Shaking Table Experiment and Its Numerical Simulation on Nonlinear Behavior of Wooden Structure with New Types of Seismic Resisting Walls

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SUMMARY
In Japan there is urgent need to strengthen old wooden houses for their improved seismic safety. However, many have remained untouched yet because seismic retrofitting is costly and troublesome in its actual implementation. Thus, we need to develop a new seismic retrofitting technology that can be easily implemented, but make a house withstand a severe earthquake. Therefore, a new seismic restraining member, "Wall of Columns" has been invented. To prove their performance as seismic retrofitting device, several single-storied wooden frames were tested by using a shaking table. Through the tests for strong motions observed during the 1995 Kobe earthquake, it has been successfully proved that the proposed retrofitting technology can improve significantly the seismic deformability of wooden structures. Finally, I built numerical models for this retrofitting technique with a well-designed FEM analysis program, SNAP. The basic characteristics of dynamic behaviours observed in the shaking table tests has been successfully reproduced.

Keywords: *Wooden houses, Seismic retrofitting, Shear resistant wall, FEM analysis*

1. INTRODUCTION

Around 50 years prior to the next Tokai, Tonankai, and Nankai earthquakes, researchers had anticipated that southwest Japan would enter a period of vigorous seismic activity. Southwest Japan is thought to have entered that period as of the Hyogo-ken Nanbu (Kobe) earthquake in 1995. Since many residential houses in Japan are made of wood, earthquake-resistant reinforcement is an urgent issue that must be addressed, especially for old, conventional wood-framed structures that lack earthquake-resistant reinforcement. Local authorities have taken steps to implement a range of supportive measures for earthquake-resistant reinforcement; however, the actual progress has been quite slow. In addition to the high cost of implementing a plan to enhance the level of structural strength to that required by current seismic standards, the main factor behind the slow progress is the necessary construction technique that involves major modifications to existing structures in order to reinforce them with earthquake-resistant members. Therefore we must develop a method that can be implemented without major modifications to existing structures. Various methods have been reviewed here in order to develop a reinforcement member that is highly resistant to seismic activity and that can be easily retrofitted to an existing structure without having the residents live in temporary accommodation during the modification.

Thus, a new earthquake-resistant construction technique with a connected column wall is proposed here to provide earthquake-resistant reinforcement to an existing wood-frame structure. This new earthquake resistant construction technique was being validated through static stress tests and shaking table tests, however, testing all types of existing wood-frame structures that require earthquake-resistant reinforcement is virtually impossible because they come in all shapes and sizes while laboratory tests are limited to a few representative examples due to cost and time constraints. To this end, an analytical model must be developed that adequately considers the characteristics of the reinforcement member employed in this construction technique so that the effectiveness of the reinforcement with respect to various plans can be verified through dynamic response analysis.

2. EXPRIMENT OVERVIEW

This section gives an overview of the analytical targets used in the shaking table experiments. Seismic waves of various amplitudes were used as inputs. These waves are based on those recorded by the Japan Meteorological Agency in Kobe during the 1995 Hyogo-ken Nanbu earthquake at the Kobe Marine Observatory. Their peak accelerations were 818 cm/s^2 in the north-south direction and 617 cm/s^2 in the east-west direction.

2.1. Earthquake-resistance Reinforcement Technique with Wall of Columns

Figures 2.1-1 and 2.1-2 show the X- and Y-planes, respectively, of the elevation plans of a test structure built according to an earthquake-resistant reinforcement technique with a connected column wall (hereinafter, the "Wall of Column” method). This test structure is composed of a structure in the X-plane constructed by the continuous column wall method and a structure in the Y-plane constructed by a conventional method that uses braces for reinforcement (Hirokawa et al, 2009).

