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A DISCUSSION OF THE EFFECT OF TORSIONAL OSCILLATION OF FULL-SCALE WOODEN HOUSES ON EARTHQUAKE RESPONSE CHARACTERISTICS

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SUMMARY

When building structures with non-uniform mass or stiffness are subjected to earthquake ground motions, torsional oscillation due to the rotation of floors will be caused. Bearing shear walls of most wooden houses are not arranged uniformly, hence such wooden structures have eccentricity and the influence of torsional oscillation cannot be neglected when discussing earthquake response characteristics. We present earthquake response characteristics with torsional oscillation for full-scale wooden-framed house models having eccentricity, and also elasto-plastic restoring-force characteristics. The ductility factor and the base shear coefficient of the respective frames consisting of the models, are shown, and the differences of dynamic response properties between our model and a damped mass system one are made clear.

INTRODUCTION

When building structures with non-uniform mass or stiffness are subjected to earthquake ground motions, torsional oscillation due to the rotation of floors will be caused[1)]. Bearing shear walls of most wooden houses are not arranged uniformly. Therefore, such wooden houses have eccentricity and the influence of torsional oscillation cannot be neglected when discussing earthquake response characteristics.
In this paper, we show the earthquake response characteristics with torsional oscillation of full-scale wooden frame house models when subjected to the recorded ground motions[2)]. Here, the responses of the models, whose mass and stiffness are non-uniform, represent the ductility factors and the base shear coefficients of the frames from which the models are built. We examine the effect of the rotation component by torsional oscillation on the total deformation of the models. The general characteristics of the earthquake responses of the wooden house models with uniaxial and biaxial eccentricities and the response characteristics of two kinds of models are also shown.

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ANALYTICAL METHOD

In order to discuss the torsional oscillation due to the rotation of floors or building structures with non-uniform mass or stiffness when subjected to earthquake ground motions, we use a simple one-story structural model (Fig.1) instead of a full-scale wooden-framed house. The model is assumed to have a rigid floor. In this figure, the frames with stiffnesses, ${}_i k_x$ and ${}_j k_y$, are positioned, in which the suffixes, i and j,represent the number of frames in the x and y directions. The motion of the floor is prescribed by the two horizontal displacements, x and y, and the rotation angle, θ, at the center of gravity. Therefore, this model is 3-degree-of-freedom system (x, y and θ). When the structural model is subjected to two-directional earthquake ground motions ($\ddot{x}_G$, $\ddot{y}_G$), as shown in Fig.1, the equations of motion on the horizontal displacement and the rotation angle at the center of gravity of the rigid floor are as follows:

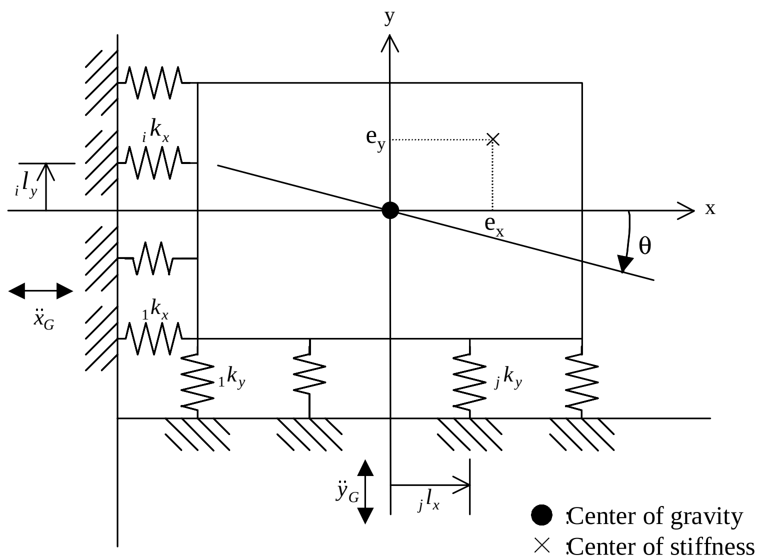


Fig. 1 1-story structural model with rigid floor (plan)

$$M\ddot{x} + C\dot{x} + \sum {}_i F_x = -M\ddot{x}_G \tag{1}$$

$$M\ddot{y} + C\dot{y} + \sum {}_j F_y = -M\ddot{y}_G \tag{2}$$

$$I\ddot{\theta} + \sum {}_i l_{x\,i} F_x - \sum {}_j l_{y\,j} F_y = 0 \tag{3}$$

in which, M = mass; C = viscous damping; and $F_\kappa(\kappa = x, y)$ = the restoring-force of the respective frames. By introducing the yield rotational angle, ${}_i\delta_\kappa$, and the distance from each frame to the center of gravity, $l_\kappa(\kappa = x,\ y)$, we can rewrite F_κ of the Eq. (3) as Eq. (4).

