Experimental Study on Torsional Behaviour of Two-Story Timber Houses with Eccentricity

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SUMMARY:
Static and tests were carried out for 1/3 scale timber houses with various unsymmetric plans. Based on the test results, numerical simulations are torsional behaviour of unsymmetric-plan timber houses. A method of estimating the maximum response of each wall in an unsymmetric-plan timber house is proposed.

Keywords: Timber house, Torsional behavior, 1/3 scale model, Shaking table test, 3D frame model

1. INTRODUCTION

The seismic performance of timber houses in Japan has been improved especially after the 1995 Kobe earthquake. However, there are many timber houses with large opening on the south or with opening facing to the road for garage. Such houses are likely to have unsymmetric plan of structural walls. So these houses tend to separate the center of mass from the center of rigidity. On the other hand, most timber houses without large opening also have eccentricity. So houses without eccentricity are few.

Because of these concerns, many studies about eccentricity have been carried out. But most of them targeted on single-story buildings. In addition, the Japanese seismic design method for eccentricity is based on the rigid floor assumption and assumes the equivalent seismic force was proportional to the floor mass. Furthermore, it considers the balance of walls on each floor individually. So this method does not give enough consideration to the dynamic effect and ignores the influence of the torsional motion of a story to the other stories.

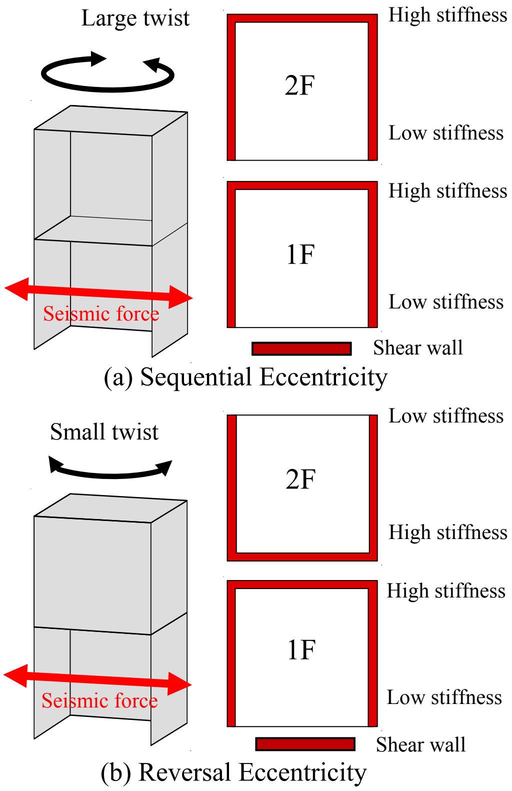


Figure 1. Sequential and Reversal Eccentricity

In Japan, there are many two-story and three-story timber houses. Previous studies [1] showed that torsional behavior of a story of a two-story unsymmetric house can affect other stories and discussed the need to clarify the mechanism of torsional behavior of multi-story buildings (Fig.1). Knowing the exact torsional behavior of buildings will give valuable information not only to improve the seismic performance but also to better plan dampers for the mitigation of torsional motions.

This study assesses the torsional behavior of multi-story unsymmetric-paln timber houses by shaking table test of 1/3 scale models and numerical analysis of 3D frame models. A method of predicting the maximum response for each wall is proposed.

2. PREVIOUS STUDIES

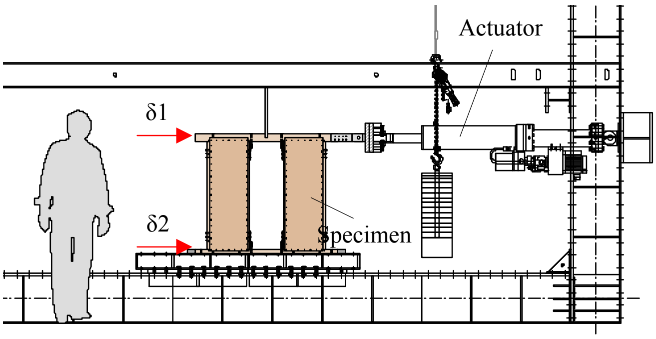
For symmetric-plan houses, seismic forces will be borne by each walls dependent on their stiffness. On the other hand, for unsymmetric houses, the disruption of stiffness balance leads to concentration of stress in low stiffness walls. By assuming elastic walls, previous study [1] proposed a method which calculates the shear stress concentration ratio of individual walls for two-story timber houses. Low stiffness walls could, however, become plastic during even minor earthquakes because these walls are likely to concentrate the deformation. So both elastic and plastic behavior of shear walls should be considered.