As shown in Figure 2.1-1, this reinforcement technique creates an integral wall in which nine columns (10.5 cm × 10.5 cm; constructed using lumber from forest thinning) are placed together between the *hangen* columns (placed according to a 910 mm module, the standard half-size column distance for a Japanese-style house) that stand below the ceiling and above the floor. These nine columns are tightly coupled by embedded H-shaped metal connectors, lug-screw bolts and long bolts to increase the shear force resistance between the columns. In addition, the central column and its immediate neighbors are also coupled by long bolts, and to increase the shear force resistance of these columns, round oak dowels are embedded between them. The locations of the bolts, H-shaped metal connectors (which look like "I"s in the figure) and dowels are as shown in Figure 2.1-1.

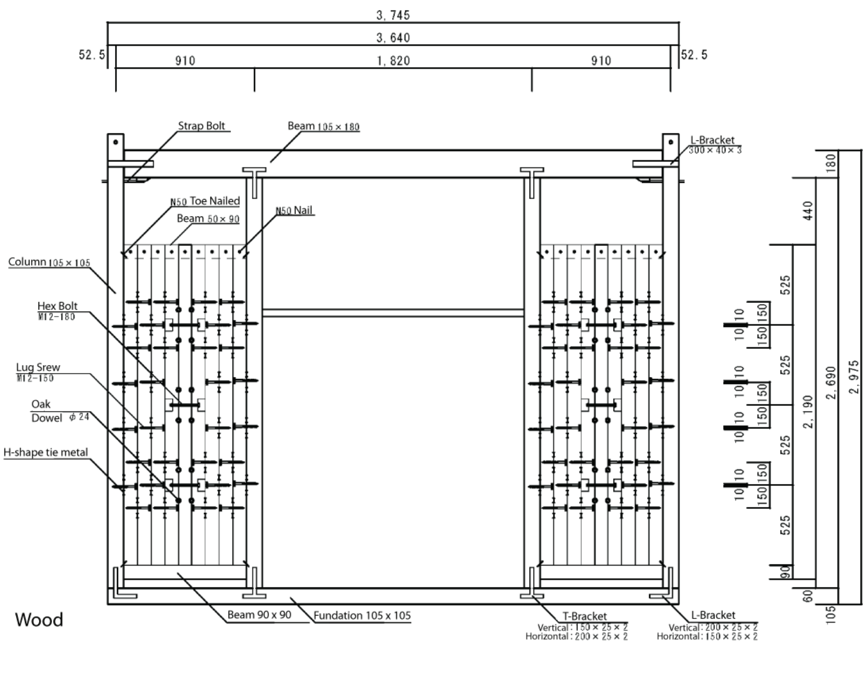

Figure 2.1-1 Elevation Plan of Structure: X-Plane of Test Structure Constructed by Continuous Column Wall Method

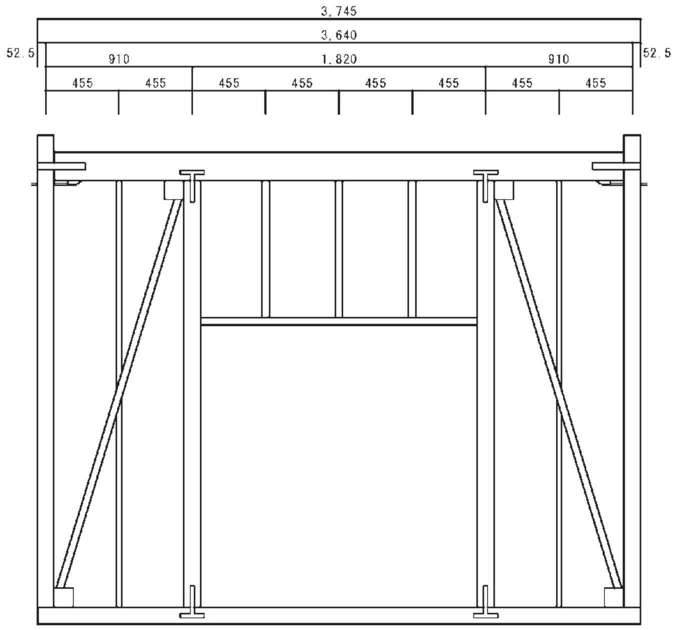

Figure 2.1-2 Elevation Plan of Structure: Y-Plane of Test Structure Constructed by a Conventional Cross Member Method

