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A STUDY ON VIBRATION CHARACTERISTICS OF WOODEN STRUCTURE BASED ON MICROTREMOR MEASUREMENTS

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ABSTRACT

This paper investigates the natural frequency of timber structures. The 1995 Hyogo-Ken Nambu Earthquake caused large scale damage to wooden houses in Japan. This damage highlighted the need for new seismic design procedures considering the severe earthquake and investigation of the dynamic behavior of wooden structures. Our research group conducted a field survey, with microtremor measurements, of Japanese traditional timber dwelling houses for seismic retrofitting Japanese timber dwelling houses on a part of the Tokai district, which is concerned of the expected damage from the Tokai earthquake or the To-Nankai earthquake. A change in the natural frequency was measured after the upper ridge, the interior material completion, the exterior material completion, the completion and after the completion of one year of each stage of construction.

The authors carried out the microtremor measurements on several timber dwelling houses of both Min-ka type construction and Machiya type construction. The natural frequency of each house is approximately 2.5 - 4.0 Hz. The natural frequency of each house after the seismic retrofitting was higher than before. In this study, we measured the change in the natural frequency of the timber structure at each stage of construction and the difference due to the seismic retrofitting.

Introduction

The location of our research group is in Mino City, Gifu Prefecture, Japan. This city has many Japanese traditional timber dwelling houses. This city is on a part of Tokai district, which is concerned with the damage that could be caused by an expected Tokai earthquake or To-Nankai earthquake. In Mino city, our research group conducted a field survey with a microtremor measurement for these houses, and evaluated its vibration characteristics. The group also started seismic retrofitting work for these houses. In Japan, there are no seismic diagnosis and legal system for the seismic retrofitting of a wooden building. Therefore, the purpose of this paper study is to implement seismic diagnosis and seismic retrofitting of the wooden houses and using the microtremor measurements, to confirm the effect of the microtremor measurement.

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Method of Microtremor Measurements

Our research group has measured the natural frequency of timber structures using a portable vibration measurement machine, SPC-51, with six velocity-meters, VSE-15D of the servo-mechanism. The SPC-51, VSE-15D and a view of microtremor measurement is shown Fig. 2. The six sensors were set up on the first and second floors at the north-south and east-west corners.

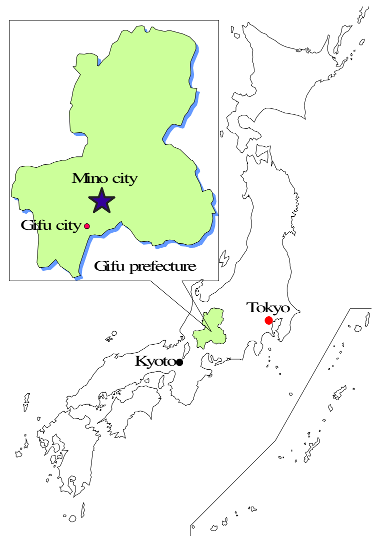


Figure 1 Location of Mino.

The full range of measurement is 100 mm/sec, and the sampling frequency is a Rene 100 Hz. To compute the natural frequency and the damping ratio a fast Fourier transform is calculated with the steady 1024 points data, which were obtained during measurements. The second floor spectrum was divided by the first floor spectrum to consider ground vibration. In the fast Fourier transform, ten times smoothing was used. The damping ratio was calculated by a way of a root two.

Figure 2 Portable Vibration Measurement Machine, Velocity-meters and view of Microtremor measurement.

Literature Research

The relationship between the constructed year and the natural frequency by microtremor measurement for a range of previous studies (Yamabe 1989, Onozuka et al. 1998, Hirayama et al. 1998, Kohara 2001) is shown in Fig. 3. This figure shows that the natural frequency of a typical modern wooden house is approximately 6.66 Hz. In other words, the natural period of a typical modern wooden house is approximately 0.15 seconds.