3. ELEMENT TESTS

3.1. SHEAR WALL TESTS

3.1.1. Outline

Fig.2 shows specimens and Table.1 shows specifications of elements. Specimens scaled full scale shear wall 1/3 times larger (1P=303mm). Column capitals and column bases manufactured stub tenon. In addition, column capitals and column bases were attached to the HD. Fig.3 shows set up of shear wall tests. The test method, according to [2]. Tests using specimens of the same specification were carried out 3 times.

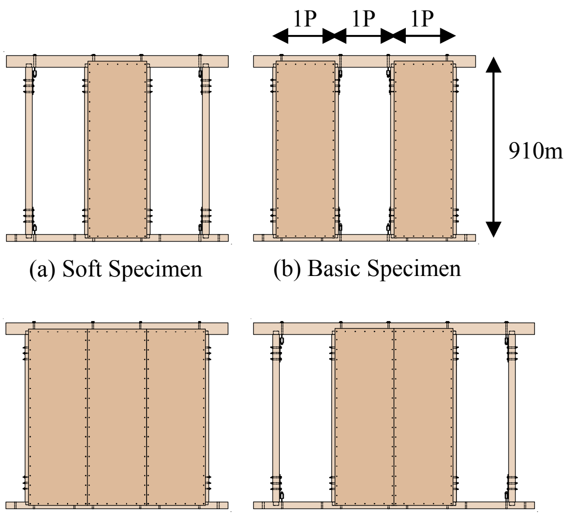


$$\theta=(\delta1-\delta2)/910[\mathrm{rad}] \quad (1)$$

Figure 3. Set Up (ex. Basic specimen)

Table 1. Specifications of Elements

Frame				
Tree Species(Laminated Timber)	Grade	Cross-Section of The Foundation B×D [mm]	Cross-Section of The Column B×D [mm]	Cross-Section of The Beam B×D [mm]
Column : Spruce	E95-F315	35×35	35×35	35×60
Beam : Pinus sylvestris	E105-F300			
Foundation : Pinus sylvestris				
Plywood		Nail		
Tree Species	Thickness t [mm]	Type of Nail		Nail Pitch [mm]
Lauan Plywood	3	L16×d0.9		@50

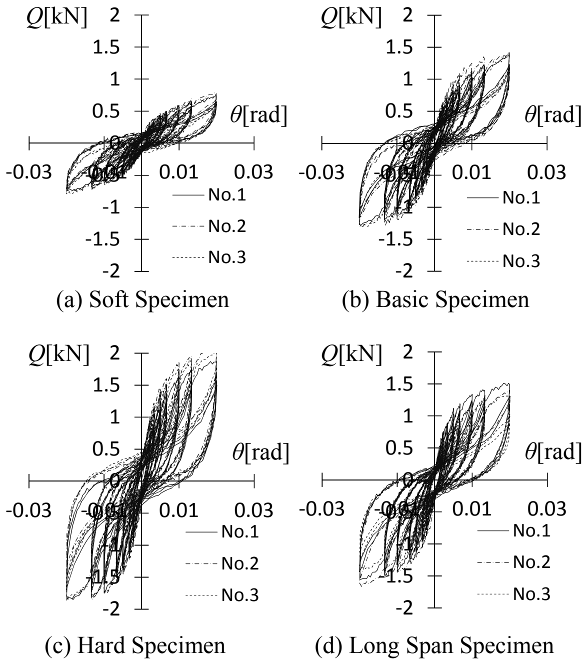


(a) Soft Specimen (b) Basic Specimen (c) Hard Specimen (d) Long Span Specimen

Figure 2. Specimens of Shear Wall Tests

3.1. 2. Result

Fig.4 shows the relationship between shear force (Q) and the apparent shear deformation angle (θ). θ is calculated by the Eq. 1. First, the failure characteristics are shown below. When θ becomes approximately 1/150rad, nail head began to lean. When θ becomes approximately 1/100rad, pull - out of nails began to be observed and nail head began to be sunk to the plywood. These destructions proceeded to approximately 1/75rad. Peeling of plywood began about a 1/50rad. Nail was completely pull - out and punching out occurred at the corner of the plywood leading up to 1/15rad. Through all the tests, most of the fracture mode was pull - out of nails. Cracking and torn off of plywood and breakage of the nail did not occurred. Next, the relationship between hysteresis and the fracture mode is shown. When nail head began to lean, stiffness was reduced gradually. Around the lifting of the plywood was observed, shear walls reached a maximum strength. After reaching the maximum strength, because the lifting of the plywood had become more pronounced, the load was reduced. In addition, specimens that were used in study had peculiar characteristics of timber structure. These characteristics are slip behavior, pinching behavior and strength degradation due to cyclic loading. In other words, hysteresis and the fracture mode were similar to that of a typical full scale shear wall. Then, do a comparison of the performance of structure of full scale specimen (Q_f) and the performance of structure of 1/3 scale specimen ($Q_{1/3}$). Fig.5 shows the comparison of shear force of each deformation angle. The value of $Q_{1/3}/Q_f$ was roughly constant. The result shows that the similarity ratio between A and B was a constant. But this value was not the value which was obtained by similarity rule.



