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QUASI-STATIC PULL-DOWN EXPERIMENT OF A REAL-SIZE WOODEN STRUCTURE WITH/WITHOUT "WALL-OF-COLUMNS" SEISMIC RETROFIT IMPLEMENTATION

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Abstract

During the Hyogo-ken Nanbu earthquake of 1995 we had devastating damage to structures, especially to wooden houses. It revealed that wooden houses in Japan are not vulnerable to seismic input motions with only high peak ground accelerations (PGAs) but they are vulnerable to those with both high PGAs and high peak ground velocities (PGVs). This means that severe damage will occur if structures are subject to strong ground motions with high PGA and PGV. Therefore it is our urgent need to strengthen old wooden houses in Japan. However, about 6 million old wooden houses still remain untouched because the current seismic retrofitting is very costly and troublesome in its actual implementation. So we need to develop a new retrofitting method that can be easily implemented, and yet can make a house withstand even for a severest ground motion with high PGA and PGV.

For that purpose we have invented a new restraining method, the so-called "Wall of Columns", which can fit into a wooden beam-column frame of 0.9 meter in width, the module unit of the Japanese traditional wooden house. Our basic idea is to install nine wood lumbers with 9 cm x 9 cm cross section each spanning from top beams and bottom foundation members and to connect these lumbers each other by lag-screw bolts. Once installed they behave like one loosely coupled wall as a whole to horizontal motions.

To prove their performance as a retrofitting device installed only to one room at the one end, we conducted a quasi-static pull-down experiment for real-size two-storied wooden houses with and without the retrofitting walls. We applied horizontal forces on the second floor by using a 100 ton crane. The footprint of the experimental houses were 4.6 m x 8.2 m with 6.8 m in height with two stories.

For a house without a reinforcement, we obtained the maximum resisting force of 27 kN, which corresponds to about 22% of the total weight. The deformation angle at this maximum resisting force was 0.07 radian and that just before the collapse was 0.15 radian. When eight "Wall-of-Columns" were installed in a room at one end, we obtained the maximum resisting force of 120 kN, which corresponds to almost the same as the total weight. The deformation angle at this maximum level was 0.13 radian at the non-reinforced side, while it was only 0.035 at the reinforced side. The angle just before the collapse was more than 0.22 radian at both sides. Thus we have proved that a single room reinforced by the "Wall-of-Columns" system can successfully sustain unbalanced horizontal seismic force up to the same amount of its weight. Finally we built numerical models to simulate results of these two pull-down experiments with a commercial FEM program. We have successfully reproduced the basic characteristics of such quasi-static behaviors found in our field experiments.

Keywords: Seismic retrofitting, Shear resistant wall, FEM analysis

1. Introduction

Around incoming 30 years or so prior to the next Tokai, Tonankai, and Nankai mega-thrust earthquake, researchers have anticipated that southwest Japan would enter a period of vigorous seismic activity. Southwest Japan is thought to have entered that so-called "the active 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 current reinforcement technique that involves formidable work 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. So we have reviewed various methods 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.

After all, a new earthquake-resistant construction technique with loosely connected columns is proposed here to provide earthquake-resistant reinforcement to an existing wood-frame structure. This new earthquake resistant construction technique, called here the "Wall-of-Columns" (WoC hereafter) system, has been validated through static stress tests and shaking table tests as one room (3.6 m x 3.6 m) size experiments. However, engineers are concerned about the possible collapse due to unbalanced installment of the walls to the larger-sized actual houses. Eccentric placement of resisting walls may introduce strong torsional motion, which may lead the house collapsed. To prove that such a thing may not happen in an actual implementation, we perform quasi-static pull-down experiment of the full-scale models of wooden structures, one of which has no reinforcement and the other of which has "Wall-of-Columns" reinforcement only in one side of the house. Since it is impossible to perform actual size experiment for every possible types of houses, 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 quasi-static response analysis.

2. Basic Configuration of WoC system

This section gives an overview of the proposed WoC system used to reinforce a wooden house for the quasi-static pull-down experiment. Figures 1 and 2 show the X- and Y-planes, respectively, of the elevation plans of a test structure used for the shaking table experiment (Yamamoto et al. 2012 [1]). This test structure is composed of a structure in the X-plane constructed by the WoC method and a structure in the Y-plane constructed by a conventional method that uses braces for reinforcement (Hirokawa et al, 2009 [2]).

As shown in Figure 1, this reinforcement technique creates an integral wall in which nine columns (9 cm × 9 cm; constructed using inexpensive lumbers 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 loosely coupled by embedded metal pins, 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 round oak dowels embedded between them to increase the shear force resistance between these columns. The locations of the bolts, metal pins (which look like "I"s in the figure) and dowels are as shown in Figure 1.

