities of Y_1 and Y_2 planes and X_1 and X_2 ones are both $(1-\alpha):\alpha$ for Model 2. We introduce restoring force characteristics of each plane referring to the simulation results for full-scale shaking tests[9]. The characteristics consist of a quadri-linear type and a slip type models as shown in Fig.3. The combination expression of these type models is as follows using a factor, γ:

$$\Phi = \gamma\Phi_Q + (1-\gamma)\Phi_S \tag{5}$$

in which, Φ_Q and Φ_S are respectively the quadri-linear type and the slip type models. We determine the 1st, the 2nd and the 3rd yielding rotational angles of the quadri-linear type model such as 1/480, 1/240 and 1/120rad. as shown in Fig.3. The yield rotational angle of the slip type model is chosen as 1/120rad. With regard to the last stiffness of the characteristics, r_0=0.3. The critical damping ratios of the two directions are h_x=h_y=0.05. The total horizontal stiffness K_x and K_y based on the wall quantity can be represented as follows:

$$K_{x,y} = \frac{1.3R_{x,y}S}{H/120}\times\lambda \tag{6}$$

in which, R and S are the wall quantity and the floor area, respectively. The constant 1.3(kN/m) corresponds to the strength when a wall displays 1/120rad. λ is a constant which means the magnification of the total horizontal stiffness, and we call it "stiffness factor" and choose λ=5 here.

We define the ductility factor which maximum rotational response is divided by 1/120rad. and the shear coefficient which the maximum restoring force is divided by a half weight. They will be shown as functions in the *x* and *y* directions, but in this case we do not mention the plane where the maximum value occurred. Concerning the damage of the structural models, we define three regions of none or slight, low and moderate levels and the corresponding ductility factors of them are less than 1.0, between 1.0 and 2.0 and between 2.0 and 3.0. When the factor exceeds 4.0, the damage is at a serious or collapsible level.
We use the three recorded earthquake motions of El Centro(1940), Hachinohe(1968) and JMA Kobe(1995) of which the maximum velocities are adjusted to 50cm/sec, and four simulated motions such as the Uemachi plateau 3-24, the Western Osaka 4-06, the Eastern Osaka 4-26 and the Reclaimed land 4-39, which are calculated under an assumption of Uemachi activity fault[10]. They are listed in Table 1. The EW and the NS components of the motions are used to *x* and *y* directions, respectively.

EARTHQUAKE RESPONSE CHARACTERISTICS

We show the relationships between the eccentric ratio, *Re*, and various responses in Models 1 and 2 of R_x=R_y=15cm/m^2, which corresponds to the minimum value prescribed by the BSLJ. Comparison of the response characteristics of Models 1 and 2 with the ones of a modified one-story mass system model (MMS), which rectified wall quantity by *Re*, is presented. The modification coefficient, c_T, of the wall quantity by *Re* for the one-stored mass system is expressed as follows:

$$c_T = \begin{cases} 1 & ; Re < 0.15 \\ 1/(3.33Re + 0.5) & ; 0.15 \le Re < 0.45 \\ 0.5 & ; Re \ge 0.45 \end{cases} \tag{7}$$

Fig.4 shows the ratio of the fundamental period of MMS with eccentricity to the non-eccentric period of 0.364sec. It is found that when the period becomes longer, *Re* becomes larger in Models 1 and 2, and this tendency of Model 2 is remarkable compared with Model 1. It is recognized that the difference of the periods of Models 1 and 2 is not clear when *Re*<0.3. The ratios of both models about are 1.1 at *Re*=0.3 which is the maximum value prescribed by BSLJ. When *Re* becomes larger, the difference between both ratios gets larger, too. Finally the ratio in Model 2 is about 1.3 times that of Model 1 at *Re*=1.0.

Table1 Recorded and simulated earthquake motions for analysis

Input earthquake motions			a_{max} (cm/sec^2)	v_{max} (cm/sec)
Recorded motions	El Centro 1940	NS	341.7	38.5
		EW	210.1	56.9
	Hachinohe 1968	NS	311.7	56.6
		EW	306.2	42.5
	JMA Kobe 1995	NS	818.0	90.3
		EW	617.3	76.3
Simulated motions	Uemachi plateau 3-24	NS	749.8	187.7
		EW	754.8	123.2
	Western Osaka 4-06	NS	518.2	84.4
		EW	664.1	94.5
	Eastern Osaka 4-26	NS	680.7	81.5
		EW	726.8	77.7
	Reclaimed land 4-39	NS	331.9	52.5
		EW	433.2	69.9

Fig.5 (a) and (b) show the ductility factors, μ, in the x and y directions for Models 1 and 2 subjected to EW and NS components of the earthquake motions and include the ones of MMS to NS component. The thick, the ordinary and the thin lines in the figure indicate the response results of El Centro, Hachinohe and JMA Kobe, respectively. The solid and the dashed lines show the results in the x and y directions, respectively, and the chain line is the result of MMS.