(a) Soft Specimen (b) Basic Specimen (c) Hard Specimen (d) Long Span Specimen

Figure 4. Results of Shear Wall Tests (Q-θ)

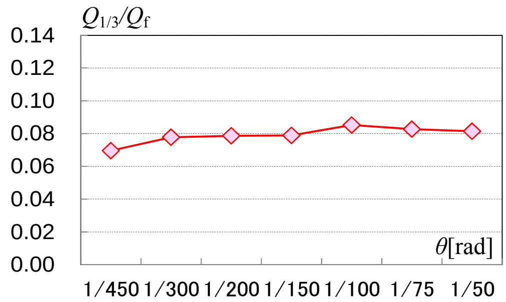


Figure 5. The Comparison of Shear Force of Each Deformation Angle ($Q_{1/3}/Q_f$)

4. ANALYSIS USING 3D FRAME MODEL

4.1. ANALYSIS OBJECTS

Analysis objects were 1/3 scale multi-story timber houses (Fig.6). Fig.7 shows floor plans of each model.In this study, 5 type models that had difference alignment of shear walls were provided. ±00±00 model has not eccentricity. ±00+44 model has eccentricity in only 1st story. +44±00 model has eccentricity in only 2nd story. +44+44 model and +44-44 model have eccentricity in 1st and 2nd story. Position of center of rigidity of the layers of +44+44 model (hereinafter called Sequential Eccentricity model) is in the same direction for the position of the center of gravity. On the other hand, position of center of rigidity of the layers of +44-44 model (hereinafter called Reversal Eccentricity model) is in the different direction for the position of the center of gravity. There are two parameters. One parameter is the ratio (k2/k1) of 2F story stiffness (k2) for 1F story stiffness (k1). In this study, k2/k1 assumed it k2/k1=0.8,0.6. When k2/k1 was changed, k1 was not changed but k2 was changed. The other is the ratio (m2/m1) of 2F story's mass (m2) for 1F story's mass (m1). In this study, m2/m1 assumed it m2/m1=0.9,0.6. When m2/m1 was changed, total mass (m1+m2) was not changed. Total mass assumed it 360kg in reference to [3] and [4].

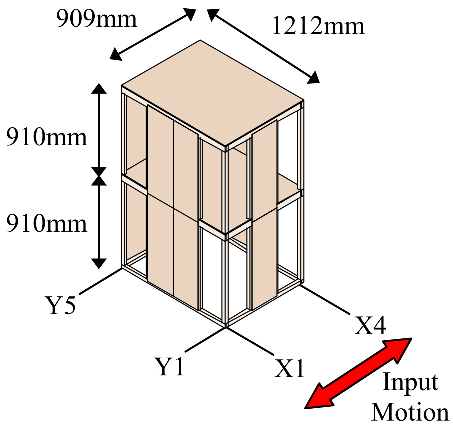


Figure 6. Analysis Objects

4.2. ANALYSIS MODEL

Analysis objects were modelled by 3D frame model(Fig.8) and shear walls were modelled by brace substitution method(Fig.9). The hysteresis model of brace was W.Stewart model [5]. Axial springs which modelled tensile performance of the joint were placed in column capitals and column bases. Mass points were arranged on the each floor so that did not change the value of the rotational inertia (I) that was calculated when mass were placed evenly on the floor. Damping model was the proportional model of initial stiffness. Damping constant was 2%.Input motion was set to unidirectional shaking (direction X). The time axis of seismic waves was shortened to times due to the reduction of the model (the mass ratio of full scale model to 1/3 scale model was 0.111 and stiffness ratio was 0.225). The input earthquake waves were 3 types JMA-KOBE waves and BCJ-LEVEL2 (hereinafter called BCJ-L2) wave. Maximum acceleration of 2

