Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 482

STUDY ON EFFECT OF ORTHOGONAL WALL OF JAPANESE TRADITIONAL WOODEN APARTMENT, NAGAYA, MODELS CONSIDERING FLOOR STIFFNESS

Akira Yamada[1] and Sanshiro Suzuki[2]

ABSTRACT

In this paper, we carry out an earthquake response analysis of Japanese traditional wooden apartment, Nagaya, models with a uni-axial eccentricity considering the floor stiffness. We examine the effects of the floor stiffness and of the wall perpendicular to the eccentric direction of the models on the earthquake response characteristics. The orthogonal wall effect means if the walls perpendicular to the eccentric direction may control the torsional vibration. We introduce the key parameters for our analysis. The main results obtained are summarized as follows: 1) The orthogonal wall effect is strongly influenced by the wall ratio of the depth direction to the width one of the model plan for the motions of V_{max} = 10cm/s. 2) On the other hand, the effect for the motions of V_{max} = 50cm/s depends on the yield shear coefficient in the depth direction of models.

Introduction

"Nagaya" (see Picture 1) is a kind of Japanese traditional one- or two-storied wooden apartments and lots of them exist in the old town. The general characteristics of Nagaya can be explained from a structural engineering point of view as follows: Nagaya is made of wooden posts, beams, floor framings and roof framings and mud walls which are made of wall clay and bamboo lath. Earthquake resistance elements are mainly the mud walls. Nagaya consists of four to five narrow-width houses of which partition is made of the mud wall. Therefore, there are many walls in the depth direction. On the other hand, there are a few walls in the width direction and a uni-axial eccentricity because of irregular wall arrangement. Stiffness of the horizontal diaphragm such as the floor and the roof of Nagaya are very low. Therefore, the torsional vibration would occur and the deformation appears in the horizontal diaphragm during earthquake. However, it is common that these behaviors are practically neglected in the design. Many studies have been made on the torsional vibration and the characteristics of torsion have been discussed (for example, Riddell et al., 1999). However, there are very few attempts on the wooden structures, especially the traditional wooden apartment. Although the effect is understood of the walls perpendicular to the eccentric direction on control of the torsional vibration qualitatively, it is not clarified quantitatively.

[1]Hirata Structural Engineers Inc., Osaka, Japan
[2]Professor, Faculty of Environmental and Urban Engineering, Kansai University, Osaka, Japan

In this paper, we carry out an earthquake response analysis of one-storied Nagaya models with a uni-axial eccentricity subjected to earthquake motions with two horizontal components considering the stiffness of the horizontal diaphragm of the models. We discuss the earthquake response characteristics of the models considering the floor stiffness and of the orthogonal wall. We define the "orthogonal wall effect" as the effect of walls perpendicular to the eccentric direction on the control of torsional vibration. Two different type models of Nagaya are used in the analysis: those are a single type and a quadric coupled one, respectively. We choose the following parameters in our analysis: the eccentric ratio, the shape ratio of the depth side to the width one on the Nagaya plan, the floor stiffness, the wall quantity and its ratio of the depth direction to the width one, and the earthquake motions. Although Nagaya is a Japanese individual apartment, the idea shown hereafter can be extended to another kind of wooden structure by changing the characteristics of the earthquake resistance elements (Yamada et al., 2004, 2008).

Picture 1. A typical Nagaya

Analytical Model

Equation of motion

It is not appropriate to assume that a floor of horizontal diaphragm is perfectly rigid in case of a wooden framed house. In addition, the house is very complicated because of the various ways of built-up of the posts, the beams, the floor frames and the roof frames. Therefore, to analyze the three-dimensional behavior of it during earthquakes, an appropriate modeling is very important.

We introduce a one-storied model, shown in Fig.1, subjected to earthquake motions with two horizontal components. The transformations of the wall and the floor are considered in this model of (m, n) elements. The equation of motion of this model is represented in Eq.(1).

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\boldsymbol{\Phi}(\mathbf{x}, \dot{\mathbf{x}}) = -\mathbf{M}\ddot{\mathbf{z}} \tag{1}$$

where **M**, **C** and **K** are the mass, the damping and the stiffness matrices, respectively, **x** and **z** the displacement vectors of the displacement response and of the ground motion. **Φ** is the non-dimensional restoring force vector which depends on the displacement and the velocity of the response. Elements of the matrices and the vectors are represented in Eqs.(2) to (5).

