Evaluation of Out-of-plane Vibration Characteristics for Walls of Historic Masonry Constructions

N. Takiyama, Y. Nambu & Y. Hayashi
Kyoto University, Japan

T. Tai
West Japan Railway Corp., Japan

SUMMARY:
We report the results of evaluation on out-of-plane vibration characteristics for unreinforced and reinforced walls of historic masonry constructions based on microtremor measurement. Major findings from the research are as follows; (1) Out-of-plane natural frequencies are approximately from 1.8 to 10.0 Hz. In case that ratio of height to length is small, natural frequencies increase nearly 1 to 2 Hz by reinforcement. (2) Using steel frame for reinforcement, vibration modes don't change remarkable. But, using shear wall, out-of-plane deformation of masonry wall is restrained. (3) 1st damping factor is between 1 and 4 percent and doesn't change remarkable by reinforcement.

Keywords: Historic masonry structures, Reinforced wall, Natural frequency, Vibration mode, Damping factor

1. INTRODUCTION

There are many historic masonry constructions all over the world. Recently, many self-governing bodies and groups have preserved or restored these constructions as symbol of local history and culture in Japan (JSCA (2001)). But, these masonry walls aren't generally reinforced and have low seismic performance. In 1995 Hyogoken Nambu Earthquake, there are some unreinforced masonry buildings broken (Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster (1998)). In Japan, many earthquakes occur, so it is importan to promote seismic retrofit of these constructions.

There are some seismic retrofitted methods such as steel frames, RC walls, inserting stainless pins and so on (Takiyama et al. (2009) and Ousalem et al. (2010)). But, it is not clear how high seismic performance is ensured with each method. The evaluation methods are not built up. Also, the structural characteristics of masonry walls needed to retrofit are unknown well. On the other hands, concerning historic masonry constructions such as national treasures or important cultural properties, there are the demands to try as less changed appearances as possible, because the preservation of cultural worth is the top priority. Under seismic retrofit for masonry constructions, it is important not only to raise strength of masonry walls but also to grasp natural frequency of masonry walls when earthquakes occur. In the past earthquakes, there are many cases that masonry walls collapsed toward out-of-plane. So, it is needed to study about behaviour toward out-of-plane. Considering the circumstances mentioned above, there are many questions to reinforce masonry buildings.

So, in this paper, we focus and study about out-of-plane vibration characteristics of masonry walls such as natural frequencies, vibration mode and damping factors. We conduct microtremor measurement for unreinforced masonry walls (Takiyama et al. (2012)) and reinforced masonry walls and understand out-of-plane vibration characteristics: steel frames and RC shear walls are adopted as the seismic retrofitted methods. We analyze the change of vibration characteristics before and after reinforcement, and understand the relation between vibration characteristics and reinforcement methods.

2. OUTLINE OF INVESTIGATION

In this chapter, we explain the outline of the investigation. We investigate seven masonry buildings and understand the vibration characteristics of masonry walls before and after reinforcement. These are all important cultural assets or incidental to them.

2.1. Method of microtremor measurement

We measure microtremor of masonry walls as shown in Fig. 2.1. (a). The measuring points are at the top of the walls, on the beams or on the 2nd story's floor as shown in Fig.2.1. (b), (c). When vibration mode is investigated, some accelerometers are arranged to horizontal and vertical directions along the walls and measurements are concomitantly conducted.

Figure 2.1. Pictures of instance: (a) masonry building's appearance, (b) microtremor measurement at the top of masonry walls, (c) microtremor measurement on 2nd story's floor

The accelerometers we use can measure two horizontal components and one vertical component. The frequency of sampled data is 100 Hz, one measurement is for 7 minutes. The measurement data is translated Fourier transform and ensemble average. It is smoothed using Parzen Window which band width is 0.1Hz.

When damping factors are identified, RD technique (random decrement technique) (Tamura et al. (1993)) is used. We select clear predominant frequency, pick out the frequency band by band pass filter and identify damping factor in RD technique.

2.2. Masonry buildings and walls which are target analyze

We investigate seven buildings in Table 2.1, and the plan shapes of buildings are shown in Fig.2.2. The plan of Bldg.III has corridor inside and the plans of Bldgs. IV to VII are rectangle. The 2nd floor and roof frame of almost all buildings are made of timbers. The buildings except for Bldg. II are two stories. Bldgs. IV to VII are reinforced.

Table 2.1. Details of measured buildings

Bldg.	Built Year	Plan / Fig.2.1	Stories	Structure built of		Reinforcement	Survey before and/or after reinforcement
				2nd Floor	Roof		
I	1906	(a)	2	Wood	Wood	X	Before
II	1895	(b)	1	X	Wood	X	Before
III	1904	(c)	2	Wood	Wood	X	Before
IV	1918	(d)	2	Wood, Steel	Wood	Steel flame	Before & After
V	1902	(d)	2	Wood	Wood	Steel flame	Before & After
VI	1902	(d)	2	Wood	Wood	RC walls	After
VII	1902	(d)	2	Wood	Wood	RC walls, Steel flame	After

Microtremor measurement is conducted at Bldg.I to V before reinforcement and at Bldg.IV to VII after reinforcement. The details such as wall's name, length, height or thickness of unreinforced and reinforced masonry walls are shown in Table 2.2. Here, length of masonry wall between orthogonal masonry walls is defined as the length of masonry wall.