$${}_i F_\kappa = {}_i F_\kappa\left({}_i u_\kappa, {}_i k_\kappa; {}_i \delta_\kappa\right) \tag{4}$$

in which

$${}_i u_x = x + {}_i l_y \theta \tag{5}$$

$${}_j u_y = y - {}_j l_x \theta \tag{6}$$

Let $z(=i\theta)$ denote the product of the radius of rotation, *i*, and the rotation angle, θ. Then Eqs. (1)-(3) can be rewritten as follows:

$$\begin{Bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{Bmatrix}+\begin{bmatrix}2h_x\omega_x & 0 & 0\\ 0 & 2h_y\omega_y & 0\\ 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{Bmatrix}+\begin{bmatrix}\omega_x^2 & 0 & \omega_x^2\bar{e}_y\\ 0 & \omega_y^2 & -\omega_y^2\bar{e}_x\\ \omega_x^2\bar{e}_y & -\omega_y^2\bar{e}_x & \omega_\theta^2\end{bmatrix}\begin{Bmatrix}\Phi_x\\ \Phi_y\\ z\end{Bmatrix}=\begin{Bmatrix}-\ddot{x}_G\\ -\ddot{y}_G\\ 0\end{Bmatrix} \tag{7}$$

in which

$$\{\bar{e}_x,\bar{e}_y\}=\{e_x/i,e_y/i\} \tag{8}$$

where $\bar{e}_x$ and $\bar{e}_y$ are called as the eccentricity ratios that mean the ratio of eccentric distance, $e_\kappa(\kappa = x,\ y)$ to the radius of rotation, *i*.

The horizontal stiffness of a building is prescribed by wall ratio and is expressed by the following equation[3).

$$K=\lambda\kappa \tag{9-1}$$

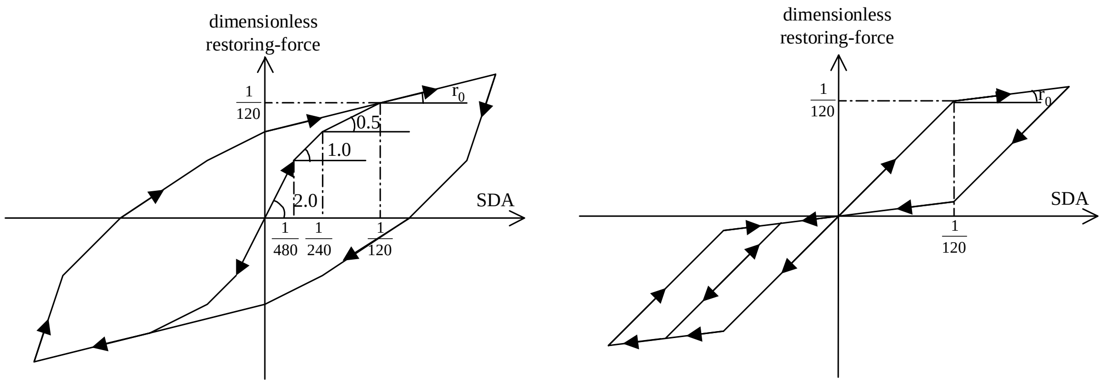
$$\kappa=\frac{0.13RS}{H/120} \tag{9-2}$$

in which K = the total horizontal stiffness of structure; k = the horizontal stiffness of bearing shear wall calculated from the wall ratio ; λ = the stiffness factor ; R = the wall ratio ; S = the area of floor ; and H = the height. The coefficient, 0.13 (ton/m) represents the standard strength of a bearing shear wall per unit length (1m) for the wall factor 1.0 when the wall deforms to 1/120 (rad).