During the shaking table test, we use conventional (one-sided) bracing method as a seismic resisting members in the perpendicular direction as shown in Figure 2, and found that such a conventional reinforcement can survive only up to 80% of the input ground motion observed at the JMA Kobe observatory during 1995 Kobe earthquake.

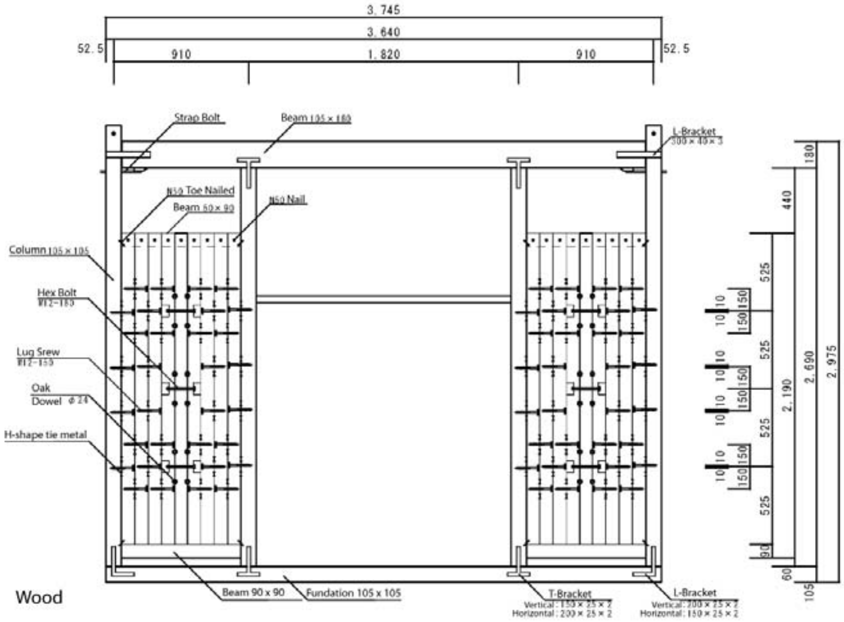

Figure 1 Elevation plan of WoC system: X-plane of a test structure for a small-scale shaking table test [1].

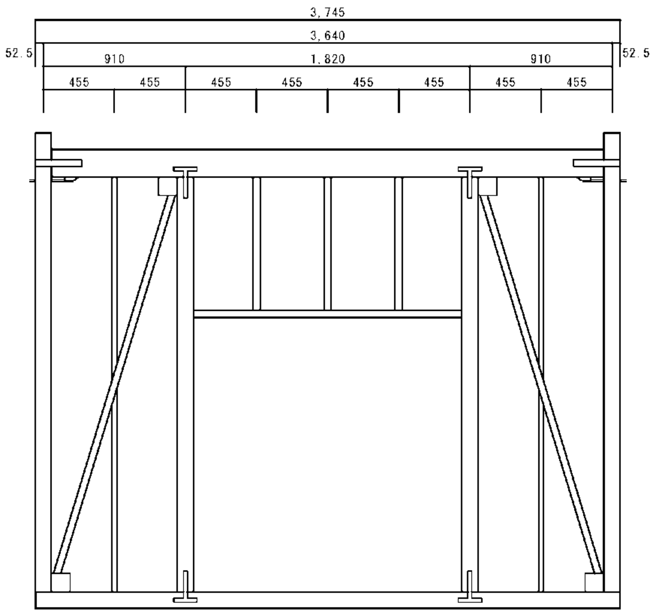

Figure 2 Elevation plan of conventional blaces: Y-plane of a test structure for a small-scale shaking table test [1].

3. Pull-down Experiment Specimen

We constructed two full-size specimen in the vacant space inside the Uji Campus of Kyoto University. The footprint of the structure was 8.19 m x 4.55 m and 6.8 m high with two stories. The horizontal plan and the elevation plan of the test specimen for pull-down experiment are shown in Figure 3. Note that four red parts correspond to the installed position of the WoC system for the “With WoC” specimen. For the “Without WoC” specimen, these red parts are replaced by the conventional two-sided braces. Red allows show direction of applied force to pull down the house.