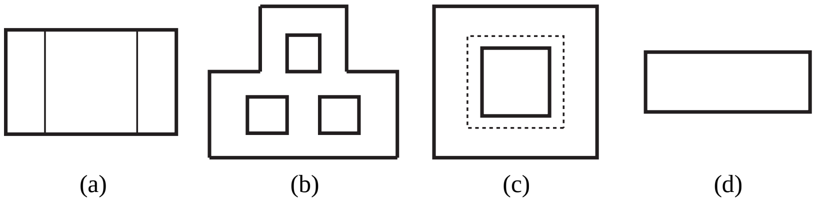

Figure 2.2. Plan shapes of buildings

Table 2.2. Details of masonry walls and the results before and after reinforcement

Bldg.	No.	Length (m)	Height (m)		Thickness (m)		Before reinforcement		After reinforcement	
			1F	2F	1F	2F	f_1 (Hz)	h_1 (%)	f_1 (Hz)	h_1 (%)
I	A	21.8	6.0	6.1	0.82	0.70	3.6	2.0	-	-
IV	L	71.6	7.4	3.1	0.47	0.36	1.8	0.9	2.8	1.0
	S	17.7	7.4	3.1	0.47	0.36	4.0	1.1	4.0	-
V	L	72.2	4.6	2.7	0.57	0.47	2.2	1.3	3.5	1.4
	S	10.3	4.6	2.7	0.57	0.47	5.9	1.4	8.8	-
VI	L	72.2	4.4	2.9	0.56	0.46	-	-	[L1] 4.1, [L2] 3.6	1.2
	S	10.3	4.4	2.9	0.56	0.46	-	-	7.3	1.3
VII	L	72.2	4.6	2.6	0.56	0.46	-	-	4.0	0.9
	S	10.3	4.6	2.6	0.56	0.46	-	-	-	-

2.3. Reinforced walls

The reinforcement is performed at Bldg. IV, V, VI and VII. The main methods of reinforcement are shown in Fig. 2.3. Here, the plans of 1st floor and the arrangement of reinforcing structural members are drawn. Masonry wall is indicated by gray thick line. Steel columns, horizontal trusses and circumferential girders are by black square, black thin and thick line. RC shear wall is indicated by double line painted inner gray.

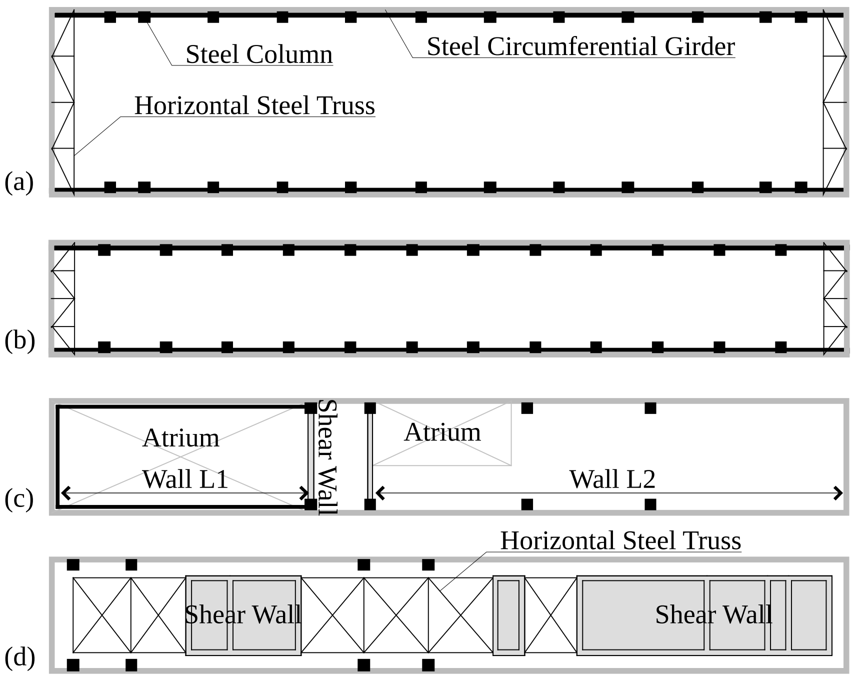

Figure 2.3. Plans of 1st floor with arrangement of reinforcing structural members: (a) Bldg. IV, (b) Bldg. V, (c) Bldg. VI, (d) Bldg. VII

At Bldg.IV and V, steel is used for reinforcement. In Bldg.IV and V, along the long sides of masonry walls, the steel columns of wide flange shapes are arranged and steel circumferential girders are arranged on the walls of 2nd floor level. Along the short sides of masonry walls, horizontal steel trusses are arranged on the walls of 2nd floor level. In Bldg.VI, the steel columns of wide flange shapes are arranged along the long sides of masonry walls. Two shear walls are founded crossing the long side of masonry walls and two atriums are made. In Bldg.VII, the steel columns of wide flange shapes are arranged along the long sides of masonry wall. So rooms enclosed by shear wall and horizontal steel truss of 2nd floor level are founded. Further, in all these buildings, steel beams are laid between the long sides of masonry walls but are out of drawing in Fig.2.3.