3. EXPERIMENTAL RESULTS OF WALL OF COLUMN METHOD

3.1. Shaking with Seismic Waves

To understand the deformation performance and load capacity performance of the test structure constructed by the Wall of Column method, the structure was shaken by the observed JMA Kobe seismic waves. After checking the sensors by simultaneously applying 1% of the observed vibration in the X- and Y-directions, the vibration in the X-direction was increased in steps from 10% to 120%. When a vibration of 120% was applied a second time in the X-direction, the foundation of the test structure cracked and therefore the test was terminated.

The nonlinear hysteretic characteristics of the story are determined by generating a scatter graph in which the horizontal axis refers to the relative story deflection angle obtained by dividing the difference in displacement between the top and bottom of the floor by its height (or rather the height between the observation points) and the vertical axis refers to the story shear force obtained by multiplying the acceleration with the total weight of the 2nd floor (i.e., roof). Figures 3.1-1 and 3.1-2 show the scatter graphs when 10% and 100% vibrations were applied in the X-direction, respectively. The behavior was almost linear when 10% vibration was applied. Figure 3.1-3 shows the different hysteretic characteristics when the vibration level was increased from 10% to 120%. According to these results, the shear capacity reached 80 kN and the maximum deformation angle reach 1/6. Even with 120% vibration, the structure reinforced by the Wall of Column method remained undamaged, which indicates that the wall retains a high load-bearing ability.

This result validates the Wall of Column method as a quite effective technique for providing the safety to severe earthquake input. The most important and characteristic capability of this reinforcement technique is its large deformability without losing lateral load bearing capacity. This is the key factor to reinforce old traditional wooden structures because beam-column frames of such structures are quite flexible and relatively weak so that too strong reinforcement concentrated in one part can easily destroy beam-column frames during strong shaking.

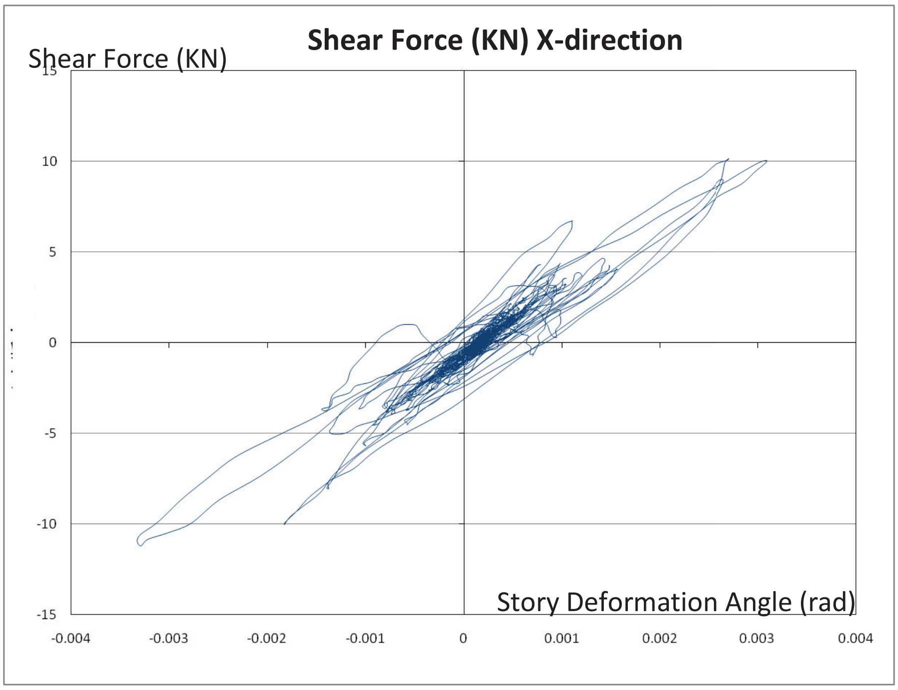

Figure 3.1-1 Experimental Results in X-direction with 10% Vibration of JMA Kobe Waves: Relation between Story Deformation Angle and Story Shear Force (Acceleration × Weight)