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} \mathbf{K}_{11} & \mathbf{K}_{12} \\ \mathbf{K}_{21} & \mathbf{K}_{22} \end{bmatrix} \tag{2}$$

$$\mathbf{C} = (2h/\omega_1)\mathbf{K} \tag{3}$$

$$\mathbf{x} = \{x_1 \quad \cdots \quad x_i \quad \cdots \quad x_m \quad y_1 \quad \cdots \quad y_j \quad \cdots \quad y_n\}^T \tag{4}$$

$$\mathbf{z} = \{x_g \quad \cdots \quad x_g \quad y_g \quad \cdots \quad y_g\}^T \tag{5}$$

where

$$\mathbf{M}_{11} = \begin{bmatrix} \ddots & & 0 \\ & \sum_{j=1}^{n_y} m_{ij} & \\ 0 & & \ddots \end{bmatrix}, \quad \mathbf{M}_{22} = \begin{bmatrix} \ddots & & 0 \\ & \sum_{i=1}^{n_x} m_{ij} & \\ 0 & & \ddots \end{bmatrix} \tag{6}$$

$$\mathbf{M}_{12} = \mathbf{M}_{21} = [0] \tag{7}$$

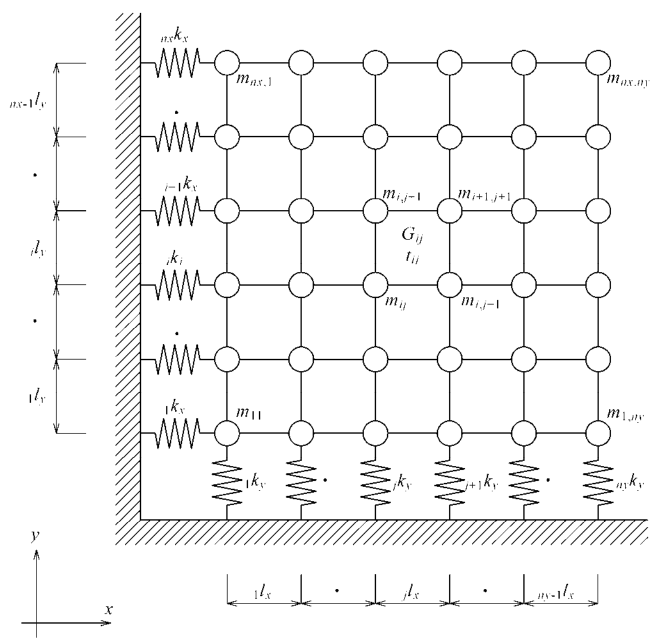


Figure 1. Analytical model

$$\mathbf{K}_{11} = \begin{bmatrix} \ddots & \ddots & & & 0 \\ \ddots & \ddots & \ddots & & \\ & -\sum_{j=1}^{n_y-1} G_{i-1,j}\cdot t_{i-1,j}\cdot {}_j l_x / {}_{i-1} l_y & {}_i k_x + \sum_{i=i-1}^{i}\sum_{j=1}^{n_y-1} G_{ij}\cdot t_{ij}\cdot {}_j l_x / {}_i l_y & -\sum_{j=1}^{n_y-1} G_{ij}\cdot t_{ij}\cdot {}_j l_x / {}_i l_y & \\ & & \ddots & \ddots & \ddots \\ 0 & & & \ddots & \ddots \end{bmatrix} \tag{8}$$

$$\mathbf{K}_{12} = \mathbf{K}_{21}^{\mathbf{T}} = \begin{bmatrix} G_{11}t_{11} & \cdots & -G_{1,j-1}t_{1,j-1} + G_{1,j}t_{1,j} & \cdots & -G_{1,n_y-1}t_{1,n_y-1} \\ \vdots & & \vdots & & \vdots \\ -G_{i-1,1}t_{i-1,1} + G_{i1}t_{i1} & \cdots & \begin{matrix} G_{i-1,j-1}t_{i-1,j-1} - G_{i-1,j}t_{i-1,j} \\ -G_{i,j-1}t_{i,j-1} + G_{ij}t_{ij} \end{matrix} & \cdots & G_{i-1,n_y-1}t_{i-1,n_y-1} - G_{i,n_y-1}t_{i,n_y-1} \\ \vdots & & \vdots & & \vdots \\ -G_{n_x-1,1}t_{n_x-1,1} & \cdots & G_{n_x-1,j-1}t_{n_x-1,j-1} - G_{n_x-1,j}t_{n_x-1,j} & \cdots & G_{n_x-1,n_y-1}t_{n_x-1,n_y-1} \end{bmatrix} \tag{9}$$

$$\mathbf{K}_{22} = \begin{bmatrix} \ddots & \ddots & & & 0 \\ \ddots & \ddots & \ddots & & \\ & -\sum_{i=1}^{n_x-1} G_{i,j-1}\cdot t_{i,j-1}\cdot {}_i l_y / {}_{j-1} l_x & {}_j k_y + \sum_{j=j-1}^{j}\sum_{i=1}^{n_x-1} G_{ij}\cdot t_{ij}\cdot {}_i l_y / {}_j l_x & -\sum_{i=1}^{n_x-1} G_{ij}\cdot t_{ij}\cdot {}_i l_y / {}_j l_x & \\ & & \ddots & \ddots & \ddots \\ 0 & & & \ddots & \ddots \end{bmatrix} \tag{10}$$

where x and y are the displacements of response, x_g and y_g the displacement of grand motion, m, k, G, l and t the mass, the stiffness of wall, the modulus of rigidity of floors, the side length, and the thickness of floors, and h and ω_1 the critical damping ratio and the first natural circular frequency of vibration, respectively.

