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SEISMIC PERFORMANCE EVALUATION OF JAPANESE TRADITIONAL L- SHAPED THATCHED WOODEN STRUCTURES, *CHUMON-ZUKURI*

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Abstract

Many earthquakes have occurred in Japan. The Hyogoken-Nanbu earthquake in 1995 (M7.3) and the Tohoku-Chiho Taiheiyo-Oki earthquake (M9.0) in 2011 damaged many structures. However, some traditional wooden structures have not collapsed, even after experiencing many such earthquakes.

The Maesawa district in Minamiaizu located in the inland Fukushima prefecture was registered as an Important Preservation District for Groups of Historic Buildings (IPDGHB) in 2011. It is a mountain village and contains many traditional thatched houses, called *Chumon-Zukuri*. In the typical plan of a *Chumon-Zukuri,* the stable, called the *Umaya*, connects with the main house, known as the *Omoya*. A *Chumon-Zukuri* house has an L-shaped plan; the *Umaya* protrudes from the *Omoya*. The thatched houses generally have a hipped roof on the *Omoya* and a gable roof or hip-and-gable roof on the *Umaya*. Their eaves are high, and their walls have a glorious exposed wooden framework. There are also some *Chumon-Zukuri* houses in Kitakata city near the Maesawa district. In a previous study conducted in the Maesawa district, some of these houses were investigated.

A relatively low five-intensity earthquake on the Japanese seven-stage seismic scale was recorded near the Maesawa preservation district; however, none of the thatched houses suffered any damage. Therefore, it is very important to understand their construction and structural characteristics.

The purpose of this study is to analyze the structural and vibrational characteristics of L-shaped thatched houses, and propose an evaluation method for such houses that have irregular plans. First, we conducted a field survey of the existing thatched houses in the Maesawa district and Kitakata city to understand their construction and maintenance methods. Second, we conducted microtremor measurements for these houses to understand the vibrational characteristics. Moreover, we calculated the yield base shear coefficient as an indicator of seismic performance based on the data obtained from the field survey. Finally, we propose an evaluation method for such irregular houses.

Keywords: traditional wooden house, thatched house, field survey, microtremor measurement, seismic capacity

1. Introduction

Many earthquakes have occurred in Japan. The Hyogoken-Nanbu earthquake in 1995 (M7.3) and the Tohoku-Chiho Taiheiyo-Oki earthquake (M9.0) in 2011 damaged many structures [4, 6]. However, some traditional wooden structures have not collapsed, even after experiencing many such earthquakes.

The Maesawa district of the inland Fukushima prefecture, which was registered as an Important Preservation District for Groups of Historic Buildings (IPDGHB) in 2011, is a mountain village [1, 2] and contains many traditional thatched houses. A low-five-intensity earthquake on the Japanese seven-stage seismic scale was recorded near the Maesawa preservation district; however, none of the thatched houses suffered any damage. Therefore, it is very important to understand their construction and structural characteristics. L-shaped traditional wooden houses also exist in Kitakata city near the Maesawa district.

The purpose of this study is to analyze the structural and vibrational characteristics of L-shaped thatched houses, and propose an evaluation method for such houses that have irregular plans. First, we carried out a field survey of the existing thatched houses in the Maesawa district and Kitakata city to understand their construction and maintenance methods. Secondly, we conducted microtremor measurements for these houses and the ground on which they stand to understand the vibrational characteristics. Moreover, we calculated the yield base shear coefficient as an indicator of seismic performance based on the data obtained from the field survey. Finally, we propose an evaluation method for such irregular houses.