Figure 2.4. State of reinforcement: (a) steel frame and circumferential girder in Bldg.V, (b) shear wall and steel beams in Bldg.VII, (c) horizontal steel truss in Bldg.VII

The appearances of reinforcement are shown in Fig.2.4. The joint by steel column, beam and steel circumferential girder in Bldg.V are shown in Fig.2.4(a). The RC shear wall, steel beams which connect shear wall to masonry wall and horizontal steel brace under 2nd floor in Bldg.VII are shown in Fig.2.4(b) and (c).

3. RESULT OF MICROTREMOR MEASUREMENT

In this chapter, mistortemor measurement is conducted in seven buildings and the results are indicated. First, the results of unreinforced building are shown such as natural frequency, vibration mode and damping factor. Next, the results of reinforced building are shown. Finally, the results before and after reinforcement are compared.

3.1. Unreinforced walls

Microtremor measurement is conducted at Bldgs.I to V before reinforcement. The results are shown in Table 2.2, Fig.3.1-3.4.

3.1.1. Natural Frequency and vibration mode

The natural frequencies are specified by Fourier spectral ratio which is the data of 2nd floor or roof flame divided by data of 1st floor. In case that there are some natural frequencies, 1st natural frequency is written f_1.

The result of wall A at Bldg.I is shown in Fig.3.1. The measurement points on 2nd story's floor level and vibration mode are indicated in Fig.3.1(a), and Fourier spectral ratio of west half of wall is indicated in Fig.3.1(b). Seven accelerometers are arranged on 2nd story's floor level along masonry wall and one accelerometer is set on 1st story's floor level.

Natural frequencies are 3.6, 6.2Hz. In both of frequencies, vibration mode is shape swelling toward out-of-plane. Amplitude on centre of wall in 2nd natural frequency is larger than that of 1st natural frequency.

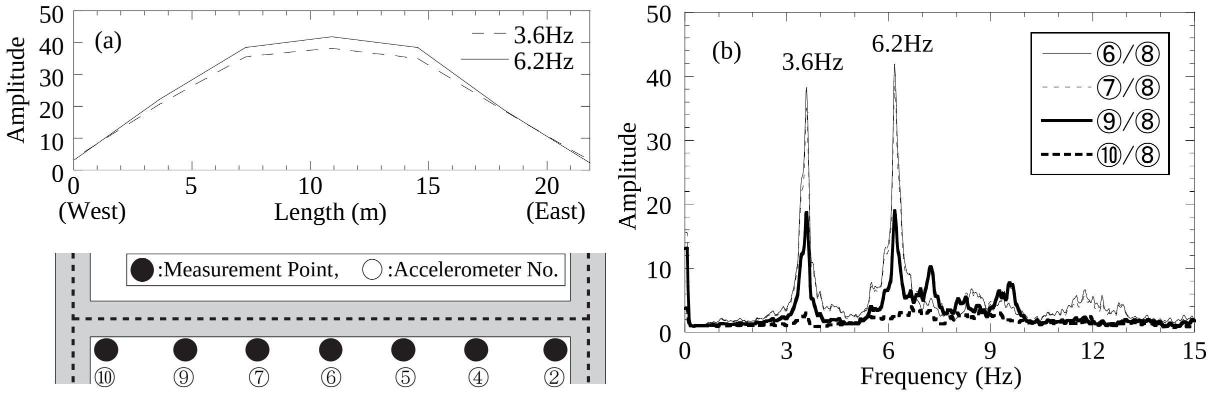

Figure 3.1. Results of wall I-A: (a) measurement points on 2 story's floor and vibration mode, (b) Fourier spectral ratio of west half of wall

The measurement results of wall L at Bldg.V are shown in Figs.3.2, 3.3. The measurement points on 2 story's floor level and vibration mode in half wall are indicated in Fig.3.2(a), and Fourier spectral ratio about out-of-plane and about in-plane are indicated in Fig.3.2(b), (c). Seven accelerometers are arranged on 2nd story's floor level along wall L and one accelerometer is set on 1st story's floor level. Measurement which some accelerometers are arranged vertically along the walls is conducted. The accelerometers are set on 1st and 2nd story's floor level and roof frame in section a, b and c as shown in the figure of arranged measurement point. Out-of-plane vertical vibration mode are indicated in Fig.3.3(a), (b).

