# STIFFNESS EVALUATION OF EXISTING WOODEN HOUSE USING MICROTREMOR OBSERVATION

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**ABSTRACT**: This research discussed how to make effective use of small-deformation tests such as microtremor observation for stiffness evaluation of existing wooden houses. To explore its absolute availability, we examined the relationship between stiffness calculated from small-deformation tests and the secant stiffness of response hysteresis in full-level shaking table test. The stiffness of microtremor observation was 3.9-6.5 times larger than the secant stiffness in 1/200rad. The ratio was small in the deteriorated walls without seismic reinforcement, while that was quite large in the continuous mortar walls or the rehabilitated walls. And it was clarified that the relative evaluation could gain larger trust based on several tests in larger-deformation to estimate weights, the influence by suffering deterioration or vibration and rehabilitation on stiffness.

**Key Words**: Existing Wooden House, Seismic diagnosis, Microtremor Observation, Shaking Table Test, Vibration Characteristics, Load-Deformation Relationship, Stiffness,

## INTRODUCTION

In order to rehabilitate the seismic performance of an existing wooden house not to collapse by a huge earthquake, the original performance should be correctly estimated. Microtremor observation is widely used for many types of structures as one of field tests because vibration characteristics can be non-destructively demonstrated with simple operation. Wooden structure, however, has a characteristic nonlinearity of stiffness-deformation relationship, and it should be paid attention that the vibration characteristics in small deformation for microtremor observation differ from that in large deformation under a huge earthquake. The seismic performance could be evaluated correctly only by microtremor observation so that it might result in evaluation in dangerous side. On the other hand, we could have the possibility of evaluating the seismic performance in a wide range of deformation more correctly in the case based on the tests in larger deformation such as man-powered vibration test, motion exciter test and strong-motion instrumentation or small-level shaking table tests. It should be examined the amplitude dependent of stiffness, how to evaluate the response values in various tests in different range of deformation.

In this research, we examine the relationship between response hysteresis in full-level shaking table test and stiffness evaluated from small-deformation tests, performing in parallel with collapse tests of actual-size structure, and discuss the possibility for relative evaluation by small-deformation tests.

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## EXPERIMENTAL OVERVIEW

### *Specimens*

In this research, three specimens were targeted, of which two were existing wooden houses and rebuilt on the shaking table ‘E-defense’ (Specimen-A, Specimen-B), and the newly built one, with the same specification as specimen-A with new members and components (Specimen-C). The sample houses (**Photo 1**) were built 31 years old (built in 1974) having mortar finish with metal lath on wood lath, inner mud wall and tiled roof (categorized as ‘heavy house’[1]), and braces and columns were jointed without joint metal and just fastened with nails. **Figure 1** illustrates the plan of the first and the second floor. Exteriors in span-direction (X) have full-height mortar walls continuing 1-2stories and inner mud, while exteriors in ridge-direction (Y) have a large amount of openings. Specimen-A and specimen-B were built at the same time and their specifications were nearly equal, but their situation of reconstruction and deterioration were slightly different. Specimen-B was rehabilitated based on the seismic diagnosis[1] in the process of experiments after placed on shaking table. **Figure 2** illustrates components and contribution percentage of the strength in 1/200rad. in the seismic diagnosis in each direction of each specimen.