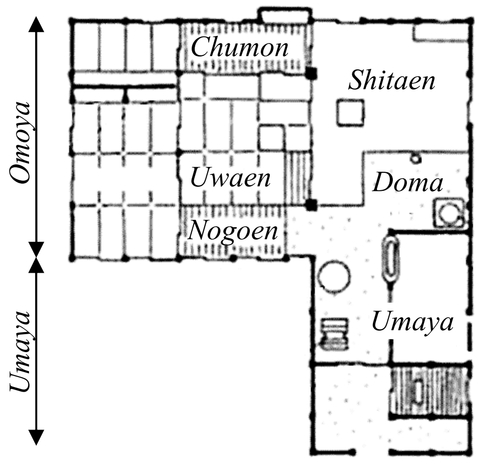
2. Structural Investigation of Traditional Houses

2.1 Location of the Maesawa Preservation District and Kitakata City

The Maesawa district is a mountain village and was registered as an IPDGHB in 2011 [5]. Many households have a thatched roof and are built on land surrounded by mountains, as shown in Fig. 1(a). The thatched houses have a large building pitch. This district has approximately 14 thatched houses: 10 L-shaped houses called *Chumon-Zukuri* and 4 rectangular-shaped houses called *Sugoya*. The Maesawa preservation district is a tourist location.

Kitakata city is located north of the Maesawa preservation district, and it is also an IPDGHB. However, this city does contain several L-shaped traditional wooden houses that were popular around the Aizu basin in the 18th century.

(a) Maesawa preservation district.



(b) Typical plan of *Chumon-Zukuri*.

Fig. 1 – *Chumon-Zukuri* in the Maesawa preservation district

2.2 *Chumon-Zukuri* House

The typical plan of a *Chumon-Zukuri* is shown in Fig. 1(b) [10]. The stable, called the *Umaya*, connects with the main house, called the *Omoya*. A *Chumon-Zukuri* house has an L-shaped plan; the *Umaya* protrudes from the *Omoya*. The thatched houses generally have a hipped roof on the *Omoya* and a gable roof or hip-and-gable roof on the *Umaya*. Their eaves are high, and their walls have a glorious exposed wooden framework including columns, beams, struts, and many penetrating tie beams. This style has been established as the top farmhouse-type construction method.

2.3 Structural Investigation Components

The thatched houses were investigated in the Maesawa preservation district in July, 2017; September, 2018; and November 2019. Houses A, C, and F were *Chumon-Zukuri* houses, and House B was a *Sugoya* house. We investigated the houses in Kitakata city in August, 2019. Houses D and E were L-shaped houses. The following steps were conducted as a part of the structural investigations.

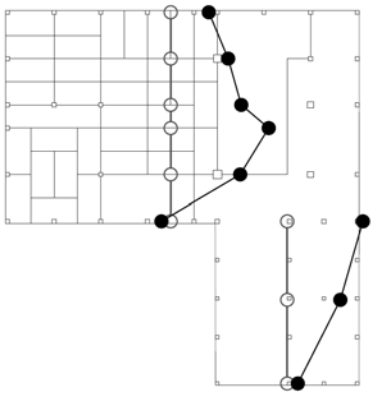
– Drawing plans: The floor and sectional plans were drawn to clarify the structural components, joint details, house weight, etc.
– Interviews: Inhabitants were asked for information concerning the house and maintenance methods.
– Deterioration check: Termite damage, column moisture content, and any inclination of the houses were confirmed.
– Microtremor measurements: Microtremor measurements were conducted for each thatched house.

Table 1 – Information of the investigated traditional wooden houses

House	Age	Uses		Style	Place	Investigated Date
		1st floor	Attic space			
A	Approx. 110 yrs.	Museum	Storage	*Chumon-Zukuri*	Maesawa	26/7/2017
B	Approx.80 yrs.	Assembly place	Storage	*Sugoya*	Maesawa	27/7/2017
C	Approx. 110 yrs.	Residence	Storage	*Chumon-Zukuri*	Maesawa	26/9/2018
D	1771 yr. relocated 29 yrs. ago	Exhibition place		L-shaped	Kitakata	5/8/2019
E	35 yrs. after moving	Exhibition place		L-shaped	Kitakata	6/8/2019
F	Unknown	Restaurant	Rest room	*Chumon-Zukuri*	Maesawa	23/11/2019

2.4 Results of a Previous Study of House A

We investigated Houses A and B in a previous study [9]. The major findings from this previous study are summarized as follows: (a) Based on the house vibrational mode, it was found that the amplitude of the ridge direction had a large gap at the joint between the *Omoya* and *Umaya*, as shown in Fig. 2. It is supposed that House A had become separated at that joint and a large burden rested on the column at the corner of the joint. (b) The thatched houses in the Maesawa preservation district had comparatively high shear forces.