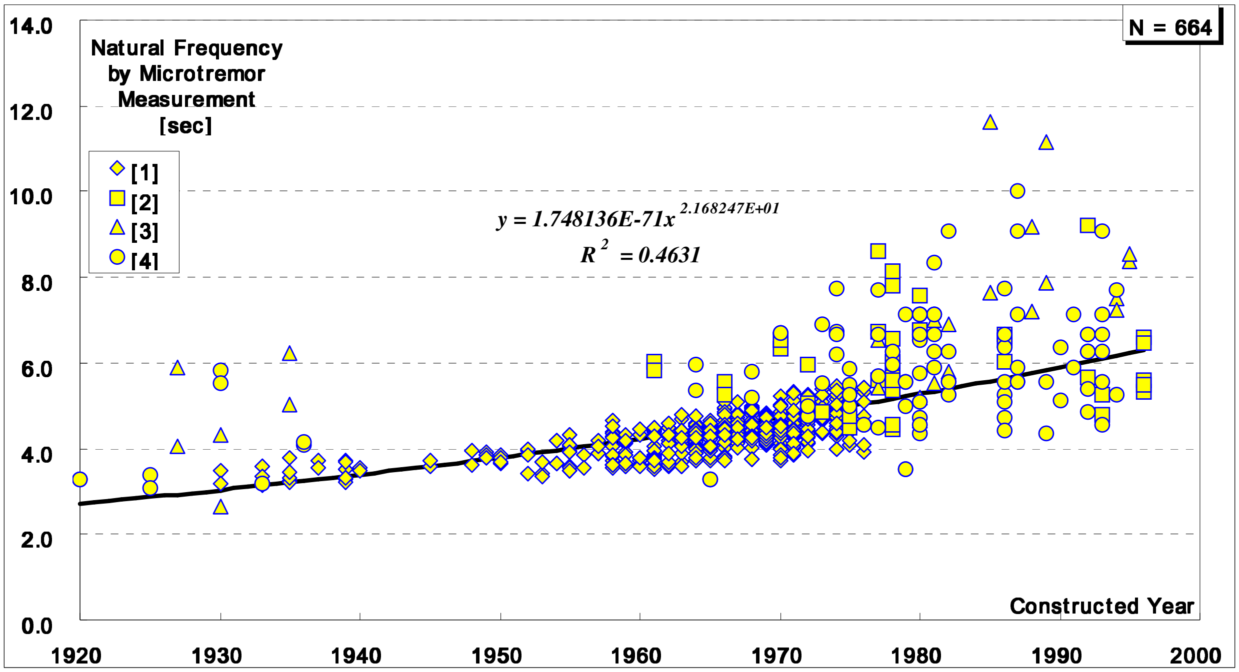
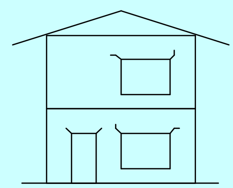
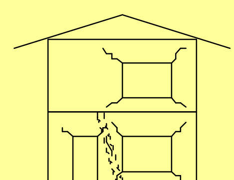
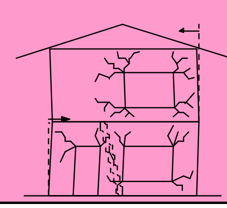


Figure 3. Natural Frequency by Microtremor Measurement and Constructed Year

The results of full scale shaking table tests on a modern house design is shown in Table 1, which provides the natural frequency and a destruction overview from microtremor measurements. In these tests, the earthquake wave of the JMA-Kobe-1995m, which was observed at the Japan Meteorological Agency by the Hyogo-ken Nanbu Earthquake in 1995, was used. The maximum acceleration is 818 gal in the horizontal direction and 630 gal in the vertical direction.

The results show that a modern timber house is destroyed (or collapses) with a natural frequency of 3-4 Hz, as measured by the microtremor measurements, and had slight damage at a natural frequency of about 6 Hz.

Table 1 Natural Frequency by the Microtremor Measurement and the Destruction Overview of Full-scale Shaking Table Tests.