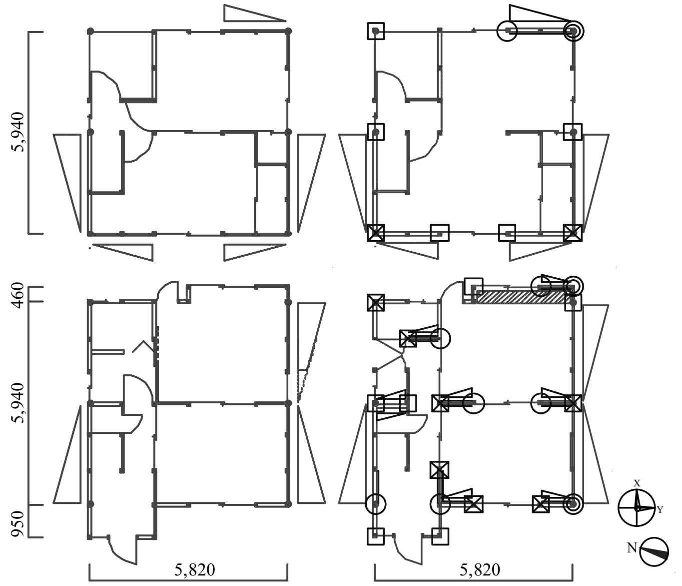


**Photo 1.** Sample House

**Figure 1.** Plan of Specimens（Left：Specimen-A、Right：Specimen-B）

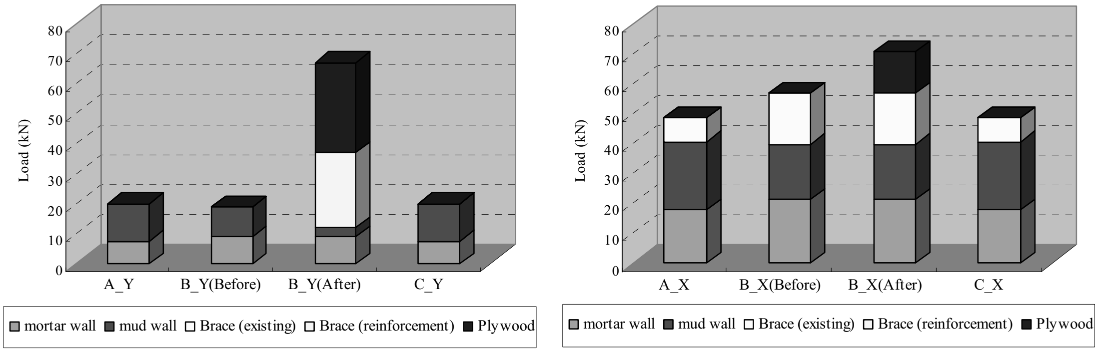


**Figure 2.** Components and Contribution percentage of Load in 1/200rad.

### *Measurement Method*

In this research, small-deformation tests were performed for specimen-A,B,C in which were [1. the phase on-site in use], [2. the phase after removing tile roofs and ceilings and the rest], [3.-10. the several phases after placed on shaking table]. **Table 1** shows the experiment schedule.

#### *-Microdisplacement measurement*

The displacement waveforms were recorded by velocimeters placed on each floor. In man-powered vibration test, the specimens were vibrated sympathetically by being pushed the column on the second floor aiming for vibrating on the natural frequency in microtremor observation. In motion exciter test, the motion exciter was placed on the 2nd floor and was made run in sine-sweep wave to obtain a resonance wave and run in sine wave on the resonance frequency.

#### *-Shaking Table Test*

The acceleration waveforms were recorded by accelerators placed on each floor. The input waves for small-level shaking table tests were white-noise waves in several levels of acceleration, sine-sweep wave and earthquake wave (5% level). For full-level shaking table test, the 3-dimensional vibration tests over displacement control by the seismic motion recorded at JR Takatori station in 1995 Hyogo-ken Nanbu earthquake (called ‘JR-Takatori’) ware performed.