ANALYTICAL MODELS

Figs. 2 (a) and (b) show two hysteretic characteristics - (a) represents the quadri-linear type, and (b) the slip one –, and these are used at the rate of 4:6 (combination factor γ = 0.4). In this analysis, the final plastic dimensionless stiffness ratio, r_0 = 0.3 of hysteretic characteristics, is selected with reference to the secant stiffness at the time of 1/120 (rad) deformation. The respective yield angle points of the hysteretic characteristics are shown in the figure. The critical damping ratio of the models is h_κ = 0.05 (κ = x, y direction).

The values of floor area, weight, unit weight, height, wall ratio, eccentric ratio and eccentric distance for the two full-scale wooden framed house models[4), Models A and B, introduced to the analysis are listed in Table 1. The unit weights of both models are almost average values of wooden framed houses. The wall ratio of the y direction for the models is a little bit larger than the one for the x direction. It is clear from Table 1 that Model A can be regarded as a uniaxial (y direction) eccentric model. The eccentric ratios of the two directions of Model B are almost the same, and therefore Model B must be a biaxial eccentric model. Figs. 3 and 4 show the arrangement of the columns and the walls, and the frame number of the two directions of Models A and B, respectively. Symbols ● and × in the figure represents the positions of the center of gravity and the center of stiffness, respectively. The thick solid line in the figure represents the shear wall of about 91cm, and all of the wall ratios are assumed to be 1.0. Model A has 14 (A-N) and 7 (1 - 7)frames in the x and y directions, respectively. On the other hand, Model B has 9(A-I) and 8 (1 - 8) frames, respectively.



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

Fig. 2 Two kinds of hysteretic characteristics

Table 1 Properties of two analytical models

		Model A	Model B
Floor area (m²)		121.32	98.37
Weight (kN)		238.04	163.37
Unit weight (kN/m²)		1.96	1.66
Height (cm)		300	300
Wall ratio (cm/m²)	x	22.50	19.84
	y	28.13	26.69
Eccentric ratio	Rex	0.021	0.085
	Rey	0.229	0.073
Eccentric distance (cm)	x	1.21	-56.07
	y	119.82	38.85

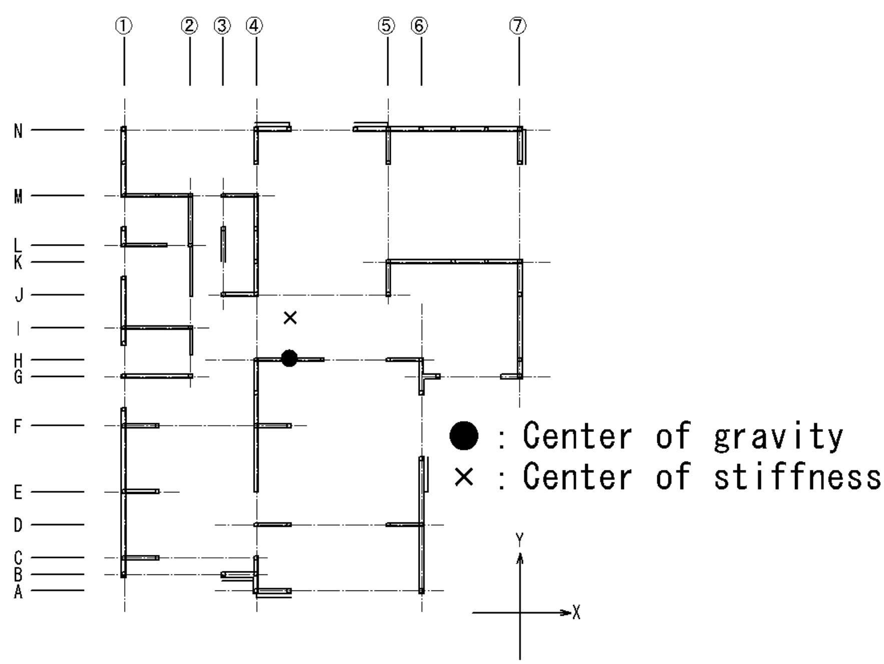


Fig. 3 Bearing shear walls and frame numbers of Model A (plan)