Natural Frequency before the Excitation			Natural Period before the Excitation			Type A in Tadotsu 	Type B in Tadotsu 	Results of the full-scale shaking tests of two story wodden dwelling houses
Hz			sec					
6.5	~		0.154	~				
6.0	~	6.5	0.167	~	0.154		There is no damage of body most. In the 1st and the 2nd floor, gypsum boards around opening have slight crack. On the 1st floor north and south surface, bearing walls have shear crack	There is no damage of body most. The interior and exterior materials around opening have slight crack. There is no residual story drift most.
5.5	~	6.0	0.182	~	0.167		There is no body damage most. Cracks of gypsum board and mortars develop. Wrinkles are seen by the cross of the living room.	
5.0	~	5.5	0.200	~	0.182	At three points on the north side, gypsum boards have crack. Sidings have a minute crack. On the south side, a half of roofing tiles drop. There is no residual story drift most.	There is no damage of body most. A crack doesn't develop. There is no residual story drift most.	
3.5	~	4.0	0.3	~	0.3	The hold-down hardwares are deformed. The nail of brace's edge float. Gypsum boards have crack Siding boards have developed crack. There is residual story drift of 4mm to the east. The 14 braces of X direction in the 1st floor. : The one of them on the south is bend. The one of them on the north is buckling. The one of them on the north is tencil destruction. The one of them on middle street is como off a nail.	In the 1st floor, 2/4 braces have a buckling deformation. On the north side in the 1rst floor, 2/6 braces have a buckling destruction. On the north side in the 2nd floor, a brace have the buckling deformation and joint destruction. The entrance side HD ha	The braces have buckling destruction. The joints of brace have tencil destruction. There are many base fractures. The nails of joint hardware float. There is residual story drift about 1/350 radian. 
	~	2.5		~	0.400	Brace does buckling, and that joint is destroyed. 3/6 braces of the south side, 2/2 braces of the middle side and 5/6 braces of the north side destroy in the excitation direction on the 1st floor. 4/4 braces of the south side and 4/4 braces of the nort		There is heavy damage of body. Each story is transformed in the antiphase. Column of balloon framing is bend. 

* Each Shaking Table Test refers to Kohara (2001).

The relationship between the natural frequency by microtremor measurment and the effective wall length ratio is shown in Fig. 4. The correlation coefficient is 0.6628.

$$\mathbf{y = 5.5242\ x^{0.29}} \tag{1}$$

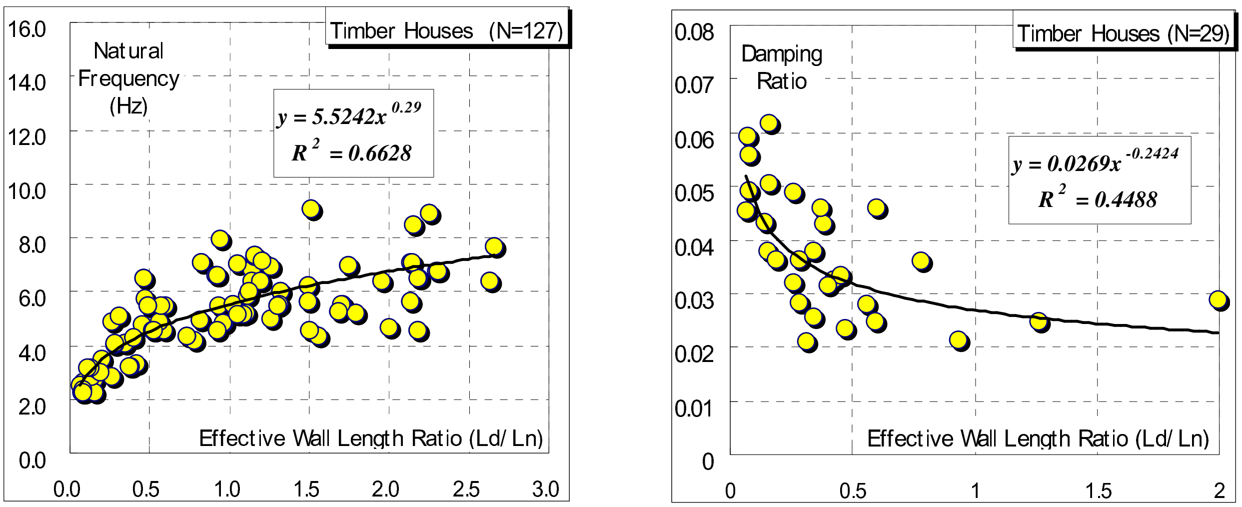


Figure 4. Natural Frequency and Effective Wall Length Ratio, Damping Ratio and Effective Wall Length Ratio.