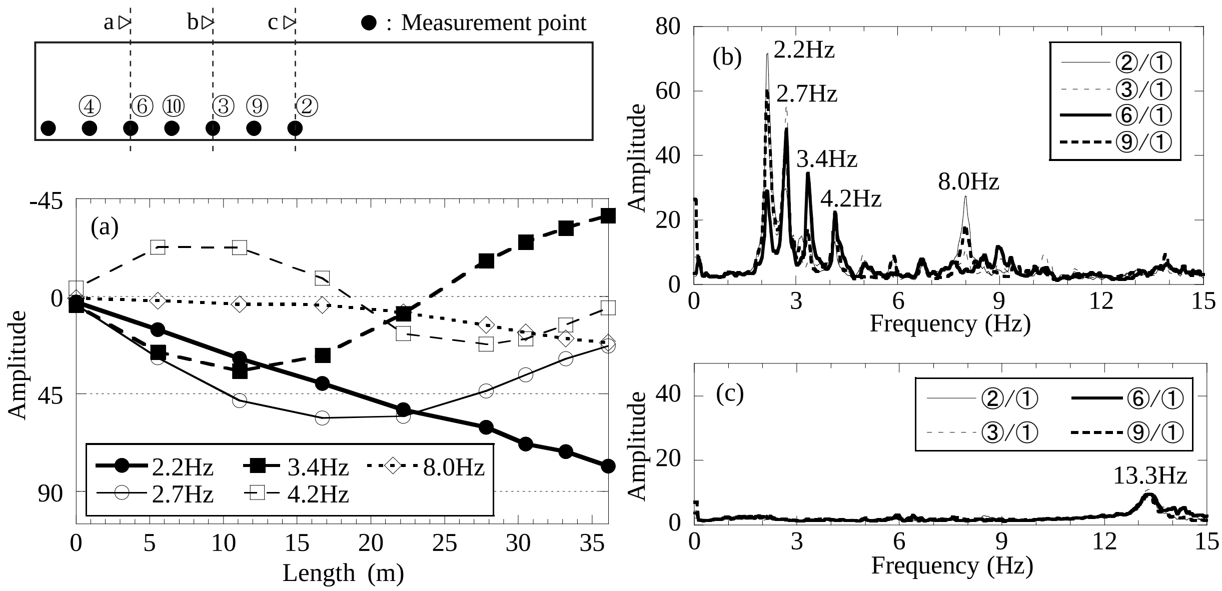

Figure 3.2. Results of half wall V-L: (a) measurement points on 2 story's floor and horizontal vibration mode in half wall, (b) Fourier spectral ratio about out-of-plane, (c) Fourier spectral ratio about in- plane

In case of out-of-plane, there are some natural frequencies from 2.2Hz to 8.0Hz. On the other hands, in case of in-plane, there is only small peak at 13.3Hz but no clear peak. In this paper, we focus on vibration characteristics about out-of-plane of masonry wall. Figure 3.2(a) shows vibration mode about five natural frequencies which appear in Fig.3.2(b). Here, half vibration mode is drawn but it is confirmed that the shape is symmetry or anti-symmetry. Differed from wall A at Bldg.I, higher mode are appeared. It is caused by the length of wall. Both edge of wall are nearly fixed support.

In vertical vibration mode at 2.2Hz, phase in 2 story's floor level and roof frame is same. But in 8.0Hz, phase in 2 story's floor level and roof frame is opposite.

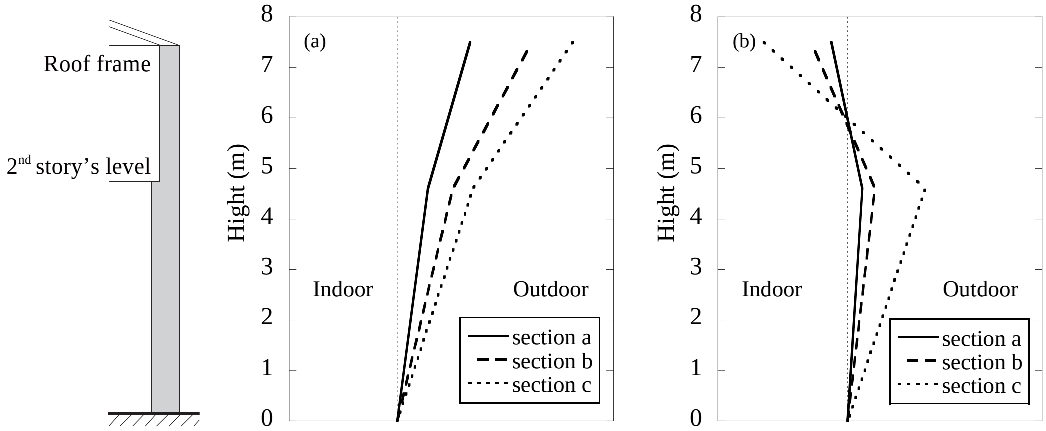

Figure 3.3. Vertical vibration mode about out-of-plane of wall V-L: (a) 2.2 Hz, (b) 8.0 Hz

3.1.2. Damping facter

About Bldgs.I to V, 1st damping factor h_1 against 1st natural frequency f_1 is identified by RD method. The results are shown in Table.2.2 and Fig.3.4(a) with regression equation. Here, R is correlation coefficient. The damping factor h_1 is distributed between 1 and 4 percent. It is depended on 1st natural frequency f_1 and is able to approximate exponential function. Regression equation is can be written as

$$h_1 = 0.83 \times e^{0.14 f_1} \tag{3.1}$$

At Bldgs.IV and V, including higher one, damping factors h_i (i =1,2,3,…) against natural frequencies f_i (i =1,2,3,…) are shown in Fig.3.4(b), (c). In identical wall, it is founded that h_i is roughly equal to h_1.