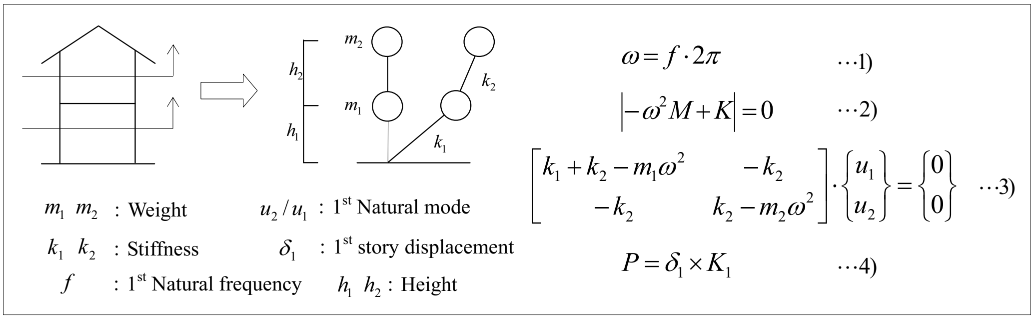
### *Analysis Method*

In this research, we modeled the specimens of 2-mass system and analyzed the seismic performance of 1st story focused on the 1st vibration mode. The stiffness of 1st story was calculated by 1st natural frequency in each transfer function and natural mode (**Figure 3**). The amplitude in small-deformation vibrations was determined by displacement in barycentric position on 2nd floor and that in small-level shaking table tests was determined by double integral of acceleration. The load-deformation relationship in each test was described with the deformation and the shear force multiplied the stiffness and the deformation of 1st story. In full-level shaking table test, the response hysteresis was determined by record of displacement at barycentric position of 1st story and acceleration on each floor. The seismic performance of X- and Y-direction was referred in this thesis.

**Table 1.** Test Schedule

| Phase | | | Live load on 2nd | | | Test |
|---|---|---|---|---|---|---|
| | | | A | B | C | |
| On site | Change of load | **1. In use** | 1 | 1 | - | MT |
| | | **2. After tile roofs, etc..** | $0^{*}$ | $0^{*}$ | - | MT |
| On shaking table | | **3. Case1** | - | - | $0^{**}$ | MT / MV |
| | | **4. Case2** | - | - | $1/2^{**}$ | MT / MV |
| | | **5. Case3** | - | - | $1^{**}$ | MT / MV |
| | | **6. Case4** | - | - | $2^{**}$ | MT / MV / ME |
| | **7. Before shaking table tests** | | 1 | $1^{***}$ | 1 | MT / MV / ME |
| | Small-level shaking table tests | | 1 | 1 | 1 | SS |
| | **8. After shaking table tests** | | 1 | 1 | 1 | MT / MV / ME |
| | Reinforcement work for specimen-B | | | | | |
| | **9. After reinforcement** | | - | $1^{****}$ | - | MT / MV / ME |
| | Small-level shaking table tests | | 1 | 1 | 1 | SS |
| | Full-level shaking table tests | | 1 | 1 | 1 | FS |

*Decreasing weights of tile roofs, mortar at roof, ceiling, tatami and live load on 2nd floor
**Unloaded weights of mortar at roof
***Performed microtremor observation only for B
****Decreasing weights of demolished mud wall



$$\omega = f \cdot 2\pi \qquad \cdots 1)$$

$$\left| -\omega^2 M + K \right| = 0 \qquad \cdots 2)$$

$$\begin{bmatrix} k_1 + k_2 - m_1\omega^2 & -k_2 \\ -k_2 & k_2 - m_2\omega^2 \end{bmatrix} \cdot \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad \cdots 3)$$

$$P = \delta_1 \times K_1 \qquad \cdots 4)$$

**Figure 3.** Analysis method of Stiffness

## RELATIONSHIP OF AMPLITUDE AND STIFFNESS IN SMALL-DEFORMATION TEST

In this chapter, the relationship between the response hysteresis in full-level shaking table tests and the stiffness in small-deformation tests was demonstrated focused on amplitude. The tests were analyzed, in which the specification and the weights of the specimens were the same as those in the full-level test.

### *Difference of Level of Amplitude*

**Table 2** shows the amount of deformation on 2nd floor. As for Y-direction, the amount in microtremor observation was 1-2$\times10^{-7}$rad. , that in man-powered vibration was 2-5$\times10^{-5}$rad., that in motion exciter test was 4-8$\times10^{-5}$rad., that in small-level shaking table test in 40gal was 7-8$\times10^{-4}$rad., that in 100gal was 2-3$\times10^{-3}$rad.. In X-direction, the amount in microtremor observation was 3-5$\times10^{-8}$rad. , that in man-powered vibration was 6-13$\times10^{-6}$rad., that in motion exciter test was 2-3$\times10^{-5}$rad., that in small-level shaking table test in 40gal was 6-7$\times10^{-4}$rad., that in 100gal was 2$\times10^{-3}$rad.. The deformation level of each specimen was nearly comparable in each test, but in resonant vibration such as in man-powered vibration or motion exciter test, the amount widely ranged among specimens. In microtremor observation, which is one of vibrations using ordinary wave, the range seemed wide. And the level of deformation of 'with many openings' Y-direction was different from that of 'with continuous mortar wall' X-direction.