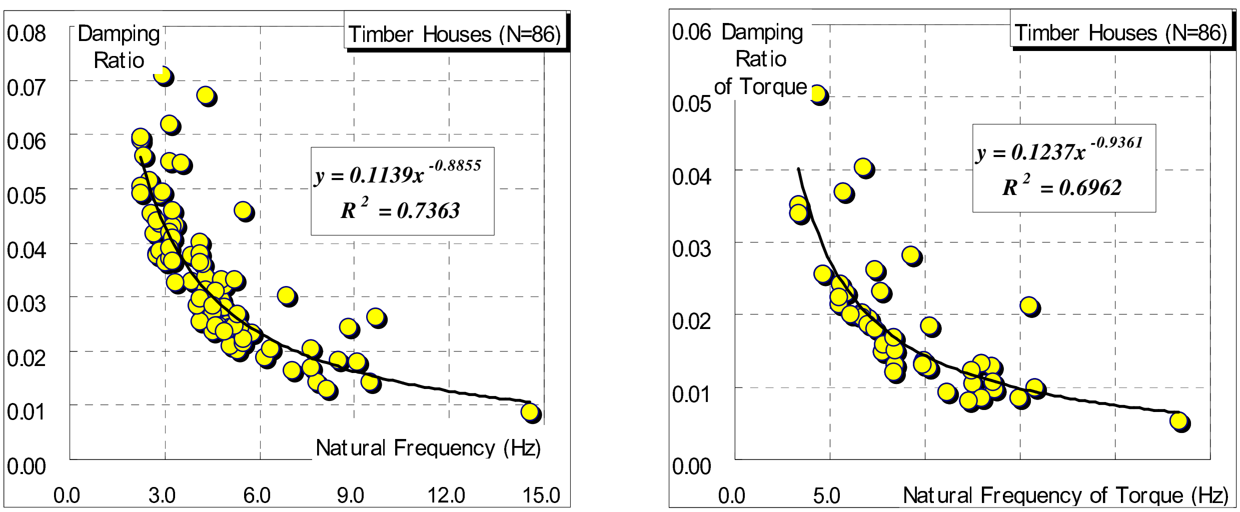


Figure 5. Damping Ratio and Natural Frequency, Damping Ratio of Torque and Natural Frequency of Torque.

The relationship between the damping ratio by microtremor measurment and the effective wall length ratio is shown in Fig. 4. The correlation coefficient is 0.4488.

$$\mathbf{y = 0.0269\ x^{-0.2424}} \tag{2}$$

The relationship between the damping ratio by microtremor measurment and natural frequency by microtremor measurment is shown in Fig. 5. The correlation coefficient is 0.7363.

$$\mathbf{y = 0.1139\ x^{-0.8855}} \tag{3}$$

The relationship between the damping ratio of torque by microtremor measurment and natural frequency of torque by microtremor measurment is shown in Fig. 5. The correlation coefficient is 0.6962.

$$\mathbf{y = 0.1237\ x^{-0.9361}} \qquad (4)$$

Vibration Characteristics of Wooden Structure on Each Construction Phase

Outline of Each New Wooden Structure

The outline of each new measured wooden structure is shown in Table 2. In this table, Ld represents the length of the seismic walls in design and Ln represents the necessary length of seismic walls in the Japanese Building Code (JBC) to each direction. The natural frequency and the damping ratio are measured by a microtremor measurement at completion. The structural specifications are shown at completion. In the direction, EW means the east-west direction, NS means the north-south direction and T means the twist.

These structures are two storied or three storied houses of Japanese timber frame structure. In each structure, the measured construction phase is different. As many construction phases as possible were measured. For example, these construction phases include; a phase of framework-rising, a phase of outer side wall finishing, a phase of inner side wall finishing, a phase of completion, and a phase after moving in.

It was assumed the wall magnification used a square bracket. The wall magnification is the wall strength and rigidity in Japan. For example, the wall magnification of a standard plywood wall is 2.5, the one of a standard brace wall is 2.0, and the one of a standard crey wall is 0.5.