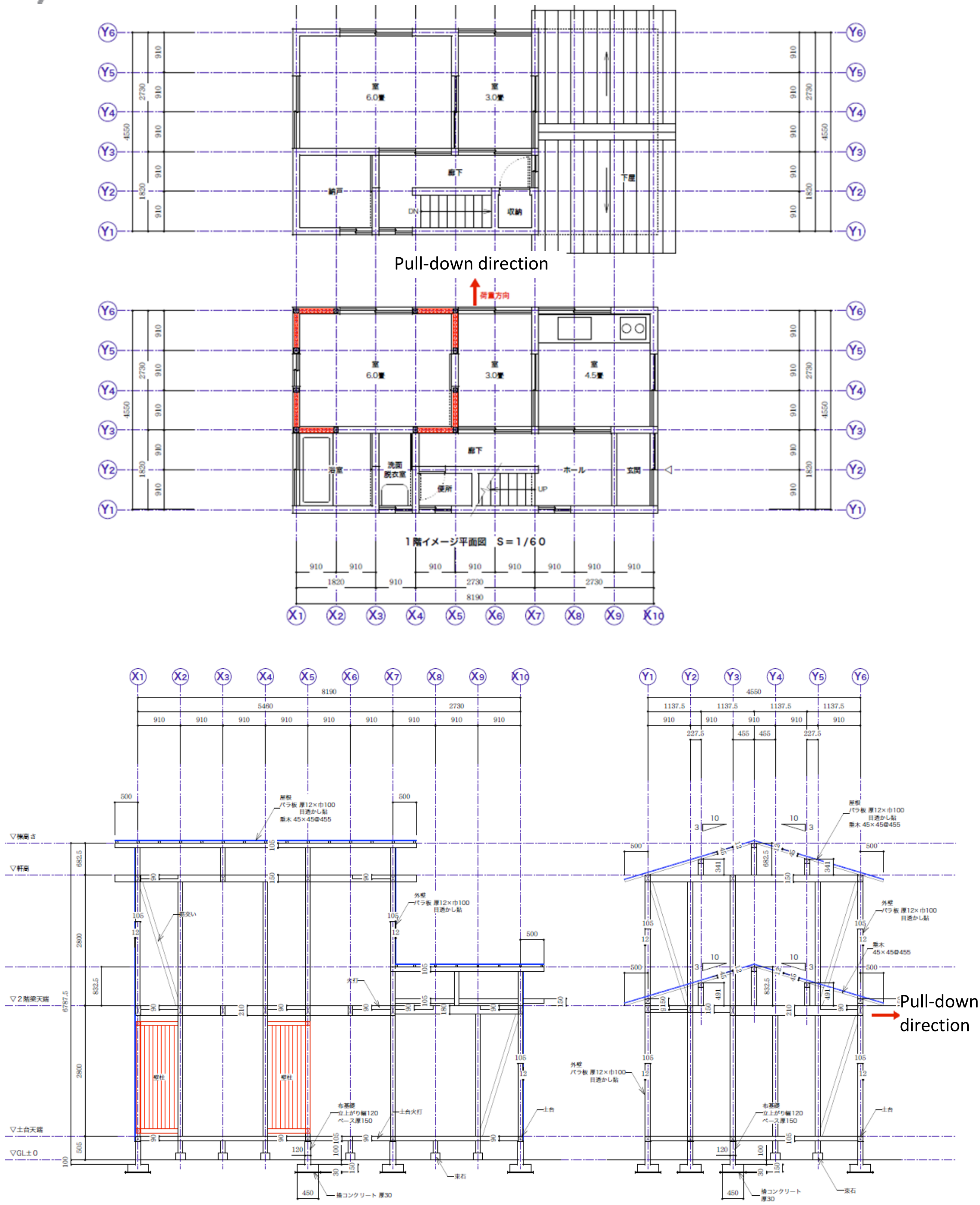

Figure 3 Horizontal plan and elevation plan of the full-sized specimen with WoC.

4. Quasi-Static Pull-Down Experiment "Without WoC"

First we constructed experiment with the specimen "Without WoC system" and performed the quasi-static pull-down experiment. To apply force we used 100 ton crane truck. Two separated H-shaped steel beams were installed on the second floor and two strands of steel wires were used to apply forces as balanced as possible even after a part of the house starts to collapse.

Photo 1 shows the final stage of the pull-down experiment without WoC. Almost equal horizontal displacements were introduced at all the rows of columns. The maximum sustainable deformation angle of the second floor was 0.07 radian, about 1/15.

Photo 1 The final stage of the pull-down test just before the collapse in the case of "Without WoC".

