STUDY ON EARTHQUAKE RESPONSE CHARACTERISTICS AND EFFECTS OF ORTHOGONAL WALLS OF JAPANESE TRADITIONAL WOODEN APARTTMENT CALLED NAGAYA

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ABSTRACT:

This paper presents the fundamental earthquake response characteristics of two-dimensional wooden-framed house models, Nagaya, with the uni-axial eccentricity. Differences of earthquake responses between the one- and four-unit Nagaya models are shown. The effect of wall quantity variation of the orthogonal direction on the vibration control is examined. It is found from the analytical results that the displacement responses of the one-unit model are larger than those of the four-unit one; therefore scrapping Nagaya consisted of several houses leads to the bad amenity during earthquake. When setting the orthogonal wall quantity of the models to one and half times as much as eccentric directional wall quantity, torsional vibration would be rarely caused.

KEYWORDS: wooden-framed Nagaya, eccentricity, torsional vibration, effect of orthogonal wall

1. INTRODUCTION

Nagaya is a Japanese traditional urban apartment made of wood. The general properties of Nagaya apartments are that the whole structure consists of four to five narrow-width house units, and that the walls forming the width of each unit are irregularly arranged. Therefore, the torsional vibration, which is caused by the uni-axial eccentricity, must be considered. In this paper, we carry out an earthquake response analysis of the Nagaya models with the uni-axial eccentricity, show the response characteristics and examine the orthogonal wall effects. The orthogonal wall effect means how walls perpendicular to the eccentric directional walls will control the torsional vibration. Two different type models of two-dimensional one-storied Nagaya are used in the analysis: a one-unit type and a four-unit type. We choose the following parameters for our analysis: the shape ratio of the depth to the width on the Nagaya plan, the eccentric ratio, the wall quantity and its ratio, the restoring force characteristics of the walls and kinds of input earthquake motions [Yamada, et al., 2006].

2. ANALYTICAL MODEL

2.1. Equation of Motion

We introduce a one-storied model, shown in Fig.1, subjected to two horizontal directional earthquake motions. The model has frames of amount of m and n in x and y directions, respectively. The equation of motion of this model is expressed by the displacements, x and y, and the rotational angle, θ, of the center-of-mass of the floor as follows:

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{Bmatrix} + \begin{bmatrix} C_x & 0 & 0 \\ 0 & C_y & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{Bmatrix} + \begin{Bmatrix} F_x \\ F_y \\ F_\theta \end{Bmatrix} = - \begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix} \begin{Bmatrix} \ddot{x}_G \\ \ddot{y}_G \\ 0 \end{Bmatrix} \tag{2.1}$$

where,

$$\left.\begin{aligned} C_x &= 2h_x\sqrt{K_x M} \quad \left(K_x = \sum_{i=1}^{n} {}_i k_x\right) \\ C_y &= 2h_y\sqrt{K_y M} \quad \left(K_y = \sum_{j=1}^{m} {}_j k_y\right) \end{aligned}\right\} \tag{2.2}$$

$$\left.\begin{aligned} F_x &= \sum_{i=1}^{n} {}_i f_x = \sum_{i=1}^{n} {}_i k_x \, {}_i \varPhi_x\left({}_i u_x, {}_i \dot{u}_x\right) \\ F_y &= \sum_{j=1}^{m} {}_j f_y = \sum_{j=1}^{m} {}_j k_y \, {}_j \varPhi_y\left({}_j u_y, {}_j \dot{u}_y\right) \\ F_\theta &= \sum_{i=1}^{n} {}_i f_x \, {}_i l_y - \sum_{j=1}^{m} {}_j f_y \, {}_j l_x \end{aligned}\right\} \tag{2.3}$$

$$\left.\begin{aligned} {}_i u_x &= x + {}_i l_y \theta \\ {}_j u_y &= x - {}_j l_x \theta \end{aligned}\right\} \tag{2.4}$$

In equations (2.1) to (2.4), M, I, C and F are respectively the mass, the rotational inertia, the damping coefficient and the restoring force of each direction. x_G and y_G are the two directional grand displacements. f and k are the restoring force and the stiffness of each frame. $\varPhi$ is the restoring force characteristics normalized by the horizontal stiffness at 1/120rad. u and l are the displacement of each frame and the distance from the center-of-mass to each frame, respectively. h is the critical damping ratio.

