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STUDY ON THE SEISMIC PERFORMANCE OF TRADITIONAL JAPANESE BUILDING WITH THE THICK EARTHEN WALL

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Abstract

The earthen walls also have been used in Japan since long time ago. The box-shaped wall structure constructed with the thick earthen walls is one of the traditional Japanese building, called "*Dozo-dukuri*"; referred to as dozo structure in this paper. In the northern Kanto region of Japan, there remain examples of many dozo structures, forming a distinctive historical townscape. Examples of dozo structures include *Misegura* (dozo townhouses intended to be multiuse shops or dwellings) and storehouses called *Dozo*. Dozo structures have earthen walls that are 200-300 mm thick at their outer circumference for fire protection.

In the 2011 Tohoku Region Pacific Offshore Earthquake, the traditional townscapes and dozo structures of the Kanto region were seriously damaged. Damage to historical structures not only creates a safety hazard for people in and around them but also is a blow to the vitality of a community. Therefore, it is desirable to understand the seismic performance and take measures to reduce damage. However, there is very little information on the seismic performance of dozo structures. So we have to make the evaluation method of seismic performance for these traditional and existing houses and buildings.

This study aims to clarify the seismic performance of dozo structures. We first surveyed the specifications of earthen walls in the northern Kanto region. Then, we performed out horizontal loading tests on full-scale walls produced according to the survey results to determine the structural performance of the walls under a horizontal force, e.g., an earthquake. Finally, the restoring strength characteristics of the whole building were evaluated from the restoring strength characteristics of the wall alone obtained from the tests, and the seismic performance of the townhouse building was verified using the calculation of response and limit strength.

According to the horizontal loading test on full-scale wall, the maximum proof strength of an earthen wall was 37.1 KN; the deformation angle at that time was 1/30 rad. After the maximum proof strength, maintaining a proof strength of 84% or more of the maximum up to the final deformation by balancing the mud wall panel resistance and the penetrating tie beams resistance, we confirmed the toughness of the thick earthen walls.

The seismic performance verification was performed for the standard type of the existing townhouse building called Misegura. In the current building condition, the Y direction could be determined that the possibility of the building collapse due to the assumed ground motion was low. In the X direction, had a large opening, there were fewer the wall quantity than in the Y direction, especially on 1st story and the proof strength was small. Therefore, the response deformation angle was over 1/15 rad in the current condition, there was a high risk of collapse. However, it was confirmed that the possibility of collapse could be prevented by reinforcing the additional shear wall so that it would not interfere with the use of the building.

Keywords: Traditional Japanese building, Box-shaped wall structure, Mud wall, Horizontal loading test

1. Introduction

Methods of mixing soil with organic fibers such as straw and fixing the soil on a substrate knitted with bamboo or wood have been used for construction worldwide [1-7]. The earthen walls also have been used in Japan since long time ago. The box-shaped wall structure constructed with the thick earthen walls is one of the traditional Japanese building, called "*Dozo-dukuri*"; referred to as dozo structure in this paper. In the northern Kanto region of Japan, there remain examples of many dozo structures—built from the end of the Edo Period to the early Showa Period (about 70–180 years ago)—, forming a distinctive historical townscape. As shown in Fig. 1, examples of dozo structures include *Misegura* (dozo townhouses intended to be multiuse shops or dwellings) and storehouses called *Dozo*. Dozo structures have earthen walls that are 200-300 mm thick at their outer circumference for fire protection. These structures came to be used not only as stores or warehouses, but also as parlors and other kinds of buildings in modern times.

In the 2011 Tohoku Region Pacific Offshore Earthquake, the traditional townscapes and dozo structures of the Kanto region were seriously damaged [8,9]. The Kumamoto and Tottori Earthquakes that occurred in 2016 also caused great damage to the shear walls of dozo structures. Damage to historical structures not only creates a safety hazard for people in and around them but also is a blow to the vitality of a community. Therefore, it is desirable to understand the seismic performance and take measures to reduce damage. However, there is very little information on the seismic performance of dozo structures. So we have to make the evaluation method of seismic performance for these traditional and existing houses and buildings.

This study aims to clarify the following aspects of dozo structures. First, we clarify the original structural performance of earthen walls for dozo structures. Second, we clarify the seismic performance of townhouse building called Misegura. Therefore, we first survey the specifications of mud walls in the northern Kanto region. Then, we perform out horizontal loading tests on full-scale walls produced according to the survey results to determine the structural performance of the walls under a horizontal force, e.g., an earthquake. Finally, the restoring strength characteristics of the whole building are evaluated from the wall alone performance that is obtained from the tests, and the seismic performance of the townhouse building is verified using the calculation of response and limit strength.