(a) Appearance (b) 1st mode, ridge dir. (3.3 Hz)

Fig. 2 – House A

3. Structural Investigation of Traditional House D

This chapter concerns House D in Kitakata city. House D was built in 1771 and was relocated 29 years ago.

Fig. 3 – Appearance of House D

3.1 Deterioration and Damage History

The humidity was 62.2% in the underfloor, 68.6% on the first floor, and 59.7% in the attic space. Termite damage was not found. The diameters of the central and standard columns are 230 mm and 135 mm, respectively. The column inclinations were measured. The maximum deformation angle of the first floor is 17/1000 rad towards the east, and the average angle is 3/1000 rad towards the east in the span direction. The maximum deformation angle is 19/1000 rad towards the south, and the average angle is 4/1000 rad towards the north in the ridge direction. The moisture contents of the columns had a maximum of 25.8% and an average of 13.3% on the first floor.

3.2 Drawing Plans and Weight Calculation

The front facade of the House D is shown in Fig. 3, and the structure of the house is shown in Fig. 4. The plan is shown in Fig. 4(a). This is a one-storied house. The cross section along the span, S1 and S4, is shown in Figs 4(e) and (c), respectively, and the ridge cross section, S2 and S3, is shown in Figs 4(b) and (d), respectively. The columns are set on the ground sill.

Table 2 shows the structural parameters of House D. The weight of the house was calculated based on the timber volume determined from a drawing [3]. The number of columns per unit area was 0.34 m^{-2}, and the weight of each column was 14.93 kN.