2.2. Structural Model

We assume that the length of the width and the depth on the plan of the single Nagaya unit are respectively A=3.64m and $B=\beta A$ ($0.5 \le \beta \le 3$, β is the shape ratio), and call this model "one-unit type" witch is shown in Fig.2(a). This type means that a single house unit of the Nagaya exists and the other units are scraped. The wall elements are arranged around the outside on the plan. Arranging the four one-units in the width direction, we

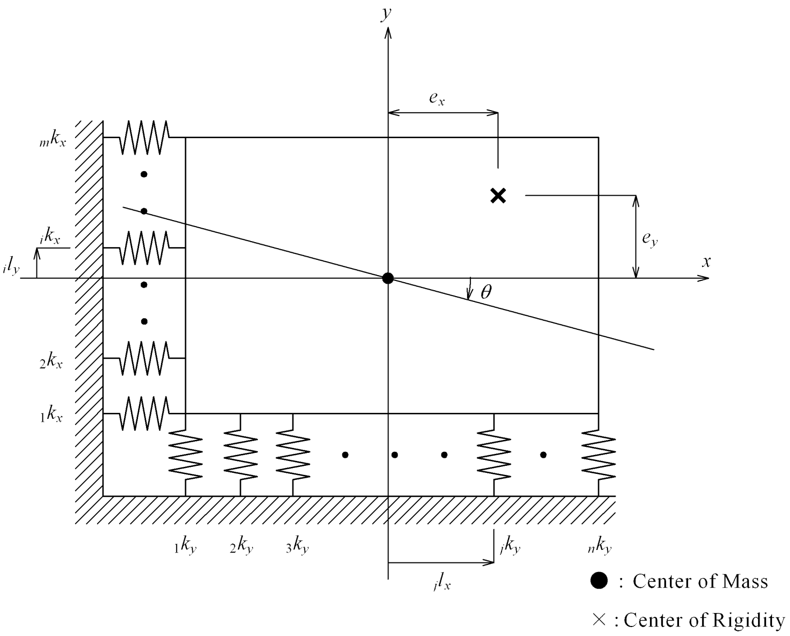


Fig.1 Vibration model

call this model “four-unit type” witch is shown in Fig.2(b). This type corresponds to the typical Nagaya in existence. The weight and the height of the model are 2.5kN/m^2 and H=3.0m, respectively. We assume that parametric changing of α shown in Fig.2 causes the uni-axial eccentricity. The critical damping ratios are h_x=h_y=0.05.