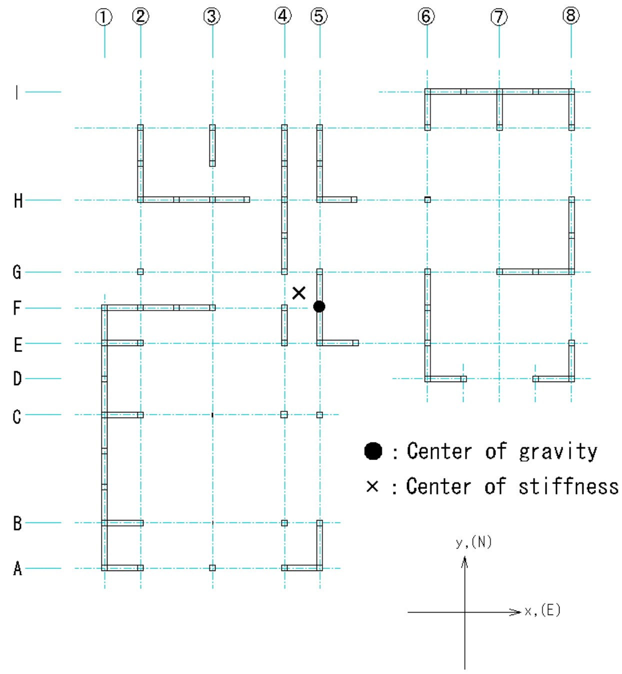


Fig. 4 Bearing shear walls and frame numbers of Model B (plan)

Table 2 shows the natural periods for 3-dimensional (3-D) models and the models replaced by a damped mass system. Here, a stiffness factor of $\lambda = 4$ is introduced on the basis of past studies. The 1st and 2nd natural periods of the 3-D model correspond to the ones, written in parentheses, of the x and y directions of the damped mass system model, respectively. The 1st natural period of Model A is slightly longer than the one of the damped mass system model. This means that the interaction effect appears on the period when torsional oscillation is thought to occur in the 3-D model. However, this difference in the period may be neglected. Model A is regarded as the uniaxial eccentric model, and therefore the 2nd natural period is actually in agreement with the damped mass system model one. In Model B, the natural periods of the 3-dimensional model are longer than the damped mass system model ones in the x and y directions. This means that the influence of torsional oscillation on the period can be seen in Model B. Model A has a longer natural period than the one of Model B.

Table 2 Natural period

		Model A	Model B
Natural period of 3-dimensional structural models (sec)	1st	0.370(0.352)	0.341(0.338)
	2nd	0.314(0.314)	0.299(0.292)
	3rd	0.276	0.260

From the solution of the eigen equation, the three eigen vectors, $\mathbf{u}_1$, $\mathbf{u}_2$ and $\mathbf{u}_3$ show the 1st, 2nd and 3rd eigen vectors, respectively. The x and y components are dominant in vectors $\mathbf{u}_1$ and $\mathbf{u}_2$, respectively. It is clear that the rotation component is more dominant in vector $\mathbf{u}_3$ as compared with $\mathbf{u}_1$ and $\mathbf{u}_2$. The values of eigen vectors are as follows.

Comparison of eigen vectors: $$\mathrm{u} = \begin{Bmatrix} x \\ y \\ \theta \end{Bmatrix}$$

For Model A:

$$\mathbf{u}_1 = \begin{Bmatrix} 1.000 \\ -0.004 \\ -0.001 \end{Bmatrix} \qquad \mathbf{u}_2 = \begin{Bmatrix} 0.006 \\ 1.000 \\ 0.000 \end{Bmatrix} \qquad \mathbf{u}_3 = \begin{Bmatrix} 1.000 \\ -0.021 \\ 0.005 \end{Bmatrix}$$

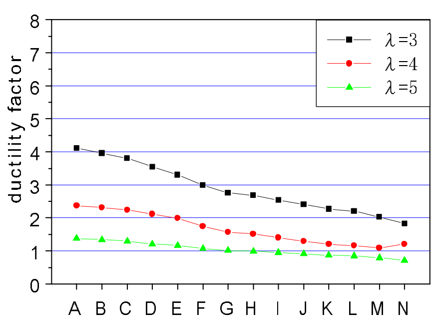
For Model B:

$$\mathbf{u}_1 = \begin{Bmatrix} 1.000 \\ 0.050 \\ -0.000 \end{Bmatrix} \qquad \mathbf{u}_2 = \begin{Bmatrix} -0.116 \\ 1.000 \\ -0.001 \end{Bmatrix} \qquad \mathbf{u}_3 = \begin{Bmatrix} 0.216 \\ 1.000 \\ 0.004 \end{Bmatrix}$$

