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Experimental Study on Restoring Force Characteristics of Japanese Traditional Timber Frames with Strip-Shaped Mud-Walls

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Abstract

Mud-walls are important structural elements of the seismic performance of traditional timber buildings in Japan. Although in such buildings, mud-walls with or without openings are both effective, the structural characteristics of walls with openings, such as hanging walls (*Tarekabe*) or window back walls (*Koshikabe*), are ignored in structural design today. In the structural design of traditional wooden buildings, it is also very important to estimate properly the restoring force characteristics of timber frames with strip-shaped mud-walls, called *Kokabe*. The objective of this study is to confirm the effect of height differences of mud-walls on the restoring force characteristics of *Kokabe*, based on full-scale tests. Comparison of test results demonstrates the accuracy of the proposed estimation method.

Cyclic shear loading experiments using electric actuators were carried out in Tottori University of Environmental Studies (TUES) in 2014 and 2018. There are 6 types of specimens; 3 types of *Tarekabe* (hanging wall) and 3 types of *Koshikabe* (window back wall). The lenghs of *Tarekabe* and *Koshikabe* were 300 mm, 900 mm and 1500 mm each. The total height dimensions common to sample walls were 2730 mm in height and 1820 mm in length with sills (*Dodai*). The deformation angle was increased in 10 incremento on each wall from 1/480 rad to more than 1/10 rad, and each deformation was repeated three times. During the experiment, load and displacements were measured to obtain the load-deformation curves.

From the tests results, when the lengths of *Tarekabe* and *Koshikabe* are the same, their restoring force characteristics, load-deformation curves and their maximum horizontal bearing force were comparable. In addition, the shear failures of the mud-walls, as well as the shear fracture were similar. The timing of cracked mud fall was also similar. In summary, there was no difference in the restoring force and failure process if the wall length was the same.

The estimation method used in this study is to obtain the restoring force of whole wall by calculating the mud-walls part and the frame part separately, and adding them. The outline of the estimation method is: (1) calculate the restoring force of only mud-wall Q_w, (2) Calculate the bend deformation of columns by each Q_w, and calculate restoring force including the *Kokabe* and frame part (Q), (3) calculate the moment resistance of timber joint Q_h, (4) obtain the restoring force characteristics by adding Q_w and Q_h. Comparison of test results and estimation results showed that estimation method could be calculated close to the test results, and reproduce the failure process.

Keywords: Mud-Wall; Strip-shaped mud-wall; Restoring force characteristics; Full-scale tests

1. Introduction

In the Japanese traditional timber buildings, mud-walls are frequently used as structural members. Mud-walls without openings are important structural elements of seismic performance. In addition, mud-walls with openings (*Kokabe*), such as hanging walls (*Tarekabe*) or window back walls (*Koshikabe*) are also effective. Nevertheless, *Tarekabe* and *Koshikabe* are ignored in structural design today. For that reason, it is important to find out the restoring force characteristics and destructive properties, and to be able to calculate the restoring force of *Kokabe*. The objective of this study was to confirm the restoring force characteristics of *Kokabe* within different height walls. Furthermore, by comparing the test results with estimated restoring force, the accuracy of the proposed estimation method was also demonstrated.