**Table 2.** Deformation and Stiffness in Each Test

| | Deformation (rad.) | | | | | | Ratio to the secant stiffnessof response hysterisis in 1/200 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A_X | B_X | C_X | A_Y | B_Y | C_Y | A_X | B_X | C_X | A_Y | B_Y | C_Y |
| MT | 5.1*10$^{-8}$ | 2.9*10$^{-8}$ | 4.3*10$^{-8}$ | 1.6*10$^{-7}$ | 1.1*10$^{-7}$ | 1.0*10$^{-7}$ | 6.21 | 4.48 | 4.76 | 6.50 | 3.85 | 5.18 |
| MV | 6.2*10$^{-6}$ | 7.4*10$^{-6}$ | 1.3*10$^{-5}$ | 1.9*10$^{-5}$ | 4.7*10$^{-5}$ | 2.5*10$^{-5}$ | 6.15 | 4.21 | 4.68 | 5.38 | 3.41 | 4.65 |
| ME | 3.3*10$^{-5}$ | 2.6*10$^{-5}$ | 1.8*10$^{-5}$ | 7.8*10$^{-5}$ | 3.6*10$^{-5}$ | 4.2*10$^{-5}$ | 4.51 | 3.44 | 4.09 | 3.22 | 3.10 | 3.92 |
| SS(WN40gal) | 7.2*10$^{-4}$ | 6.8*10$^{-4}$ | 6.4*10$^{-4}$ | 7.9*10$^{-4}$ | 7.0*10$^{-4}$ | 8.7*10$^{-4}$ | 4.67 | 3.48 | 3.77 | 2.93 | 3.21 | 2.84 |
| SS(SW) | 1.7*10$^{-3}$ | 1.7*10$^{-3}$ | 1.7*10$^{-3}$ | 2.1*10$^{-3}$ | 1.9*10$^{-3}$ | 2.0*10$^{-3}$ | 4.23 | 2.18 | 3.21 | 1.31 | 2.60 | 2.31 |
| SS(WN100gal) | 1.9*10$^{-3}$ | 1.8*10$^{-3}$ | 1.7*10$^{-3}$ | 2.8*10$^{-3}$ | 2.2*10$^{-3}$ | 2.5*10$^{-3}$ | 3.02 | 2.24 | 2.66 | 1.36 | 2.48 | 2.15 |
| FS(1/200rad.) | 5.0*10$^{-3}$ | | | 5.0*10$^{-3}$ | | | 1.00 | | | 1.00 | | |

#NOTE MT: Microtremor observation, MV: Man-powered vibration, ME: Motion exciter test
SS: Small-level shaking table test (WN: white noise wave, SW: sine-sweep wave), FS: Full-level