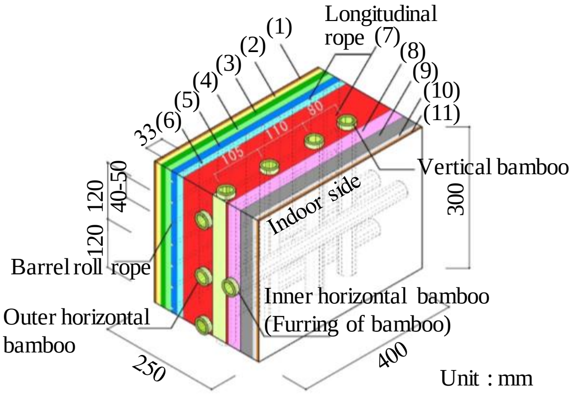

(a) Misegura (b) Dozo

Fig. 1 – Examples of dozo structures

2. Outline of the structural performance evaluation tests of the earthen wall

2.1 Specifications of the earthen wall used in dozo structure

A detailed view of the inner earthen wall after the sampling survey is shown in Fig. 2 and a detailed cross-sectional view around a pillar is shown in Fig. 3. Two types of mud—rough wall mud and intermediate coating mud—are used on earthen walls. The rough wall mud is clay mixed with straw that is about 50 mm



(1) Stucco 5 mm
(2) Undercoating 11 mm
(3) Intermediate coating (ICM) 13 mm
(4) Retouch (ICM) 15 mm
(5) Barrel roll and Rope hiding (RWM) 15 mm
(6) Longitudinal rope and Rope hiding (RWM) 15 mm
(7) Rough wall (RWM) 100-110 mm
(8) Backing (RWM) 20-30 mm
(9) Rammed earth 30-50 mm
(10) Undercoating 10 mm
(11) Stucco 5 mm

RWM: Rough wall mud ICM: Intermediate coating mud

Fig. 2 – Details of the interior of the dugout wall

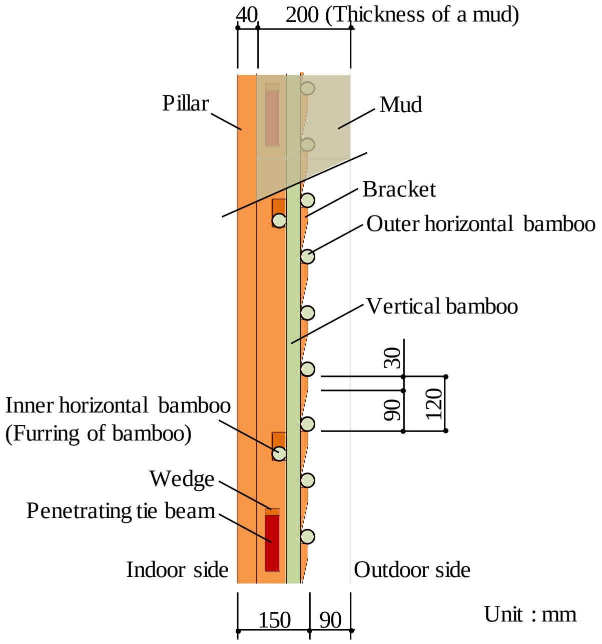


Fig. 3 – Detailed cross-sectional view

long, kneaded with water. The intermediate coating mud is clay mixed with sand and fibrous straw that is about 20–30 mm long and kneaded with water. Traditional Japanese wooden structures feature walls constructed with exposed timber pillars, but in dozo structures the thick earthen walls were used like a covering for the outside pillar. For that reason, the base layer bamboo is not split; round bamboo is used. First, the inner horizontal bamboo is hung between the pillars on both sides in a frame. On the outside, vertical bamboo is installed; the outer horizontal bamboo is placed into sawblade-shaped bracket cut out of the pillar, so that the weight of the mud is transferred from the outer horizontal bamboo to the pillars. The intersections of bamboo are tightly tied with straw rope to produce a solid substrate. In constructing parts of a wall where the cross section becomes smaller due to the timber frame, the rough wall, longitudinal rope, barrel roll, and straw rope are densely arranged, to maintain the integrity of the mud. Furthermore, when increasing the wall thickness, rough wall mud is used, with intermediate coating mud thinly plastered to reinforce the fixing of the rough wall mud and to smooth the wall surface. After that, retouching is done and the finishing materials are plastered.