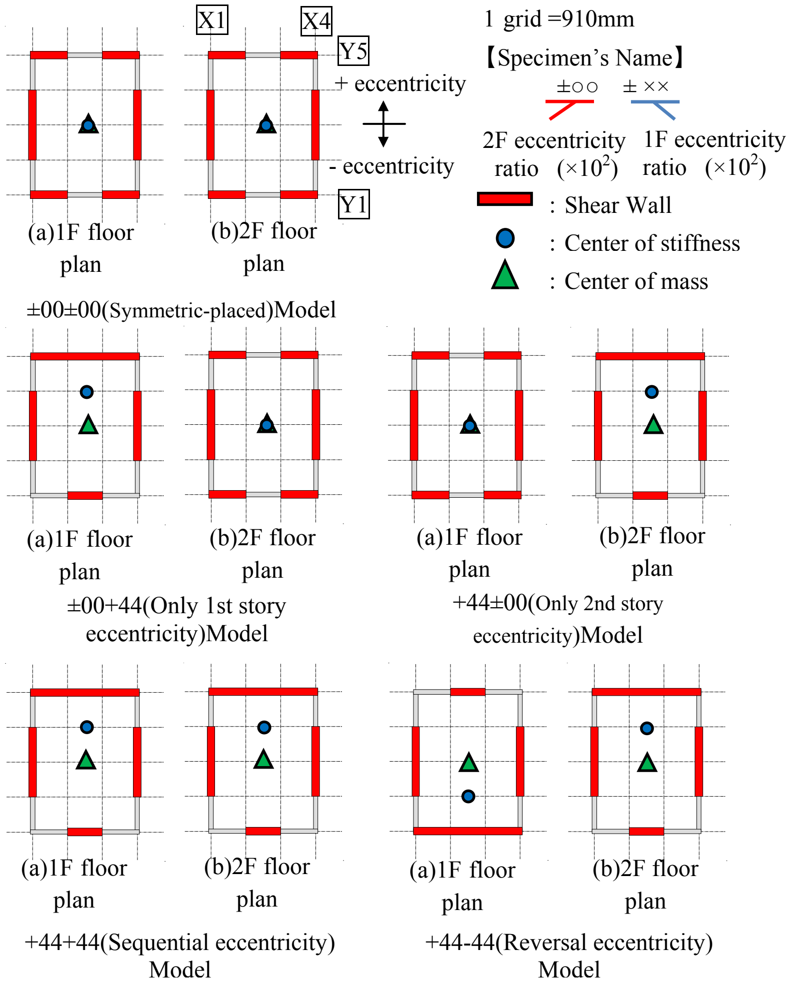


Figure 7. Floor Plans of Each Model

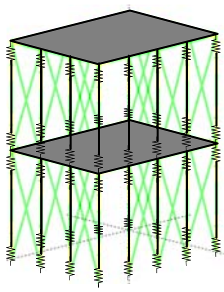


Figure 8. 3D Frame Model of Specimen

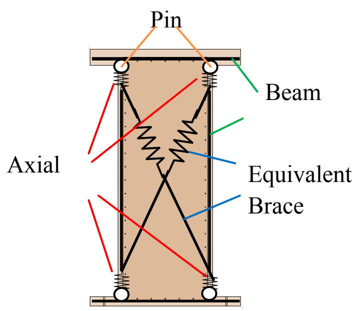


Figure 9. Frame Model of Shear Wall

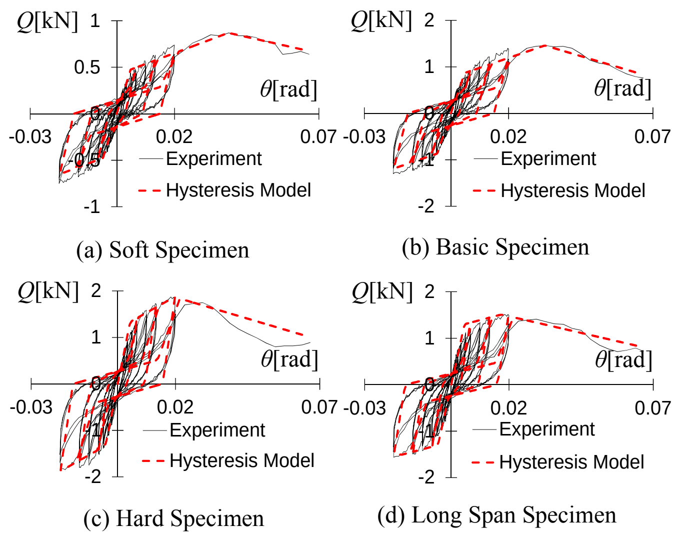


Figure 10. The Hysteresis Model of Each Wall

types JMA-KOBE waves was standardized. 1st type JMA-KOBE wave's acceleration was 0.2G (hereinafter called KOBE_0.2G), 2nd type JMA-KOBE wave's acceleration was 0.6G (hereinafter called KOBE_0.6G), and 3rd JMA-KOBE wave was original wave (hereinafter called KOBE_Ori).