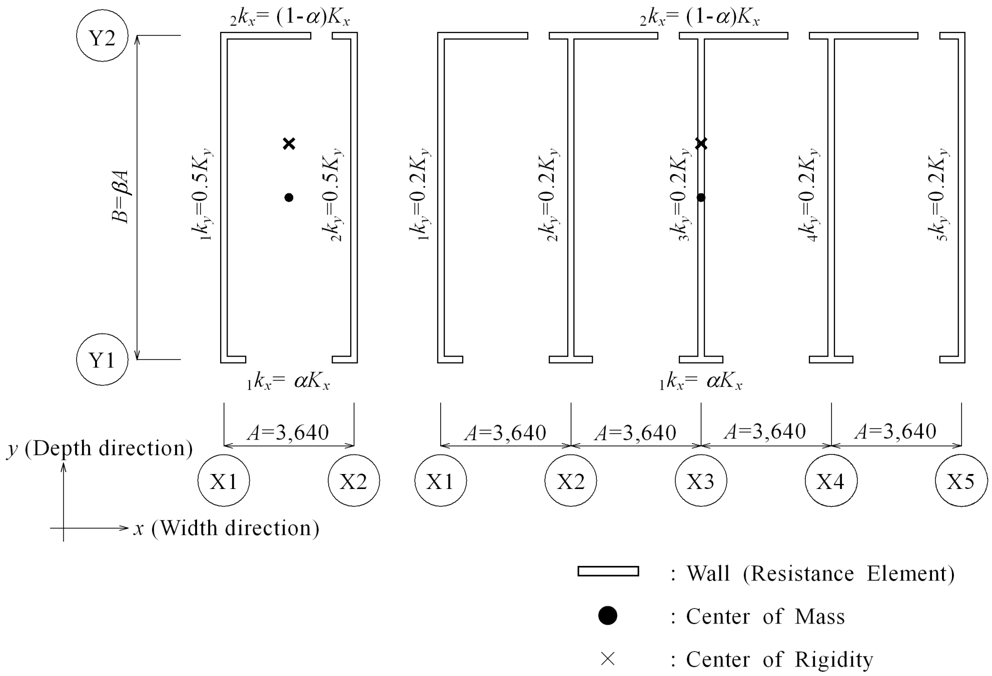
Structural model

A typical Nagaya is generally consists of four to five narrow width houses. Fig.2 shows the model of Nagaya. The length of the width side and the depth side of the model are A = 3.64m and $B = \beta A$ respectively (Fig.(a)), where β represents the shape ratio of the plan and we call this house as a "single type" model. The wall is arranged around the model on the plan. We arrange four houses in the width direction shown in Fig.(b), and call this as a "quadric type" model. The weight per unit area and the height are w =2.5kN/m^2 and H =3.0m respectively. Parametric changing of α which presents the wall distribution factor causes the uni-axial eccentricity of the model. The damping ratio is h = 0.05. These values correspond to the size of the typical Nagaya.

Fig.3 (a) shows the skeleton curves which characterize the restoring force of the mud wall frame, the hanging or the spandrel wall frames, and three combination, of which axis of ordinates is normalized by the maximum strength. The walls in the figure are made of wall clay and bamboo lath. As for the hysteresis rule, we use the combination characteristics of both the quadri-linear type and the slip one. The combination is represented in Eq.(11).

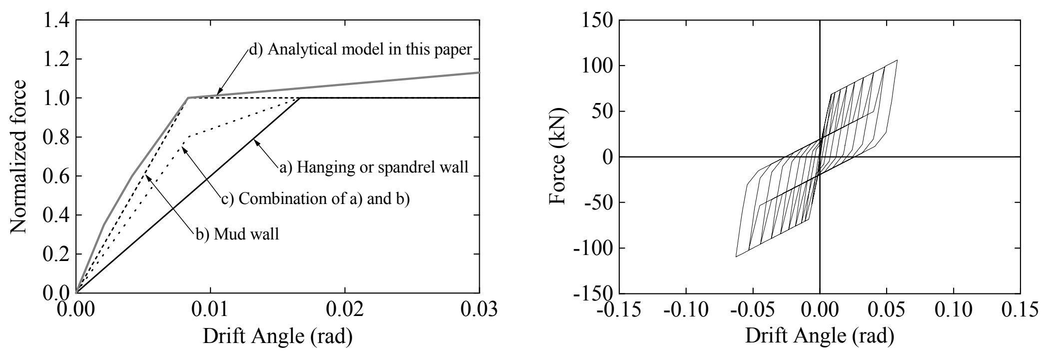
$$\Phi = \gamma \Phi_Q + (1-\gamma)\Phi_S \tag{11}$$

where Φ_Q and Φ_S are the quadri-linear characteristics (Asano, 1977) and the slip ones (Suzuki, 1985), respectively. γ is called as a "combination factor" and governs the combination rate. We choose γ = 0.4 (Yamada et al., 2008). The first to the third yield angles of Φ_Q are selected 1/480, 1/240 and 1/120rad, respectively. The yield angle of Φ_S is 1/120rad. The ratio of the last stiffness