Vibration Characteristics of Each New Wooden Structure

Each new wooden structure is shown Figure 6, and each vibration characteristic of the new wooden structures is shown Figs. 7 - 8. The average natural frequency of a standard two storied timber house in Japan is about 6.0 Hz. The I-House, the K-House and the N-House have a natural frequency of 7.0 Hz or more. The O-House is a three storied house, which has a natural frequency of approximately 6.0 Hz.

Each natural frequency of completion is 1.10 - 1.27 times as high as one of framework-rising. This is because the rigidity of a building increases by the establishment of the seismic bearing walls and of the inside exterior material.

I - House K - House O - House N - House

Figure 6. Outline of Each New Wooden Structure.

Table 2. Outline of Each New Wooden Structure.

I-House	Direction	Completion		Completion
Ld/Ln	EW	1.666	Story	2
	NS	1.666	Finishing of Roof	Aluminium-Zinc Alloy (Galvalume) Steel Sheet
Natural Frequency (Hz)	EW	8.300	Bearing Wall	Brace (105 x 45) [2.0]
	NS	8.490		Grid Shear Wall [1.0]
	T	12.200		---
Damping Ratio	EW	0.025		---
	NS	0.012	Bearing Roof	Plywood [2.0]
	T	0.010	Bearing Floor	Plywood [2.0]

K-House	Direction	Completion		Completion
Ld/Ln	EW	1.261	Story	2
	NS	1.261	Finishing of Roof	Aluminium-Zinc Alloy (Galvalume) Steel Sheet
Natural Frequency (Hz)	EW	7.031	Bearing Wall	Three Layered Jointing of Boards from Japanese Cedar [2.5]
	NS	9.960		Plywood [2.5]
	T	13.378		---
Damping Ratio	EW	0.023		---
	NS	0.012	Bearing Roof	Lumber Boards [0.3]
	T	0.009	Bearing Floor	Three Layered Jointing of Boards from Japanese Cedar [2.5]

O-House	Direction	Completion		Completion
Ld/Ln	EW		Story	3
	NS		Finishing of Roof	Aluminium-Zinc Alloy (Galvalume) Steel Sheet
Natural Frequency (Hz)	EW	5.957	Bearing Wall	Rigid Frame of Lumber [3.1]
	NS	6.250		Three Layered Jointing of Boards from Japanese Cedar [2.5]
	T	6.542		---
Damping Ratio	EW	0.031		---
	NS	0.043	Bearing Roof	Three Layered Jointing of Boards from Japanese Cedar [3.0]
	T	0.019	Bearing Floor	Three Layered Jointing of Boards from Japanese Cedar [3.0]

N-House	Direction	Completion		Completion
Ld/Ln	EW	1.185	Story	2
	NS	1.682	Finishing of Roof	Crey Tile
Natural Frequency (Hz)	EW	7.031	Bearing Wall	Three Layered Jointing of Boards from Japanese Cedar [2.5]
	NS	7.617		---
	T	10.058		---
Damping Ratio	EW	0.022		---
	NS	0.016	Bearing Roof	Lumber Boards [0.3]
	T	0.130	Bearing Floor	Three Layered Jointing of Boards from Japanese Cedar [3.0]

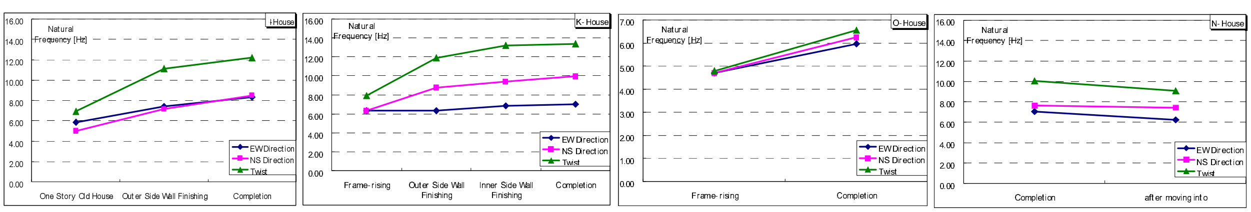


Figure 7. Natural Frequency of Each New Wooden Structure.