From the figures, we can see that μ increases rapidly when Re>0.2-0.3 and varies greatly. Figure 5(a) shows that μ in the y direction with eccentricity is large compared with x direction without eccentricity, and affects μ in the x direction. In the cases of El Centro and Hachinohe, μ exists between 0.6 and 1.5 when Re<0.2, and the damage corresponds to the none or slight level. When Re>0.2 in the case of El Centro, μ increases rapidly and reaches to about 2, and the damage corresponds to the moderate level at Re=0.3. When Re>0.6, μ becomes 4 or more and the damage corresponds to the serious or collapsible level. In the case of JMA Kobe, μ is about 2.1 at Re=0, the damage corresponds to the moderate level, and the damage becomes greater with an increase in Re, and it reaches the serious or collapsible level.

In figure 5(b) μ increases gradually when 0<Re<0.2, and this is the same as the tendency of the figure (a). However, when Re>0.2 the tendency differs from figure (a). μ in the both directions increase rapidly and are almost the same. The response becomes the maximum value when Re=0.4-0.8, and it decreases when Re>0.8 as in the case of JMA Kobe. The ductility factor of MMS in Fig.5 is compared with the ones in the y direction of Models 1 and 2. The response characteristics of MMS are similar to those of both models. The damage level of MMS agrees with the ones of the two models Re<0.45 but it becomes different when Re>0.45 because the response of MMS is small. Therefore, in the case of wooden-framed houses having large eccentricity, they may suffer from serious earthquake damage.

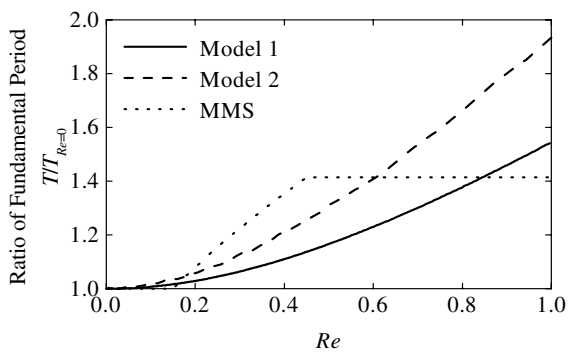
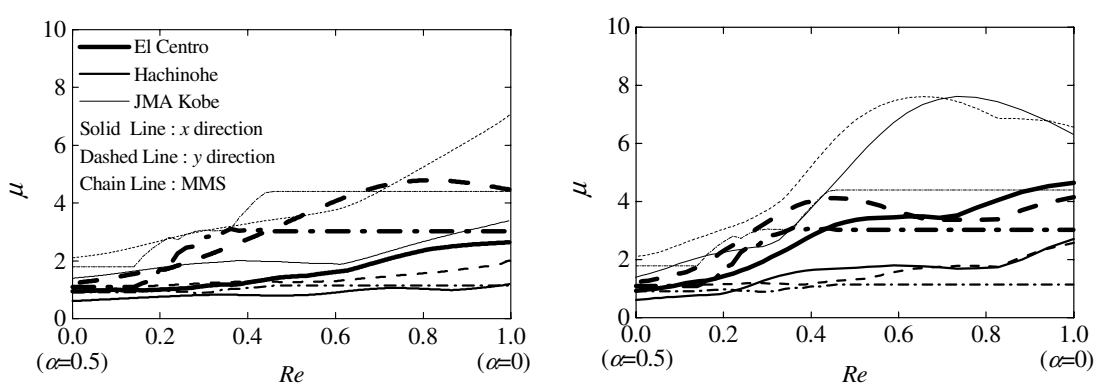


Fig.4 Ratio of fundamental period of eccentric to the one of non-eccentric models