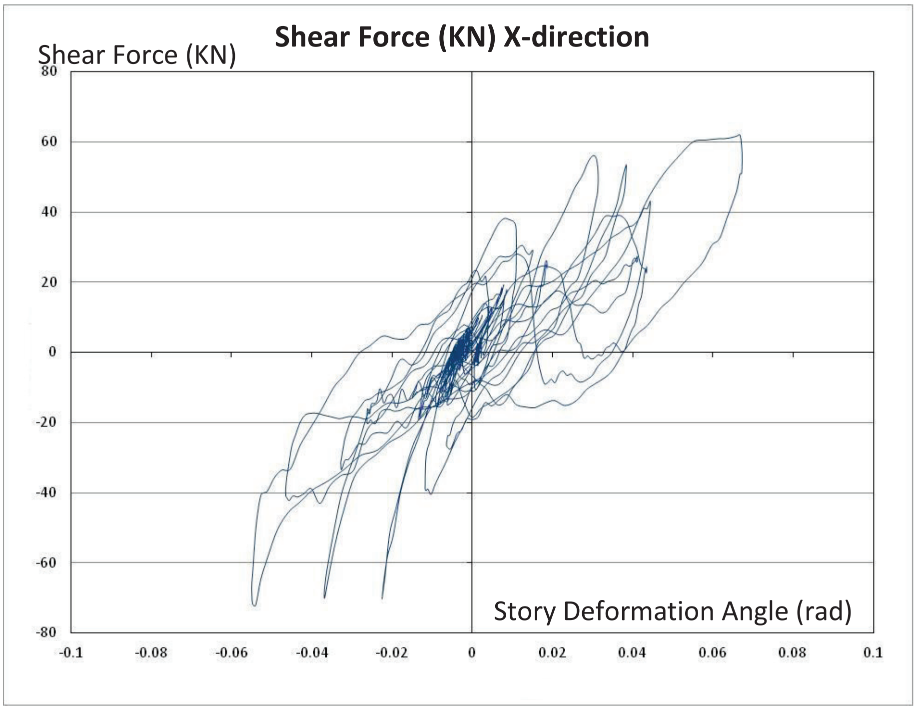

Figure 3.1-2 Experimental Results in X-direction with 100% Vibration of JMA Kobe Waves: Relation between Story Deformation Angle and Story Shear Force (Acceleration × Weight)