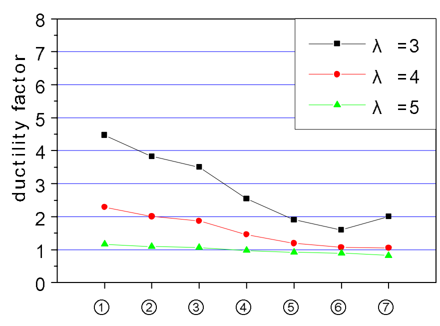
RESULTS

In this paper, the NS and EW components of El Centro recorded accelerograms (1940) are introduced in the analysis. The maximum velocity value of the NS component is adjusted to 75 cm/sec, so called as Level 3. The NS and EW components are used as input ground motions in the y and x directions of the model, respectively. The ductility factor response μ in this study is defined as a value in which the maximum deformation angle is normalized by the yield angle 1/120 (rad) for the models. The coefficient of base shear is a value in which absolute acceleration of response is normalized by the gravitational acceleration. When μ exceeds 4.0, it is assumed that the corresponding model suffers severe damage or collapse. This is the severest criterion. The other criteria are determined by damage levels in proportion to the angle responses.

Figs. 5 and 6 show the relationship between the ductility factor response μ and the respective frames of x and y directions for Models A and B, respectively. In the figures, the stiffness factor value λ (= 3, 4, and 5) is used as a parameter. In Model A, it is seen that the μ is large in frame A of the southern end side and in frame 1 of the western end side (see Fig. 5). In case of λ =3, however, the total horizontal stiffness of the model is underestimated, and therefore, the frames 1 and A remarkably deform. When λ = 4 and 5, however, no model suffers severe damage. On the other hand, in Model B, μ of all frames does not remarkably deform. In frame 8, the μ is slightly larger than the other frames in the x and y directions.



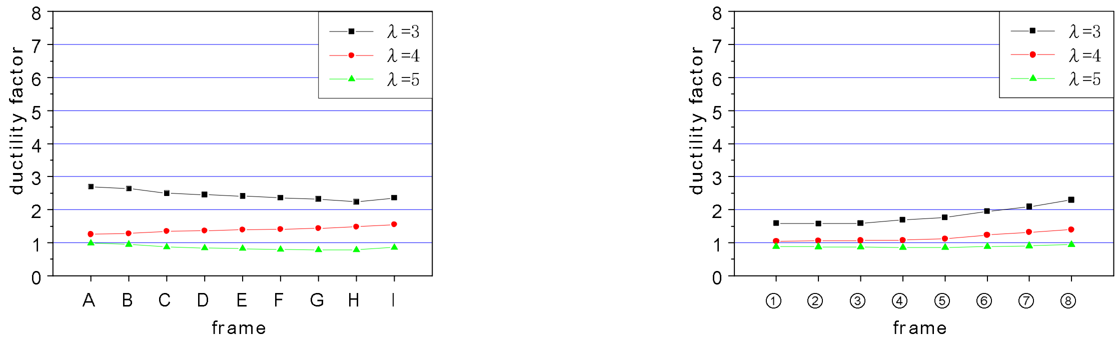
(a) x direction



(b) y direction

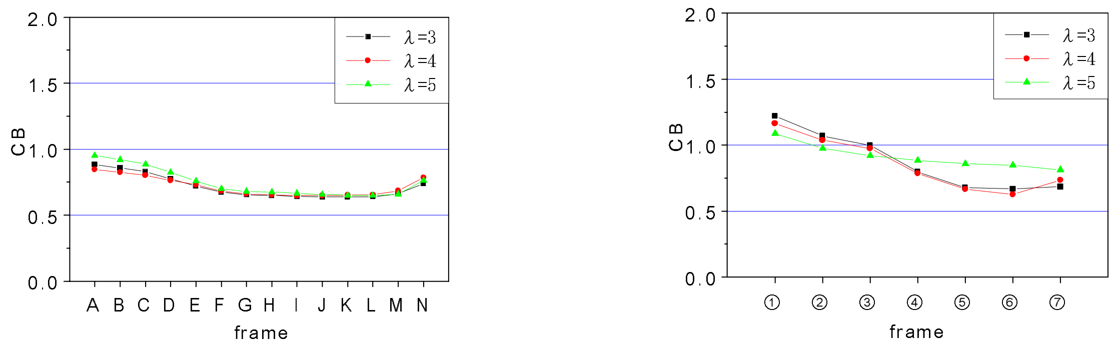
Fig. 5 Ductility factor response (Model A)

The relationships between the coefficient of base shear, CB, corresponding to the ductility factor response, and the respective frames are shown in Figs.7 and 8 for Models A and B, respectively. The CB of the y direction is larger than that of the x direction. It is clear from Table 1 that the wall ratio of the y direction is 6-7 cm/m^2 larger than that of the x direction.
Figs. 9 and 10 show the contribution of the rotational component to the ductility factor response for the two models. These figures show that the degree of contribution in Model A is larger than that of Model B.