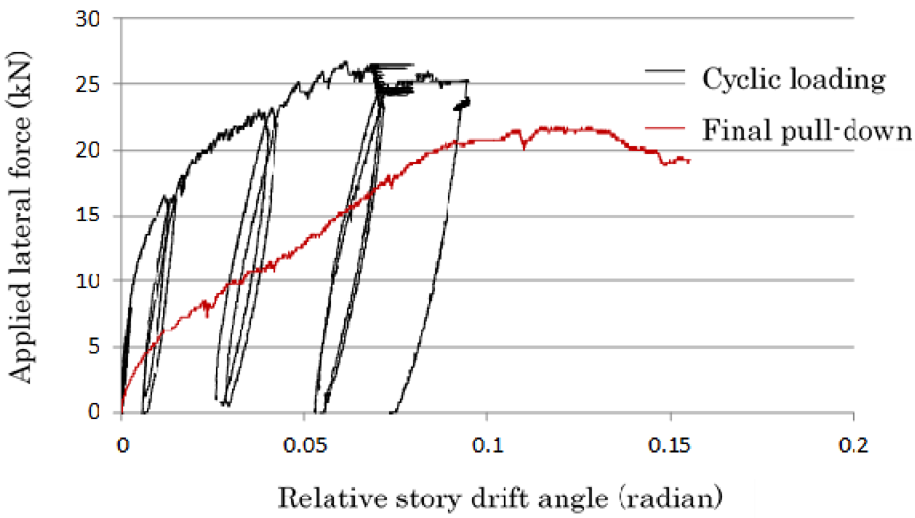

Figure 4 The applied horizontal force versus the relative story drift angle in radian in the weak-side corner.

In Figure 4 we plot the diagram of the horizontal applied force and the second floor's deformation as a relative story drift angle in radian in the weak-side corner. Black lines are those for cyclic loading experiments in which we release the force completely then pull again to have larger deformation. A red line shows the final pull-down experiment in which we restored the deformation by pulling back to the original vertical position before the experiment. The maximum (yield) resisting force is turned out to be 27 kN at the drift angle of 0.07. The final deformation angle just before the toppling down was 0.15 radian, which is larger than expected from previous experiments. Even just before the toppling down the resisting force was still 75% of the maximum force as shown in Figure 4.

The obtained maximum restoring force of 27 kN corresponds to about 22% of the total weight. According to the building code in Japan, it is expected to have 20% of resisting capability of weight at 0.825 (1/120) radian. Since this "Without WoC" house is designed based on the building code in force in 1970s so that its restoring force at 0.825 radian seems lower than the current code requirement.

5. Quasi-Static Pull-Down Experiment "With WoC"

Next we constructed experiment with the specimen "With WoC system" and performed the quasi-static pull-down experiment in a similar manner. The house used was first constructed exactly as the hose without WoC to mimic the practical procedure of reinforcement for houses built already. Then we installed eight WoC systems, four in X direction and four in Y (i.e., loading) direction in the left-hand side room as shown in Figure 3. Again two separated H-shaped steel beams were installed on the second floor and two strands of steel wires were used to apply forces as balanced as possible even after a part of the house starts to collapse.

Photo 2 shows the final stage of the pull-down experiment with WoC. Differently from the previous experiment, significantly different displacements were produced at the rows of columns because of the unbalanced installment of the WoC reinforcement. The deformation angle of the second floor before the collapse was 0.22 radian, more than 1/5. As can be seen, the right-hand side room without reinforcement were totally collapsed, however, even at this final stage no partial toppling-down phenomenon took place.

Photo 2 The final stage of the pull-down test just before the collapse in the case of "With WoC".

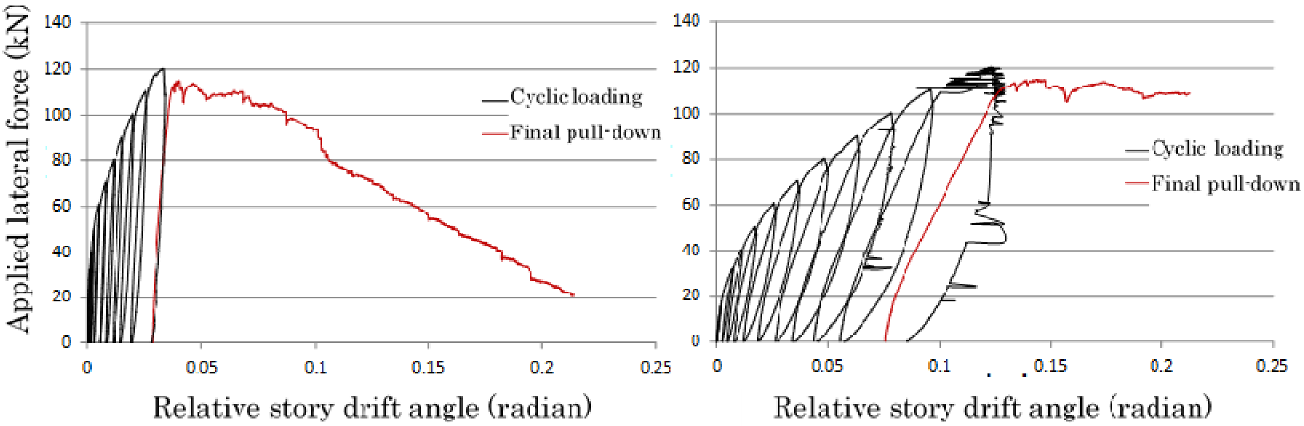

Figure 5 The applied horizontal force versus the relative story drift angle in radian in the strong-side (left) and weak-side (right) corners.