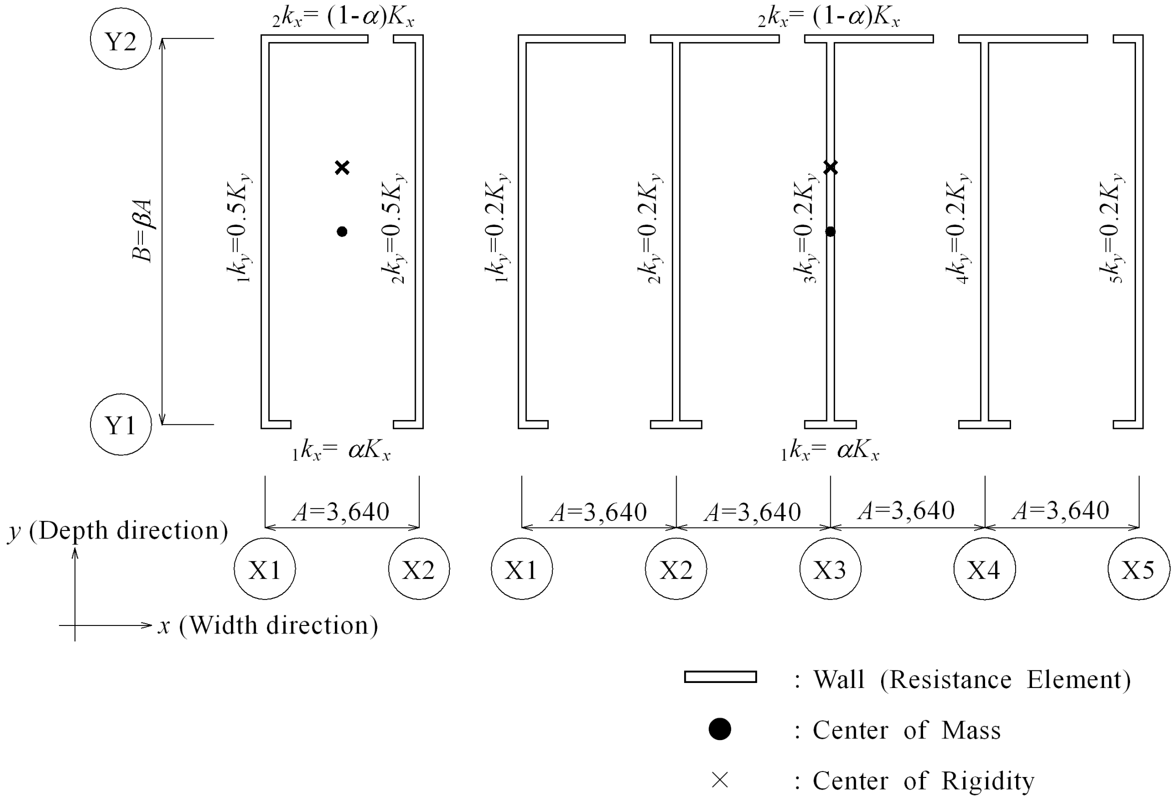
Fig.3 shows the skeleton curve of the restoring force characteristics of the mud wall frame, the hanging or spandrel wall frame and these combinations, which are normalized by the maximum strength. These walls are made of wall clay and bamboo lath. As for the hysteresis rule, we use the combination characteristics consists of the quadri-linear type and the slip type. The combinational expression of these types is as follows:

$$\Phi = \gamma\Phi_Q + (1-\gamma)\Phi_S \qquad (0 \le \gamma \le 1) \tag{2.5}$$

where, Φ_Q and Φ_S are the quadri-linear type characteristics [Asano, 1977] and the slip type one [Suzuki, 1985], respectively. γ is the combination factor, and we choose γ=0.4. We assume that the 1st to 3rd yielding rotational angles of the quadri-linear type are respectively 1/480, 1/240 and 1/120rad, because the elastic- and the plastic-region of a wooden-frame cannot be clarified. The yield angle of the slip type is 1/120rad. The ratio of the last stiffness to the equivalent one at 1/120rad is r_0=0.05.

Fig.4 shows the restoring characteristics of the existing wooden framed house by the static horizontal lording test [Nakaji, et al., 2007]; Fig.5 shows the analytical result obtained from Eqn. 2.5 using above-mentioned parameters. It is found out from these figures that the analytical result is resembles the experimental one. Therefore, there is considerable validity in the parameters.

We choose four recorded earthquake motions: El Centro (1940), JMA Kobe (1995), Hachinohe (1968) and Taft (1952), of which are adjusted to PGV=50cm/sec. They are listed in Table 1.