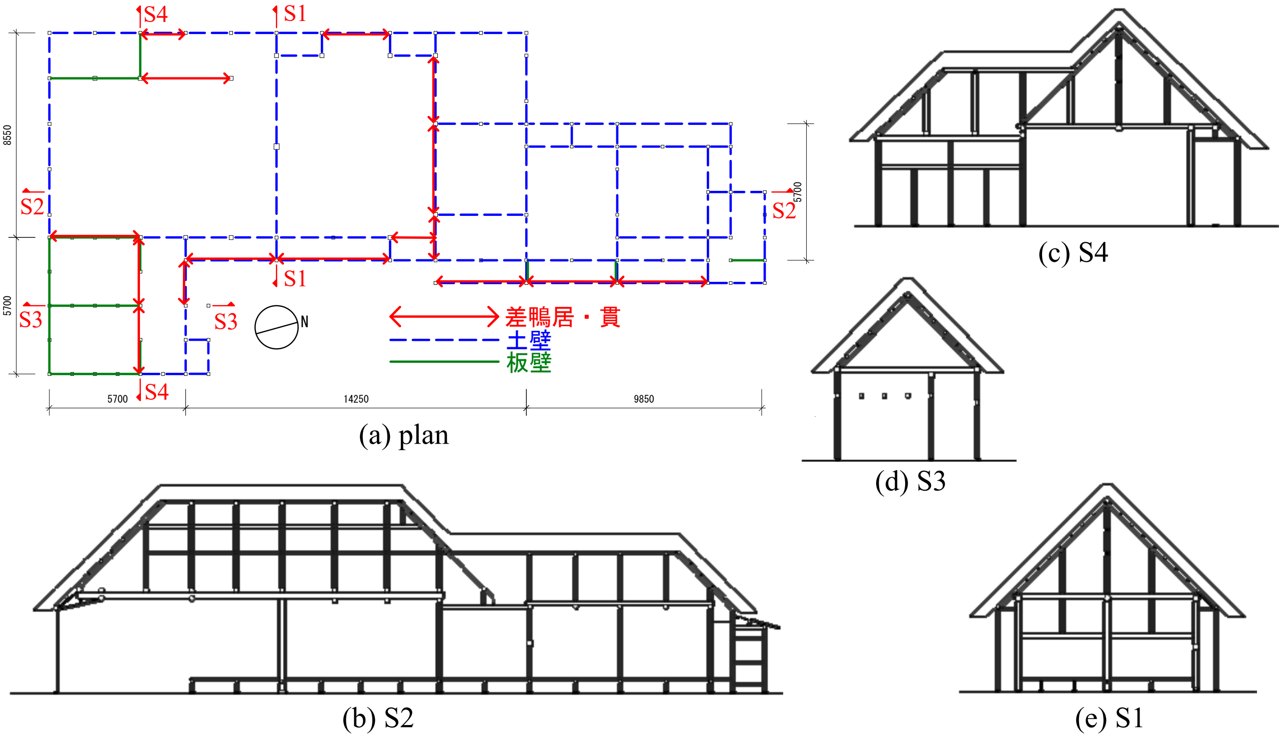


Fig. 4 – Plan of House D

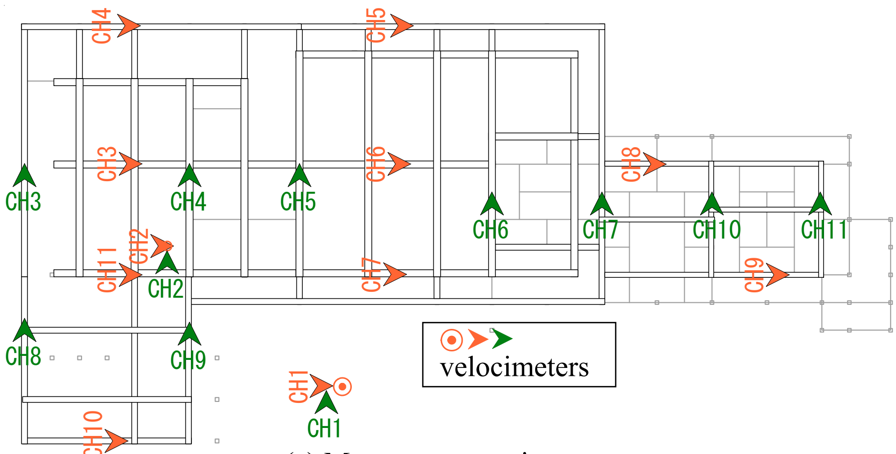
Table 2 – Structural parameters of Houses D

Story height (mm)	**Weight (kN)**	**Floor area (m^2)**	**Number of columns**	**First frequency, f_1 (Hz)**		**Base shear coefficient**	
				Ridge dir.	**Span dir.**	**Ridge dir.**	**Span dir.**
4000	1448.4	279	97	2.9	2.9	0.36	0.32

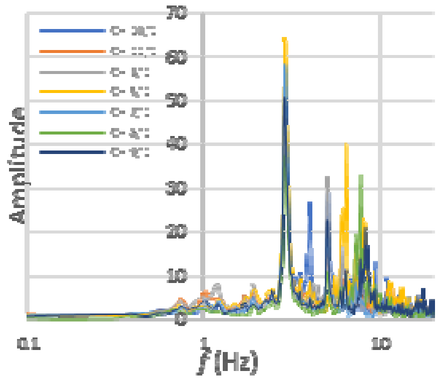
3.3 Vibrational Characteristics and Microtremor Measurements

Microtremor measurements were conducted. Several overdamping velocimeters were used, and simultaneous measurements were conducted for 500 s (approximately 8 min).

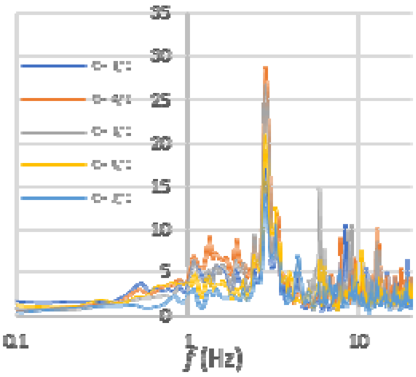
The microtremor measurement results for House D are shown in Figs 5 and 6. The measurement points are indicated in Fig. 5(a). One velocimeter was installed on the ground, while others were installed in the attic. The first natural frequencies, f_1, are provided in Table 2. The first natural frequency in the ridge direction is 2.9 Hz, as shown in the Fourier spectrum ratio in Fig. 5(b); that in the span direction is also 2.9 Hz. The vibration modes are shown in Fig. 6. Unlike House A, it was found that House D had not become separated at the joint between the *Omoya* and *Umaya*.