(a) Single type (b) Quadric type

Figure2. Model plan of Nagaya



(a) Shelton curve (b) Hysteresis loop

Figure 3. Restoring force characteristics

to the equivalent one at 1/120rad is r_0 = 0.05. Fig.3 (b) shows the scheme obtained from Eq.(11) with the values of above-mentioned parameters.

The floor is assumed to be elastic and the modulus of rigidity of floor is represented as follows:

$$G = 150 \cdot 1.96 \cdot \Delta Q_E \tag{12}$$

where ΔQ_E is called as a “floor factor”, the value of 1.96(kN/m) corresponds to the standard strength when a floor model is deformed to 1/150rad.

Four recorded earthquake motions are chosen: i.e. El Centro (1940), JMA Kobe (1995), Hachinohe (1968) and Taft (1952) and two artificial motions: i.e. BCJ L1 and L2, which reflect the earthquake response spectrum for design and distributed form the Building Center of Japan. These motions are adjusted to V_{max} = 10 or 50cm/sec and listed in Table 1.

Table 1. Input earthquake motions

	NS Comp.			EW Comp.		
	A_{max} (cm/s/s)	V_{max} (cm/s)	Input direction	A_{max} (cm/s/s)	V_{max} (cm/s)	Input direction
El Centro 1940	341.7	33.5	X	210.1	36.9	Y
JMA Kobe 1995	818.0	90.7	X	917.3	76.0	Y
Hachinohe 1968	229.6	34.4	X	180.2	37.8	Y
Taft 1952	152.7	15.7	Y	175.9	17.7	X
BCJ L1	207.3	29.1	X	207.3	29.1	Y
BCJ L2	355.7	27.4	X	355.7	57.4	Y

Analytical Results

To understand the fundamental response characteristics, we show the relationship between the yield shear coefficient, C_y, and the maximum relative story displacement response of the non-eccentric model with the perfectly rigid floor in Fig.4, subjected to ten kinds of motions. It is recognized that the responses for the motions of V_{max} = 10cm/s do not reach to 1/60rad, and that the responses for the motions of V_{max} = 50cm/s are less than 1/20rad except the BCJ L2 motion.

Fig.5 shows the relationship between the wall distribution factor, α, and the eccentric ratio, Re, as a parameter of the shape ratio, β. $\alpha = 0.3$ corresponds to $Re \approx 0.3$ in case of the single type model with $\beta = 1$. $Re = 0.3$ is the upper limited value of the Japanese wooden structure regulation, therefore, $\alpha = 0.3$ is chosen in this paper. Re varies 0.18-0.43 and 0.04-0.37 for the single type model and the quadric type one respectively, for $0.5 \leq \beta \leq 5.0$.

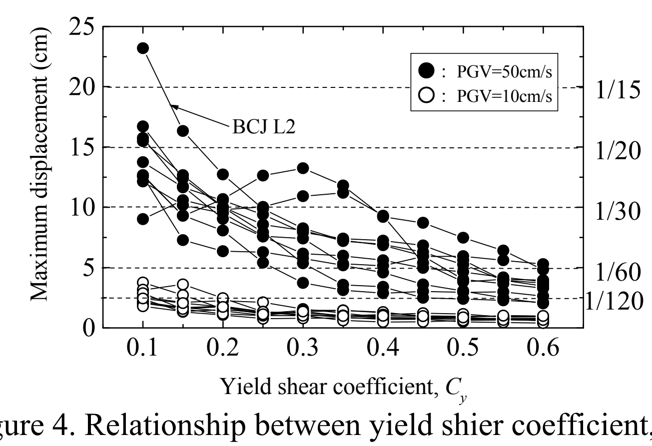
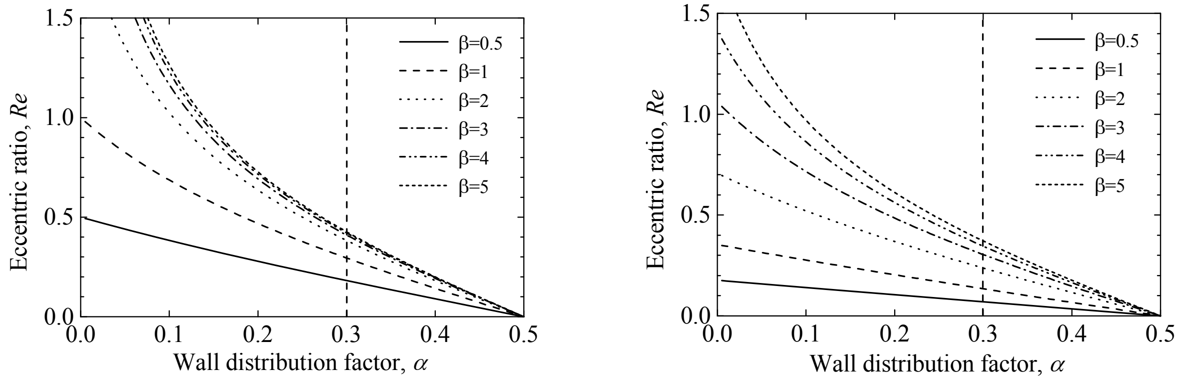