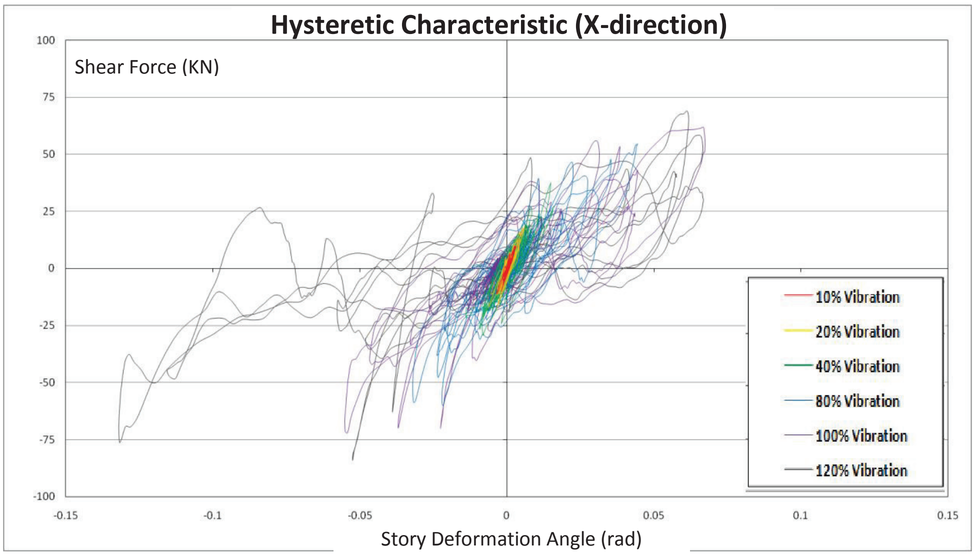

Figure 3.1-3 Experimental Results in X-direction at All Vibration Levels of JMA Kobe Waves Relation between Story Deformation Angle and Shear Force (Acceleration × Weight)

4. SIMULATION BASED ON EXPERIMENT OF WALL OF COLUMN METHOD

A simulation was conducted by using "Seismic Nonlinear Analysis Program (SNAP)", an elastoplastic analysis software for three-dimensional frames. SNAP performs dynamic response analysis, stress analysis and incremental analysis with respect to the elastoplasticity of an arbitrarily shaped structure at the structural member level.

4.1 Basic Model Setup

To construct the simulation of the test structure, the L-shape and T-shape metal ties used as beam-to-column connectors were modeled by axle, shear and rotational springs, where the stiffnesses were obtained by the slope deflection method. The metal connectors used on the braces in the Y-plane of the structure were modeled by axle springs, and the slope detection method was employed to obtain the stiffnesses as in the case of the beam-to-column connectors. The connected column wall was also substituted for a brace in the model. Here, the substituted brace was considered to be the same as those in the Y-plane, and the same values were used for the spring stiffnesses of the connectors.

4.2 Natural Value Analysis

Natural value analysis was performed using the model described in Section 4.1. Table 4.2-1 lists the resonant frequency and resonance period that were obtained from the experimental results. To match the vibration frequency of the model in the X-direction with that found experimentally, the cross section of the brace and the stiffnesses of the connection springs used to model the connected column wall were increased by 1.3 times. Similarly, to match the vibration frequency in the Y-direction, the stiffnesses of the brace connection springs were decreased to 1/6 in the model. Table 4.2-2 lists the natural frequency results obtained from this analysis.

Table 4.2-1 Resonant Frequency and Resonance Period According to Test Results

Direction	X-direction	Y-direction
Vibration Frequency (Hz)	4.67	3.38
Resonance period (s)	0.21	0.30

Table 4.2-2 Resonant Frequency and Resonance Period According to Simulations

Direction	X-direction	Y-direction
Vibration Frequency (Hz)	4.699	3.358
Resonance period (s)	0.213	0.298

4.3 Incremental Analysis

A nonlinear model was created by replacing the beam-to-column connection springs with nonlinear springs represented by a 4-link model for wooden structures (Y. Matsunaga, I. Masuda and Y. Miyazu(2007). Nonlinear Model Setup of Restoring Force Characteristic of Wooden Structures, Proceeding the 2007 Annual Meeting of the AIJ, Architectural Institute of Japan: 201-204). As shown in Figure 4.3-1, the natural loading and unloading curves of the springs are expressed by high-order curves that are dependent on the unitized relative values. Here, the shear capacity was determined to be 1.5-fold of that found through repeated static loading test results. Figure 4.3-2 shows the results from a repeated static loading test that was conducted by the General Building Research Corporation of Japan, and Figure 4.3-3 shows the results of the current incremental analysis. On the basis of these results, the values of the model parameters were determined as follows:

$$\begin{aligned} K_0 &= 3.28, \\ d_y &= 23.666, \\ \alpha &= 0.0396, \\ \beta &= 0.0108, \\ \gamma &= 0, \\ \mu &= 14.4. \end{aligned} \tag{4.3-1}$$