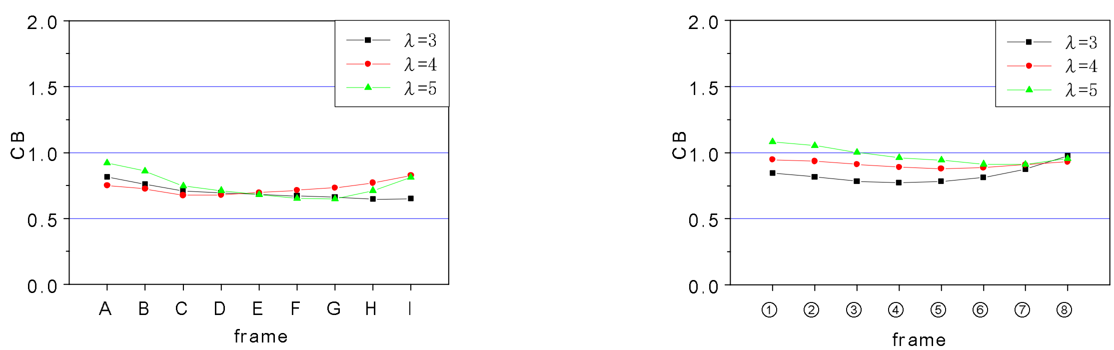
(a) x direction **(b) y direction**

Fig. 6 Ductility factor response (Model B)



(a) x direction **(b) y direction**

Fig. 7 Coefficient of base shear, CB (Model A)

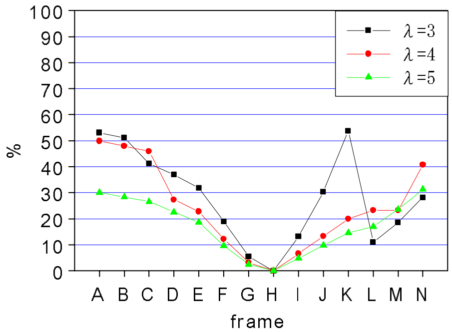


(a) x direction **(b) y direction**

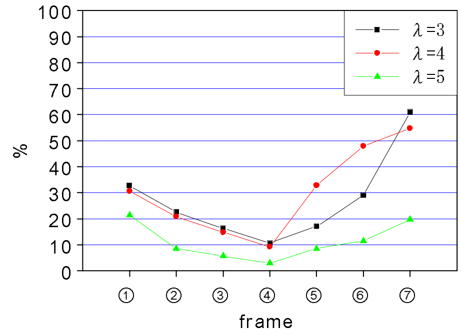
Fig. 8 Coefficient of base shear, CB (Model B)

It is obvious that the maximum contribution is about 70 %, that of the end frame is larger, and that there is no contribution on the frame, which is at the center of gravity position. However, we can see some frames with a different tendency when the maximum μ or the maximum rotation angle occur in a frame. This is a case of the difference of the time between the maximum occurrences.

Figs.11 and 12 show the maximum deformation of $l\theta$ with the rotation component as a function of the frame numbers for the two models. From the result for Model A , in the case of λ = 3, almost all frames enter into the plastic region, and in some frames the μ approaches the value of 3. In the case of λ = 4 and 5, its value is smaller than 2. In the case of Model B, no frame enters into the plastic region.