Figure 4. Relationship between yield shier coefficient, C_y, and maximum displacement response



(a) Single type (b) Quadric type

Figure 5. Relationship between wall distribution factor, α, and eccentric ratio, *Re*

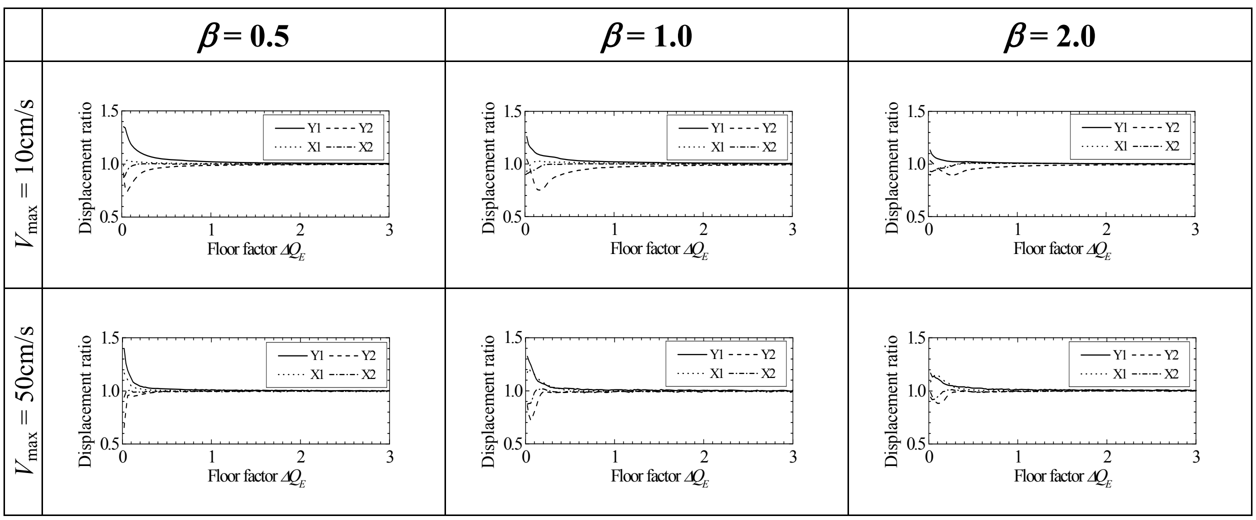


Figure 6. Relationship between floor factor and displacement ratio ($\alpha = 0.3$, ${}_xC_y = {}_yC_y = 0.2$)

Fig.6 shows the relationship between the floor factor, ΔQ_E, and the displacement ratio for the model of $C_y = {}_xC_y = {}_yC_y = 0.2$. “This ratio” is defined as the ratio of the maximum displacement of the non-rigid floor model with eccentricity to the one of the rigid floor model without eccentricity. The lines in the figure present the average value of the ratios for six kinds of input motions. We can recognize from the figure as follows: When the ratio of Y1 plane (solid line, weak side in eccentric direction) becomes smaller, the ratio of Y2 plane (dashed line, strong side) becomes larger gradually, and those converge to 1.0. In case of V_{max} = 50cm/s, the variance of lines with the increase of ΔQ_E appear remarkably compared with the case of V_{max} = 10cm/s. It is thought that this tendency is caused by the non-linearity of the response. The ratio is less than 1.05 when $\Delta Q_E \geq 0.5$, therefore, the floor could be concluded to be rigid when $\Delta Q_E \geq 0.5$.

Fig.7 shows the relationship between the yield shear coefficient in the depth direction, ${}_yC_y$, and the displacement ratio of Y1 and Y2 planes of the single type model subjected to six kinds of motions of V_{max} = 10 and 50cm/s. Where ${}_xC_y$ = 0.1, 0.2 and 0.3, ${}_yC_y$ = 0.05-1.5, ΔQ_E = 0.5, $\alpha = 0.3$ and $\beta = 1.0$.