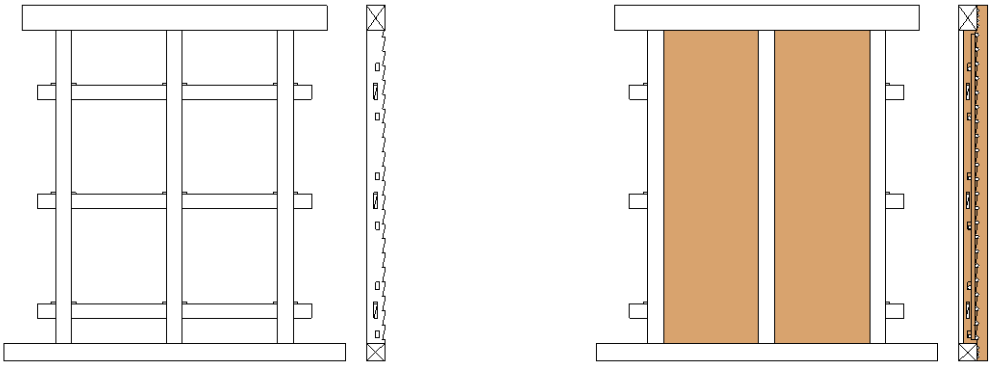

(a) Type A (b) Type B

Fig. 4 – Schematic of the specimens

2.2 Overview of the specimens

This study included the construction and load testing of two types of specimen, as described in Fig. 4. Type A specimen was of the framework only, to confirm the effect of the penetrating tie beams. Type B specimen was used to clarify the strength, deformation performance, and damage state of the original earthen wall of a dozo structure. Type B was constructed based on specifications clarified in the above survey, such as including the fitting of bamboo in the wall, the production process, and the preparation of wall mud plaster (rough wall mud and intermediate coating mud). The shapes and dimensions of Type B are shown in Fig. 5, the materials and specifications used are shown in Table 1. The shapes and dimensions of the specimens and the materials used were basically the same: their width was two 910 mm spans, with a height of 2730 mm. Also, the joint between the pillar and the horizontal frame was shaped so that the end of the pillar did not touch the horizontal frame, even in the case of significant deformation. By doing so, we ignored the resistance caused by the pillar sinking into the horizontal frame, so that we could observe only the performance of the wall panel. The compression strength test results of the rough wall mud and the

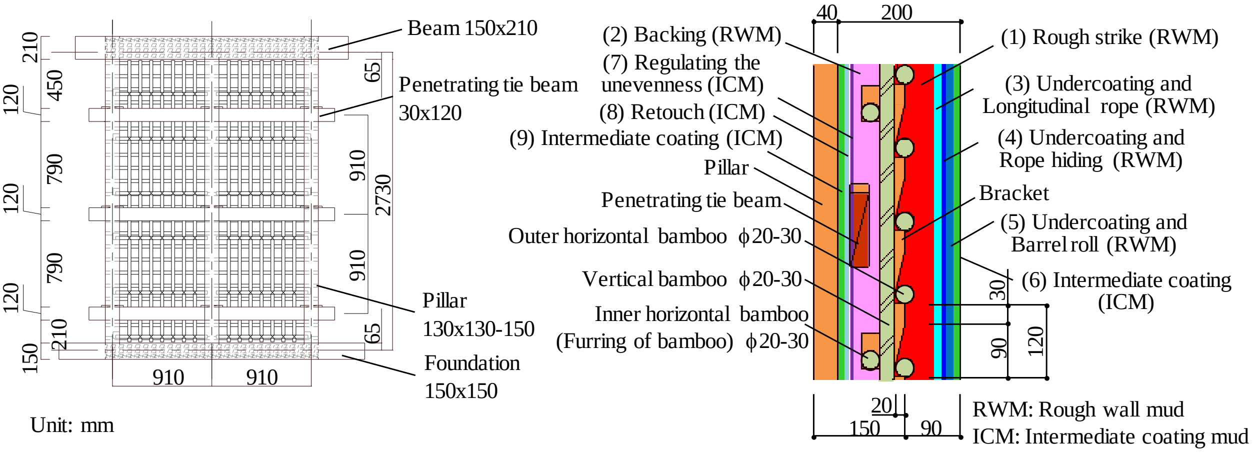


Fig. 5 – Shapes and dimensions of Type B

Table 1 – Outline of the elements and specifications

Elements			Specifications
Type A Type B	Pillar	Material	Japanese cedar
		Size	Width 130mm x Depth 130-150mm (Bracket 20mm)
	Foundation	Material	White cedar
		Size	150mm x 150mm
	Beam	Material	White cedar
		Size	Width 150mm x Depth 210mm
	Penetrating tie beam	Material	Japanese cedar
		Size	Width 30mm x Depth 120mm
	Wedge	Material	White cedar
Type B	Surface protection of penetrating tie beam	Material	Rush (Ryukyu) L=250mm
	Bamboo	Material	Long-jointed bamboo (Madake)
		Size	Diameter: 20-30mm
	Mud wall	Thickness	Plan: 200mm Product: 204mm

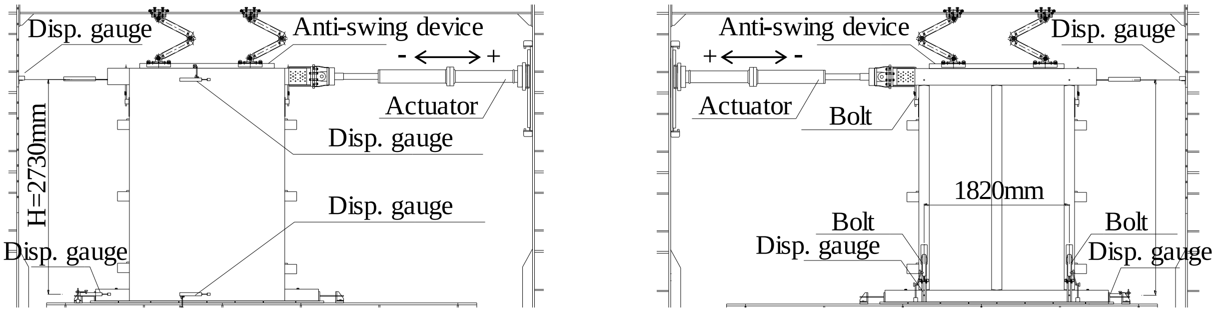
Table 2 – Compression strength test results of the mud