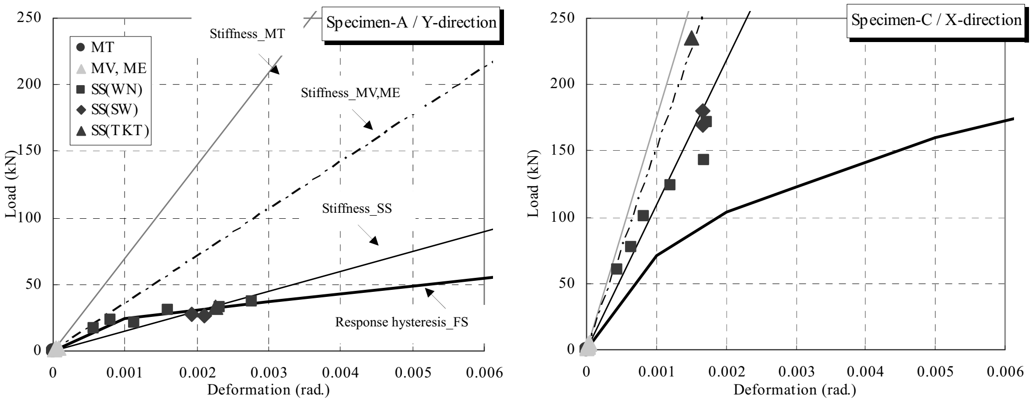


**Figure 4.** Stiffness in Each Test and Skelton Curve in Full-level Shaking Table Tests

### *Difference of Level of Stiffness*

**Table 2** also shows the stiffness of 1st story in each test. **Figure 4** illustrates the load-deformation relationship in each small-deformation test and the response hysteresis in full-level shaking table test. The stiffness was calculated higher from tests in smaller level of deformation. The stiffness in microtremor observation was about twice as large as that in shaking table test using sine-sweep wave. Based on the stiffness in 1/200 rad. in response hysteresis, the ratio of the stiffness of Y-direction in microtremor observation was 3.9-6.5, that in man-powered vibration was 3.4-5.4, that in motion exciter test was 3.1-3.9, that in small-level shaking table test in 40gal was 2.8-3.2 and that in 100gal was 1.4-2.5. As for X-direction, the ratio in microtremor observation was 4.5-6.2, that in man-powered vibration was 4.2-6.2, that in motion exciter test was 3.4-4.5, that in small-level shaking table test in 40gal was 3.5-4.7 and that in 100gal was 2.2-3.0. For specimen-A in Y-directions, the ratios in small deformation were extremely large, but that went smaller in larger deformation (specimen-A in X-direction, specimen-C in Y-direction were in the same group). For specimen-B in Y-direction, the ratios in small deformation were small and that varied little by deformation (specimen-B in X-direction, specimen-C in X-direction were in the same group). Refer to **figure 2**, the latter was characterized as the specimen with new wall or rehabilitated wall of high stiffness and the former was specimen with deteriorated wall and so on with low stiffness.

## RELATIVE EVALUATION OF SEISMIC PEFORMANCE OF SPECIMEN BASED ON SMALL-DEFORMATION TESTS

In this chapter, the relative availableness of small-deformation vibration tests for evaluation of the seismic performance of existing wooden houses was experimentally demonstrated. The difference of vibration characteristics were figured out by performing small-deformation vibrations for specimens in different situation or phase. And we determined the appropriateness of relative evaluation of performance shift of specimens based on the results in small-deformation vibration test, refer to other measurement results and so on.

### *Influence of Difference of Weights*

It is important for evaluation of seismic performance of structure to estimate the weights, which of existing wooden houses are calculated according to the enforcement order in Building Standard Law, the guideline of load for building structures and the seismic diagnosis and so on. In this part, we examined the way for estimating the weights correctly and briefly by using several results in small-deformation test. The weights of specimen-A and B in existing situation were calculated from the shift of weights and natural frequency in microtremor observation, supposing that there weren't shift of stiffness among the two phases; [1. in use] and [2. after removing roofs, ceilings and so on] (**Table 3**). The weight of specimen-C, same as that in full-level shaking test, was calculated by evaluation of the shift of vibration characteristics through performing microtremor observation and man-powered vibration with four-level live load. The precision of the calculated value based on the actual weight was examined. We estimated the sum amount of weights for calculating shear force of 1st and 2nd floor. **Figure 5** and **figure 6** illustrate the natural frequency in microtremor frequency and the estimated weights. **Figure 6** illustrates the mode distribution in elevation. The weights based on microtremor observation of specimen-A and B in Y-direction were calculated 47.5kN (specimen-A) and 265kN (specimen-B). Both results differed considerably and the value of specimen-B was approximate to actual weight, but specimen-A was estimated too light. It was unable to estimate from results in X-direction. Tests for specimen-A, B were performed on site so that they were probably influenced by input variance. The decrease of the stiffness of horizontal plane might have influence on the natural frequency when the weight of each story was shift due to the removal of tile roofs, roof mud, ceilings and so on. It was difficult to estimate the weights of specimen-A, B from the results in microtremor observation under about 29% difference of weights based on the actual weights.

In the tests for specimen-C, which were performed by variance of live load on 2nd floor, there found some cases that the weight was properly evaluated (the error was about 10% or less) under the minimum difference of weights (10.37kN). The estimation precision was about the same between in X- and Y-direction. It tends to be possible to estimate the weight more correctly in reducing live load than in adding it based on the situation in full-level shaking table tests because the shift of natural frequency was larger. In this research, the estimation precision in microtremor observation was a little bit higher than that in man-powered vibration.