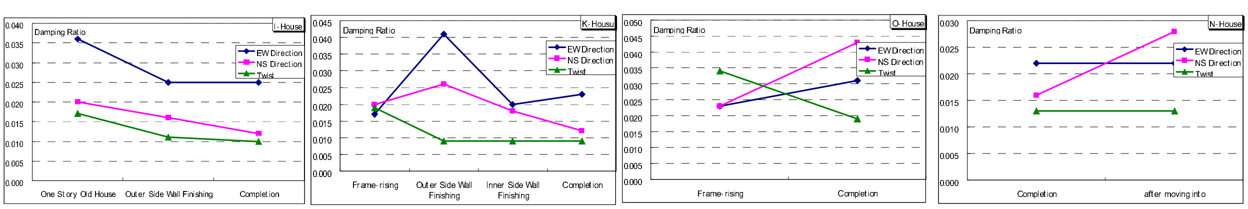


Figure 8. Damping Ratio of Each New Wooden Structure.

Vibration Characteristics of Wooden Structure on Retrofit Phase

Outline of Each Retrofit Wooden Structure

The outline of the measured retrofit wooden structure is shown in Table 3. These structures are one storied or two storied Japanese timber frame structures. Measurements were taken before and after the retrofit construction phases.

AA - Museum SN - House AO - House SK - House

Figure 9. Outline of Each Retrofit Wooden Structure.

Table 3. Outline of Each Retrofit Wooden Structure.

AA-Musium	Direction	Before Retrofit	After Retrofit		Before Retrofit	After Retrofit
Ld/Ln	EW	0.000	1.044	Story	2	
	NS	0.000	1.924	Finishing of Roof	Colonial Tile	
Natural Frequency (Hz)	EW	2.734	4.394	Bearing Wall	Sheathing Wall Board	Three Layered Jointing of Boards from Japanese Cedar [2.5]
	NS	3.515	9.570		---	Plywood [2.5]
	T	4.199	15.030		---	Plaster Board [1.0]
Damping Ratio	EW	0.052	0.033		---	---
	NS	0.085	0.010	Bearing Roof	Sheathing Roof Board	Plywood t=9mm [2.0]
	T	0.050	0.009	Bearing Floor	Lumber Board	Plywood t=28mm [3.0]

SN-House	Direction	Before Retrofit	After Retrofit		Before Retrofit	After Retrofit
Ld/Ln	EW	0.153	1.183	Story	2	
	NS	0.321	1.224	Finishing of Roof	Crey Tile	
Natural Frequency (Hz)	EW	4.785	6.054	Bearing Wall	Crey Wall [0.5]	Three Layered Jointing of Boards from Japanese Cedar [2.5]
	NS	4.785	5.957		Brace [1.5]	---
	T	7.320	8.789		---	---
Damping Ratio	EW	0.029	0.021		---	---
	NS	0.029	0.030	Bearing Roof	Sheathing Roof Board	Sheathing Roof Board
	T	0.018	0.014	Bearing Floor	Lumber Board	Plywood

AO-House	Direction	Before Retrofit	After Retrofit		Before Retrofit	After Retrofit
Ld/Ln	EW	0.370	1.580	Story	1	
	NS	1.012	3.960	Finishing of Roof	Crey Tile	
Natural Frequency (Hz)	EW	3.223	4.980	Bearing Wall	Crey Wall [0.5]	Crey Wall [0.5]
	NS	3.223	4.988		---	Plywood [2.5]
	T	5.468	10.156		---	Plaster Board [0.0]
Damping Ratio	EW	0.037	0.024		---	---
	NS	0.046	0.029	Bearing Roof	Sheathing Roof Board	Sheathing Roof Board
	T	0.023	0.013	Bearing Floor	Sheathing	Sheathing

SK-House	Direction	Before Retrofit	After Retrofit		Before Retrofit	After Retrofit
Ld/Ln	EW	0.190	0.380	Story	2	
	NS	0.280	0.280	Finishing of Roof	Crey Tile	
Natural Frequency (Hz)	EW	3.027	3.222	Bearing Wall	Crey Wall [0.5]	Crey Wall [0.5]
	NS	4.003	4.100		---	Plywood [2.5]
	T	7.617	14.063		---	Plaster Board [0.5]
Damping Ratio	EW	0.036	0.043		---	---
	NS	0.028	0.036	Bearing Roof	Sheathing Roof Board	Sheathing Roof Board
	T	0.023	0.030	Bearing Floor	Sheathing	Plywood (Partial)

Vibration Characteristics of Each Retrofit Wooden Structure

Each new wooden structure is shown in Fig. 9, and each vibration characteristic of the new wooden structuresis shown Figs. 10 and 11.