2. Outline of specimens

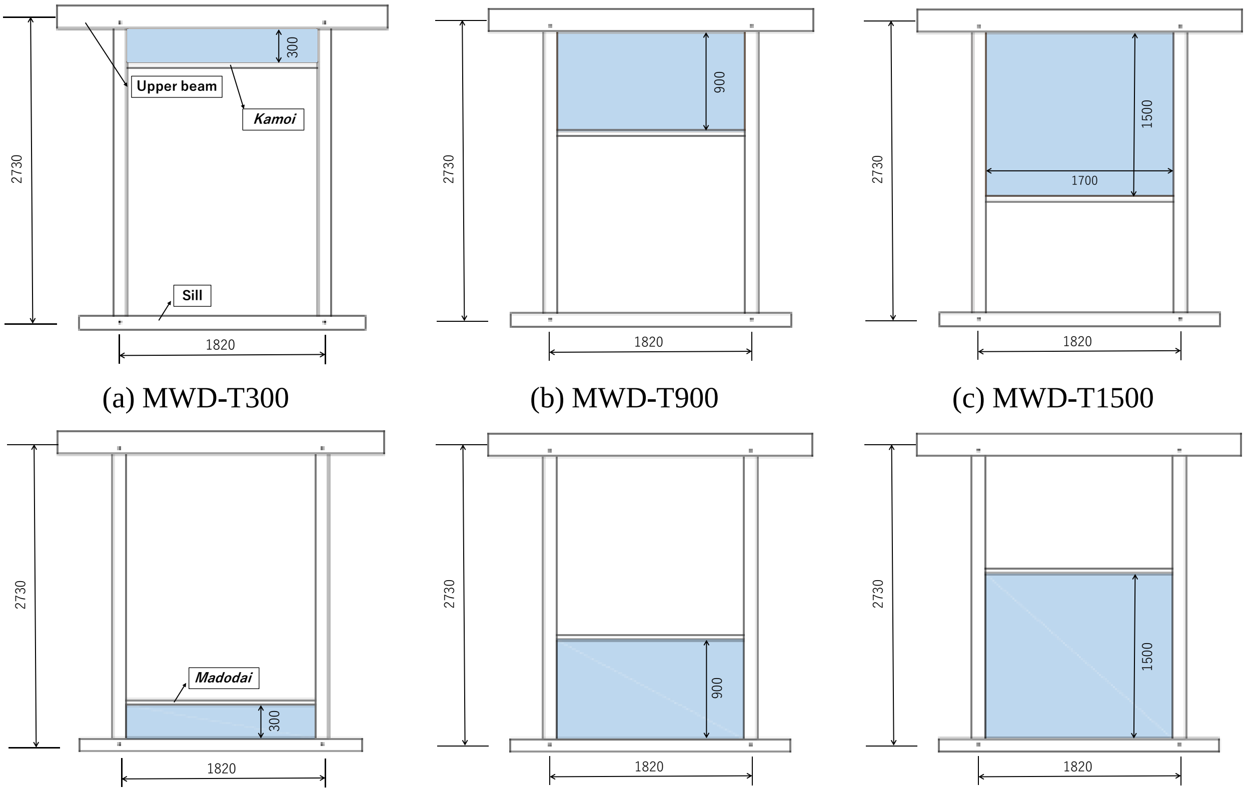
There are 6 types of *Kokabe* mud-wall specimens; 3 types of *Tarekabe* and 3 types of *Koshikabe*: MWD-T300, MWD-T900, MWD-T1500, MWD-K300, MWD-K900 and MWD-K1500. In the specimen name, "MW" means Mud-Wall, the letter "D" means *Dodai* (a sill), "T" means *Tarekabe* and "K" means *Koshikabe*. The number after "T" or "K" means the length (vertical dimension) of mud-wall. Fig. 1 shows the details of the specimens. The shaped part indicates the mud-wall. *Kamoi* or *Madodai* are horizontal members that edge. The common specifications are as follows:

- Column: 120 mm×120 mm (cedar)
- Upper beam: 120 mm×210 mm (cedar)
- Sill: 120 mm×120 mm (Japanese cypress)
- *Nuki* (penetrating tie beam): 18 mm×105 mm
- *Kamoi* or *Madodai* (horizontal member): 105 mm×45 mm
- The inside measurement between each *Komaidake* (bamboo lattice) was about 45 mm
- Thickness of mud-wall was 60 mm (t_w), finished by *Nakaruni* coat on both side
- Wall height (beam-sill span) 2730 mm (H)
- Wall length (column span) 1820 mm (L)

3. Outline of full-scale tests

3.1 Cyclic shear tests

Cyclic shear loading tests of mud-walls were carried out in Tottori University of Environmental Studies (TUES). The loading tests of MWD-T300, MWD-T900 and MWD-T1500 were carried out in 2014 [1, 2], and the loading tests of MWD-K300, MWD-K900 and MWD-K1500 were carried out in 2018. The axial force was applied to columns by using 19.24 kN of steel weight. Horizontal cyclic force was applied at the level of the upper beam of the specimen. The deformation angle was increased in 10 increment on each wall from 1/480 rad to more than 1/10 rad, and each deformation was repeated three times. During the experiment, load and displacements were measured to obtain the load-deformation curves. As one example, Photo 1 shows the setup of MWD-T300, and Fig. 2 shows the measurements of MWD-T300. The horizontal displacement and the pull-out displacement was measured (blue arrows), and the strain was measured (red squares).