4.3. RESULT

In this paper, describes only the case of k2/k1=0.8 and m2/m1=0.9. Fig.11 shows the maximum displacement of each wall when the displacement of the center of mass of each story was maximum. Fig.12 shows the response rate of twist (⊿u/uc.m.)[6]. ⊿u/uc.m. is the ratio of the displacement that the incremental displacement caused by the torsional (⊿u) for the displacement of the center of mass (uc.m.). ⊿u/uc.m. means the degree of twist. Though the 1F of +44±00 model and the 2F of ±00+44 model had not eccentricity, torsional deformation occurred on the both stories. So this result shows that the existence of torsional interaction. First, make a comparison between the models for ⊿u/uc.m.. Focus the models which have eccentricity in both stories. ⊿u/uc.m. of reversal eccentricity model is smaller than ⊿u/uc.m. of sequential eccentricity model. The reason for these results is shown below. Because 1st and 2nd stories of Sequential Eccentricity model (+44+44) twisted in the same direction, torsional deformation of Sequential Eccentricity model was got a helping hand. On the other hand, because 1st and 2nd stories of Reversal Eccentricity model (+44-44) twisted in the opposite direction, torsional deformation of Reversal Eccentricity model was became suppressed. Next, consider the transition of the ⊿u/uc.m.. The larger uc.m., ⊿u/uc.m. was increased once. When uc.m. was increased further, ⊿u/uc.m. was decreased. This phenomenon was considered to be due to changes in the characteristic mode shapes of each story which were caused by the damage of shear walls.

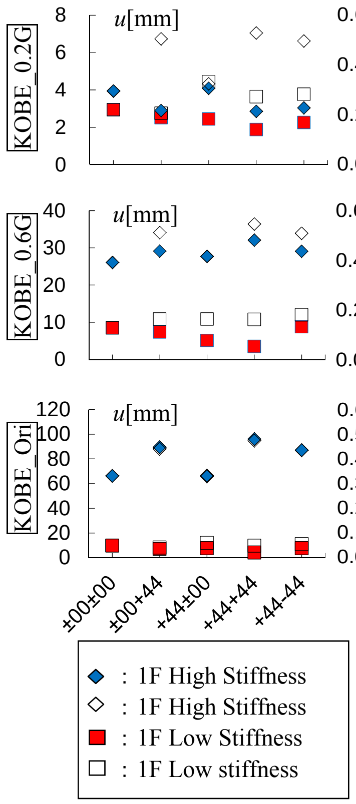


Figure 11. The Maximum Displacement of Each Wall

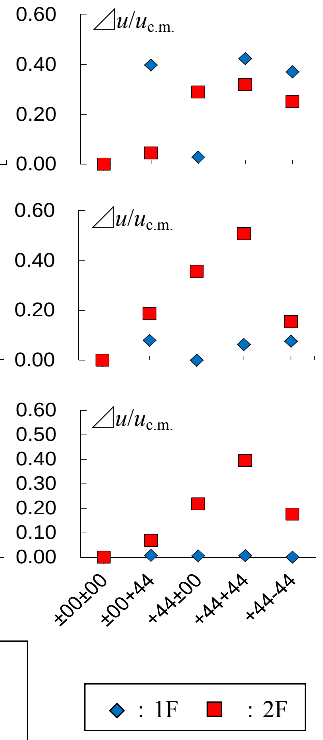


Figure 12. The Response Rate of Twist

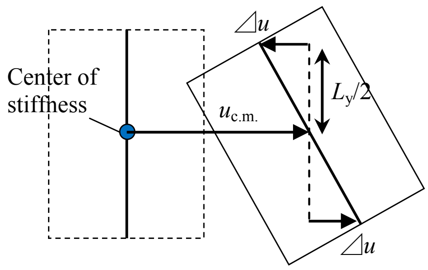


Figure 13. The Response Rate of Twist (⊿u/$u_{c.m.}$)