**Table 3.** Equation of Estimation of Weights

Known: $f_i \quad u_{2i}/u_{1i} \quad f_{i+1} \quad u_{2i+1}/u_{1i+1} \quad \Delta m$

Unknown: $k_1 \quad k_2 \quad m_1 \quad m_2$

$$\omega_i = f_i \cdot 2\pi \qquad \cdots 5) \qquad \left| -\omega_i{}^2 M_i + K \right| = 0 \qquad \cdots 6)$$

$$\begin{bmatrix} k_1 + k_2 - m_1\omega_i{}^2 & -k_2 \\ -k_2 & k_2 - m_2\omega_i{}^2 \end{bmatrix} \cdot \begin{Bmatrix} u_{1i} \\ u_{2i} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad \cdots 7)$$

$$\omega_{i+1} = f_{i+1} \cdot 2\pi \qquad \cdots 8) \qquad \left| -\omega_{i+1}{}^2 M_{i+1} + K \right| = 0 \qquad \cdots 9)$$

$$\begin{bmatrix} k_1 + k_2 - (m_1 + \Delta m) \cdot \omega_{i+1}{}^2 & -k_2 \\ -k_2 & k_2 - m_2\omega_{i+1}{}^2 \end{bmatrix} \cdot \begin{Bmatrix} u_{1i+1} \\ u_{2i+1} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad \cdots 10)$$

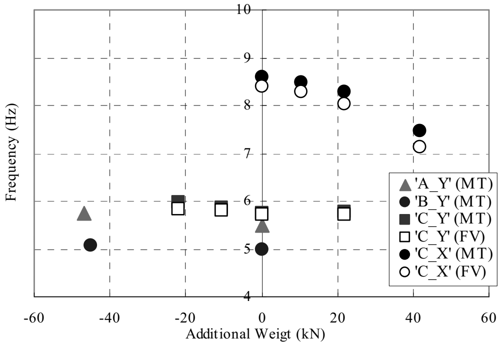


**Figure 5.** Additional Weight and Natural Frequency

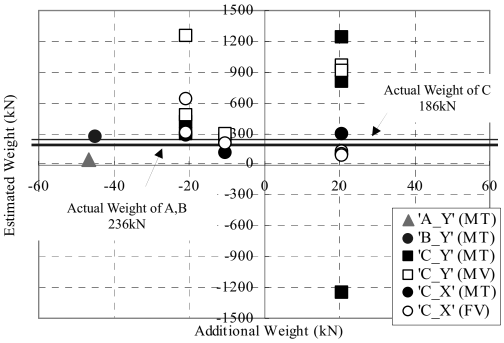


**Figure 6.** Additional Weights and Estimate Accuracy

### *Influence of Deterioration and Degradation*

An existing wooden house might have the possibility of containing the deteriorated members and components and it should cause decrease of the seismic performance. Specimen-A, B (before reinforcement) and C were with almost the same specification, but specimen-A and B suffered deterioration and degradation due to aging, and especially specimen-B had severely deteriorated mortar walls. The influence of deterioration on decreasing of the seismic performance was examined by comparing vibration characteristics of specimens in the same phase. **Figure 7** illustrates the stiffness of specimen-A, B, and C based on the results in microtremor observation, man-powered vibration, motion exciter test and small-level shaking table test. Refer to small-level shaking table tests, the stiffness of specimen-A in Y-direction was 26-47% smaller than that of specimen-C and that of specimen-B was 21-35% smaller than that of specimen-A. The degrading rate was calculated larger in microtremor observation. Comparing the seismic performance of between mortar walls picked from existing wooden house and the newly rebuilt walls, that of the picked walls in microtremor observation were 23% smaller and that in small-level shaking table tests were about 30% smaller than that of the newly rebuilt walls, which showed the same tendency as this project.

By contrast, in 'with continuous mortar walls' X-direction, refer to the result in small-level shaking table test, the stiffness of specimen-A was 3-23% smaller than that of specimen-C and that of specimen-B was 17-29% smaller than that of specimen-A. Vibration characteristics in small deformation might reflect the seismic performance of exterior walls with high stiffness. There was difference in the mode distribution in elevation in small deformation between mortar walls in X-direction, constructed as continuous walls, and walls in Y-direction, lack of continuity and the difference might come to be evaluated so small for the degrading rate in X-direction.