(a) One-unit type (b) Four-unit type

Fig.2 Plan of Nagaya model

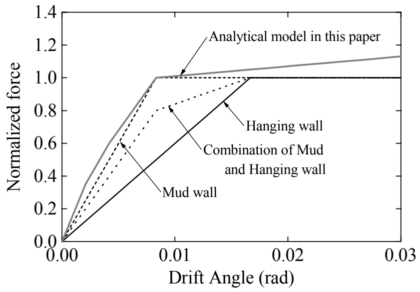


Fig.3 Skeleton curve

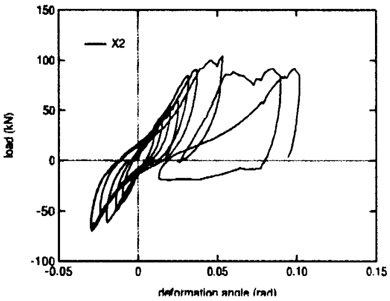


Fig.4 Experimental result

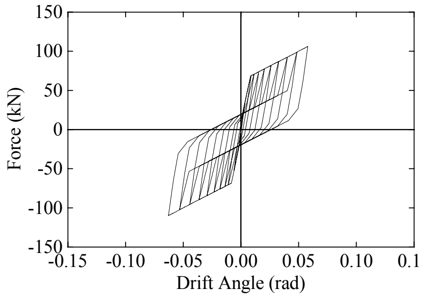


Fig.5 Analytical result

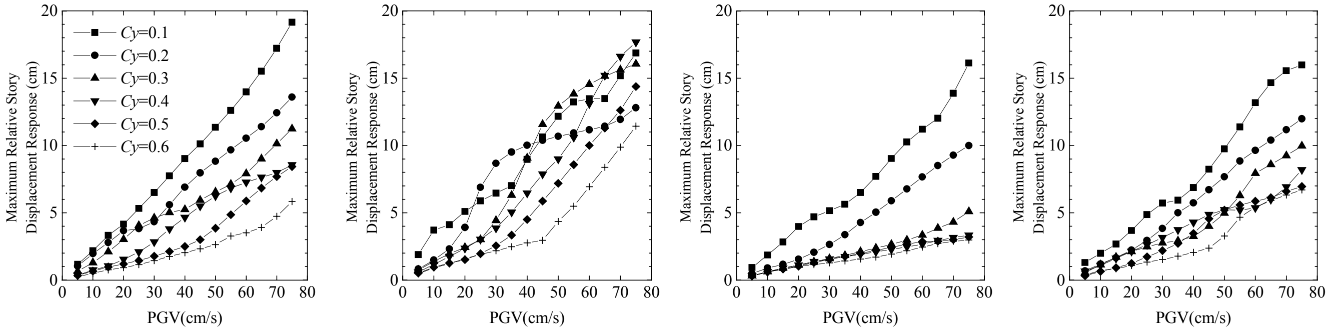
Table 1 Input earthquake motions

Earthquakes	PGA (cm/s/s) and input direction	
	NS comp.	EW comp.
El Centro 1940	510.8 (*x*)	284.6 (*y*)
JMA Kobe 1995	453.2 (*x*)	404.4 (*y*)
Hachinohe 1968	332.7 (*x*)	242.6 (*y*)
Taft 1952	485.7 (*y*)	496.8 (*x*)

3. ANALYTICAL RESULTS

3.1. Responses Characteristics of Non-eccentric Models

Fig.6 (a) to (d) shows the relationship between the peak ground velocity of the input motions (PGV) and the maximum responses of relative story displacement of the non-eccentric model subjected to four kinds of input motions. The yield shear coefficients are taken into parameter in this figure. It is recognized that the conditions for which the maximum responses are less than 2.5cm (drift angle, 1/120rad) are $C_y<0.3$ and PGV<10 or 15. And if C_y is about 0.3, maximum responses for the motions with PGV=50cm/s would be less than 15cm (1/15rad).



(a) El Centro NS (b) JMA Kobe NS (c) Hachinohe NS (d) Taft EW

Fig.6 Relationship between PGV and maximum response of relative story displacement

3.2. Responses of One- and Four-unit Models

Fig.7 shows the relationship between α and the eccentric ratio, Re, of the one- and the four-unit models. In this figure, the shape ratio and the yield shear coefficients in the width and the depth direction are respectively $\beta=2.0$ and ${}_xC_y={}_yC_y=0.3$. In Japanese seismic design practice of wooden-framed houses, it is regulated that the mutual wall quantity ratio of both quarter sides on the plan must be larger than 0.5. α corresponding to this regulation is less than 0.33. It is clear that *Re* for any α of the one-unit model is larger than that of the four-unit model. Therefore, partial scrapping of Nagaya consists of four-unit houses is danger from the viewpoint of the eccentricity.

Fig.8 (a) and (b) shows the relationship between α and the maximum responses of relative story displacement of the one- and the four-unit models. The parameters β, ${}_xC_y$ and ${}_yC_y$ are the same value as Fig.7, and the level of input motions is PGV=50cm/s. We see from these figures that the responses in the width direction of the four-unit type are large, in comparison with that of the one-unit type. Therefore, the differences of the one- and four-unit type have an effect on the responses and the comfortability during earthquakes.