Sample	Thickness [mm]	Number of samples	Age [day]	Maximum compression strength [N/mm^2]			Density
				Min.	Max.	Average	[g/cm^3]
Rough wall mud	70	6	43	0.371	0.391	0.378	1.30
Intermediate coating mud	70	6	41	0.700	0.801	0.758	1.62

intermediate coating mud used for test specimens are shown in Table 2. Here, compression strength tests were carried out according to the method developed by the Japanese Housing and Wood Technology Center [10].

2.3 Methods of the load-measuring

Measurement and loading were performed by the method shown in Fig. 6. Positive and negative alternating loading by displacement control was performed. The loading schedule of gradually increasing the shear deformation angle to 1/600 rad, 1/450 rad, 1/300 rad, 1/200 rad, 1/150 rad, 1/100 rad, 1/75 rad, 1/60 rad, 1/50 rad, 1/40 rad, and 1/30 rad in three cycles was followed by one cycle of 1/20 rad loading. Finally, we applied loading (with a deformation angle of about 1/7 rad) to pull up to the allowable jack stroke. The measurement items common to all specimens were as follows: the horizontal load, horizontal displacement of the beam and foundation, lifting displacement of pillar bases, and axial strain of the pillar top/base fixing bolts. In addition, in Type B, we regarded the occurrence of cracks and the main crack width when each controlled deformation was reached.



(a) Outdoor side (b) Indoor side

Fig. 6 – Methods of measurement and loading

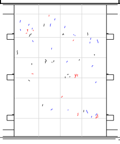
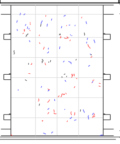
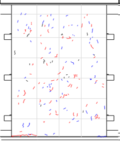
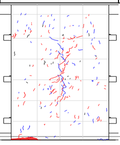
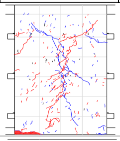
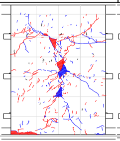
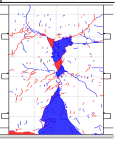
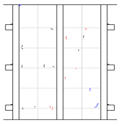
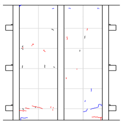
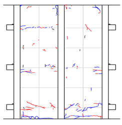
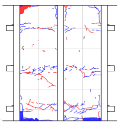
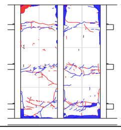
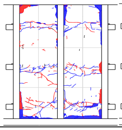
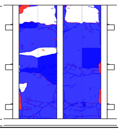
3. Results of the structural performance test

3.1 Damage situation of earthen wall

About Type B, Table 3 shows the crack states when reaching the target deformation peak in the first cycle of positive and negative loading, the ratio of the proof strength to the maximum proof strength, and the residual deformation for each deformation angle.

First, fine cracks occurred at the corners at deformation angles of 1/600–1/450 rad. Then, cracks along the penetrating tie beams on the indoor side began to occur at 1/450–1/300 rad. At 1/100–1/75 rad, the corners of the indoor side began to undergo compressive fracture; peeling of the outdoor side legs in the out-of-plane direction was confirmed at almost the same deformation level. When a load of 1/75 rad was applied, shear cracks occurred near the central pillar of the outdoor side, and cracks appeared on the outdoor side along the uppermost transverse penetrating tie beam at 1/60–1/50 rad. At this time, cracks along the penetrating tie beams on the indoor side were connected over the length of the inner width of the pillar. The crack width also progressed, so 1/50 rad was judged to be the restoration limit state. Applying further loading increased the damage to the wall and the proof strength began to decline, such that large shear cracks occurred near the central pillar of the outdoor side of the wall when applying -1/30 rad, causing the mud of the outer wall to flake off, whereas from 1/30 to 1/20 rad, multiple cracks along the transverse penetrating tie beam of the outermost top row joined into one crack. For Type B specimen, we applied a load at 1/7.1 rad. The outdoor side did not collapse on a large scale until the end of the experiment because

Table 3 – Damage to Type B specimen

Deformation angle [rad]		1/600	1/450	1/200	1/75	1/50	1/40	1/30	1/20	Final
Type B Damage state Blue: Positive+ Red: Negative-	Outdoor side	Loading direction − + ⟷					► Maximum strength			
	Indoor side	Loading direction + − ⟷								
Typical damage process		Fine cracks occurred at the corners. Cracks along the penetrating tie beams on the indoor side began to occur. Shear cracks occurred the outdoor side. Cracks appeared on the outdoor side along the penetrating tie beam. The corners of the indoor side began to undergo compressive fracture. Peeling of the outdoor side in the out-of-plane direction was confirmed. Large shear cracks occurred the outdoor side. The mud of the outer wall flaked off.								
Ratio of the proof strength to the maximum proof strength [%]		21	27	48	80	88	96	100	98	85
Residual deformation [$x10^{-3}$rad]		0.4	0.4	1.2	3.7	6.7	9.4	14.8	25.2	-

of the mud's adhesion with the straw rope. As described above, we elucidated the damage at each deformation level, obtaining useful knowledge that can estimate the residual seismic performance of dozo structures damaged by earthquakes.