(a) MWD-T300 (b) MWD-T900 (c) MWD-T1500

(d) MWD-K300 (e) MWD-K900 (f) MWD-K1500

Fig. 1 – Details of specimens

Photo 1 – Set up of MWD-T300

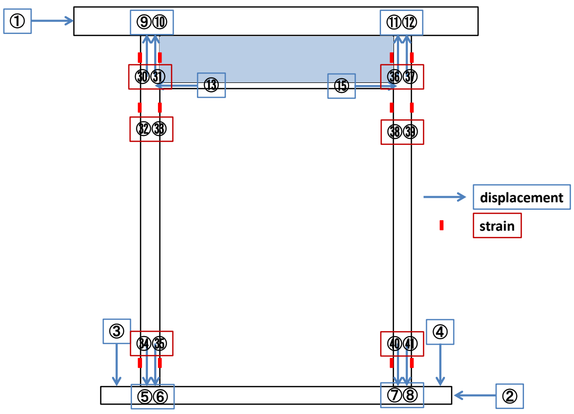


Fig. 2 – Measurements of MWD-T300

3.2 Test results

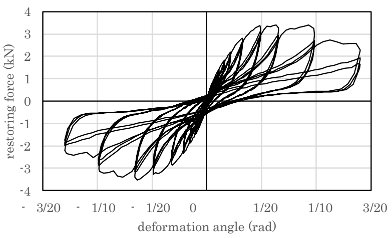
The P-Delta effect on the load deformation curves by steel weight was removed by using Eq. (1) and (2). Where:

- γ: Deformation angle (rad)
- d_1: Horizontal displacement of upper beam
- d_2: Horizontal displacement of *Dodai*
- P': Restoring force (kN)
- P: Measured load (kN)
- W: Steel weight (kN)

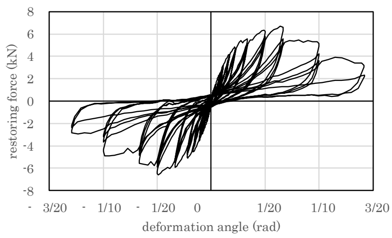
$$\gamma = \frac{(d_1 - d_2)}{H} \tag{1}$$

$$P' = P + W \tan\gamma \tag{2}$$

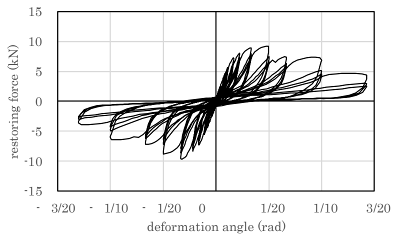
Fig. 3 shows the load-deformation curves. From each curve in Fig. 3, the first peak points at deformation angle 1/480 rad, 1/240 rad, and so on were used to draw the envelope curves. Fig. 4 shows skelton curves and Table 1 shows maximum horizontal bearing force. From the test results, when the length of *Tarekabe* and *Koshikabe* were the same, their restoring force characteristics, load deformation curves and their maximum horizontal bearing force were comparable.