(a) Model 1 (b) Model 2

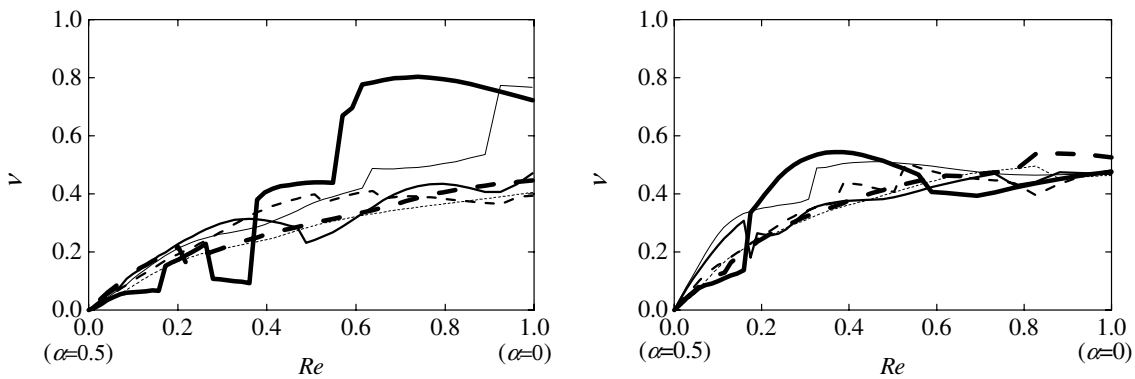
Fig.5 Re-μ Relation

Fig.6 indicates the relationship of the rate of torsion contributable to the displacement factor and *Re*. Here the contribution factor is $\nu = l\theta / u$. Compared with results of Models 1 and 2, ν in Model 1 varies greatly by the difference of the earthquake motions, and this tendency is remarkable as *Re* becomes larger. Figure 6(a) shows that ν increases when $0<Re<0.5$ of all earthquake motions and that almost all the values of ν converge to around 0.4 when $Re>0.5$. The characteristics of ν are sensitive to the change in *Re*. This is because the occurrence time of the maximum displacement response differs as *Re* changes. Except for result in the *x* direction of El Centro, the tendency of figure (a) is almost the same as figure (b) and ν is about 0.5 when $Re>0.5$. This result means that the influence of eccentricity on the earthquake responses is not clear when $Re>0.5$.

Fig.7 shows the base shear coefficients, C_B, of Models 1 and 2 and MMS, which correspond to Fig.5. The variation of the coefficient of Model 1 is remarkable compared to Model 2. Except for the result of MMS, the coefficient increases slightly as *Re* increases.

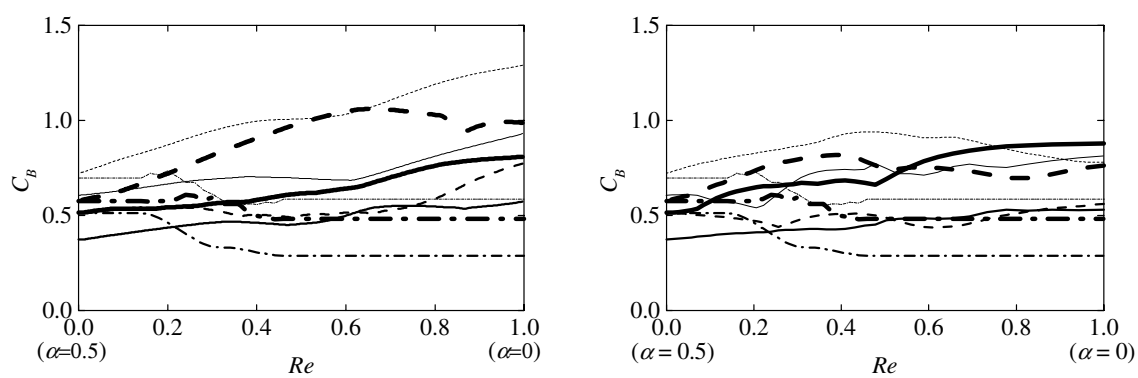
EFFECT OF WALL QUANTITY ON VIBRATION CONTROL

The effect of the increase of the wall quantity of the orthogonal direction on the vibration control is examined for the uni-axial eccentric model (Model 1). The wall quantity in the *y* direction with eccentricity is constant as R_y=15cm/m^2. The wall quantity, R_x, in the *x* direction, which is perpendicular to the eccentric plane, changes from 10 to 50cm/m^2, and the characteristics of the ductility factor and the corresponding shear force coefficient are shown. The eccentricity α={0.5, 0.4, 0.3, 0.2, 0.1, 0.0} and then *Re*={0.0, 0.1, 0.3, 0.5, 0.7, 1.0}.