3.2 Characteristics of the elasto-plastic behavior

The relationship between the horizontal load and the shear deformation angle of Types A and B (as obtained from loading tests) are described in Fig. 7. The strength of Type A specimen was significantly less than that of the Type B. However, as deformation increased, because the resistance caused by the penetrating tie beams sinking into the pillars became larger, the proof strength—which continued to rise in proportion to deformation—was confirmed even if the deformation reached 1/7 rad or more. The maximum proof strength of Type B was 37.1 KN; the deformation angle at that time was 1/30 rad. Fig. 8 shows the skeleton curves during positive loading of Types A and B. This figure also shows the restoring force of only the mud wall panel subtracted Type A from Type B at the same deformation. After the maximum proof strength, the resistance strength of the mud wall panel decreased, but—as with Type A, described above—the resistance

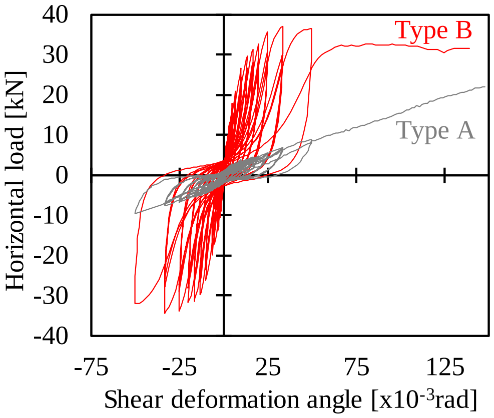


Fig. 7 – Relationship between the horizontal load and the shear deformation angle

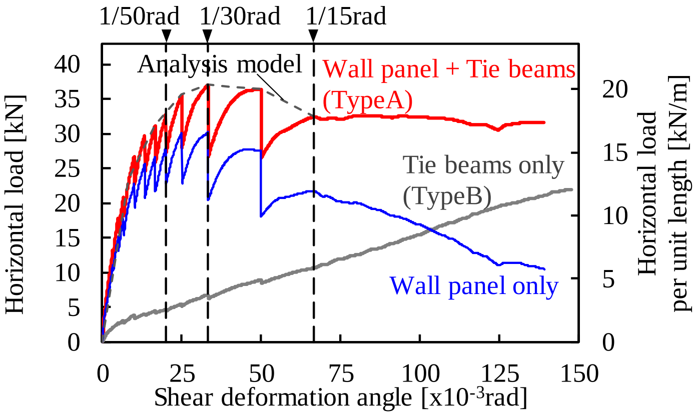


Fig. 8 – Skeleton curve comparison during positive loading

strength of the penetrating tie beams increased with the horizontal deformation. Maintaining a proof strength of 84% or more of the maximum up to the final deformation by balancing the mud wall panel resistance and the penetrating tie beams resistance, we confirmed the toughness of the thick earthen walls.

4. Verification of seismic performance of the existing townhouse building

4.1 Overview of the target building

In order to clarify the seismic performance of townhouse building called Misegura, this chapter verifies the seismic performance for the standard type of the existing building. The target building is a two-story dozo structure located in a city in Tochigi Prefecture, constructed in 1929, and has seven spans in the X-direction and six spans in the Y-direction. Figs. 9–10 show the elevation view and the plan view of the target building. The building weight was evaluated using the weight per unit area shown in Table 4. The weight of 1st story is 192.4 KN, and the weight of 2nd story is 189.6 KN.

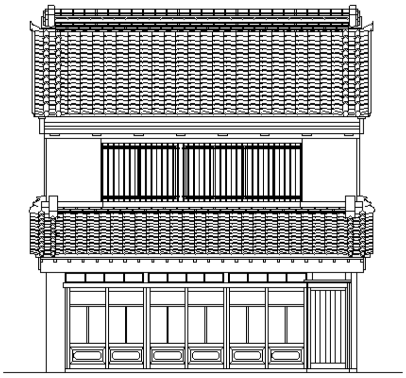
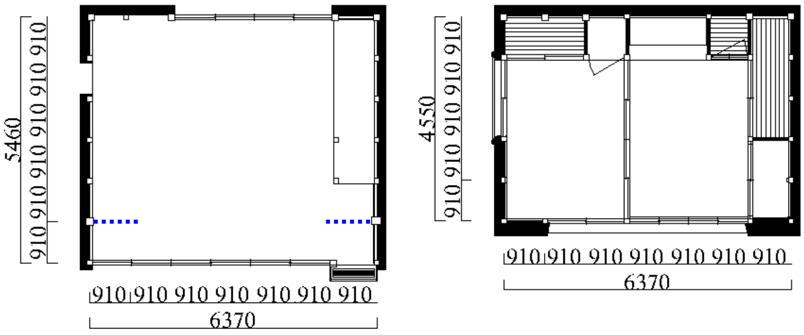


Fig. 9 – Elevation view (X-dir.)