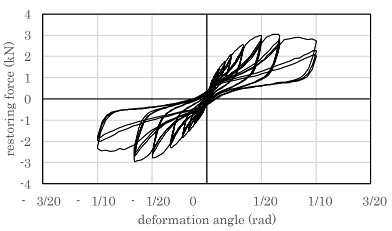
(a) MWD-T300



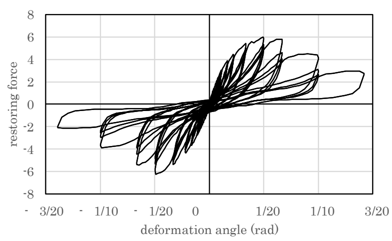
(b) MWD-T900



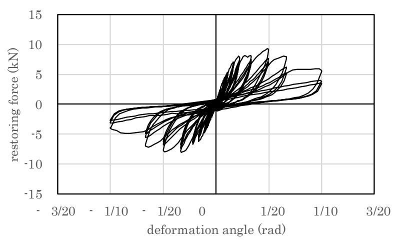
(c) MWD-T1500



(d) MWD-K300

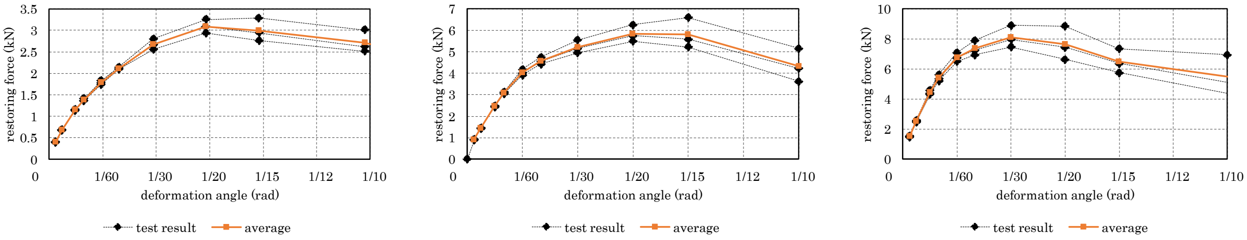


(e) MWD-K900

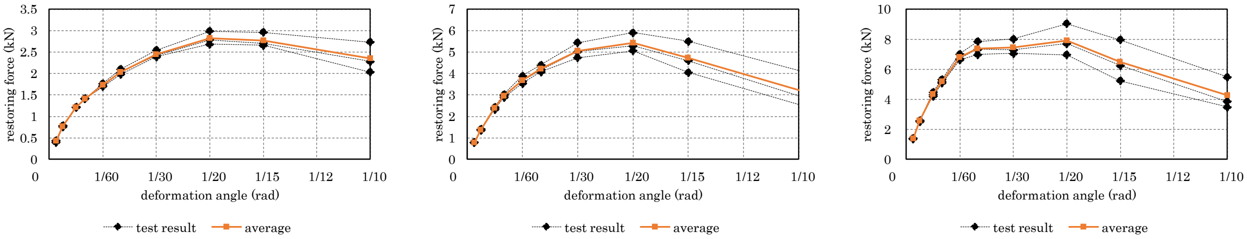


(f) MWD-K1500

Fig. 3 – Load-deformation curves



(a) MWD-T300 (b) MWD-T900 (c) MWD-T1500



(d) MWD-K300 (e) MWD-K900 (f) MWD-K1500

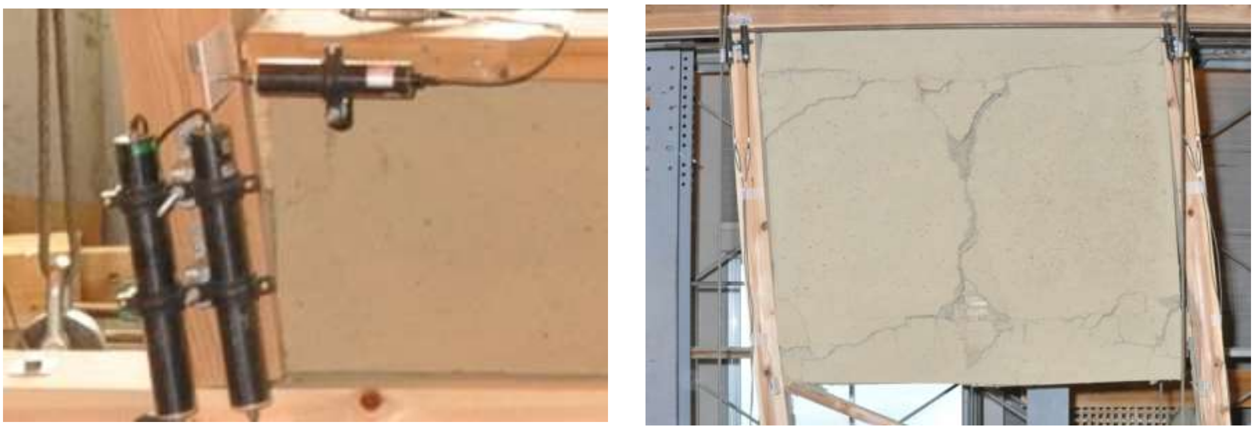
Fig. 4 – skeleton curves

Table 1 – Maximum bearing force

specimen	deformation angle (rad)	maximum bearing force (kN)
MWD-T300	1/15	3.28
MWD-T900	1/15	6.59
MWD-T1500	1/30	8.91
MWD-K300	1/20	2.99
MWD-K900	1/20	5.91
MWD-K1500	1/20	9.04

