Experimental study on the performance and improvement of a frictional damping wall using a full scale steel structure

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Abstract

A frictional damping wall, which consists of concrete blocks and reinforcing bars, was recently proposed. In this system each element is un-bonded for future reuse and stronger pre-stressed force is introduced in each layer of the wall than the top of the layers, where a connecting L-shaped steel plate to the upper beam will be placed and slide smoothly as the relative story drift between the lower and upper beams is generated. In the past studies, it was confirmed that friction is generated quite stably between the top blocks and the L-shaped steel plate even for large relative story drift. In this study, we verified the effectiveness of this wall on a five-storied full-scale experimental steel structure which was constructed at the Kyoto University Uji Campus.

First, we conducted forced vibration tests in order to grasp the wall behavior during consecutive shaking and check the effectiveness of the friction damping system. Two damping walls are set on the east-west long-span direction of the full scale steel structure. We did the experiment twice, before and after the improvement in the damper sliding system. The purpose of the test is to know how much we will see the changes in the natural frequency when the prescribed prestress force are introduced to the damper. The introduced prestress force was 2kN per one bolt before the improvement, and was 3kN per one bolt after the improvement. The damping walls both before and after the improvement have 36 bolts in total.

Next, we conducted static loading tests in order to grasp the wall behavior with large deformation. In this time, only a case on a damping wall after the improvement was performed because the case of the wall before the improvement had done. There is a three layered steel structure next to the five layered full-scale steel structure as a target. The static load test was performed through two hydraulic pressure jacks between three layered steel structure and the target full-scale steel structure, and we grasp the behavior on the concrete block frictional damping wall. The loading was performed at 3rd and 4th floors. The two pillars on the eastern side were loaded in the horizontal direction to the west. The maximum adding power of hydraulic pressure jack is 50 ton per one jack, so the total applied force was 100 ton. The applied prestress force was 4kN per one bolt. The total prestress force was changed by the numbers of bolts used, and the patterns of the total prestress forces are 0kN, 48kN, 96kN, and 144kN.

Through the results of the static loading test, we measured the stiffness before and during frictional sliding and obtained sliding frictional forces when blocks and angle steel plates are sliding. Combining the results of the static loading test with the shear stiffness obtained from the result of preceeding study, we constructed a trilinear restoring force model for the wall.

Finally, we conducted seismic response analysis in order to grasp the efficiency of the frictional damping wall.

Keywords: Frictional damping wall, Full-scale steel structure, forced vibration test, static load test, seismic response analysis

1. Introduction

The 2011 Off the Pacific Coast of Tohoku Earthquake happened on March 11th 2011, and skyscrapers suffered enormous damage by the long-period ground motions generated by the earthquake. Considering this, the Japanese Government promoted the predicted input seismic motions of the Nankai-Trough mega-thrust earthquake, which can happen in the near future, as aM9 class event. Therefore, the requests of the safety of structures in the time of an earthquake, the defection of damage points of structures by an earthquake, the seismic retrofitting of an existence structure, and the actual damage prediction keep increasing day by day.

The Nankai-Trough earthquake is thought to generate long-period ground motions. Long-period ground motion will be amplified because of accumulated layers which lie from the surface of the ground to the deep underground bedrock. Therefore, it is thought that plains like Tokyo, Osaka, and Nagoya where accumulated layers are thick tend to be affected seriously when a disastrous earthquake occurs. Long-period ground motions are thought that they will affect skyscrapers and base isolated buildings which have long natural periods. Installation of dampers to them is effective for the measure of suppressing extraordinary shaking.

We have been developing a concrete block frictional damping wall (Figure1), which can be installed easily to reinforce existing buildings against earthquake even though people are staying inside. Assuming the Nankai-Trough earthquake, in order to apply the frictional damping wall to existent skyscrapers, and for the purpose of grasping its performance and improving it, we do the vibration generator experiment and static load testing using the five layered full scale steel structure which is in Kyoto University Uji Campus. In this paper, we report the results.

2. Concrete Block Frictional Damping Wall

2.1 Feature of concrete block frictional damping wall

The special feature of the proposed damping wall is that it is easy to discreet and can reuse and recycle, it is easy to bring into and reinforce buildings though ordinary elevators, and it is low-cost, all bcause it consists of only concrete blocks and steel bolts,. In addition, the damping wall can controll its stiffness and damping capacity by the prestress force introduced, so that it can controll the amount of energy absoption by the friction force proportional to the normal prestress. It works as elastic body in a small deformation regime, it works as an efficient frictional damper in a middle deformation regime, and it gives stiffness and attenuation to the building by block failure in a ultimate deformation regime. Another good feature of the wall is its high capability of out-of-plane elastic deformation.

2.2 Necessity of improvement on the friction system

We mentioned in 2.1 that the frictional damping wall can controll the amount of energy absoption by the friction force proportional to the normal stress intoroduced; however, on the damping wall before improvement, the frictional force and amount of energy absoption tend to saturate on the way though the prestress force was getting raised. Additionally, as the damper was loaded repeatedly, its maximumstrength was getting down. We thought that there would be a problem assocaited with the friction system where we insert a steel plate between the concrete-blocks and let both sides slides with friction by introducing prestress between them. We show the detail of the friction system before improvement in Figure2.