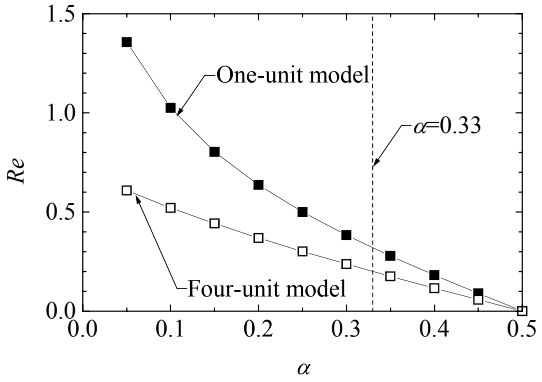
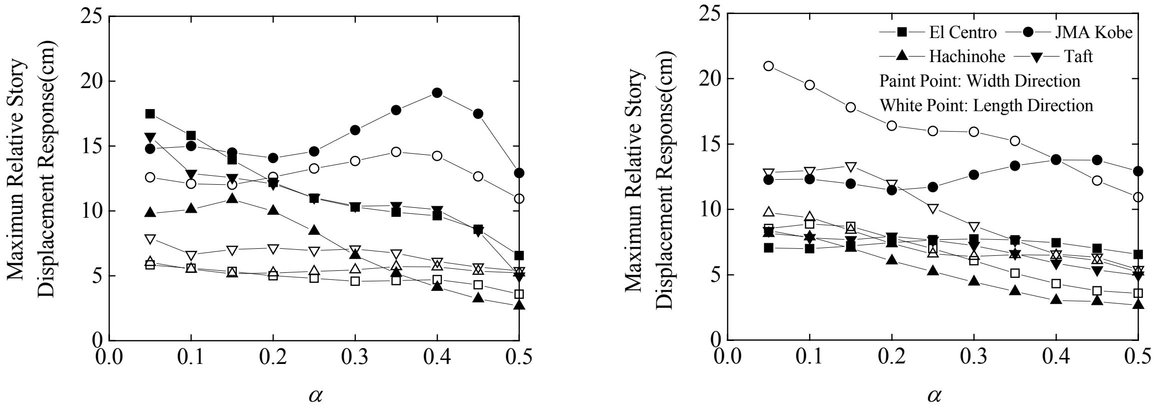


Fig.7 Relationship between α and eccentric ratio, *Re*, (β=2.0, ${}_xC_y={}_yC_y$=0.3)



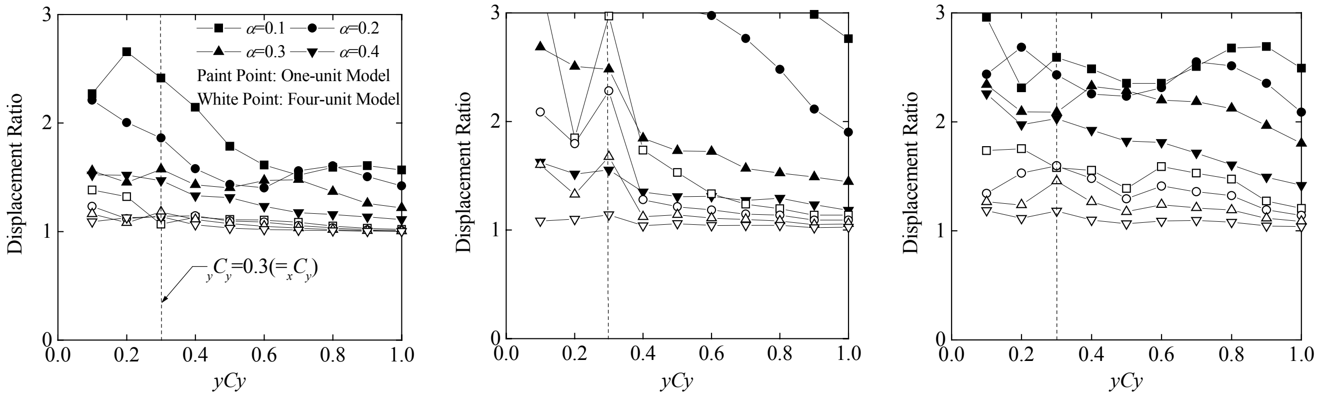
(a) One-unit type (b) Four-unit type

Fig.8 Relationship between α and maximum response of relative story displacement
(β=2.0, ${}_xC_y={}_yC_y$=0.3, PGV=50cm/s)