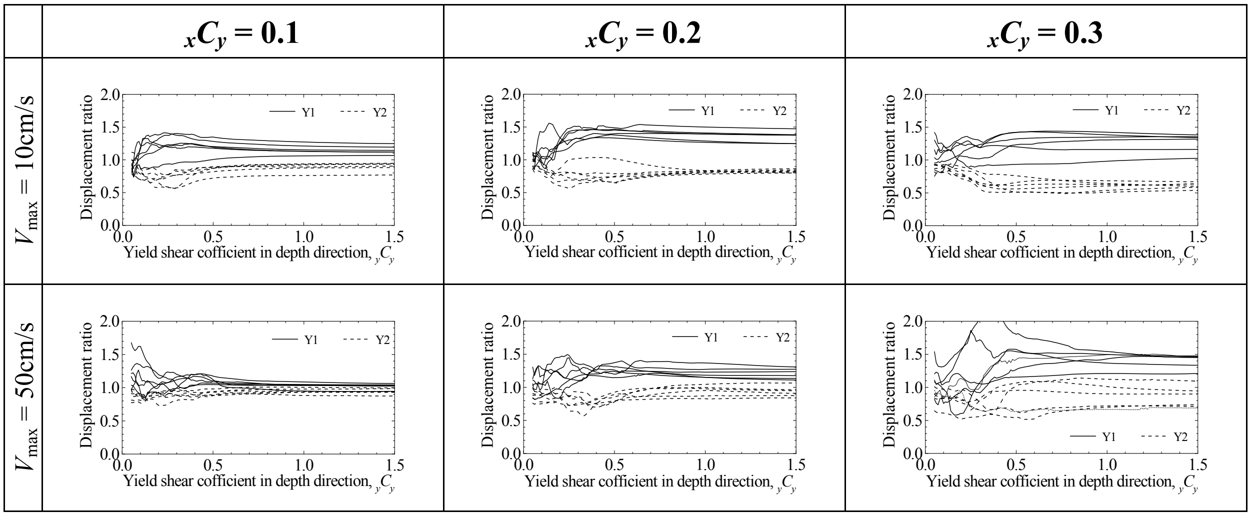


Figure 7. Relationship between yield shear coefficient in depth direction, $_yC_y$, and displacement ratio for six kinds of input motions (Single type model, $\Delta Q_E = 0.5$, $\alpha = 0.3$, $\beta = 1.0$)