(a) 1st floor (b) 2nd floor

Fig. 10 – Plan view

Table 4 – The weight per unit area for evaluation of the building weight

Elements		Weight per unit area	
Roof	Tile-roofing	Per roof area	600N/m^2
	Roofing board and rafter for double roofing		150N/m^2
	Roof truss		250N/m^2
	Ceiling board	Per ceiling area	150N/m^2
Wall	Outer earthen wall (t=250mm)	Per wall area	3269N/m^2
	Innner earthen wall (t=65mm)		950N/m^2
	Framework		180N/m^2
2nd floor	Cross member	Per floor area	170N/m^2
	Tatami-flooring		340N/m^2
	Floor board		150N/m^2
2nd floor fittings		Per elevation surface	200N/m^2
Live load	(Evaluation only on the second floor)	Per floor area	600N/m^2

4.2 Methods of the seismic performance verification

In this study, we verified the seismic performance to extremely rare earthquakes (large earthquakes) of Japanese seismic design standard by the calculation of response and limit strength. Here, the seismic performance evaluation by the limit strength calculation was performed with using the manual of the Japan Structural Consultants Association as Reference [11].

The acceleration response spectrum used for the seismic verification is a spectrum for extremely rare earthquake defined in Japanese seismic design standard. Here, the ground surface amplification was evaluated according to the simplified method of Japanese seismic design standard. Fig. 11 shows the acceleration response spectra (h = 5%) at the open engineering bedrock and the ground surface amplification.

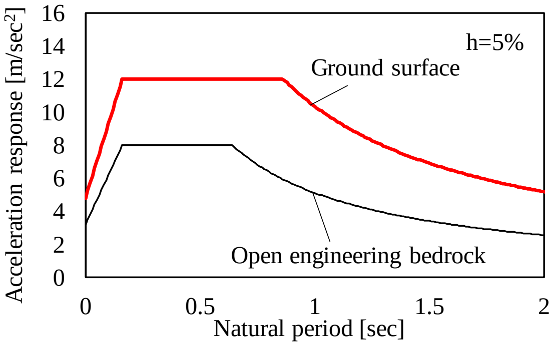


Fig. 11 – The acceleration response spectra

In order to accurately evaluate the restoring strength characteristics of the building, it is necessary to add that of all horizontal strength resistance elements; examples of the horizontal strength resistance element of the target building include the earthen walls and the hanging walls, the bearing of penetrating beam and timber connection, etc. However, due to contribute of the strength of the full surface earthen walls arranged so as to surround the outer periphery of the building is very dominant; in this study, the restoring strength characteristic of the building was simply evaluated considering only the full surface walls. By the way, the X direction has a large opening and the wall quantity is extremely small. Especially, the story shear strength of the 1st story is low. Therefore, we also verified for the seismic performance of Retrofit Model, attached the timber grid walls to the position of blue line shown in the plan view of 1st floor in Fig. 10. The timber grid walls were installed in the positions where there were no shear walls on the lower floor; the example of the installation of this wall is shown in Fig. 12. By arranging the walls this position, the arrangement balance between the height direction and the plane of the horizontal strength resistance elements is improved. Fig. 13 shows the skeleton curves used for the restoring strength evaluation. The restoring strength characteristics of the inner earthen wall and the timber grid wall shown in the Figure were modeled using the test results of References [12,13]. The restoring strength characteristic of the target building was evaluated by multiplying the horizontal strength per unit length, calculated by dividing the horizontal strength of the test result by the specimen width of 1.82 m, by the wall length for each floor and each direction. Fig. 14 shows restoring strength characteristics of each story and the equivalent single degree of freedom (SDOF) model in each direction. The base shear coefficients at the maximum proof strength were 0.15 (Retrofit Model: 0.33) at the X direction and 0.53 at the Y direction.