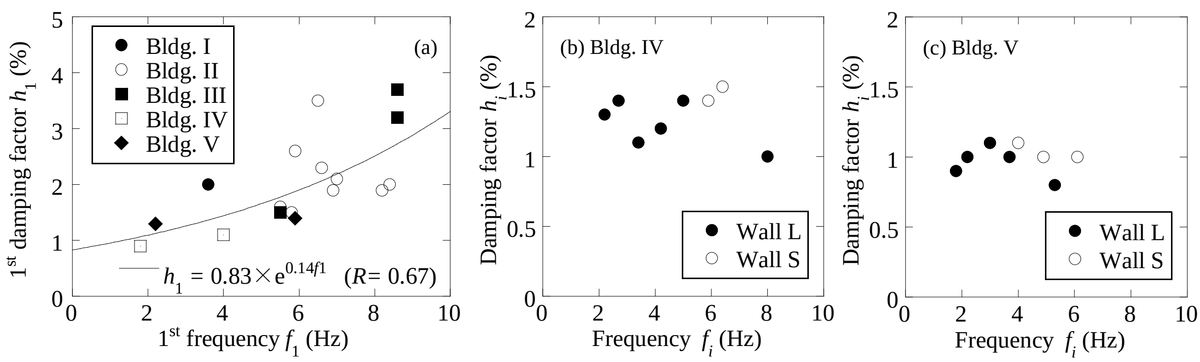

Figure 3.4. Relation between frequency and damping factor: (a) 1st frequency f_1 and damping factor h_1 in Bldg. I to V, (b), (c) predominant frequency f_i (i =1,2,3,…) and damping factor h_i (i =1,2,3,･･･) in Bldg. IV and V

3.2. Reinforced walls

Microtremor measurement is conducted at the same measurement points at Bldg.IV to VII after reinforcement. The results are shown in Table 2.2, Fig.3.5-3.8.

3.2.1. Change of Natural Frequency and vibration mode

Figure 3.5 shows comparison of Fourier spectral ratio of the long sides of masonry walls before reinforcement and after reinforcement at Bldgs.IV to VII. Here, at Bldg.VI, the wall of a large atrium side from shear wall is called wall L1 and the opposite wall is called wall L2. At Bldgs.VI and VII, measurement before reinforcement isn't conducted. So, because building date, structure, shape and size of building are nearly equal in three buildings, it is supposed that the buildings before reinforcement at Bldgs.VI and VII are same as Bldg.V. In following analysis, the results before at unreinforced Bldg.V and reinforced Bldgs.VI and VII are compared.

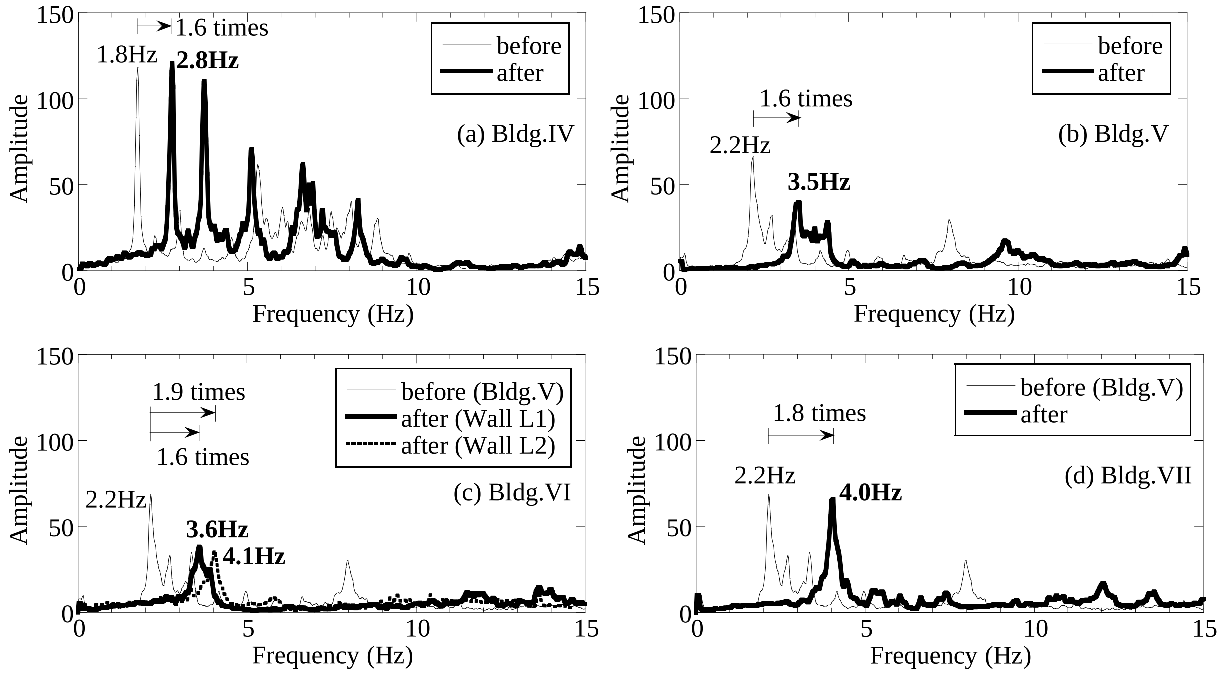

Figure 3.5. Comparison of Fourier spectral ratio of long sides of masonry walls by reinforcement