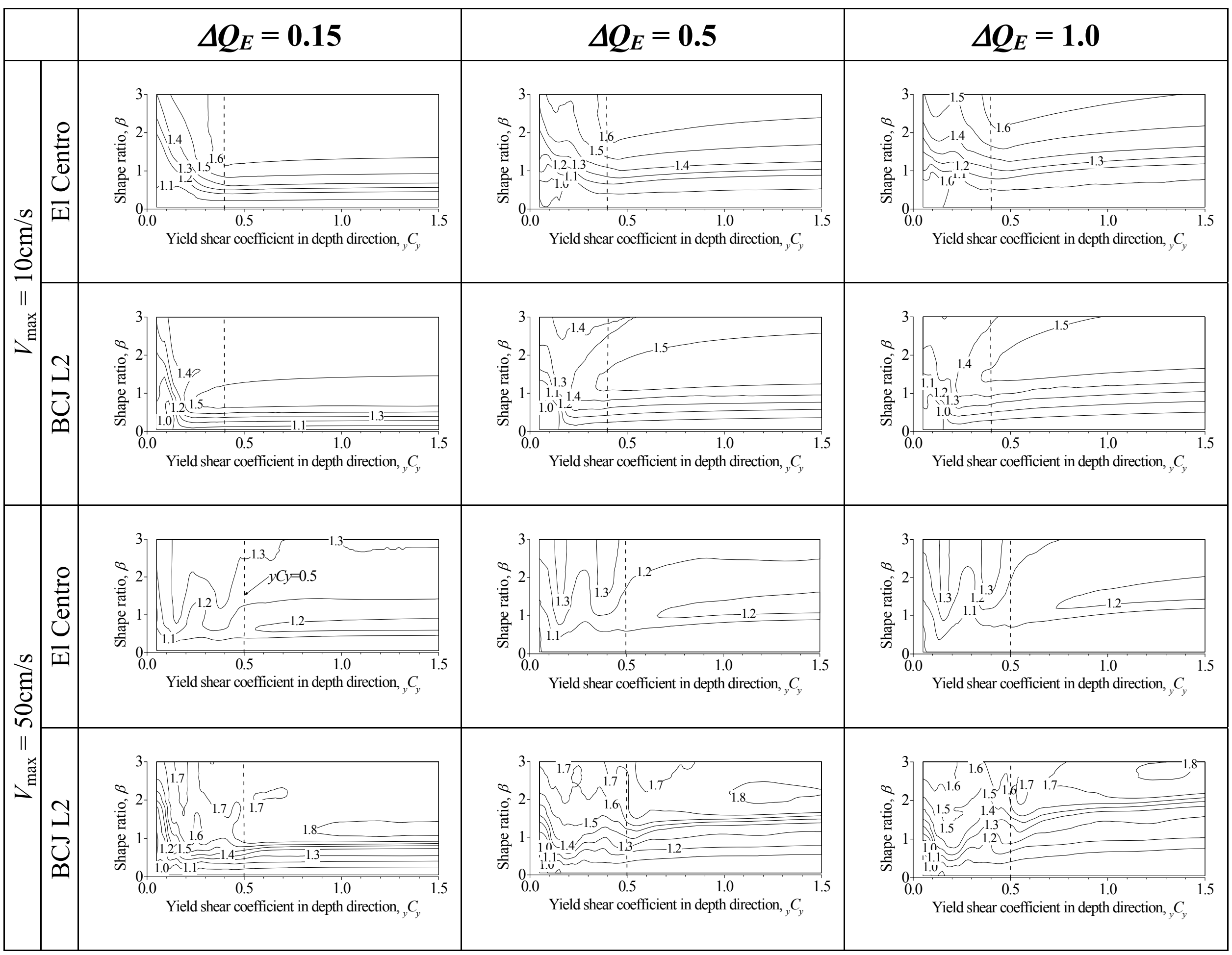


Figure 8. Displacement ratio of Y1 plane (Single type model, $_xC_y = 0.2$, $\alpha = 0.3$)

It is found that the ratios of both Y1 and Y2 planes become stable and converge to any value when ${}_yC_y$ becomes larger and larger. Those converged value exists between 1.1 and 1.8. Different input motions and $V_{\max}$ do not have an influence on the orthogonal wall effect when ${}_yC_y$ becomes large. The quantity of the orthogonal wall is required ${}_yC_y \geq 2{}_xC_y$ for the motions of $V_{\max}$ = 10cm/s. On the other hand, ${}_yC_y \geq 0.5$ is required for motions of $V_{\max}$ = 50cm/s.

To examine the influence of the shape ratio, β, on the orthogonal wall effect, Fig.8 shows the contour line of the displacement ratio of Y1 plane. This is the single type model, the yield shear coefficient in the width direction is ${}_xC_y$ = 0.2, the wall distribution factor α = 0.2, and the floor factor ΔQ_E = 0.15, 0.5 and 1.0. The input motions are El Centro and BCJ L2 of $V_{\max}$=10 and 50cm/s.

We can recognize from the figure as follows: In case of motions of $V_{\max}$ = 10cm/s, a tendency or a rule can be seen from the contour line on each figure. The displacement ratio strongly depends on β and is irrelevant to ΔQ_E when the shear coefficient in the depth direction is given by ${}_yC_y \geq 2{}_xC_y$ = 0.4. When β becomes large, the ratio also becomes large.