Fig. 12 – Installation example of the timber grid wall

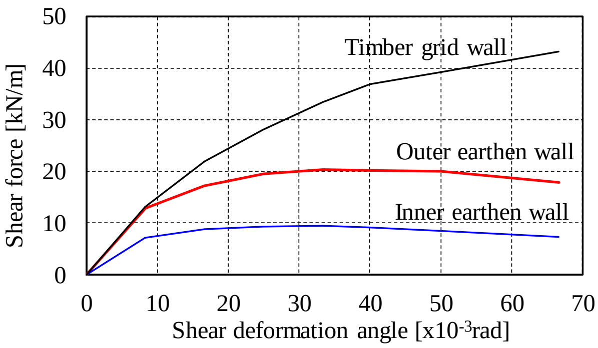
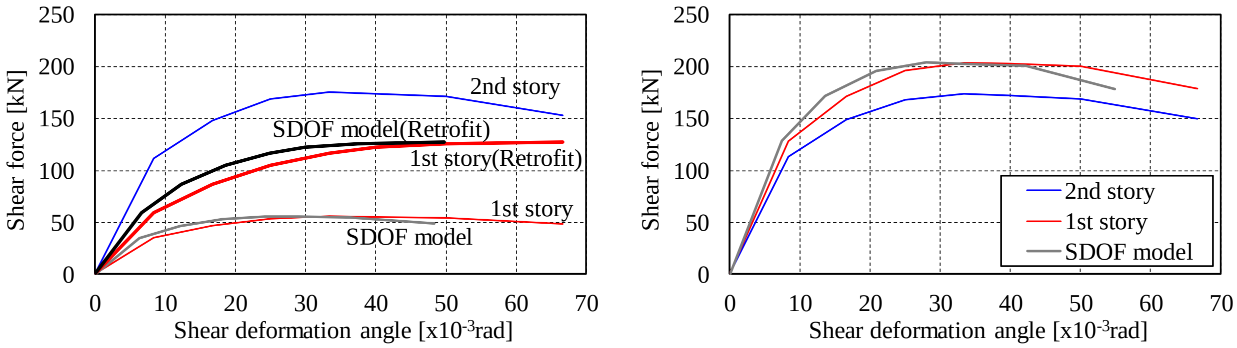


Fig. 13 – The horizontal strength per unit length used in the evaluation



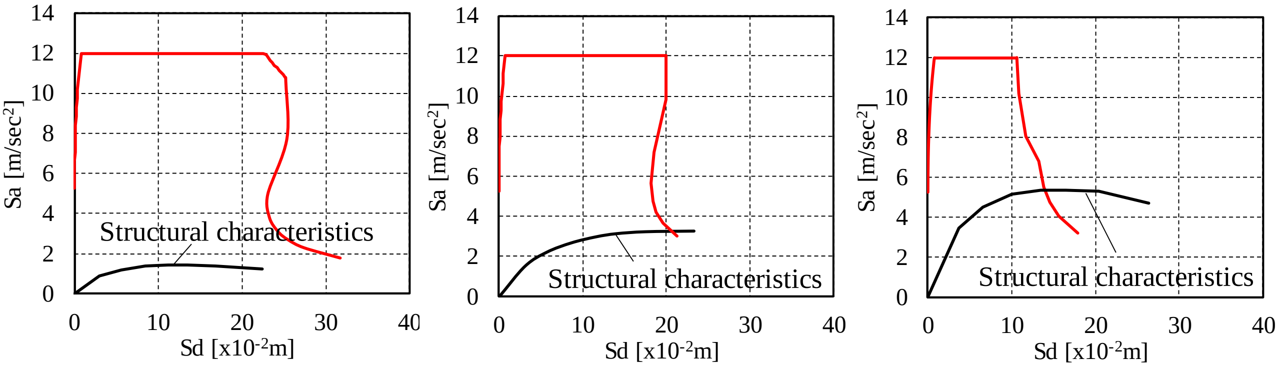
(a) X-direction (b) Y-direction

Fig. 14 – Restoring force characteristics

4.3 Results of the seismic performance verification

Fig. 15 shows the structural characteristic curves (Sa-Sd spectra) of the SDOF model, and Table 5 shows the maximum response deformation angle and the base shear coefficient at that deformation.

Focusing on the seismic performance of the current building condition, the maximum response deformation angle of the SDOF model was 1/35 rad at the Y direction, but there was no intersection even if it greatly exceeds 1/15 rad at the X direction. It is said that traditional timber frame structures in Japan can often be judged to have sufficient deformation capacity up to story deformation angle of about 1/15 rad. In addition, the performance of the earthen wall was confirmed a certain level of strength even at a large deformation of 1/15 rad or more without brittle fracture. Furthermore, the planar shape of the target building is rectangular and the influence of torsional vibration is small. The maximum response deformation angle of 1st story in the Y direction according to this study was 1/29 rad: the Y direction can be determined that the possibility of the building collapse due to the assumed ground motion is low. At the X direction, has a large



(a) X-direction(Current condition) (b) X-direction(Retrofit Model) (c) Y-direction(Current condition)

Fig. 15 – The structural characteristic curves (Sa-Sd spectra) of the SDOF model

Table 5 – The maximum response deformation angle

		Current conditions		Retrofit
		X-dir.	Y-dir.	X-dir.
Maximum response deformation angle (rad)	SDOF	-	1/35	1/23
	2nd story	-	1/59	1/128
	1st story	-	1/29	1/17
Base shear coefficient at the maximum response deformation		-	0.53	0.33

opening, there are fewer the wall quantity than at the Y direction, especially on 1st story and the proof strength is small. Due to the response deformation angle is over 1/15 rad in the current condition, there is a high risk of collapse. On the other hand, it could be confirmed that the deformation of the SDOF model in the Retrofit Model was 1/23 rad, the response deformation of the 1st story was about 1/17 rad; it was confirmed that the possibility of collapse could be prevented by reinforcing the additional shear wall so that it would not interfere with the use of the building.