(a) Measurement points

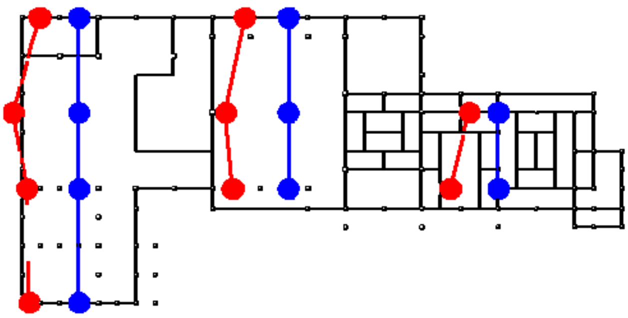


(b) Fourier spectral ratio of the ridge direction

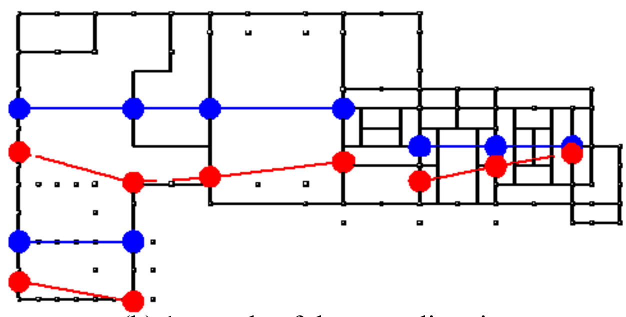


(c) Fourier spectral ratio of the span direction

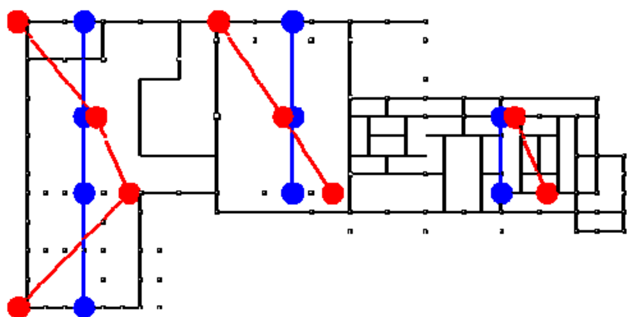
Fig. 5 – Microtremor measurements of House D



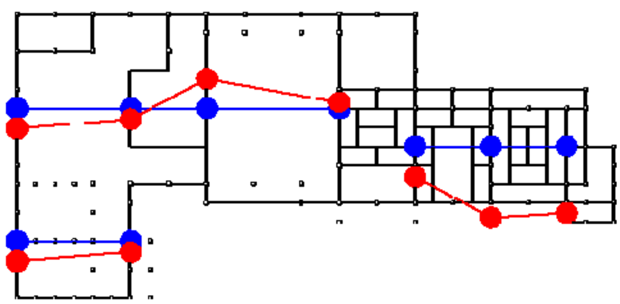
(a) 1st mode of the ridge direction



(b) 1st mode of the span direction



(c) 2nd mode of the ridge direction



(d) 2nd mode of the span direction

Fig. 6 – Vibration modes of House D

4. Estimation of Earthquake Response Values

4.1 Yield Base Shear Coefficient of House D

The yield base shear coefficient of House D was calculated by simply combining the restoring forces using the limit-strength calculation [7, 8]. In the conventional method, the base shear coefficient at 1/30 rad is used as the yield base shear coefficient, C_y. Using C_y as an indicator, the seismic resistance was evaluated.

The base shear coefficient of House D is shown in Fig. 7. The yield base shear coefficient was 0.36 at 1/30 rad in the ridge direction and 0.32 at 1/30 rad in the span direction.