3.3. Effect of Orthogonal Wall

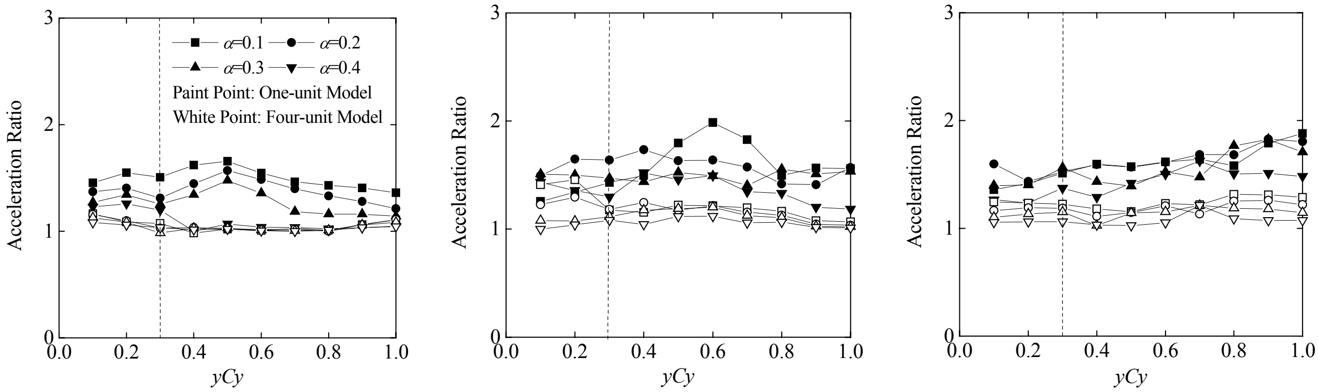
Fig.9 (a) to (c) shows the relationship between the yield shear coefficient in the depth direction, ${}_yC_y$, and the displacement ratio, which is defined as the ratio of the maximum displacement response of the eccentric model with α to that of the non-eccentric model. α (=0.1, 0.2, 0.3 and 0.4) is taken into the parameter in this figure. The shape ratio and the yield shear coefficient in the width direction are respectively β=2.0 and ${}_xC_y$ =0.3. The level of input motions is PGV=50cm/s. It is recognized form the figures that the displacement ratio is decreasing with the increasing of ${}_yC_y$. This tendency is remarkable in case of the one-unit type, in comparison with the four-unit type. The ratio of the one-unit type is larger than that of the four-unit type. In case of four-unit type, the ratio is approximately constant when ${}_yC_y$>0.3.

Fig.10 (a) to (c) shows the relationship between ${}_yC_y$ and the acceleration ratio, which is defined as the ratio of the maximum acceleration response of the eccentric model to that of the non-eccentric model. Parameters in this figure are same value as Fig.9. We see form these figure that the ratio is constant except for the ratio to Taft.



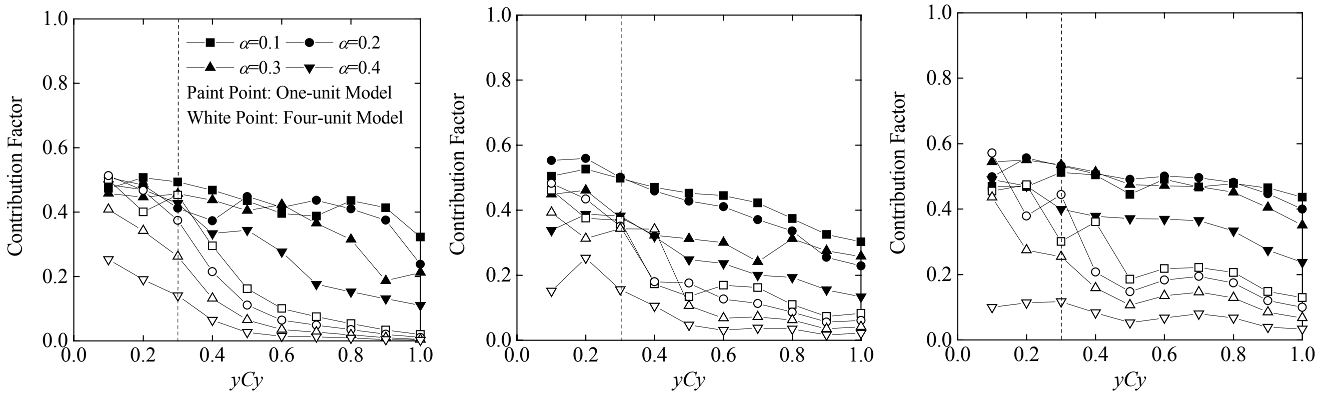
(a) El Centro (b) Hachinohe (c) Taft

Fig.9 Relationship between yield shear coefficients in depth direction, ${}_yC_y$, and displacement ratio in width direction (β=2.0, ${}_xC_y$=0.3, PGV=50cm/s)