(a) Model 1 (b) Model 2

Fig.6 *Re*-ν Relation



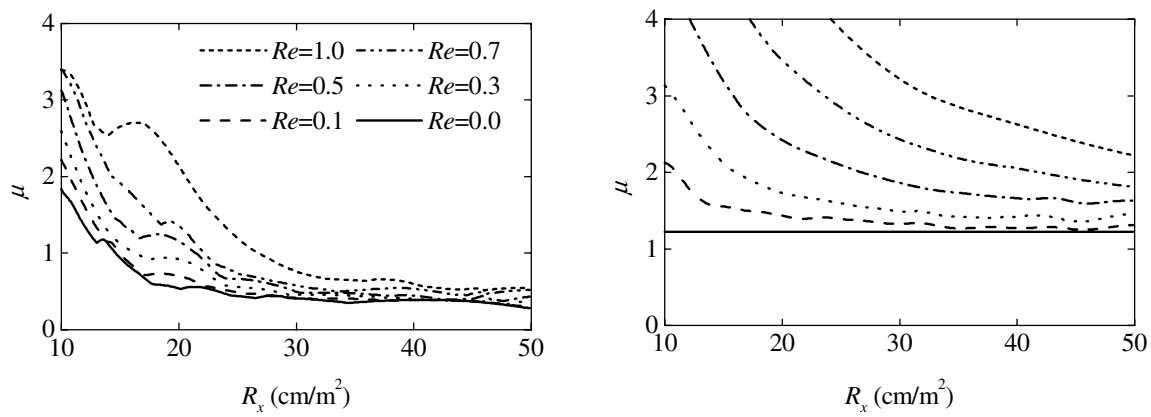
(a) Model 1 (b) Model 2

Fig.7 *Re*-C_B Relation

Fig.8 shows the relationships of ductility factors, μ, in the x and y directions and the wall quantity in the x direction, R_x, as a parameter of Re in the case of El Centro. It is seen that the variation of μ is large in $10<R_x<30$cm/m^2 by the change of Re, and that μ decreases rapidly with the increase in R_x. When $R_x>30$cm/m^2, μ in the x direction becomes small and turns into a constant value, and the variation of μ decays by the change in Re. The damage is at the low level at Re=0. $\mu<2$ when $Re<0.5$ and $R_x>30$cm/m^2, and its damage corresponds to the low level and is the same level of the non-eccentric model.

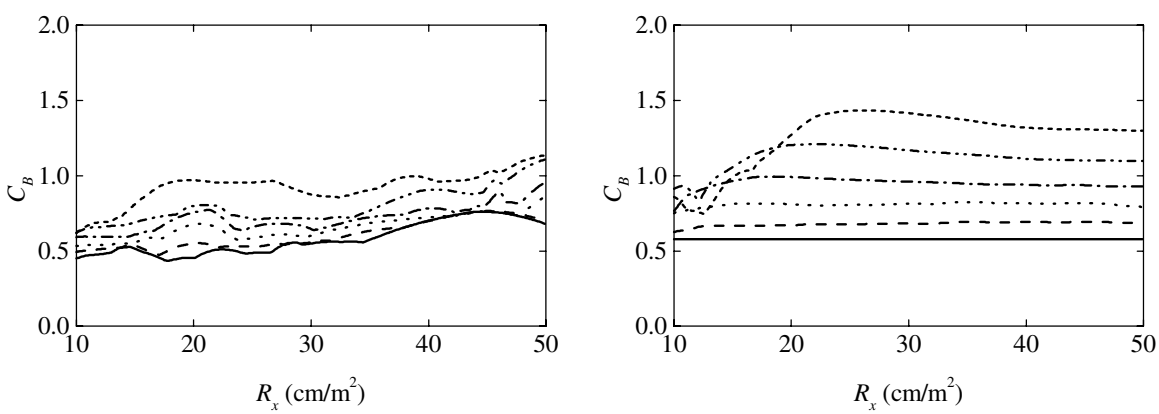
Fig.9 shows the relationship between R_x and C_B corresponding to Fig.7. From the figure (a), it is found that C_B varies gradually as R_x increases and exists within 0.5-1.2. From the figure (b), it is recognized that C_B becomes stable and constant over all values of Re when $R_x>30$cm/m^2. This means that the increase of the wall quantity of the orthogonal direction does not relate to the increase of the horizontal strength or stiffness of the model, directly. This is the case that the wall quantity is more than twice that of the wall quantity of the eccentric direction.