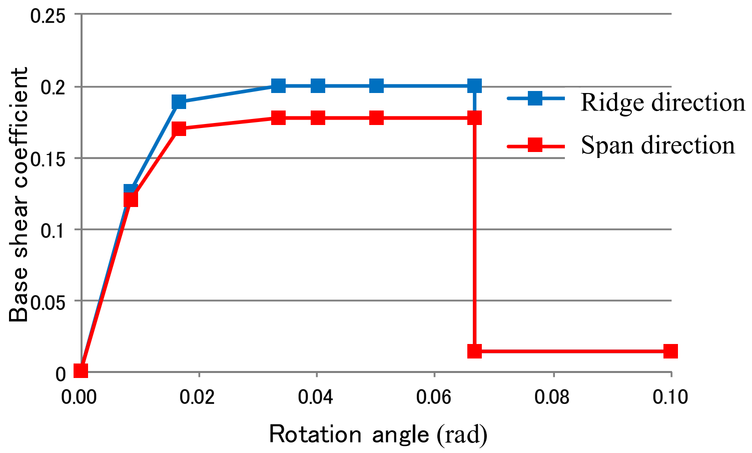
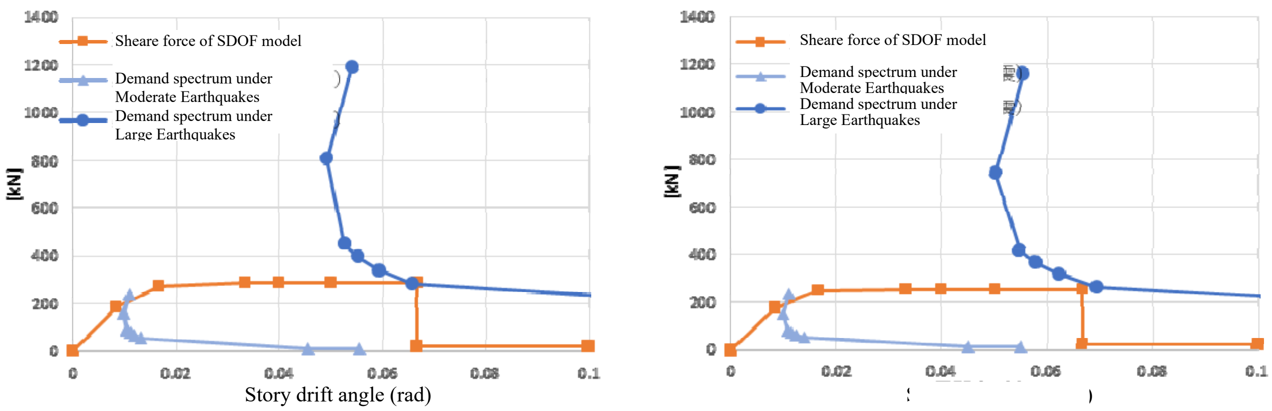


Fig. 7 – Base shear coefficients of House D

4.2 Earthquake Response Values

The earthquake response value of House D was calculated via the conventional limit-strength calculation, as shown in Fig. 8. The response deformation angle of House D is shown in Table 3 with the corresponding values for House A. In the conventional method, the response deformation angle of House A is 0.011 rad for a moderate earthquake and 0.066 rad for a large earthquake. Likewise, the response deformation angle of House D is 0.010 rad for a moderate earthquake and 0.066 rad for a large earthquake.



(a) Ridge direction (b) Span direction

Fig. 8 – Earthquake response values of House D

Table 3 – Response deformation angles of Houses A and D

House	For Moderate Earthquake		For Large Earthquake	
	Conventional method	**Proposed method**	**Conventional method**	**Proposed method**
A	0.011 rad	0.009 rad	0.066 rad	collapse
D	0.010 rad	0.011 rad	0.066 rad	collapse

5. Proposal of an Improved Reducing Method

5.1 Outline of the Improved Reducing Method

In the conventional calculation method, single mass points are reduced for each layer. Because of the L-shaped structures of these houses, earthquake-resistant factors may not function within one body. We therefore propose a new reducing method for equivalent single degree of freedom (SDOF) systems in the ridge direction.

The proposed reducing procedure is as follows:

1) Calculate the weight of each mass point and restoring force of spring each displacement step based on Fig. 9(a).