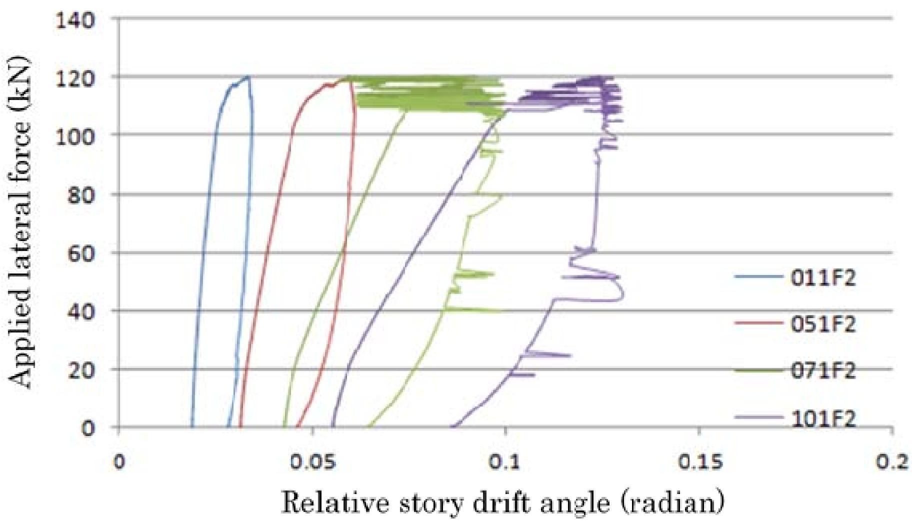

Figure 6 The applied horizontal force versus the relative story drift angles in radian in different rows of columns in the last cycle loading.

In Figure 5 we plot the diagram of the horizontal applied force and the second floor's relative story drift angle in radian in the strong side corner as well as the weak-side corner. Black lines are those for cyclic loading experiments in which we release the force completely then pull again to have larger deformation. A red line shows the final pull-down experiment in which we pulled down the loading wire until the house toppled down. The maximum (yield) resisting force is turned out to be 120 kN at the drift angle of 0.035 in the strong (reinforced) side and 0.13 in the weak (not-reinforced) side. This maximum resisting force corresponds almost the same as the total weight of the house from above the middle of the first floor.

In Figure 6 we plot the relative story drifts for four rows of columns to see the rotational (torsional) deformation generated by the eccentric stiffness distribution due to reinforcement. We can see almost linear distribution of deformation; that is, the second floor was moving in a rigid body manner. As for the in-plane stiffness of the floor there is no regulation to constrain the stiffness or yield capacity of the floor in the current code and it is always the subject of discussion. This experiment proved that the floor will behave like a rigid body for eccentric loading out of the center of the stiffness. This would be primarily because the roof panel makes in-plane stiffness quite large. In the subsequent simulation we used equivalent braces to represent floors.

6. Simulation by 3D Flame Models

First we constructed a three-dimensional (3D) flame model to reproduce the observed pull-down experiment by using a commercial flame-based nonlinear response analysis software, SNAP. We put crossing fictitious braces to represent the floor in-plane stiffness, which is very important to evaluate the torsional motion [3]. For the brace reinforcement we initially assumed the stiffness directly based on the dimensions of the lumbers and steel plates attached at the corner. Nonlinear behaviour of wooden flames was represented by the expanded NCL model, initially proposed for reinforced concrete beams [4]. After initial trial it turned out that we need to increase or decrease to reproduce the observed behaviour during the experiment without WoC, primarily initial stiffness of the braces and the floor panels. After a couple of try-and-error modifications, we have a 3D flame model that can reproduce observed behaviour as shown in Figure 7. The nonlinear behaviour used for seismic resisting (conventional) walls are shown schematically in Figure 8.

After modification we compare the observed loading-unloading behaviour of the pull-down experiment and quasi-static nonlinear behaviour of our final model in Figure 9 for a model without WoC. As we can see maximum yielding force and average deformation angles can be reproduced quite well. However, the distribution of the horizontal motions among different rows is not similar; the simulation gives too uneven distribution. This means that the floor in-plane stiffness is quite large, even after we increased four times from the original estimate.