Fig.10 and Fig.11 are the results in the case of JMA Kobe. In the Fig.10, μ of the x direction decreases rapidly when $10<R_x<25$cm/m^2 and becomes 0.3-2.0 when $R_x>25$cm/m^2. The damage in the x direction is at the same level as the non-eccentric model in the y direction when $Re<0.5$. The variation of μ is small as compared with the result of El Centro. C_B has almost the same tendency and same value in the case of El Centro.



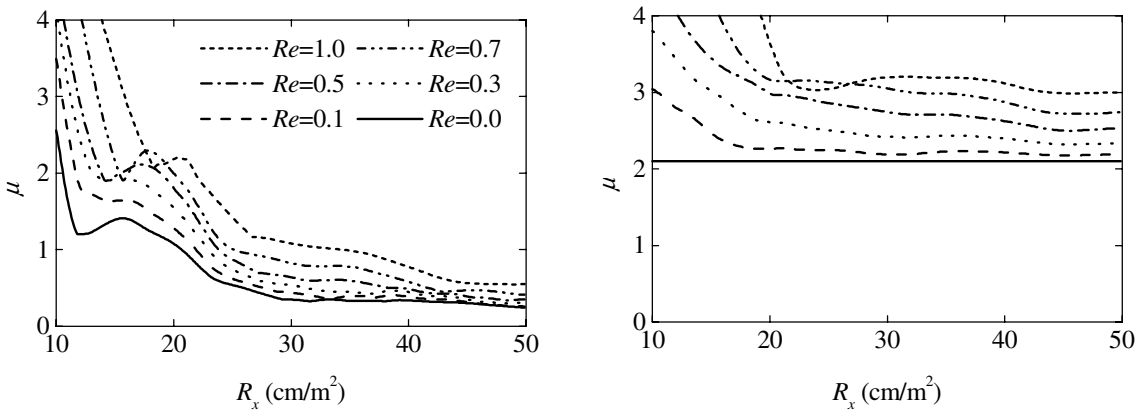
(a) x direction (b) y direction

Fig.8 μ and R_x relationship of Model 1 in case of El Centro



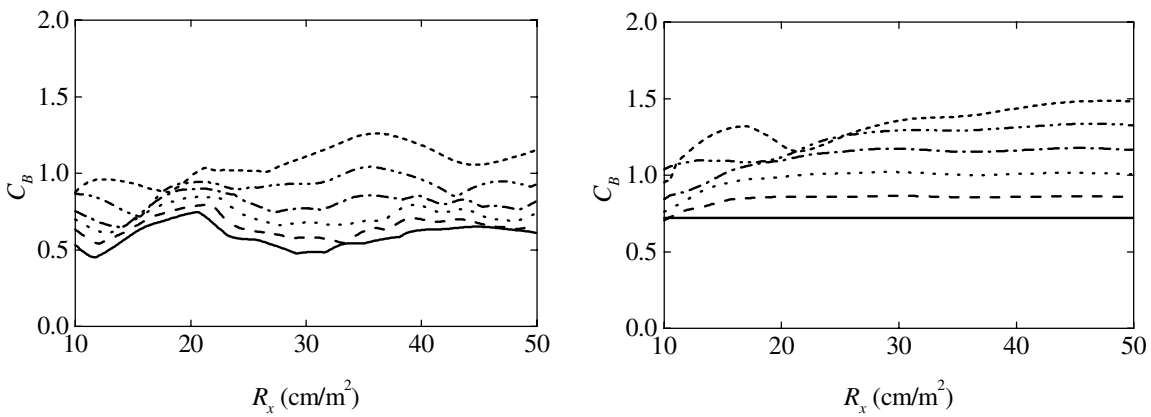
(a) x direction (b) y direction

Fig.9 C_B and R_x relationship of the Model 1 in case of El Centro



(a) x direction (b) y direction

Fig.10 μ and R_x relationship of Model 1 in case of JMA Kobe



(a) x direction (b) y direction

Fig.11 C_B and R_x relationship of the uniaxial in case of JMA Kobe

As a result, when the wall quantity in the orthogonal direction is twice that of the eccentric direction, the damage would be at the same level as the non-eccentric model under the assumption of the uni-axial eccentric model where the wall quantity in the non-eccentric direction is 15cm/m^2 and Re<0.5.