The deterioration of mortar walls of specimen-A and B might have a quantity of influence on the stiffness of specimens, whereas it doesn't be reflected on the grade in the sophisticated seismic diagnosis.

### *Influence of Experience of Shaking*

It is examined about the influence of suffering shaking on the stiffness by comparing the vibration characteristics of specimen-A and C before and after small-level shaking tests.

**Figure 8** illustrates the stiffness in small-deformation vibration and small-level shaking table tests. The stiffness in microtremor observation of specimen-A after tests ('after-stiffness') was 11% smaller than that before tests and that in C was 13% smaller. The difference of the stiffness in Y-direction before and after tests tended to be smaller in lager deformation, specimen-A was 7%, specimen-C was -1% smaller in shaking table tests in 100gal. In X-direction of specimen-C, the difference was 5-14%.

In both specimens, damage after tests weren't identified according to visual check in appearance. Therefore, the specimen had suffered little influence on the stiffness in larger deformation after 100gal input, in which its stiffness by microtremor observation decreased only 13% without damage by appearance. Comparing the influence by deterioration and suffering shaking table tests, deterioration had severer impact on the stiffness in small deformation.

### *Influence of Seismic Reinforcement*

The effect of reinforcement on stiffness was examined by comparing vibration characteristics of specimen-B between before and after reinforcement. The scores in the seismic diagnosis came up from 0.48 to 1.84 in Y-direction and from 1.27 to 1.97 in X-direction (both of 1st floor).

**Figure 9** illustrates the stiffness of specimen-B in microtremor observation, small-level shaking table tests and seismic diagnosis. The stiffness-deformation relationship in full-level shaking table tests ('specimen-A' corresponds to 'specimen-B before reinforcement' in the graph), the stiffness in the sophisticated seismic diagnosis in 1/1000 rad. and in 1/200 rad. were illustrated in the same figure. The stiffness after reinforcement ('after-stiffness') by microtremor observation was estimated 133% (Y-direction), 122% (X-direction) higher than that before reinforcement. The 'after-stiffness' in Y-direction was estimated 480% higher in 100gal that means the progress rate went larger in larger deformation, signifying the effect of reinforcement with plywood and half-sawing braces. The progress of stiffness was identified in X-direction rehabilitated with plywood (138% in 100gal input motion). However by checking the stiffness-deformation relationship in full-scale shaking table tests, the 'after-stiffness' in microtemor observation might be calculated too large, while it was estimated in safe side by the seismic diagnosis. It has been ever considered that reinforcement with plywood had little influence on the stiffness in small deformation, however we could confirm the raise of the stiffness in wide range of deformation in this research.

## CONCLUSION

Achievements and problems in this research are followings.

1) The relationship between response hysteresis and the stiffness in small-deformation vibration test was shown as follow.

(a) The level of deformation and stiffness in microtremor observation, forced vibration test, motion exciter test and small-level shaking table tests were calculated and the ratio to the secant stiffness of response hysteiris in full-level earthquake shaking table tests were examined. The ratio by microtremor observation was 3.9-6.5, that by motion exciter test was 3.1-4.5. The deteriorated walls without seismic reinforcement tended to have similar stiffness in small-deformation tests to the scant