The natural frequency before retrofit construction rises about 24%-60% after retrofit construction. This is because rigidity rose by the reinforcement, such as the establishment of the bearing walls. Though natural frequency only rose in the SK-House by about 6% before and after the retrofit, it should be noted that in this reinforcement, one bearing wall with a length of 1365mm was only installed in the south side opening. The damping ratios before retrofit construction in the AA-Museum, SN-House and AO-House, where a large-scale seismic retrofit was carried out, decreased by about 11%-74 % after the retrofit. This could be because the whole crevice (especially, in such cases as the joint or the gap of a soil wall) of the building decreased as a result of the seismic retrofit. But, compared to before the retrofit, the damping ratio of SK-House after the retrofit is 119% (EW direction) and 128% (NS direction). Because the SK-House was partially retrofit as mentioned above, it can be thought that it is because the whole crevice of the building does not decrease that much.

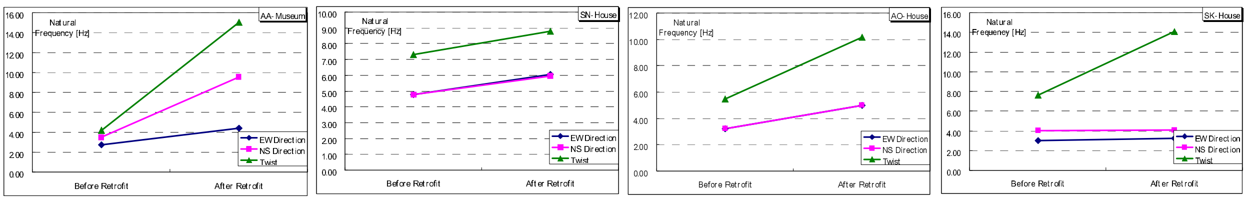


Figure 10. Natural Frequency of Each New Wooden Structure.

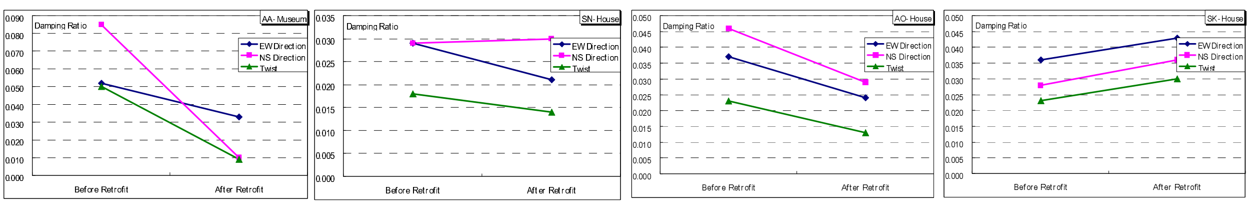


Figure 11. Damping Ratio of Each New Wooden Structure.

Conclusions

In this report, a method for increasing wall quantity and decreasing weight in a seismic retroffiting is discussed. The rise of the natural frequency could be confirmed after seismic retrofitting in both ways. Because the client could be shown a value after seismic retrofitting by the microtremor measurement, it was possible to have consented to a client in any case. Effective seismic retrofit, based on microtremor measurement of timber structure, is proposed. The natural frequency at each stage of construction rose from the upper ridge to the completion by about 10%-27 %. About 10% was reduced when a move was made after the completion. Also, the natural frequency after the earthquake-proof reinforcement rose by about 24%-60 %. It was found that a change in the rigidity of the building could be confirmed by using the natural frequency by the microtremors measurement. However, it is necessary to continue to accumulate data.

Acknowledgments

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