DAMAGE PREDICTION OF THE MODEL

We try to predict the damage of the wooden-framed house models subjected to the simulated motions in Table 1, as functions of eccentric ratios and wall quantity. We also obtain the required wall quantity coefficient, which is a ratio of the wall of the eccentric model to the non-eccentric model, so that the damage of both models are the same. The models used are shown in Fig.2. The wall quantities are R_x=R_y (namely, K_x=K_y), and α is changed to make the models eccentric. The required wall quantities are calculated by the iteration method, and the shear coefficient quantity is calculated from the wall quantities. The damaged regions of Model 1 are shown in Fig.12, which were obtained from the previous four damage levels for the eccentric ratio, Re, and the wall quantity, R, and the shear coefficient, C_B, subjected to the motion of Uemachi Plateau 3-24. R and C_B increase with Re, and R requires 18cm/m^2 and 23cm/m^2 at Re=0 and 0.3 at least. This model does not suffer from serious damage but collapses. In case of the wall quantity of the minimum value, the damage must reach the serious or collapsible level. The required wall quantities are respectively 31cm/m^2 and 38cm/m^2 at Re=0 and 0.3, so that damage of the model is at the

low level. From the figure on the right, it is found that the shear coefficient seems to be independent of the damage levels and increases little by little with *Re*.

Fig.13 is the result of Model 1 in case of Reclaimed Land 4-39 and both of the wall quantity and the shear coefficient are small compared with Fig.12. This is because the maximum acceleration and velocity values of the motion are small and the spectrum characteristics differ with each other.

Figs.14 and 15 show results of Model 2. Fig.14 shows that the required wall quantity to make the damage of the model to be at a low level increases rapidly when *Re*>0.4. However, *R* in Fig.15 depends on *Re*, and is almost constant, and the values of *R* is about 10, 14, and 17cm/m^2, which express the limitations of low, moderate, and serious or collapsible levels, respectively.

Fig.16 indicates the wall quantity and the damage level of the non-eccentric model subjected to four simulated motions. Irrespective of the damage level, the wall quantity in the case of Uemachi Plateau 3-24 is the largest. When the wall quantity is 15cm/m^2, the damage for three motions except Reclaimed Land 4-39 are at the serious and collapsible level. It turns out that the required wall quantity to make a model be below the serious or collapsible level is about 20cm/m^2.

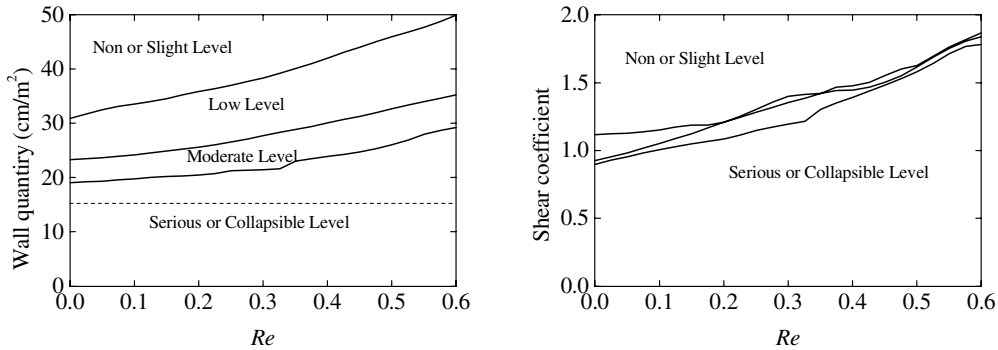


Fig.12 Damage level obtained from R_e and R, or C_B (Standard earthquake 3-24, Model 1)

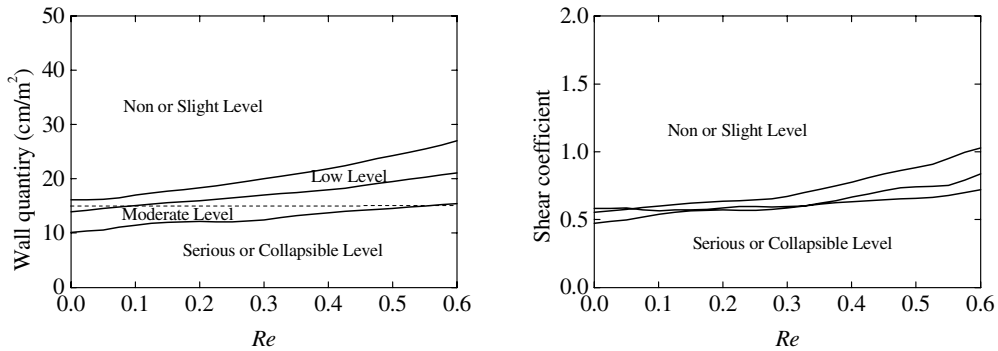


Fig.13 Damage level obtained from R_e and R, or C_B (Standard earthquake 4-39, Model 1)