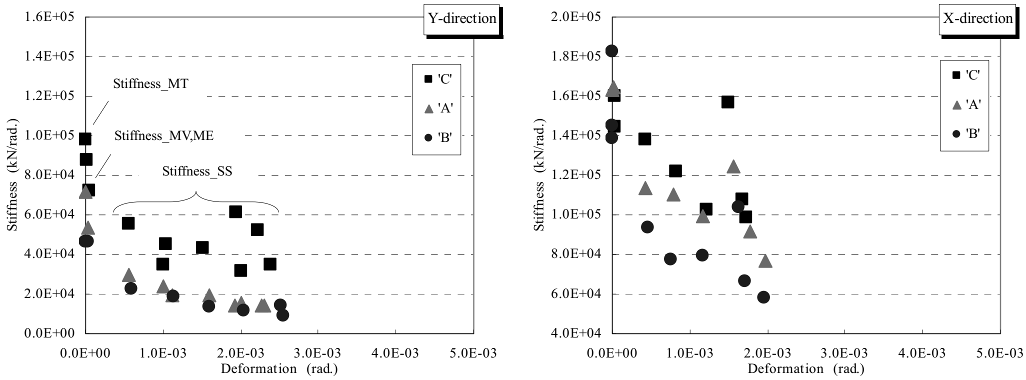


**Figure 7.** Decrease of Stiffness Due to Deterioration

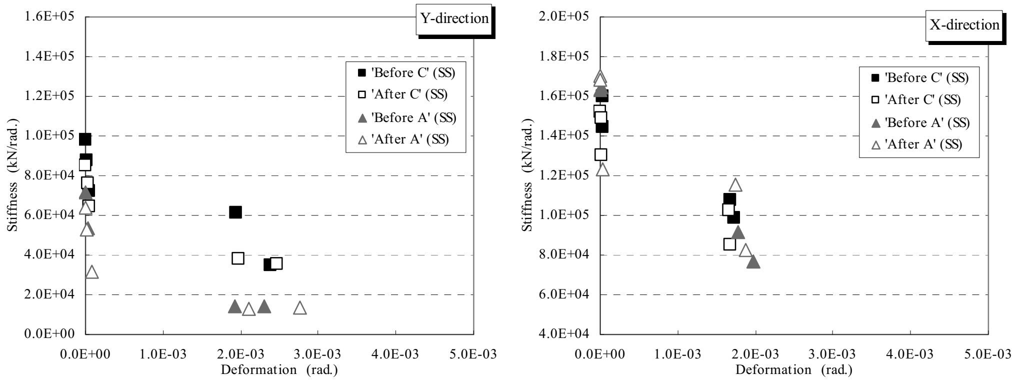


**Figure 8.** Decrease of Stiffness Due to Experience of affecting disaster

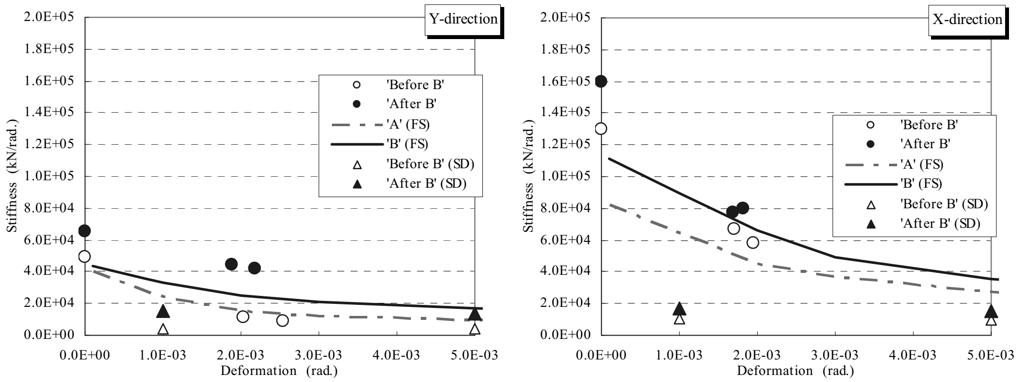


**Figure 9.** Rise of Stiffness with Benefit of Reinforcement

stiffness, while it was quite different in continuous mortar walls and rehabilitated walls.

2) As a result of relative evaluation of the seismic performance by small-deformation tests, the followings were shown.

(a) The weights could be evaluated by microtremor observation in case that there loaded 10kN on the 2nd floor.

(b) The specimen with severer deteriorated mortar walls had smaller stiffness in small deformation than the newly one , which was 26-47% while response deformation was 1/500rad. The decreasing ratio was different between X- and Y-direction.

(c) The specimen suffering 100gal input motion had no damage in appearance and the decreasing ratio of the stiffness in 1/500 rad. was so small.

(d) The progress of the stiffness of the specimen after reinforcement with plywood shear walls was examined.

According to this research, it is clarified that the relative evaluation could gain the larger trust by estimation based on larger-deformation tests, such as man-powered vibration, motion exciter test and strong-motion observation. This research reported only the three houses. With more measurement cases, the application method of small-deformation vibration would be demonstrated.

## ACKNOWLEDGMENT

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