3.3 Failure process

From the mud-wall tests, two types of failure modes of mud-walls were observed as shown in Photo 2. one type was bending failure, a compression failure at the corners of the mud-walls, and the other was shear failure, oblique cracks in the center of the mud-walls. Photo 3 shows the damage to specimens at deformation angle 1/10 rad. In the cases of MWD-T300 and MWD-K300, cracks in the mud along *Nuki* and bending failure at the corners were observed. In the cases of MWD-T900, MWD-T1500, MWD-K900 and MWD-K1500, after bending failure was observed in the smaller deformations, shear failure at the center of each specimen was observed during large deformations. In the cases of MWD-T900, MWD-T1500, MWD-K900 and MWD-K1500, *Kamoi* or *Madodai* were detached from the columns. When the wall height was the same, the timing of cracked mud slippage was also similar.



(a) Bending failure (MWD-TK300) (b) Shear failure (MWD-T1500)

Photo 2 – Failure modes

(a) MWD-T300 (b) MWD-T900 (c) MWD-T1500

(d) MWD-K300 (e) MWD-K900 (f) MWD-K1500

Photo 3 – Final damage at deformation angle 1/10 rad

4. Comparison the test results with estimated restoring force

4.1 Estimation method

In this study, we used the estimation method proposed by the editorial committee of a design manual for traditional wooden buildings [3]. This estimation method is useful to obtain the restoring force of a whole wall by calculating the mud-wall part and the frame part separately, and adding them. The outline of the estimation method is as follows:

1) Calculate the restoring force of mud-wall (Q_w)

2) Calculate the bend deformation of columns by each Q_w, and calculate restoring force including the *Kokabe* and frame part (Q)

3) Calculate the moment resistance of timber joints (Q_h)

4) Obtain the restoring force by adding Q and Q_h

Restoring force of mud-wall part was determined by 4 failure modes as shown in Fig. 5. First, we calculated the each Q_{ws} (shear failure) and Q_{wb} (bending failure) for each deformation, and the minimum value was the restoring force (Q_w) of mud-wall part (Eq.(2)). In the Eq. (2), τ_s and τ_b are the shear stresses per horizontal cross-sectional area shown in Table 2 [3].

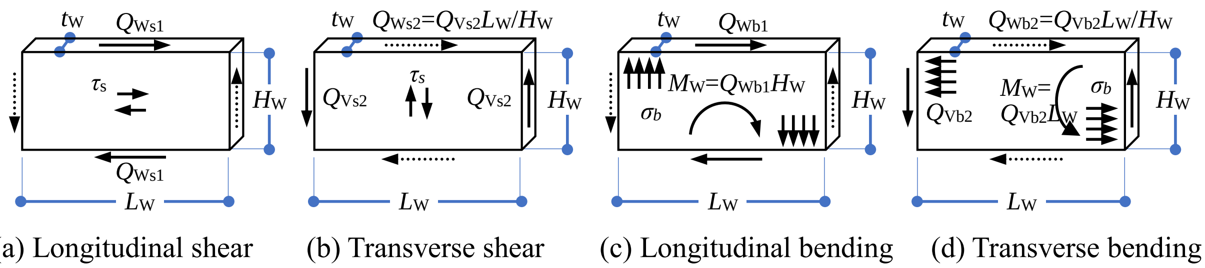


Fig. 5 – Four mud-wall failure modes

$$
\begin{aligned}
Q_w &= \mathrm{Min}(Q_{ws}, Q_{wb}) \\
Q_{ws} &= \tau_s t_w L_w \\
Q_{wb} &= 3.25\tau_b t_w L_w \mathrm{Min}\left(\frac{H_w}{L_w}, \frac{L_w}{H_w}\right)
\end{aligned}
\tag{2}
$$