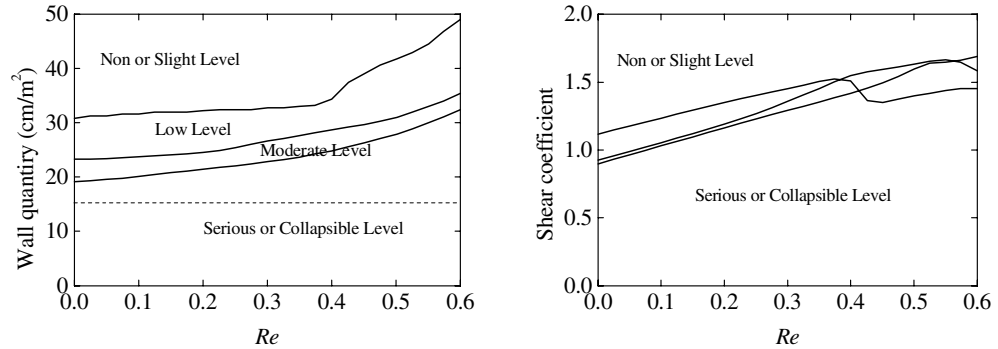


Fig.14 Damage level obtained from R_e and R, or C_B (Standard earthquake 3-24, Model 2)

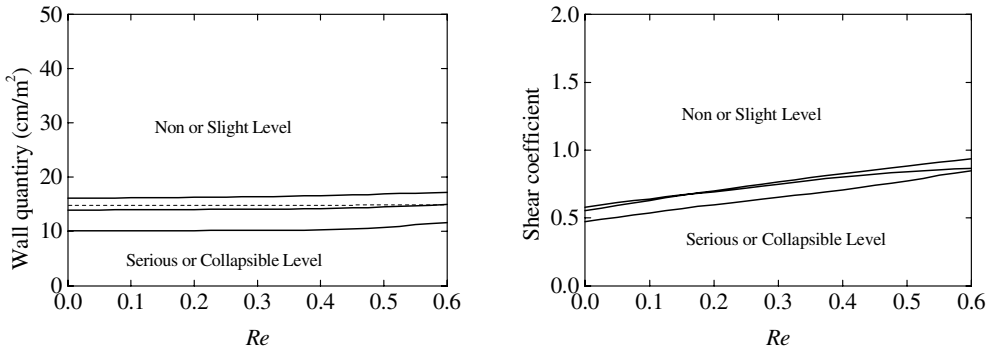


Fig.15 Damage level obtained from R_e and R, or C_B (Standard earthquake 4-39, Model 2)

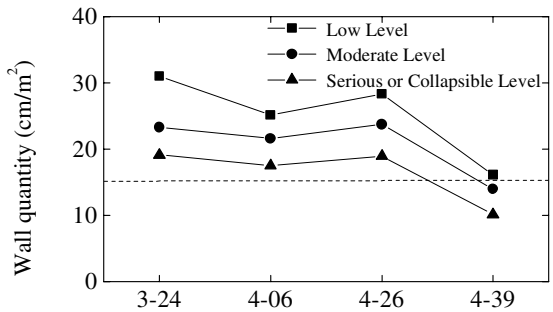
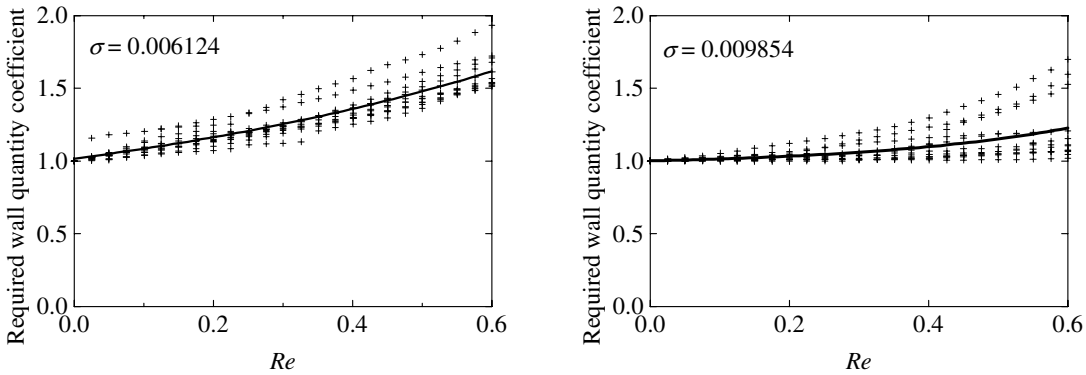