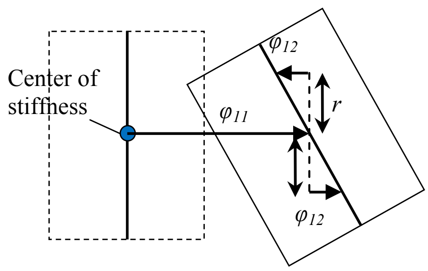


Figure 14. The Characteristic Mode Shapes of Each Story

Fig.15 shows the change of characteristic mode shape which was caused by the damage of shear walls if the walls yielded in order of low stiffness wall, high stiffness wall, and orthogonal wall (Pattern1). First, when the low stiffness walls yield, spring radius is decreased. So twist component of the mode shape is increased. Next, when the high stiffness walls yield, spring radius is increased. So twist component of the mode shape is decreased. Finally, when the orthogonal walls yield, spring radius returns to the initial state. So twist component of the mode shape returns to the initial state too.Fig.16

shows the change of characteristic mode shape which was caused by the damage of shear walls if the walls yielded in order of low stiffness wall, orthogonal wall and high stiffness wall (Pattern2). As well, in this study, all yield patterns was (Pattern1).Then changes in the value of the characteristic mode shape and ⊿u/uc.m. were similar.In other words, the impact of the change of characteristic mode shape on the torsional behaviour of house with eccentricity is great.

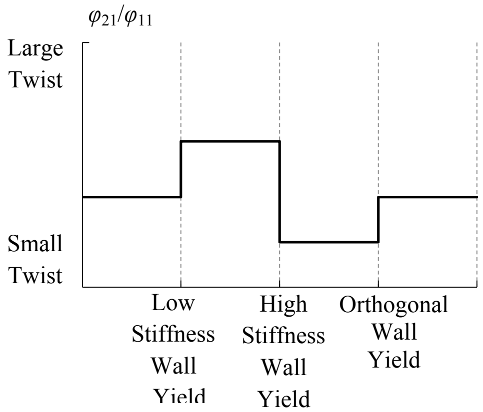


Figure 15. The Change of Characteristic Mode Shape (Pattern1)

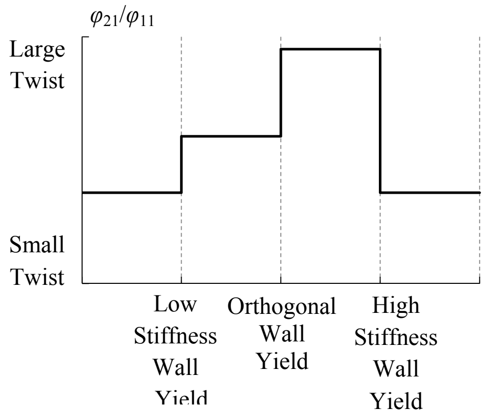


Figure 16. The Change of Characteristic Mode Shape (Pattern2)

5. RESPONSE PREDICTION

The proposed method which will be shown in this chapter is the approximative estimation which is calculated using the characteristic modes shapes of each story and the characteristic mode shapes which ignored the torsional deformation. The following shows the procedure.

<How to get the approximative characteristic mode shape>

STEP1 : Calculate mode shapes of the layers each layer independently (Fig.14).

↓

STEP2 : Calculate the mode shape which ignored the torsional deformation (Fig.17).

↓

STEP3 : Superimpose mode shapes which was calculate in STEP1 and STEP2.

<How to get the approximative characteristic period>

STEP4 : Calculate the equivalent layer stiffness (Keqi) which is added the apparent degradation of layer stiffness due to eccentricity.

↓

STEP5 : Calculate the characteristic period which ignored the torsional deformation using Keqi.

<How to predict the maximum response of each wall>

STEP6 : Calculate the maximum response on arbitrary point.

↓

STEP7 : Calculate the maximum response of each wall using this maximum response and the mode shape which calculate in STEP2

Because the proposed method uses the characteristic mode, the examination structure needs to be linear essentially. If the examination structure is non-linear, the stiffness of each wall needs to use equivalent stiffness. The following shows the detail of each STEP.

※
m_i= The mass of iF , I_i= The rotational inertia of iF
K_{xi}= The layer stiffness of iF , $K_{\theta i}$= The torsional rigidity of iF
ω_{xi}= m_i / K_{xi} , $\omega_{\theta i}$= I_i / $K_{\theta i}$, e_{yi}= The eccentric distance of iF in the y derection
r_i= Radius Gyration of iF , ω_{in}= nth character frequency of iF , ω_n= Character frequency of iF
$\bar{e}_{yi}$ = the ratio of eccentricity$\left(= e_{yi} / r_i\right)$

STEP1 : Calculate mode shapes of the layers each layer independently (Fig.14).