Table 2 – Shear deformation angle of mud-wall γ_w (rad) and standard shear stresses τ_s, τ_b (kN/m^2)

γ_w	1/480	1/240	1/120	1/90	1/60	1/45	1/30	1/20	1/15	1/10
τ_s	30	54	86	96	98	93	84	72	58	34
τ_b	15	28	48	60	70	68	65	60	52	32

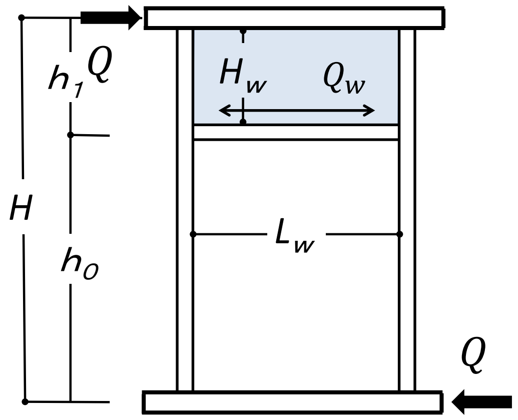
The relation between Q_w and Q is given in Eq. (3), and the deformation angle of the timber frame with *Kokabe* (γ) due to Q_w is given in Eq. (4). Where:

– E: Young's modulus of columns = 7.5 (GPa)

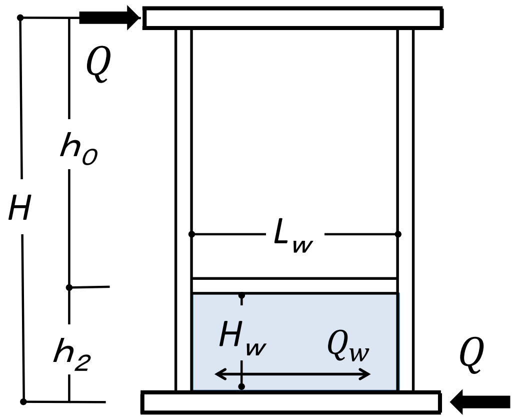
– I: Moment of inertia of area = $120^4/12$ (mm^4)

– H, h_0, h_1 and h_2: Wall heights shown in Fig. 6 and Fig. 1

When the calculating restoring force of *Koshikabe*, replace h_1 with h_2.



(a) *Tarekabe*



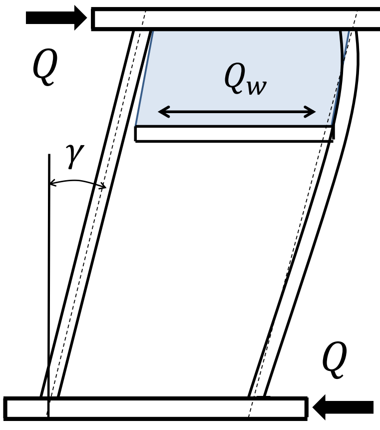
(b) *Koshikabe*

Fig. 6 – Pattern of *Kokabe*

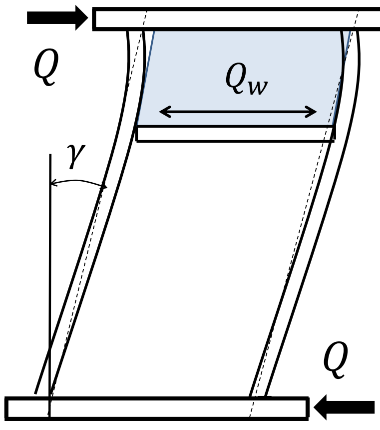
$$Q = \left(1 - \frac{h_0}{H}\right) Q_w = \frac{h_1}{H} Q_w \tag{3}$$

$$\gamma = \frac{\delta}{H} = \frac{h_0^2 h_1}{3EI} Q_w + \gamma_w \tag{4}$$

In mud-walls with openings, only one column may be affected, or both columns may be affected, depending on how the horizontal members such as *Kamoi* or *Madodai* detach as shown in Fig. 7. Therefore, it is necessary to increase the value of I in Eq. (4); if only one column is I (Fig. 7 (a)), or if the two columns are $2I$ (Fig. 7 (b)). In the case of mud-wall length of 300 mm, horizontal members did not detach during the tests, so the moment of inertia area was $2I$. In the case of mud-wall length 900 mm and 1500 mm, horizontal members detached at more than 1/30 rad during the tests, so the moment of inertia area was $2I$ for γ <1/30 rad, and I for $\gamma \geq$1/30 rad.