(a) El Centro (b) Hachinohe (c) Taft

Fig.10 Relationship between yield shear coefficients in depth direction, ${}_yC_y$, and acceleration ratio in width direction (β=2.0, ${}_xC_y$=0.3, PGV=50cm/s)



(a) El Centro (b) Hachinohe (c) Taft

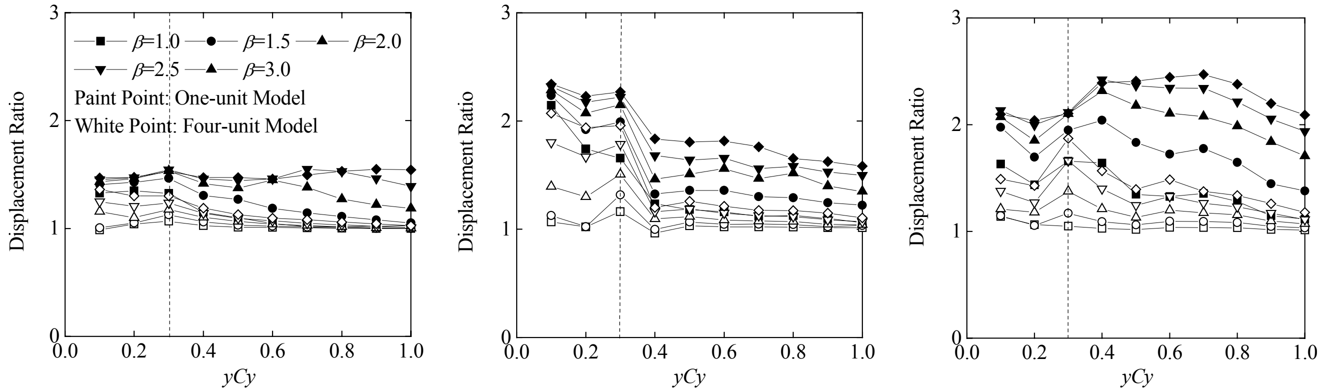
Fig.11 Relationship between yield shear coefficients in depth direction, ${}_yC_y$, and contribution factor (β=2.0, ${}_xC_y$=0.3, PGV=50cm/s)

Fig.11 shows the relationship between ${}_yC_y$ and the contribution factor, which is the rate of torsion that contributes to the displacement response. Here, this factor is defined as $l\theta/u$. It is recognized that this rate is remarkably decreasing with increasing of ${}_yC_y$ in case of four-unit type, and when ${}_yC_y>0.5 \approx 1.5{}_xC_y$, this rate becomes to very small. The rates in case of the one-unit type, however, decrease gradually.

From what has been discussed above, it seems reasonable to conclude that reinforcement of the depth directional wall is effective for reducing the displacement response of the width direction in case of the one-unit type with eccentricity. To reducing the amount of the responses in the width direction, however, it is essential to reinforce the both wall in the width and the depth direction. In case of the four-unit type, reinforcement of walls in the depth direction is effective for reducing the response. If the yield shear coefficient of the depth direction is larger than that in the width direction, the increase of displacement response due to torsion would be slight. And if the shear coefficient in the depth direction is 1.5 times as large as that in the width direction, the torsion itself would de rarely caused. This tendency is irrelevant to α.