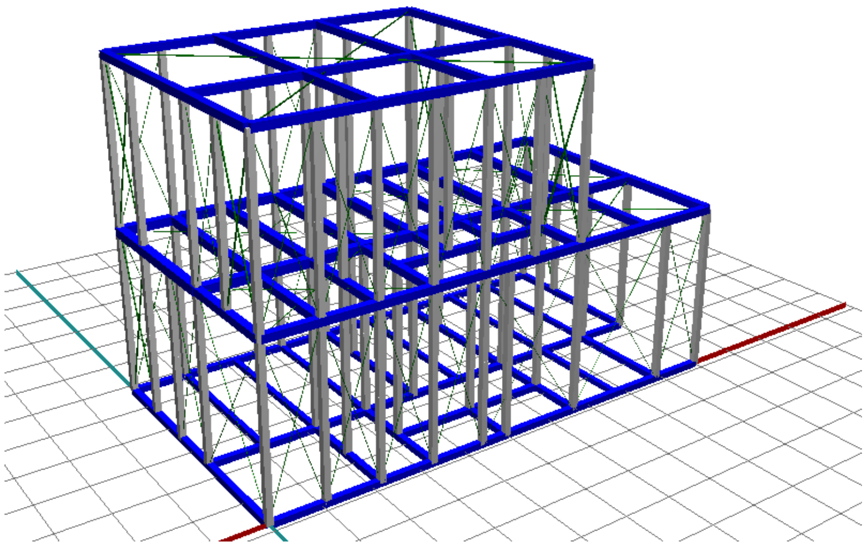

Figure 7 A 3D flame model used to reproduce responses of experiment without WoC.

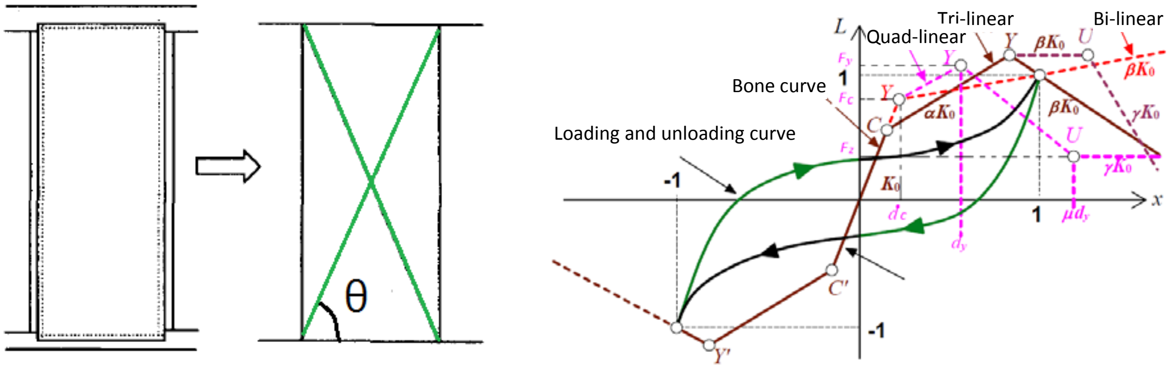

Figure 8 Brace representation of the seismic resisting wall and its nonlinear behaviour in SNAP.

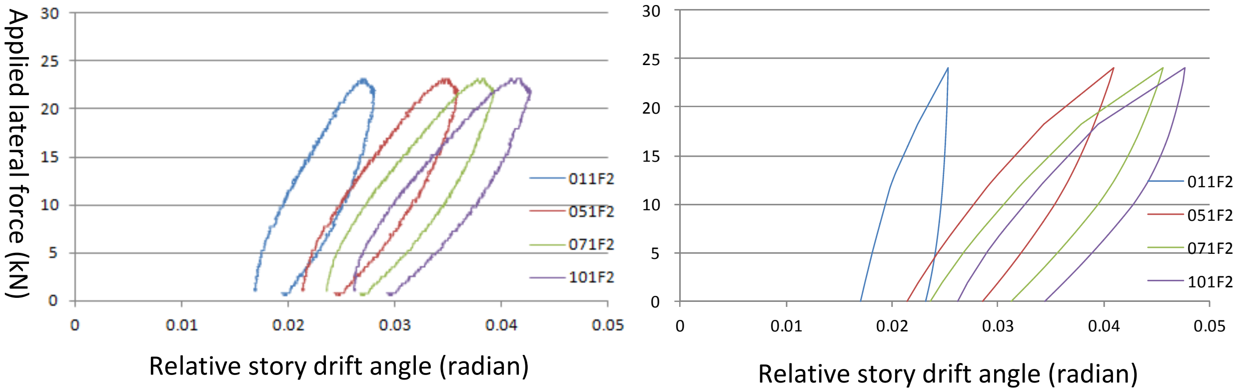

Figure 9 Behaviour of the house at each row of columns from the experiment (left) and simulation (right) for the hose without WoC.