(a) Only one column is effective



(b) Two columns are effective

Fig. 7 – Mechanical model of a timber frame with strip-shaped mud-wall

Restoring force of the frame part was determined by the moment resistance of column joints as shown in the Fig. 8 and using Eq. (5). Here, M is the moment resistance of column joint shown in Table 3 [3].

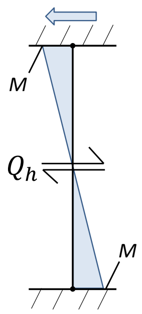


Fig. 8 – Moment resistance of column joints

$$Q_h = \frac{2M}{H} \times (\text{Number of columns}) \quad (5)$$

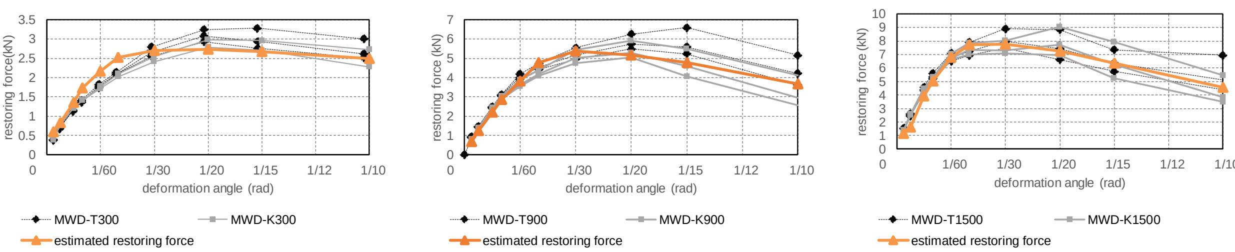
Table 3 – Rotation angle of column joint γ (rad) and moment resistance M (kNm)

γ	1/480	1/240	1/120	1/90	1/60	1/45	1/30	1/20	1/15	1/10
M	0.25	0.45	0.70	0.90	1.10	1.30	1.45	1.50	1.50	1.50

4.2 Comparison of the test results with estimated restoring force

Fig. 9 shows the comparison of test results with estimated restoring force. Although the estimated restoring forces agreed well with test results, in the cases of mud-wall length of 300 mm, the estimated restoring force was a little larger than test results when the deformation angle was smaller than 1/30 rad.

In the case of mud-wall length of 300 mm, the estimated restoring force characteristics were determined by Q_{wb}. In the case of mud-wall length of 900 mm, the estimated restoring force characteristics were determined in the range of deformation angle less than 1/120 rad, by both Q_{wb} and Q_{ws} in the range of more than 1/120 rad. And, in the cases of wall length of 1500 mm, the estimated restoring force characteristics were determined by Q_{ws}. In all cases, the observed failure modes of the test results corresponded to the estimation.



(a) Wall length 300 mm (T300 and K300)

(b) Wall length 900 mm (T900 and K900)

(c) Wall length 1500 mm (T1500 and K1500)

Fig. 9 – Comparison of the test results with estimated restoring force

5. Conclusion

Full-scale tests of different length of strip-shaped mud-walls (*Kokabe*) were carried out. If the wall height was the same, the restoring force characteristics, load-deformation curves and failure process were confirmed to be the same. In addition, by comparing the test results with the estimated restoring force characteristics, it was confirmed that the estimation method could calculate the restoring force close to the test results. Furthermore, it was confirmed that the estimation method could reproduce the failure process.

6. References

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[2] H. Nakaji, T. Nagase, K. Yamada, Y. Suzuki (2017): Restoring Force Characteristics of Timber Frame with Strip-Shaped Horizontal Mud-Wall based on Full-scale Tests. Proc. of urban cultural heritage disaster mitigation Vol. 11

[3] The editorial committee of design manual for traditional wooden buildings (2019). A manualof aseismic design method for traditional wooden buildings including specific techniques for unfixing column bases to foundation stones, Gakugei Shuppansha,