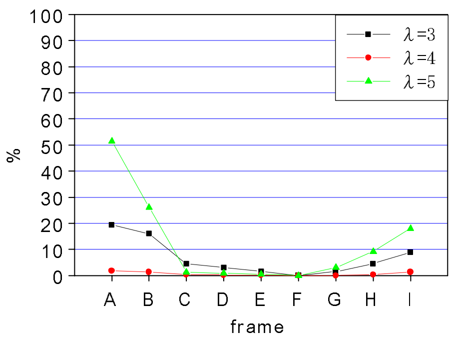


(a) x direction

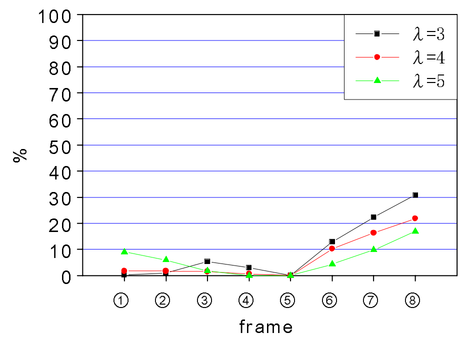


(b) y direction

Fig. 9 Contribution of rotation component to the maximum deformation (Model A)

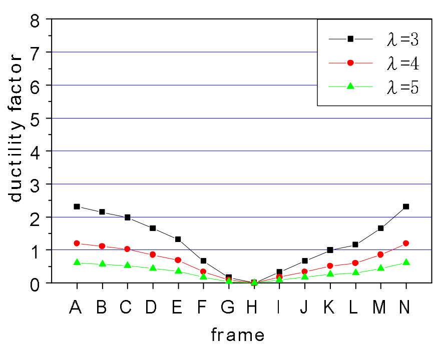


(a) x direction

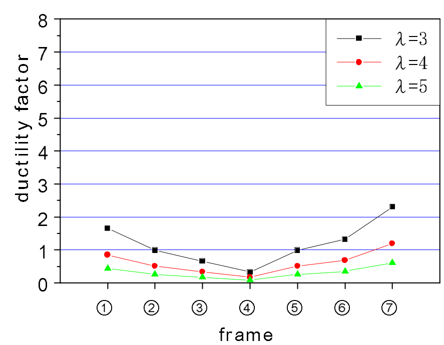


(b) y direction

Fig. 10 Contribution of rotation component to the maximum deformation (Model B)

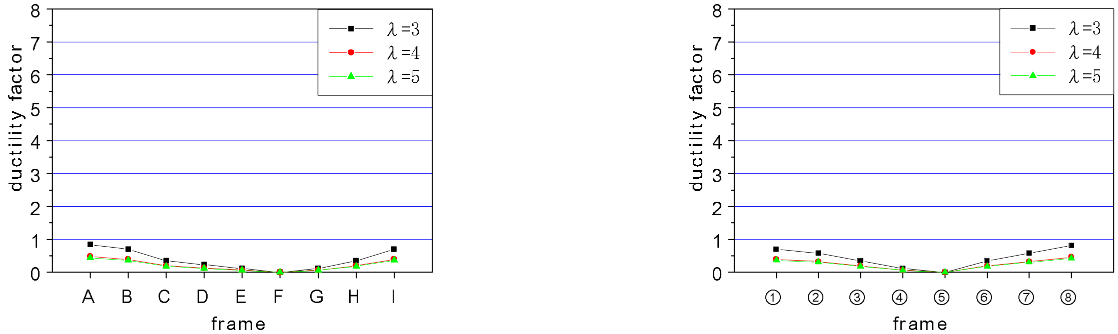


(a) x direction



(b) y direction

Fig. 11 Maximum deformation with rotation component (Model A)



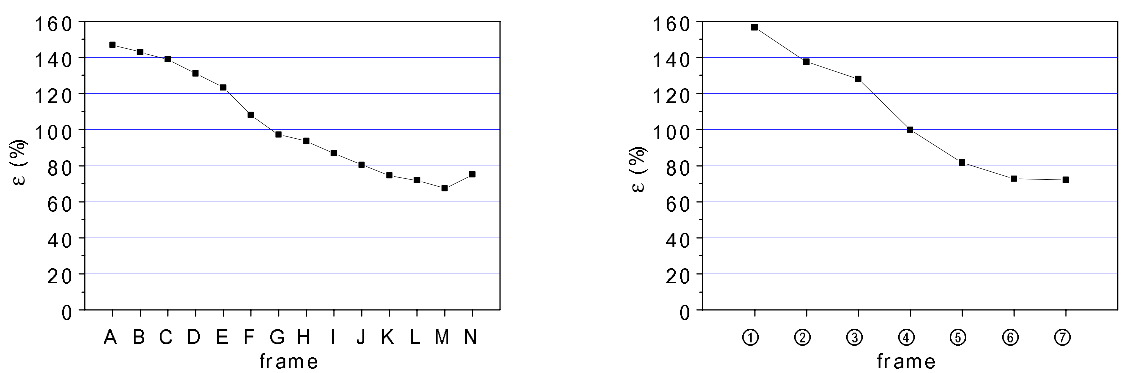
(a) x direction **(b) y direction**

Fig. 12 Maximum deformation with rotation component (Model B)

We also compare the ductility factor response of the respective frames of the 3-dimensional model with the one of the damped mass system model. By calculating the case of γ= 0.4, ratio r_0 = 0. 3, and λ = 4 for Models A and B, we can obtain the rate ε using the following equation.