Next we modelled the house with WoC in a similar manner. This time we first need to model WoC nonlinear behaviour and attached that in the eight positions installed. Since we have results from element nonlinear experiments for single WoC behaviour in the laboratory, we first use equivalent braces that reproduce laboratory experiment. In Figure 10 we show how good our initial model is to reproduce the laboratory experiment. However, the resultant deformations of the initial 3D model are much larger than the pull-down experiment, and so we increased the stiffness and the yielding capacity of WoC three times. The resultant high-stiffness model is shown in Figure 11.

After the improvement both in stiffness and yielding capacity of the WoC system, we successfully reproduced the whole behaviour as shown in Figure 12. The yield level and the story drift angles of each row can be well reproduced, although a flat part after yielding is a little bit smaller in the simulation so that energy absorption capacity of the model may be smaller than the reality.

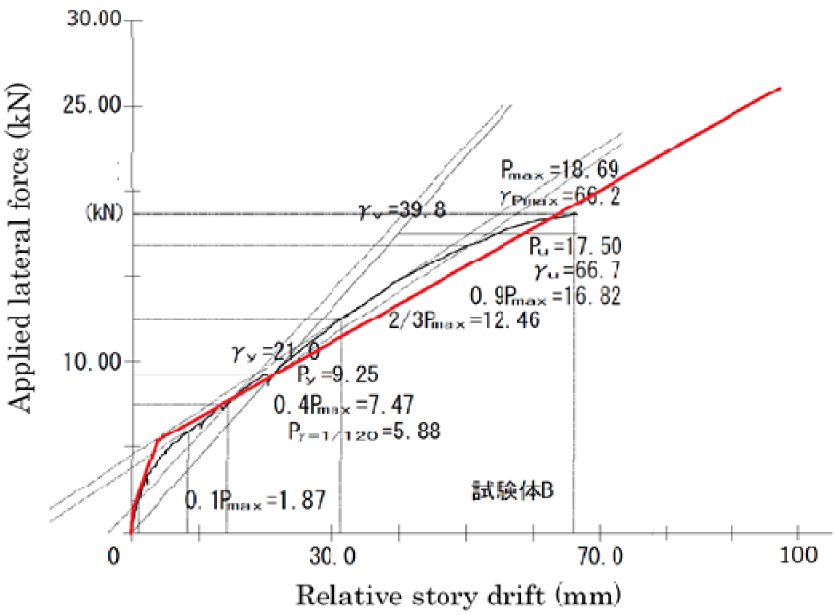

Figure 10 Laboratory experiment result and nonlinearity of the initial model for one WoC panel.

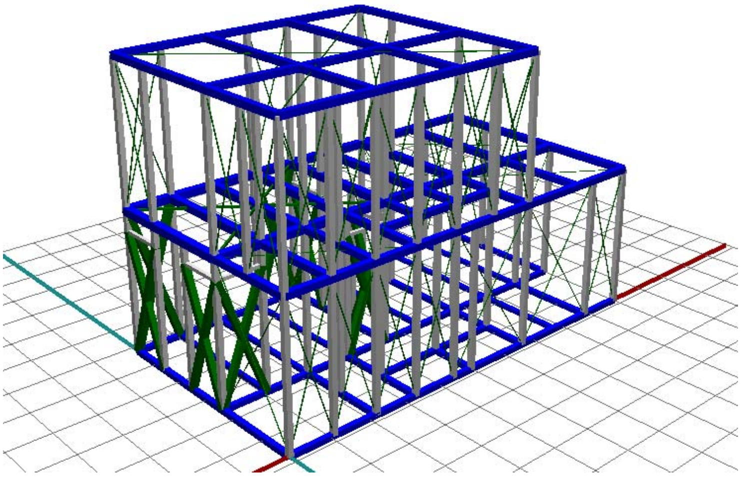

Figure 11 A 3D flame model used to reproduce the responses of experiment with WoC