Fig.16 Relations between wall quantity and damage level of non-eccentric model (Osaka Standard Earthquake Motions)



(a) Model 1 (b) Model 2

Fig.17 Required wall quantity coefficient (Osaka Standard Earthquake Motions)

In order to examine how much should the wall quantity increase in an eccentric model compared to a non-eccentric model, we introduce a "required wall quantity coefficient" and estimate it. The coefficient is the wall quantity of the eccentric model divided by the non-eccentric model referring to the respective damage levels. Fig.17 shows the relationship of the required wall quantity coefficient and the eccentric ratio for Models 1 and 2. The plotted marks show twelve kinds of calculation results, which were obtained from the three limit ductility factors corresponding to the limitations of low, moderate, and serious or

collapsible levels of the models subjected to the four motions. The required wall quantity coefficient exponentially increases against *Re*. The increasing rate of Model 1 is larger than the one of Model 2. From the figures, it is recognized that the required wall quantity coefficient increases exponentially with the increase of the eccentric ratio. The rate of increase of Model 1 is larger than the Model 2. The difference for the required wall quantity coefficient is not seen by the difference in the motions or damage levels. Hence, we try to use regression analysis on the relationship between the eccentric ratio, *Re*, and the required wall quantity coefficient, c_W. The regression curve of c_W is obtained by the least square method and is shown with the solid line in the figures, and the regression functions are obtained as following for the two models;

$$c_W = 0.562 + 0.715e^{(Re-0.323)/0.712} \quad \text{(Model 1)} \tag{8}$$

$$c_W = 0.967 + 0.689e^{(Re-0.885)/0.292} \quad \text{(Model 2)} \tag{9}$$

Substituting *Re*=0.3 into equations (8) and (9), c_W for Models 1 and 2 are 1.25 and 1.06, respectively. The required wall coefficient of Model 2 is smaller than Model 1. It is because the fundamental periods are differing as shown in Fig.4 and the different spectral characteristics of the motions among them originate even when *Re* of the two models are the same. The standard deviations, σ, of the regression curves are 0.006 and 0.009 for Models 1 and 2, respectively, and these values are very small.

CONCLUSIONS

We presented the relationships among the eccentric ratio, *Re*, the ductility factors and the shear coefficients in cases of wooden-framed house models having uxi- and bi-axial eccentricities subjected to the recorded earthquake motions. We examined the vibration control effect and predicted the damage of the models using the recorded and the simulated earthquake motions. The results obtained lead to the following conclusions:

1) In cases of uni- and bia-xial eccentric models, when *Re* becomes larger than 0.2-0.3, the ductility factor increases rapidly. Therefore, even if *Re* is smaller than 0.3, the damage of the eccentric model may become greater than the level of the non-eccentric model. If *Re* becomes large, the influence of the torsion exerted on a displacement response is remarkable, and the contribution rate of torsion is a half the total amount of modification. The shear coefficient at *Re*=0.3, which is the limit, will be about 1.5 times that of *Re*=0.
2) In the case of the uni-axial model when *Re*<0.5, if the wall quantity of the orthogonal direction is given to be twice that of the eccentric direction, the damage of the eccentric model will be at the same level as the damage of the non-eccentric model. Even though the number of shear walls perpendicular to the eccentric plane of the model is doubled, the corresponding strength of the wall equals or is less than double the strength. This tendency is the same even if the earthquake motions are different.
3) The damage predictions were carried out for the wall quantity and the eccentric ratio for the uni-axial and the bi-axial models subjected to the Osaka Standard Earthquake motions. When the wall quantity of the model at *Re*=0.3 is 1.3 times larger than the model at *Re*=0, then the damage levels of both models are the same. From this result, the regressive expressions of the required wall quantity coefficient of uni- and bi-axial models were shown.

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