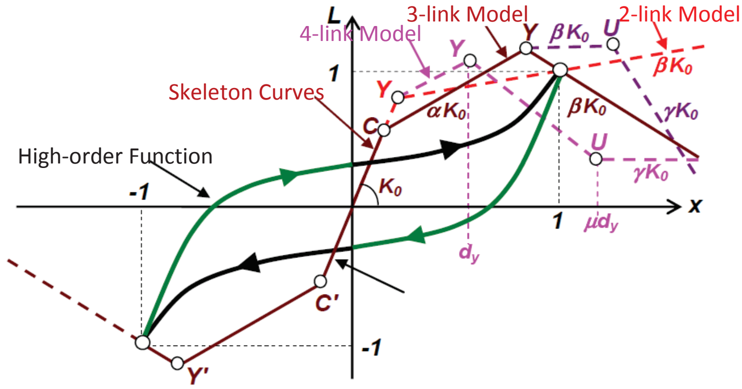

Figure 4.3-1 Loading/Unloading and Skeleton Curves

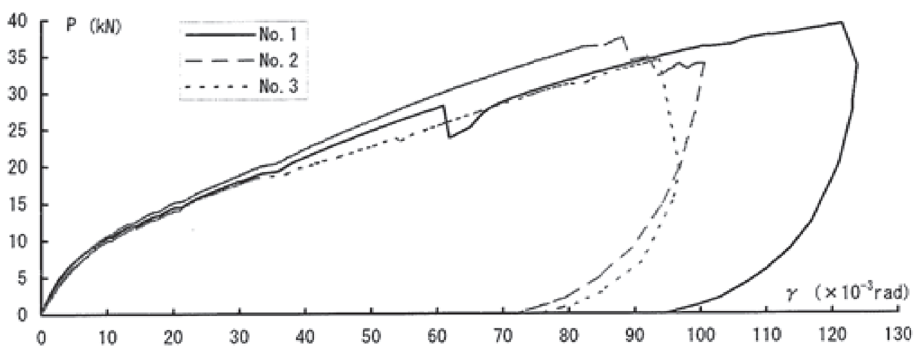

Figure 4.4-2 Static Repeated Pressing Test Results: Observed relationship between Story Deformation Angle and Shear Force of Wall of Column specimen (taken from the General Research Corporation of Japan)

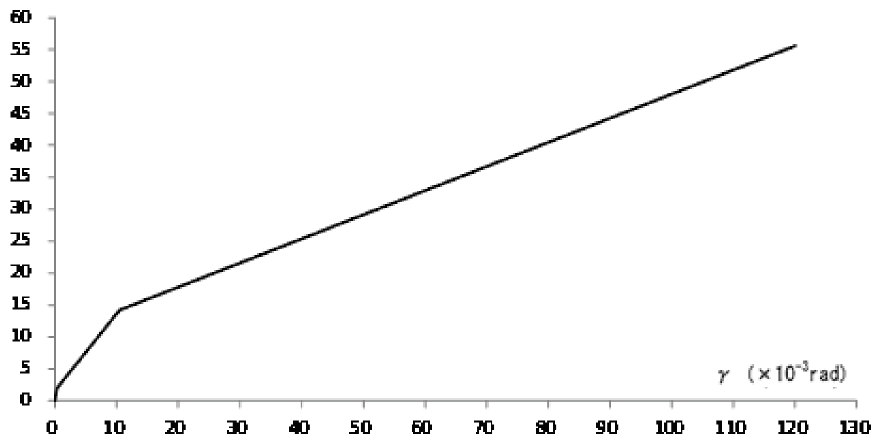

Figure 4.4-2 Incremental Analysis Results: Assumed Relationship between Story Deformation Angle and Shear Force of Wall of Column specimen.