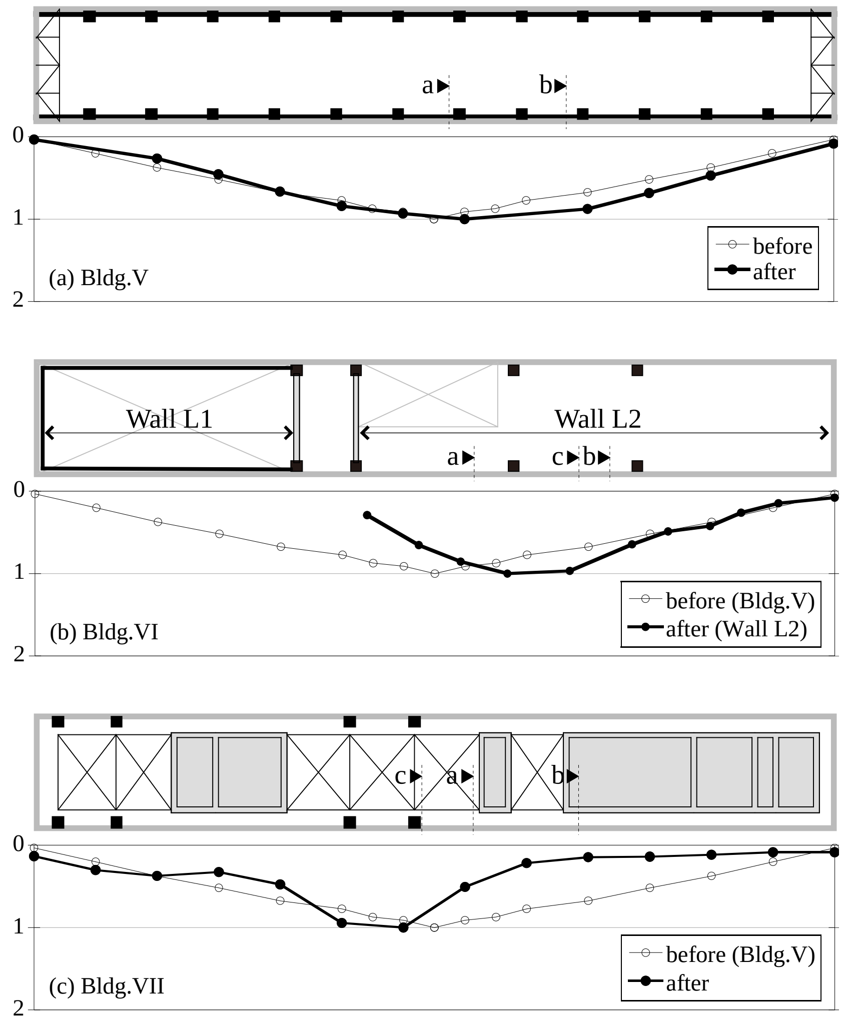

Figure 3.6. Change of horizontal vibration mode of long side of wall by reinforcement under f_1

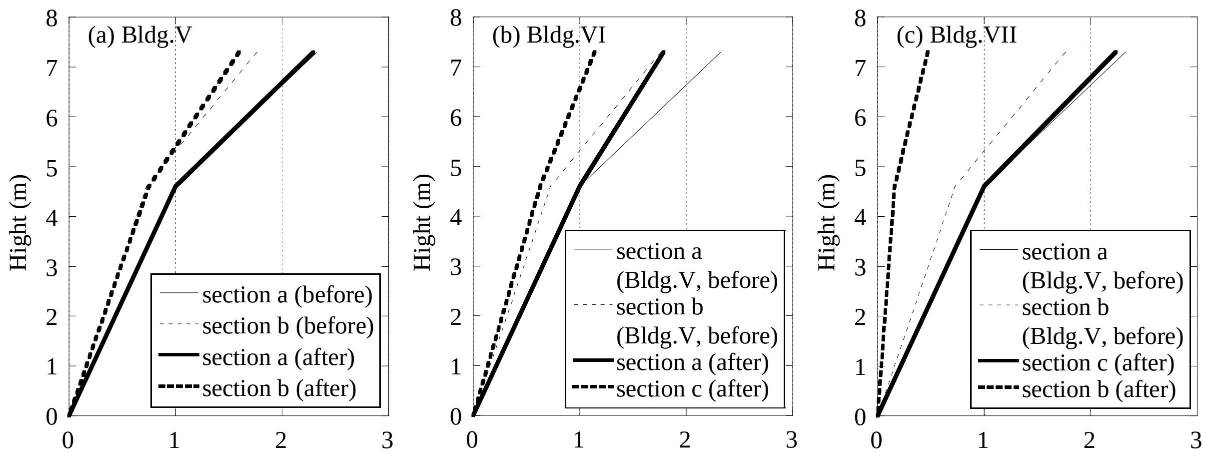

Figure 3.7. Comparison between vertical vibration mode before and after reinforcement under f_1