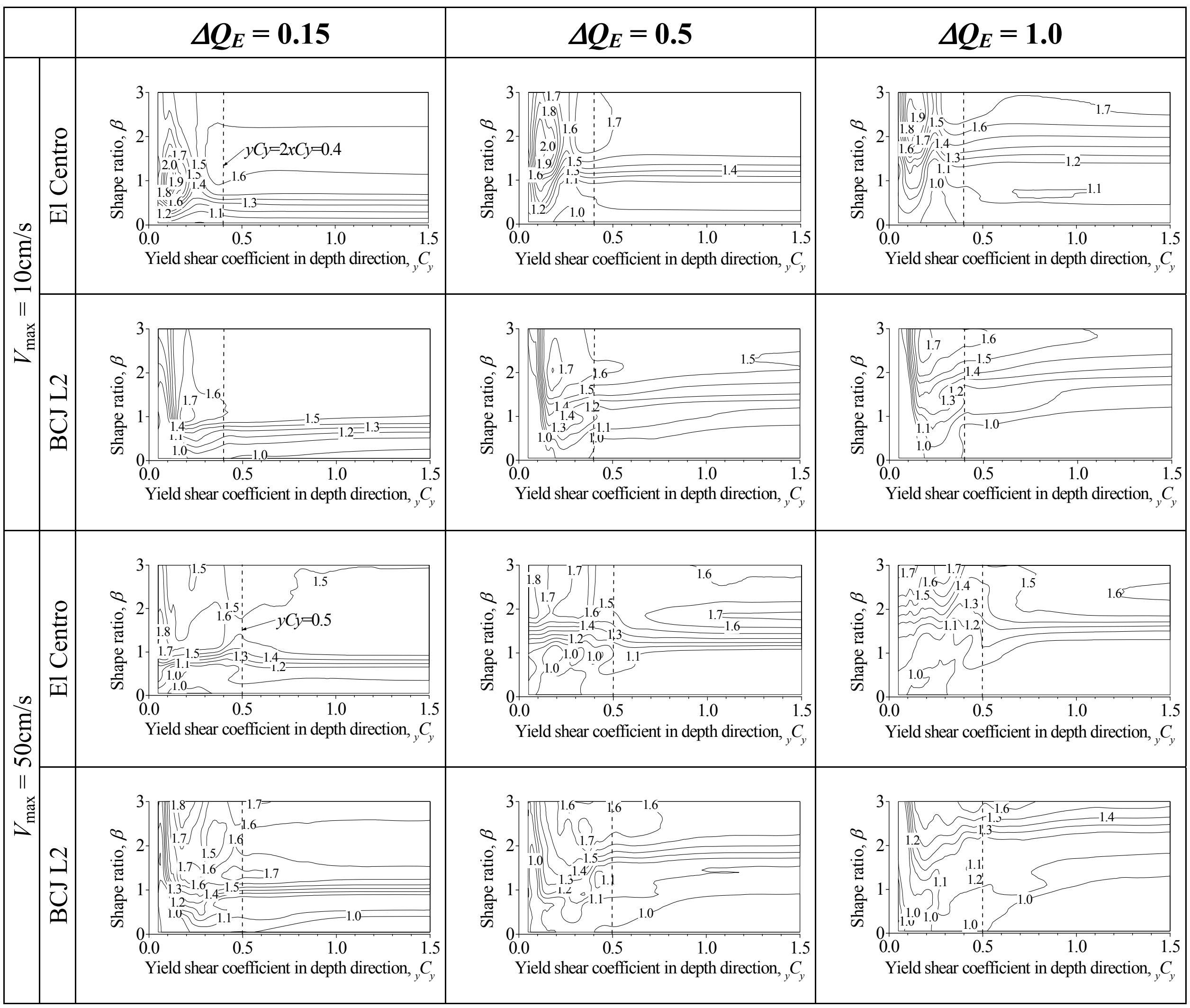


Figure 9. Displacement ratio of Y1 plane (Quadric type model, ${}_xC_y$ = 0.2, α = 0.3)

Therefore, it is noted that the narrow plan is disadvantageous with regard to the displacement ratio. When ΔQ_E becomes large, however, the contour line shifts to the upward and the interval of those lines becomes wide. This means that the floor stiffness is the important parameter for not only the displacement ratio but also the orthogonal wall effect. However, the differences in the input motions have no influence on characteristics of the contour line. In case of V_{max} = 50cm/s, a tendency nor a rule can be seen on the contour line in comparison with the case of V_{max} = 10cm/s. The displacement ratio, however, strongly depends on β when $\beta \leq 2.0$.

Fig.9 shows the examination result of the quadric type model. The parameters of the model are similar to those of Fig.7. On the right side of dashed lines in each figure, the displacement ratio strongly depends on β. This is the same tendency as the single type model.

Conclusions

In this paper, we carried out an earthquake response analysis of two type models of Nagaya with the uni-axial eccentricity subjected to earthquake motions with two horizontal components, considering the stiffness of the horizontal diaphragm. We examined the effects of the floor stiffness and of the orthogonal wall of the models on the earthquake response characteristics. The results obtained are summarized as follows:

1) In case of the rigid floor model without eccentricity, the maximum relative story angle responses does not reach to 1/120 and 1/15rad for the motions of V_{max} = 10 and 50cm/s when the yield shear coefficient is 0.3.
2) When the floor factor is 0.5 or more, the floor could be regarded as rigid from the viewpoint of quantity of the earthquake responses.
3) The orthogonal wall effect is strongly influenced by the wall ratio of the depth direction to the width one for the motions of V_{max}=10cm/s. The demanded ratio is 2.0.
4) The orthogonal wall effect depends on the yield strength in the depth direction when V_{max}=50cm/s. The yield shear coefficient 0.5 in the depth direction is demanded.
5) It is necessary to pay attention to not only the wall quantity but also the shape ratio. In addition, the combination of the wall quantity and the floor stiffness is the point to be considered.

References

Asano, K., 1977. Stochastic earthquake response analysis of the dumped mass structural system with elasto-plastic hysteretic characteristics Part 4: A single-degree-of-freedom system with poly-linear hysteretic characteristics subjected to quasi-stationary white noise excitations, *Journal of structural and construction engineering*, *Tras. of AIJ*, 258, 39-45 (in Japanese).

Suzuki, Y., 1985. Seismic reliability analysis of hysteretic structures based on stochastic differential equations, Disaster prevention research institute Kyoto University.

Riddell, R., and Santa-Maria, H., 1999. Inelastic response of one-story asymmetric-plan subjected to bi-directional earthquake motions, *Earthquake Engng. Struct. Dyn.*, 28, 273-285.

Yamada, A., Suzuki, S., and Asano, K., 2004. A study on earthquake response characteristics and damage predictions of one-storied wooden-framed house models with uni-axial and bi-axial eccentricities, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.

Yamada, A., and Suzuki, S., 2008. Study on earthquake response characteristics and effects of orthogonal walls of Japanese traditional wooden apartment called Nagaya, 14th World Conference on Earthquake Engineering, Beijing, China.