2) Calculate the stiffness matrix and mass matrix. Make a balanced expression of each mass point, as shown in Fig. 9(b).

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{pmatrix} + \begin{bmatrix} k_1 + k_3 & -k_3 \\ -k_3 & k_2 + k_3 \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (1)$$

3) Obtain the amplitude ratio at the initial stiffness using the natural circular frequency from Eq.1.

$$\frac{u_2}{u_1} = \frac{k_1 + k_3 - m_1\omega^2}{k_3} \quad (2)$$

4) Calculate the displacement, σ, of each mass point for each step using the incremental displacement method.

Calculate the horizontal displacement of mass point 1 at each step.

$$\sigma_1^{(n)} = \text{(story drift angle at n step)} \times \text{(story height)} \quad (3)$$

Calculate the horizontal displacement of mass point 2 at the 1st step.

$$\sigma_2^{(1)} = \sigma_1^{(1)} \times \frac{u_2}{u_1} \quad (4)$$

Calculate the deformation mode of mass point 2 at each step.

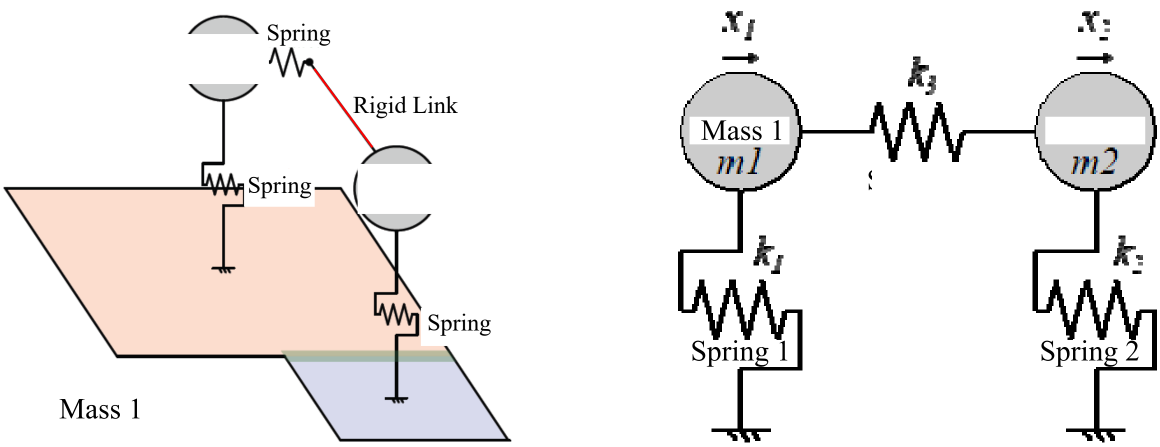
$$\sigma_2^{(n)} = \sigma_2^{(1)} \times \frac{\sigma_1^{(n)}}{\sigma_1^{(1)}} \times \frac{K_{e1}^{(n)} + K_{e2}^{(n)}}{K_{en}^{(n)} + K_{e2}^{(n)}} \times \frac{m_2}{m_1} \quad (5)$$

Here, $\sigma_1^{(n)}$ is the horizontal displacement of mass point 1 at the step *n*, $\sigma_2^{(n)}$ is the horizontal displacement of mass point 2 at the step *n*, and $Ke^{(n)}$ is the equivalent stiffness at step *n*.

5) Calculate the effective mass, *Mu*, and the representative displacement, *Δ*, to reduce the SDOF system for each step. Here, the sum of the restoring forces of springs 1 and 2 is considered to be the restoring force of the SDOF system.

$$Mu^{(n)} = \frac{(m_1\sigma_1 + m_2\sigma_2)^2}{m_1\sigma_1^2 + m_2\sigma_2^2} \quad (6)$$

$$\Delta^{(n)} = \frac{m_1\sigma_1^2 + m_2\sigma_2^2}{m_1\sigma_1 + m_2\sigma_2} \quad (7)$$