To begin with, treat each story as independent. Then write equation of motion for free vibration (Eq.2).
Solve the eigenvalue problem using this equation (Eq.3-4).

$$\begin{bmatrix} 1 & \\ & 1 \end{bmatrix}\begin{bmatrix} \ddot{u}_i \\ \Delta\ddot{u}_i \end{bmatrix} + \begin{bmatrix} \omega_{xi}^2 & -\omega_{xi}^2 \cdot \bar{e}_{yi} \\ -\omega_{xi}^2 \cdot \bar{e}_{yi} & \omega_{\theta i}^2 \end{bmatrix}\begin{bmatrix} u_i \\ \Delta u_i \end{bmatrix} = [0] \tag{2}$$

$$\omega_{i1}^2 = \frac{1}{2}\omega_{xi}^2\left[1 + (\omega_{\theta i}/\omega_{xi})^2 - \sqrt{\left\{1 + (\omega_{\theta i}/\omega_{xi})^2\right\}^2 - 4\left\{(\omega_{\theta i}/\omega_{xi})^2 - \bar{e}_{yi}^2\right\}}\right] \tag{3}$$

$$\left[\phi_1^{(i)}\right] = \begin{bmatrix} \phi_{11}^{(i)} \\ \phi_{21}^{(i)} \end{bmatrix} = \begin{bmatrix} 1 \\ \left\{1 - (\omega_{i1}/\omega_{xi})^2\right\} / \bar{e}_{yi} \end{bmatrix} \tag{4}$$

STEP2 : Calculate the mode shape which ignored the torsional deformation (Fig.17).

Write equation of motion for free vibration of the 2 D.O.F system that ignores the torsional (Eq.5).
Solve this eigenvalue problem using the formula (Eq.6-7)

$$\begin{bmatrix} 1 & \\ & 1 \end{bmatrix}\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} \omega_{x1}^2 + \dfrac{K_{x2}}{m_1} & -\dfrac{K_{x2}}{m_1} \\ -\omega_{x2}^2 & \omega_{x2}^2 \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = [0] \tag{5}$$

$$\omega_1^2 = \frac{1}{2}\left[\left(\omega_{x1}^2 + K_{x2}/m_1 + \omega_{x2}^2\right) - \sqrt{\left(\omega_{x1}^2 + K_{x2}/m_1 + \omega_{x2}^2\right)^2 - 4\omega_{x1}^2\omega_{x2}^2}\right] \tag{6}$$

$$[\phi_1] = \begin{bmatrix} \phi_{11} \\ \phi_{21} \end{bmatrix} = \begin{bmatrix} 1 \\ -\left\{\omega_{x1}^2 + K_{x2}/m_1 - \omega_1^2\right\} / (K_{x2}/m_1) \end{bmatrix} \tag{7}$$

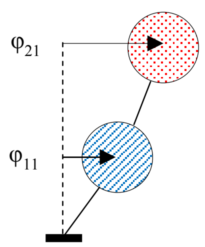


Figure 17. The Mode Shape Which Ignored The Torsional Deformation

STEP3 : Superimpose mode shapes which was calculate in STEP1 and STEP2.

φ_{11} and φ_{21} are treated as the value of the center of stiffness at each layer. (Fig.18). Fig.19 shows the comparison of the mode shapes which was calculated by eigenvalue analysis and the mode shapes which was calculated by the proposed method.