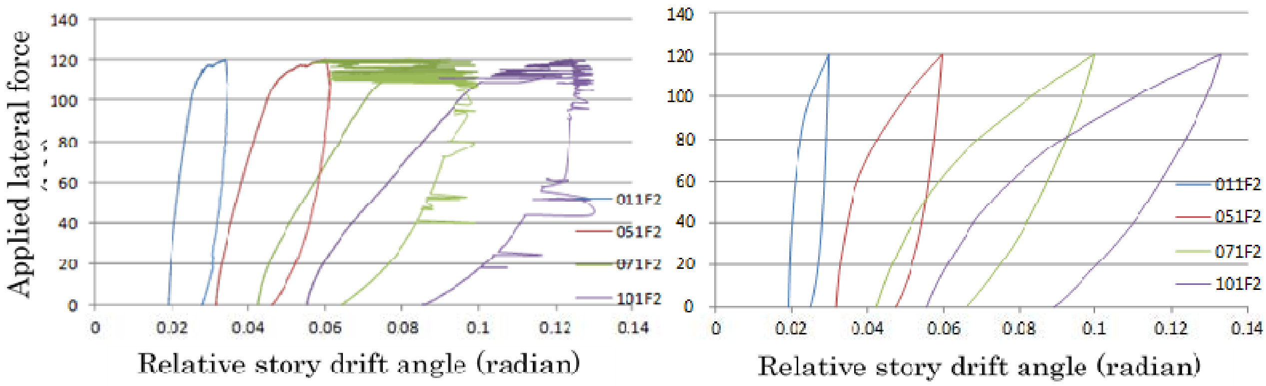

Figure 12 Behaviour of the house at each row of columns from the experiment (left) and simulation (right) for the house with WoC.

7. Conclusions

In this paper we performed field experiments for two real-sized wooden houses, one of which was designed based on the 1970s building code, and the other of which was the same but with the proposed "Wall of Columns" reinforcement system installed. The most significant feature of the system is its deformability without losing significantly its resisting capability. Because of this feature we believe that only one room is sufficient to reinforce in order to protect a whole house from as severe shaking as the observed during 1995 Kobe earthquake. However, those who have been taught that the torsional motion should be suppressed using well-balanced installment of resisting walls strongly concern the safety of such a one-room seismic reinforcement. Therefore, we set our main goal of the real-sized field experiments to prove the overall safety of the house reinforced only in one room.

After the experiments and subsequent simulations based on the observed data, we found:

1) The reinforce house was proved to be able to sustain as large shear force as its total weight and as large horizontal deformation as 0.22, although large torsional movement was taking place.
2) Even the house built based on the 1970s building code was proved to be able to survive as large horizontal deformation as 0.1, although the maximum restoring force was only 22 % of its total weight.

3) To reproduce the observed responses of the experiment we need to increase both its stiffness and yielding capacity for walls, floors, and columns. Especially we should note that the resisting capability of the proposed WoC system must be multiplied three times from the observed capacity of the laboratory experiment.

At this stage of research we do not have any way to explain the reason why we need such strong components for WoC. We need to study further the real-size effects of the WoC system for wider use of the system in near future. In the meantime a house with the WoC system, even only in one room, has been proved to be safe for strong shaking and our simulation model with the WoC resisting capacity directly from the laboratory experiment could be used as a safer-side model in retrofit design.

References

[1] Yamamoto, R., H. Kawase, S. Matsushima, T. Yamazaki, T. Okada, H. Miyake, and A. Yamaguchi (2014). Shaking Table Experiment and Its Numerical Simulation of Nonlinear Behavior of Wooden Structure with New Seismic Resisting Walls, *Proc. of 15th World Conf. on Earthq. Eng.*, Lisbon, Portuguese.

[2] Hirokawa T., Y. Nitta, H. Kawase, S. Matsushima, K. Komatsu, H. Miyake, and A. Yamagichi (2010). A proposal of New Seismic Reinforcement Methods for Wooden Houses Considering Deformability and Easy Installation, Part-5 Evaluation on Improved Wall-of-Columns Structures by Shaking-Table Tests of 1-Span, 1-Storied Model, Proceedings of the 2010 Annual Meeting of AIJ, C-1, 457-458, Architectural Institute of Japan, 2010.9 (in Japanese).

[3] Tanaka, H. and H. Kawase (2005). Construction of Three-Dimensional Nonlinear Dynamic Models for Wooden Structures Based on Actual Measurements and Experiments, J. of Structural and Construction Eng., Trans. of AIJ, No.592, 121-128 (in Japanese with English abstract).

[4] Tani, S., T. Nagasaka, and A. Hiramatsu (1972). Restoring Force Characteristics of Reinforced Concrete Aseismic Elements (Part 1) –Restoring force characteristics and modelization– , J. of Structural and Construction Eng., Trans. of AIJ, No. 202, pp.11-19 (in Japanese with English abstract).