4.4 Seismic Response Analysis

By using the observed JMA Kobe seismic waves, a response analysis was performed on the model of the test structure built by the connected column wall method. An instantaneous damping proportional to the spring stiffness was applied in this analysis. The instantaneous proportional damping matrix $[\mathrm{C}]$ was calculated from the instantaneous stiffness matrix $[\mathrm{K}]$ and $\mathrm{h_j} = 0.1$ is assumed through the following equation:

$$[\mathrm{C}] = \left(2\mathrm{h_j}/\omega_\mathrm{j}\right)[\mathrm{K}]. \qquad (4.4\text{-}1)$$

Figures 4.4-1 and 4.4-2 show the simulated relationships between the story deflection angles and shear forces when 10% and 100% of the vibrations of the JMA Kobe waves are applied in the X-direction, respectively.

When 10% vibration is applied, both the shear force and deformation are smaller than in the experimental results. In contrast, when 100% vibration is applied, the shear force and deformation are almost the same as in the experimental results. Nonlinearity seen in the simulation for 10 % input is much stronger than the observed in Figure 3.1-1. This is primarily because in the simulation after the initial elastic regime is passed nonlinearity regime starts as seen in Figure 4.3-1 and we actually put a very small amount of deformation for elastic regime. In reality this elastic regime should be much wider as seen in Figure 3.1-1 or we should assign much smaller nonlinearity if the deformation remains in the second branch. We need further investigation for tuning the nonlinear behavior of the Wall of Column reinforce method in their moderately deformed region.

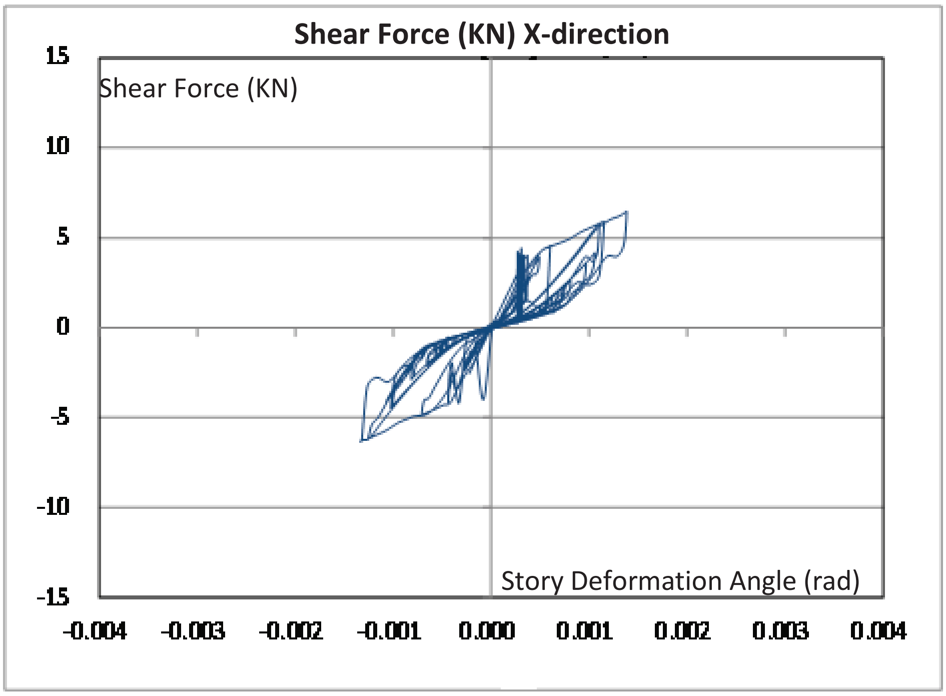

Figure 4.4-1 Response Analysis Results in X-Direction with 10% Vibration of JMA Kobe Waves: Relationship between Story Deflection Angle and Shear Force.