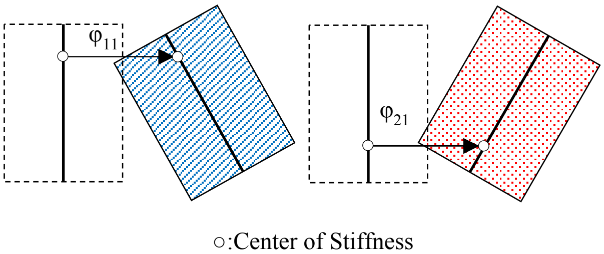


Figure 18. Superimpose Mode Shapes

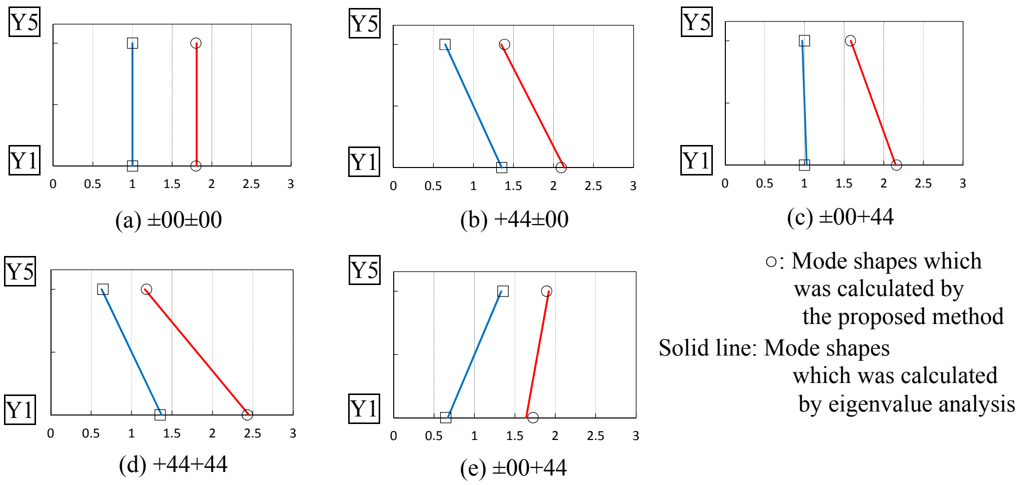


Figure 19. The Accuracy of The Proposed Method (Mode Shape)

STEP4 : Calculate the equivalent layer stiffness (K_{eqi}) which is added the apparent degradation of layer stiffness due to eccentricity.

Even if wall quantity is same, the characteristic period of the house with eccentricity is longer than the characteristic period of the house without eccentricity.
In other words, the layer stiffness is falling apparently.
This layer stiffness of iF is defines the equivalent layer stiffness (K_{eqi}).Eq.8 is the equation which calculate the equivalent layer stiffness (K_{eqi}).

$$K_{eqi} = \frac{m_i}{2}\omega_{xi}^2\left[1+(\omega_{\theta i}/\omega_{xi})^2 - \sqrt{\left\{1+(\omega_{\theta i}/\omega_{xi})^2\right\}^2 - 4\left\{(\omega_{\theta i}/\omega_{xi})^2 - \bar{e}_{yi}^2\right\}}\right] \quad (8)$$

STEP5 : Calculate the characteristic period which ignored the torsional deformation using K_{eqi}.

Substituting K_{eqi} which was calculated by Eq.8 into Eq.9, the approximative characteristic period is obtained. Table 2 shows the comparison of the characteristic period which was calculated by eigenvalue analysis and the characteristic period which was calculated by the proposed method.

$$\omega_1^2 = \frac{1}{2}\left[\left(\omega_{x1}^2 + K_{eq2}/m_1 + \omega_{x2}^2\right) - \sqrt{\left(\omega_{x1}^2 + K_{eq2}/m_1 + \omega_{x2}^2\right)^2 - 4\omega_{x1}^2\omega_{x2}^2}\right] \quad (9)$$

Table 2. The Comparison of The Characteristic Period

Model	1st Characteristic Period[s]		Comparison E.A./P.M
	Eigenvalue Analysis (E.A.)	Proposed Method (P.M.)	
±00±00	0.2282	0.2144	1.064
±00+44	0.2339	0.2213	1.057
+44±00	0.2306	0.2181	1.057
+44+44	0.2382	0.2248	1.059
+44-44	0.2338	0.2248	1.040

STEP6 : Calculate the maximum response on arbitrary point.

STEP7 : Calculate the maximum response of each wall using this maximum response and the mode shape which was calculated in STEP2.

The maximum response on arbitrary point was the maximum displacement of the center of mass of 1F which was obtained by dynamic analysis using 3D frame model. Then, calculate the maximum response of each wall was based on the mode shape which was calculated in STEP2. Fig.20 shows the accuracy of the proposed method. This result shows that the maximum response of each wall can be obtained by the proposed method.

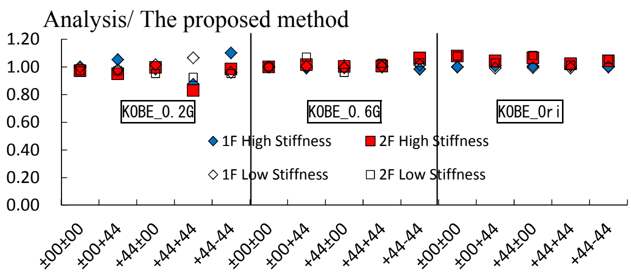


Figure 20. The Accuracy of The Proposed Method (The Maximum Response)

6. CONCLUSIONS

In this study, element tests and dynamic analysis using 1/3 scale model. Seismic behaviour of multi-story timber houses with eccentricity was understood. Maximum response prediction method has been proposed. The validity of the method was confirmed. The dynamic tests using 1/3 scale specimens are in execution now.

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