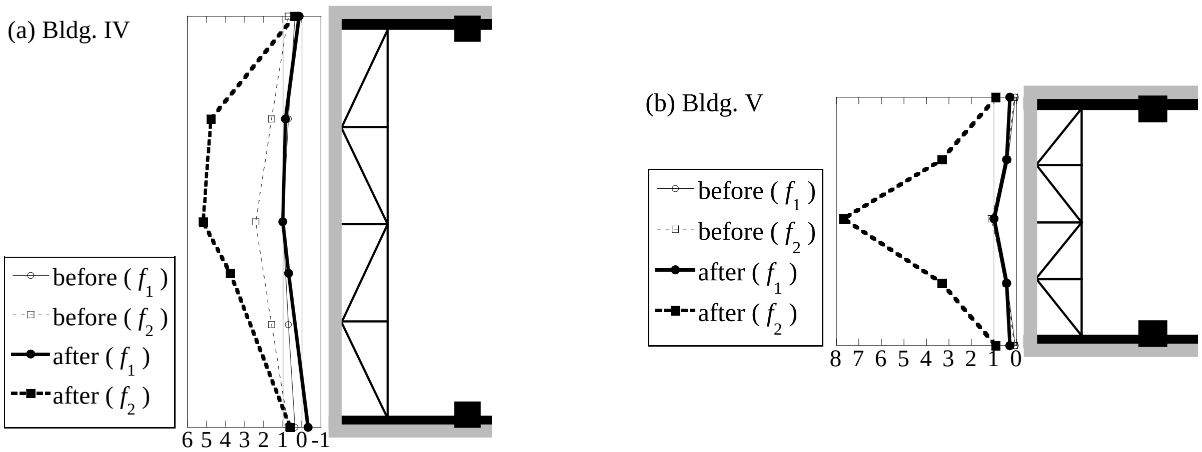

Figure 3.8. Change of horizontal vibration mode of short side of wall by reinforcement under f_1 and f_2

At all buildings, 1st natural frequency is increased approximately from 1.6 to 1.9 times by reinforcement. In case of Bldg.IV and V which are reinforced by steel frame and steel circumferential girder, each natural frequency tend to increase like parallel translation. On the other hands, in case of Bldg.VI which is reinforced by steel shear walls and steel circumferential girder, and Bldg.VII which is reinforced by steel shear walls and steel frame, some peaks which are found before reinforcement are disappeared and the number of natural frequencies is decreased. Especially, at Bldg.VI, 1st natural frequency is different between Wall L1 and L2, so it is found that vibration of both walls are independence.

Figure 3.6 shows change of out-of-plane horizontal vibration mode of the long sides of masonry walls before and after reinforcement on 2nd story's level of Bldg.V to VII in case of 1st natural frequency. Here, vibration mode is demonstrated symmetry or anti-symmetry, so vibration mode of wall is inverted to half mode. Vibration modes before and after reinforcement are normalized by maximum amplitude. Figure 3.7 shows comparison between out-of-plane vertical vibration mode before and after reinforcement at section a-c of Bldg.V to VII in case of 1st natural frequency. Here, each mode is normalized by amplitude of 2nd story's level.

At Bldg.V reinforced by steel frame, it is found that vibration modes of horizontal and vertical direction don't change remarkable before and after reinforcement. This tendency is also found at Bldg.IV. On the other hands, according to horizontal vibration mode at Bldgs.VI and VII, out-of-plane deformation of masonry wall is restrained at shear walls. At Bldg.VI, vertical vibration mode changes, but the cause is not clear.

In the short sides of masonry walls, change of natural frequency is shown in Table 2.2. And Fig.3.8 shows change of out-of-plane horizontal vibration mode before and after reinforcement on 2nd story's level of Bldgs.IV and V in case of 1st and 2nd natural frequency. Vibration modes before and after reinforcement are normalized by maximum amplitude of 1st mode.

As to 1st natural frequency, it is increase 1.5 times in Bldg.V but it doesn't change remarkable in Bldg.IV, in spite of same reinforced method. It is found that one of the causes is difference in length of wall. On the other hands, natural frequencies increase in Bldg.VI: 1st natural frequency increase 1.2 times. As to horizontal vibration mode, it doesn't change remarkable in each building.

3.2.2. Change of Damping facter

About Bldg.IV to VII, damping factor h_1 against 1st natural frequency f_1 is identified by RD method and are shown in Table.2.2. Here, in the short side of masonry walls of Bldgs.IV and V, because free vibration waveform calculated by RD method has large beat, damping factors can't be found. Damping factors of other buildings don't change remarkable.

4. DISCUSSIONS

In this chapter, based on the result of building which plan is rectangle, the change of natural frequency and damping factor by reinforcement is studied.