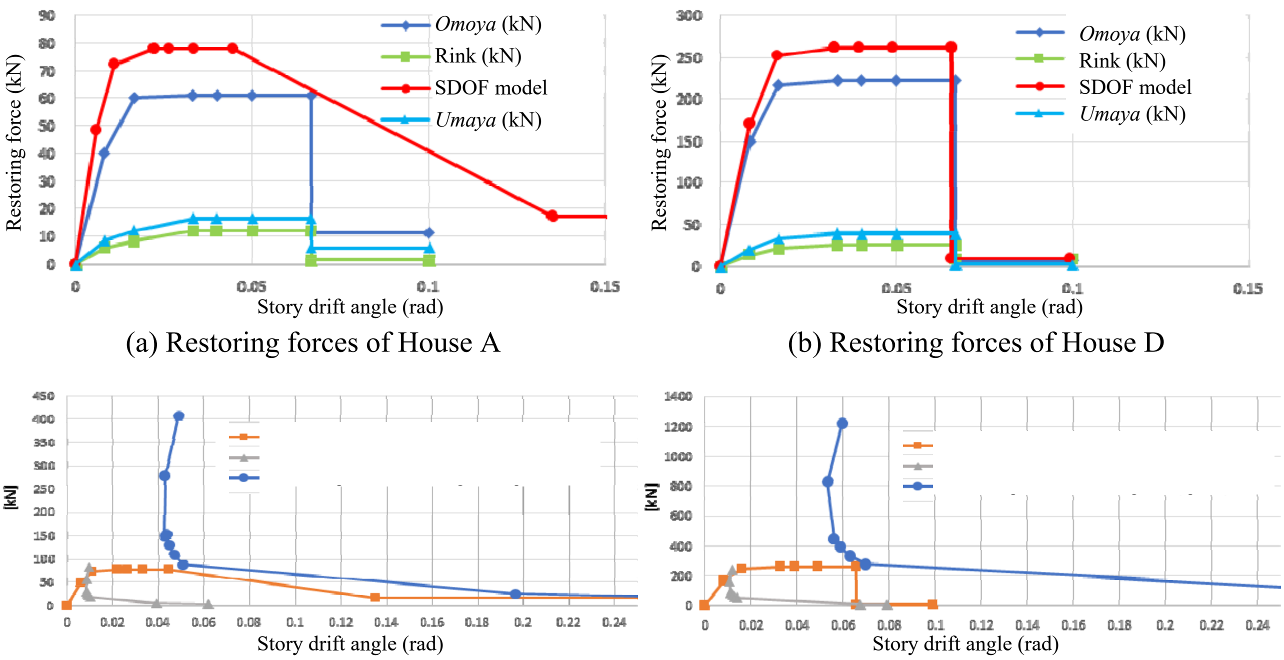


(a) 3D model (b) 2D model of the ridge direction

Fig. 9 – Model of the ridge direction of House D

5.2 Reevaluation Using the Improved Reducing Method

The earthquake response values of Houses A and D were re-calculated using the proposed method, as shown in Fig. 10. The obtained response deformation angles are shown in Table 3. In proposed method, the response deformation angle of House A is 0.009 rad for a moderate earthquake, but House A was judged to collapse for a large earthquake. Likewise, the response deformation angle of House D is 0.011 rad for a moderate earthquake, but House D was judged to collapse for a large earthquake.



(a) Restoring forces of House A (b) Restoring forces of House D

(c) Response values of House A (d) Response values of House D

Fig. 10 – Earthquake response values of the ridge directions of Houses A and D

6. Conclusions

In this study, we estimated the seismic performance of L-shaped thatched houses in the Maesawa preservation district and Kitakata city (Fukushima prefecture) through a field survey, to understand their structural and vibrational characteristics. We proposed an evaluation method for such houses with irregular plans. First, we conducted a field survey of several existing thatched houses in the Maesawa district and Kitakata city to understand their construction and maintenance methods. Second, we conducted microtremor measurements for these houses and the ground on which they stand to understand the vibrational characteristics. Moreover, we calculated the yield base shear coefficient as an indicator of seismic performance. Finally, we proposed a new reducing method of equivalent SDOF systems to evaluate the seismic properties of these irregular houses. It was found that the judgment obtained by the proposed method may be more severe than that obtained using the conventional method.

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