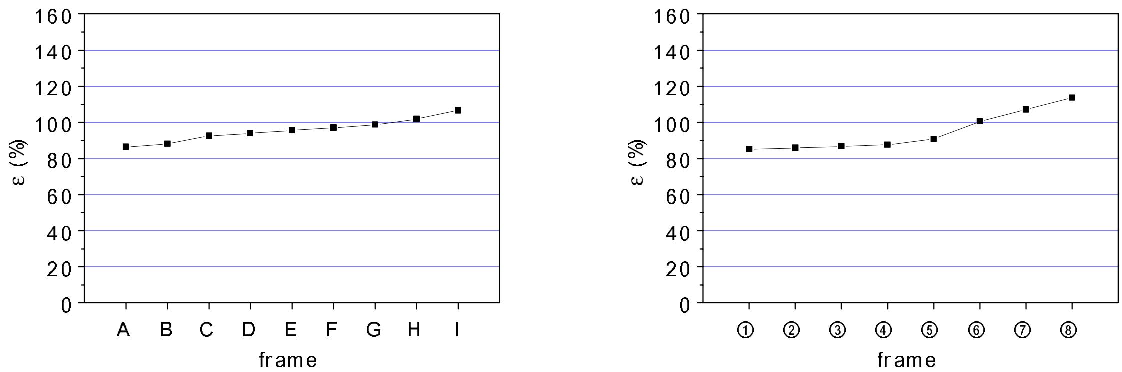
$$\varepsilon = \frac{\mu\left(\text{each frame of 3-dimensional model}\right)}{\mu\left(\text{the damped mass system model}\right)} \times 100(\%) \tag{10}$$

The results of the rate ε are shown in Figs.13 and 14 as a function of the frame number. The ductility factor responses of the frames at the center of gravity position never agree with the ones of the damped mass system for the two models. This is because the 3-D model has eccentricity and torsional oscillation takes place. As compared with the ductility factor responses of the damped mass system model, the rates of ε of the 3-D model of Model A are about 70% at the soft frame and about 150% at the stiff frame in the x and y directions. On the other hand, in the case of Model B, the rates are about 85% and about 110%, respectively. It is clear that the response characteristics of the 3-D model differ remarkably from the ones of the damped mass system model.



(a) x direction **(b) y direction**

Fig. 13 Ratio of the ductility factor in a 3-dimensional model to one of a dumped mass system model (Model A)



(a) x direction **(b) y direction**

Fig. 14 Ratio of ductility factor in a 3-dimensional model to one of a dumped mass system model (Model B)

CONCLUSIONS

In this paper, we demonstrated the earthquake response characteristics with torsional oscillation of full-scale wooden frame house models, of which mass and stiffness were non-uniform, are subjected to the recorded ground motions. Here, the responses of the models represented the ductility factors and the base shear coefficients of the frames comprising the model. We examined the effect of the rotation component by torsional oscillation on the total deformation of the models. We also showed the general characteristics of the earthquake responses of the wooden house models with uniaxial and biaxial eccentricities and the differences of response in the two kinds of models.

Using the horizontal stiffness obtained from the wall factor, when it is assumed that the stiffness factor λ = 3, the ductility factor response μ exceeds 4.0, and we note that some frames suffer serious damage or the model may even collapse. In case of λ=4 and 5, the μ is within 3, and the frames suffer only moderate damage. The response characteristics of the 3-dimensional model differ remarkably from the ones of the damped mass system model. The torsional oscillation cannot be neglected in wooden houses with non-uniform bearing shear walls. Therefore, it is necessary to arrange bearing shear walls as uniformly as possible, and to introduce and analyze the 3-dimensional model for designing wooden-framed houses in order to prevent torsional oscillation.

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