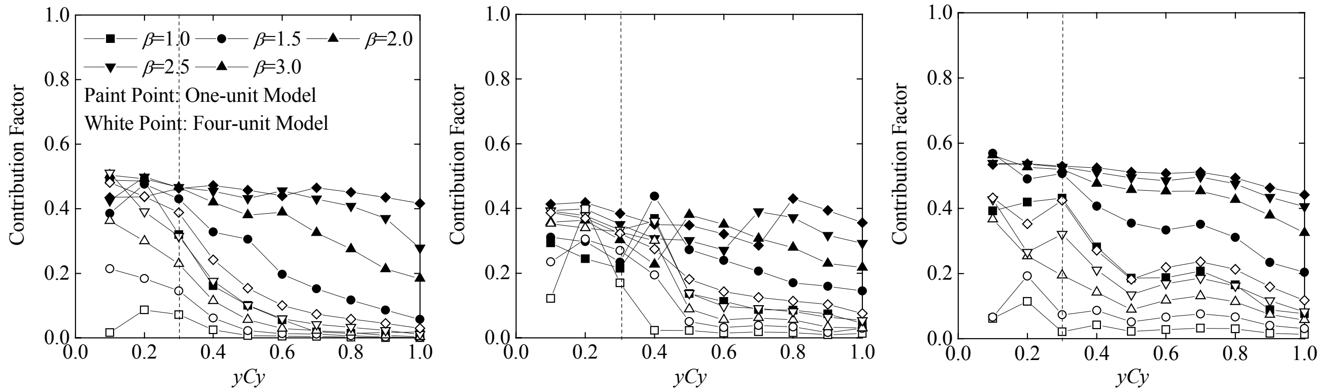
Fig.12 (a) to (c) shows that the relationship between ${}_yC_y$ and the displacement ratio. ${}_xC_y$=0.3, α=0.3 and PGV=50cm/s. The parameter in these figures is β (1.0 to 3.0). It is recognized from these figures that the displacement ratio is larger as β is larger. In case of the one-unit type, the ratios vary widely with variation of β, and the differences of ${}_yC_y$ do not have an effect on the responses in the width direction.

Fig.13 shows the relationship between ${}_yC_y$ and the contribution factor. We see from these figures that ${}_yC_y$ does not have an effect on controlling of the torsion when $\beta \geq 2.0$ in case of the one-unit type. In case of the four-unit type, however, the effect of ${}_yC_y$ on controlling torsion is expected for all β.



(a) El Centro (b) Hachinohe (c) Taft

Fig.12 Relationship between yield shear coefficients in depth direction, ${}_yC_y$, and displacement ratio (α=0.3, ${}_xC_y$=0.3, PGV=50cm/s)



(a) El Centro (b) Hachinohe (c) Taft

Fig.13 Relationship between yield shear coefficients in depth direction (${}_yC_y$) and contribution factor (α=0.3, ${}_xC_y$=0.3, PGV=50cm/s)

From the results obtained above, we can safely say that the orthogonal wall effect depends on the shape ratio, β, and the ratio must be $\beta<2.0$ in case of the one-unit type. The effect in case of the four-unit type, however, would be expected for all β.

4. CONCLUSIONS

In this paper, we carried out the earthquake response analyses of Japanese traditional wooden-framed house, Nagaya, with the uni-axial eccentricity in the width direction on the plan. Two types of models are used for our analyses: the one- and four-unit types. The following parameters are chosen for analyses: the shape ratio on the Nagaya plan, the eccentric ratio, the wall quantity and its wall ratio, the restoring force characteristics of the walls, and kinds of input earthquake motions. We presented the earthquake response characteristics of the models and examined the orthogonal wall effects. The results obtained are as follows:

1) For the model of which the yield shear coefficient is about 0.3 without eccentricity, the maximum responses of relative story angle are less than 1/120 and 1/15rad for PGV=10 and 50cm/s, respectively.
2) The displacement and the acceleration responses for the one-unit type are larger than those for the four-unit type. It leads the safety and the comfortability of the one-unit type to worth condition during earthquake, in comparison with the four-unit type.
3) Orthogonal walls are quite effective for controlling of the displacement responses for the two type models. In order to reduce the displacement response for the one-unit type, however, the supply of both orthogonal wall and eccentric one are necessary.
4) When the wall ratio of the depth to the width of Nagaya is more than 1.0, the increase of the displacement response due to the torsional vibration are slight. If the ratio is more than 1.5, the torsional vibration rarely occurs.
5) In case of the one-unit type, the orthogonal wall effect depends on the shape ratio, and its ratio should be set to 2.0 or less. In case of the four-unit type, however, the orthogonal wall effect is not dependent on the ratio.

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