5. Conclusions

According to the horizontal loading test on full-scale wall produced based on the specifications of earthen walls around the northern Kanto region in Japan, the maximum proof strength of an earthen wall was 37.1 KN; the deformation angle at that time was 1/30 rad. After the maximum proof strength, maintaining a proof strength of 84% or more of the maximum up to the final deformation by balancing the mud wall panel resistance and the penetrating tie beams resistance, we confirmed the toughness of the thick earthen walls.

The seismic performance for the standard type of the existing building was verified to clarify the seismic performance of townhouse building called Misegura. In the current building condition, the maximum response deformation angle of the SDOF model was 1/35 rad at the Y direction; the Y direction could be determined that the possibility of the building collapse due to the assumed ground motion was low. At the X direction, has a large opening, there are fewer the wall quantity than at the Y direction, especially on 1st story and the proof strength is small. Therefore, the response deformation angle was over 1/15 rad in the current condition, there was a high risk of collapse. However, it was confirmed that the possibility of collapse could be prevented by reinforcing the additional shear walls so that it would not interfere with the use of the building. When the damage situation is estimated from the damage process shown in Table 3, the large shear cracks occur at the current maximum response deformation angle even if the danger of collapse can be prevented for large earthquake. The response deformation exceeds the maximum proof strength, and it is desirable to perform seismic reinforcement to control the response deformation when emphasizing restorability and continuity of use.

Methods of mixing soil with organic fibers such as straw and fixing the soil on a substrate knitted with bamboo or wood, similar to Japanese dozo structure, have been used for construction worldwide. Therefore, this study will be useful not only for Japanese dozo structures, but also for the seismic evaluation of similar buildings outside Japan.

6. References

[1] E. Fodde (2009): Traditional Earthen Building Techniques in Central Asia. *International Journal of Architectural Heritage*, **3**(2), 145-168.

[2] Natalie Quinn, Dina D'Ayala & Thierry Descamps (2016): Structural Characterization and Numerical Modeling of Historic Quincha Walls. *International Journal of Architectural Heritage*, **10**(2-3), 300-331.

[3] M. Blondet, J.Vargas-Neumann, N.Tarque, J. Soto, C. Sosa & J. Sarmiento (2016): Seismic protection of earthen vernacular and historical constructions. *Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions*, Leuven, Belgium, 3-14.

[4] M. Maheri, A. Maheri, S. Pourfallah, R. Azarm & A. Hadjipour (2011): Improving the Durability of Straw-Reinforced Clay Plaster Cladding for Earthen Buildings. *International Journal of Architectural Heritage*, **5**(3), 349-366.

[5] Q. Ali, N. Ahmad, M. Ashraf, M. Rashid & T. Schacher (2017): Shake Table Tests on Single-Story Dhajji Dewari Traditional Buildings. *International Journal of Architectural Heritage*, **11**(7), 1046-1059.

[6] C. Kawashima. Design of private houses (2016): *Overseas version (in Japanese)*. SUIYOSHA Publishing Inc, 67-96.

[7] K. Ohta (1988): *Wooden building in Eastern Europe (in Japanese)*. SAGAMI SYOBO, 39-48.

[8] H. Yokouchi, Y. Ohashi (2012): Earthquake resistance evaluations and seismic damage assessment of Japanese traditional building in Tochigi. *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, No.1272.

[9] Joint Editorial Committee for the Report on the Great East Japan Earthquake Disaster (2015): *Report on the Great East Japan Earthquake Disaster (in Japanese)*. Building Series Volume4, Damage of Historic Buildings, Architectural Institute of Japan.

[10] National Institute for Land and Infrastructure Management (2004): *Technical manual on the shear wall factor of mud wall, surface lattice wall and inserted wooden siding wall (in Japanese)*. Japanese Housing and Wood Technology Center, 144-147.

[11] Kansai office of Japan Structural Consultants Association (2014): *Seismic Performance Evaluation and Seismic Retrofitting Manual for Wooden House and Building Mainly Using Traditional Timber Frame Construction (in Japanese)*, 2nd edition.

[12] Y. Nomura, H. Yokouchi et.al. (2013): Research on Earthquake Disaster Mitigation Measures for Groups of Historic Buildings. Part 2. *Summaries of technical papers of annual meeting (in Japanese)*, Architectural Institute of Japan, Strucuture-3, 463-464

[13] N. Kokubun, H. Yokouchi et.al. (2016): Research on Earthquake Disaster Mitigation Measures for Groups of Historic Buildings. Part 18. *Summaries of technical papers of annual meeting (in Japanese)*, Architectural Institute of Japan, Strucuture-3, 325-326