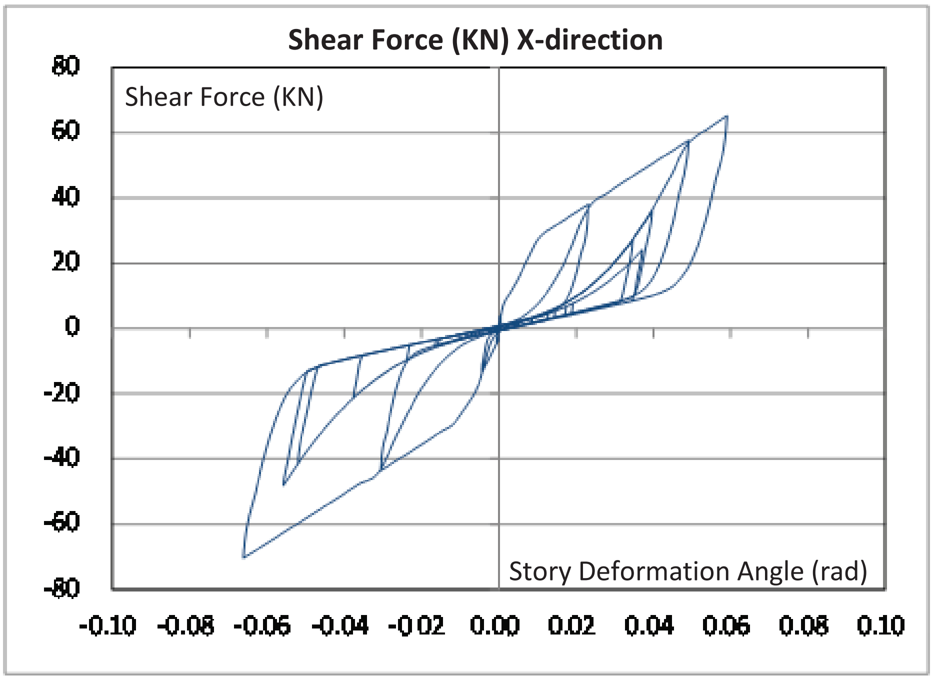

Figure 4.4-2 Response Analysis Results in X-Direction with 100% Vibration of JMA Kobe Waves: Relationship between Story Deflection Angle and Shear Force.

5. CONCLUDING REMARKS

This research aimed to measure the basic dynamic earthquake performance of new earthquake-resistant reinforcement elements and to utilize this performance in practical building designs. For this purpose, a substitute brace model for a three-dimensional frame was developed to simulate the behaviour of a test structure constructed with an earthquake-resistant reinforcement that retains high-deformation performance by employing a connected column walls, the so-called “Wall of Columns”. Applying JMA Kobe seismic waves to the simulation model, the response analysis showed that with 100% vibration—when the shear capacity was 1.5-fold of that in repeated static loading test results—the story shear force and deformation were similar to those in experimental results and roughly replicated the nonlinear behaviour. The experimental results indicated that increasing the stiffness in response to a large seismic wave will yield a larger shear force and bending moment and the stresses will be excessively loaded to the surrounding members. Hence, even if one of the structural planes is reinforced by members with a high load-bearing capacity, these members are not able to withstand loads up to this capacity unless the surrounding members are also reinforced. This problem is serious since it completely contradicts the need to minimize the area of earthquake-resistant reinforcement as much as possible. In fact, these results signify that if a structure reinforced by the conventional stiff members with high capacity but little deformability, the reinforcement would fail to provide adequate resistance for large input. Therefore, structures need to be reinforced by a system that retains a greater horizontal-bearing capacity such that large deformations can be withstood by the surrounding frames as well.

The current model needs to be improved so that both small and large vibrations can be incorporated into the analysis. Moreover, a model must be developed for the Y-direction that can be used in combination with the X-direction model presented in this analysis. After that, a model for each column of the connected column wall is required to perform additional analyses in order to explore how the shear force acting between the columns influences the dynamic behavior of the test structure. At the same time, further simulations need to be carried out with respect to other techniques such as the single room (shelter) reinforcement method with connected column wall and the earthquake-resistant panel method.

Furthermore, as an inter-column shear force transmission mechanism, some shear-key technology between the structural elements will be designed, fabricated and verified through tests in order to provide a rigid yet flexible structure that elastically resists the seismic load up to a predetermined level and then yields with large deformation without apparent fractures to the material.

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