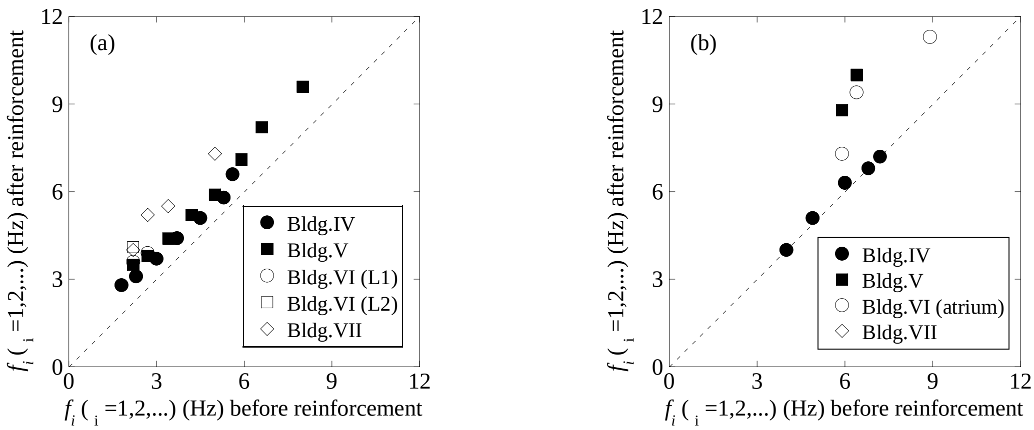

Figure 4.1. Comparison of natural frequency before and after reinforcement: (a) in the long side of masonry wall, (b) in the short side of masonry wall

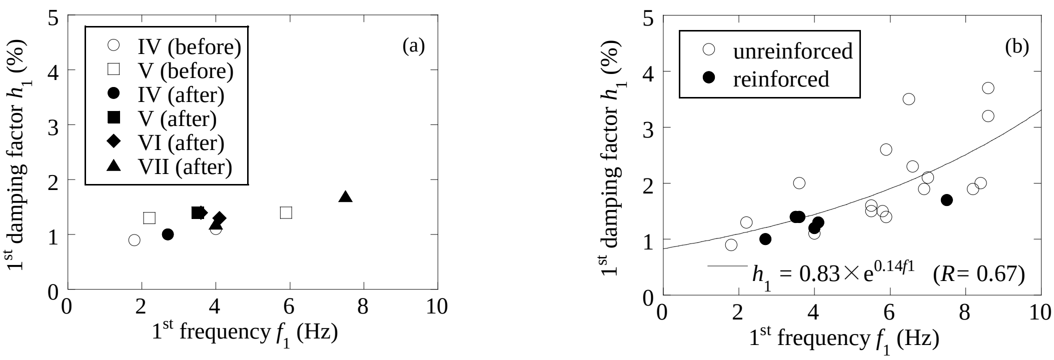

Figure 4.2. Comparison of damping factor before and after reinforcement: (a) change before and after reinforcement, (b) correspondence with Fig.2.8 (a)

The comparison of natural frequency before and after reinforcement is shown in Fig.4.1. As to the long side of masonry wall, natural frequencies after reinforcement are nearly 1 to 2 (Hz) larger than before reinforcement whatever natural frequency it is. As to the short side of masonry wall, natural frequencies increase nearly 1.2 to 1.5 times by reinforcement except for Bldg.IV.

The comparison of 1st damping factor before and after reinforcement is shown in Fig.4.2. It is found that 1st natural frequency change but damping factor doesn't change remarkable by reinforcement. Figure 4.2(b) is correspondence with Fig.3.4(a) which indicates 1st damping factor about unreinforced wall and regression equation.

5. CONCLUSIONS

We have reported the results of evaluation on out-of-plane vibration characteristics (natural frequency, vibration mode and damping factor) for unreinforced and reinforced walls of historic masonry constructions based on microtremor measurement.

Major findings are as follows;
As to unreinforced wall,
a) In case of in-plane, there is hardly any clear peak. But, in case of out-of-plane, natural frequencies are approximately from 1.8 to 10.0 Hz.
b) Vibration mode is shape swelling toward out-of-plane. The number of vibration mode increases as length of wall is longer.
c) Damping factor versus 1st natural frequency is about 1 to 4 percent and can recur by approximate exponential function. The smaller 1st natural frequency is, the smaller damping factor is.

As to reinforced wall,
d) In case that ratio of height to length is small, natural frequencies after reinforcement are nearly 1 to 2Hz larger than before reinforcement whatever natural frequency it is. In case that ratio of height to length is large, natural frequencies increase nearly 1.2 to 1.5 times.
e) Using steel frame for reinforcement, vibration modes don't change remarkable before and after reinforcement. But, using shear wall, out-of-plane deformation of masonry wall is restrained.
f) Damping factor doesn't change remarkable by reinforcement.

AKCNOWLEDGEMENT
This research was supported by Grants-in-Aid for Young Scientists (B) (No. 22760417) and The Japan Iron and Steel Federation (JISF). We gratefully acknowledge this support.

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