2.3 Frictional damping wall after improvement

In order to remedy defects of the damping wall before improvement, we change jig in the damping wall after improvement. The system of the friction is inserting a steel plate between two aluminum washers and letting two sides of aluminum slide with friction by introducing prestress between them (Figure3(b)). The system can avoid declining phenomena of the maximumstrength.[1][2][3]

The detail of the jig to connet concrete block wall to the upper beam is shown in Figure3(a). The upper-side L-shaped steel angle is jointed with the bottom of the beam below the upper floor, and the bottom-side L-shaped steel angle is jointed with the top layer of the concrete block wall (similar manner to Fig.1). These two steel plates are sandwitched with two other planner steel plates which has holes in the upper part and the lower part. The upper hole joints are combined hardly by high-tention bolts, while the lower hole joints are combined with preferred prestress since they are the key part of the improved friction system (Fig.3 (b)).

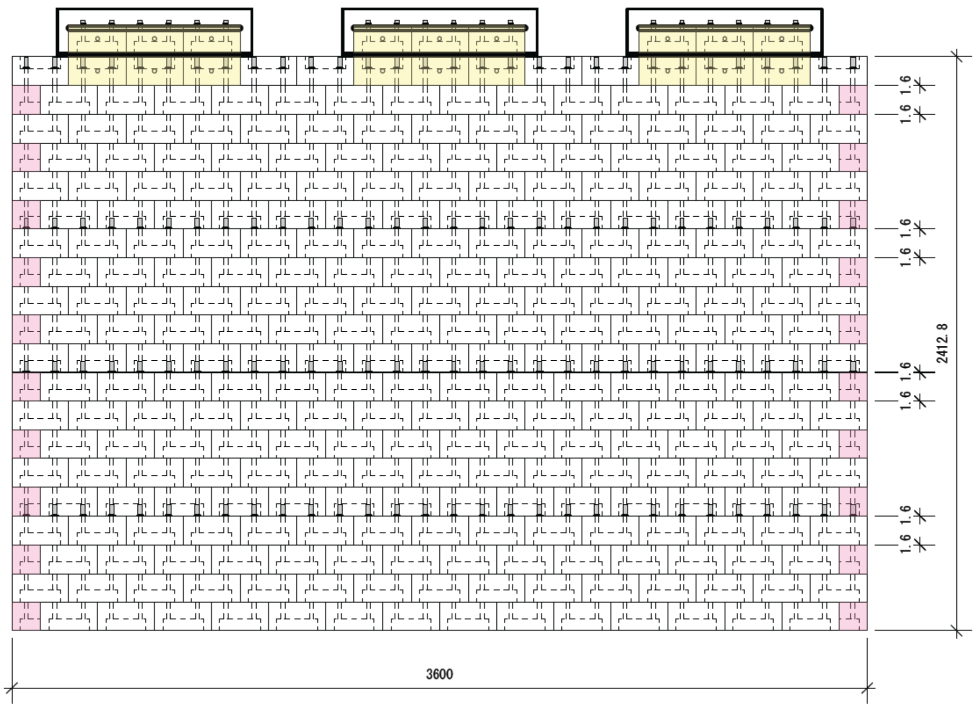
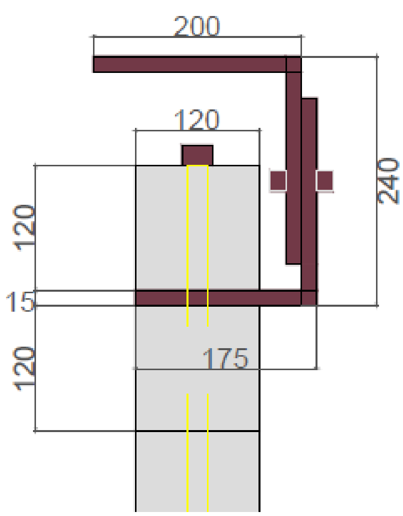
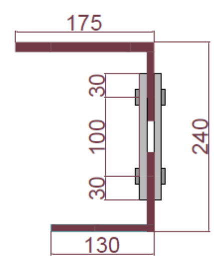
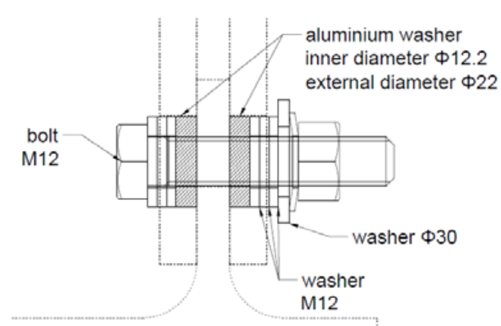


Fig. 1 – A vertical view of the design of the concrete block frictional damping wall





(a)



(b)

Fig. 2 – Friction systembefore improvement

Fig. 3 – Friction system after improvement

3. Forced Vibration Test

3.1 Plan of vibration test

The dimensions of full scale steel structure is as follows: the number of floors is five, the span is 1 by 2, the height is 16.6m, the short span length is 3.75m, the long span length is 15m, the height of each layer is 3.3m, and the weight of each layer is about 27ton. A vertical view in the long-span direction is schematically.

Two damping walls are set on the eastern long span direction of the full scale steel structure. The vibrator which is an eccentricity mass rotation system is set on the top of the structure. The frequency was changed in a steady-state manner with approximately every 0.1Hz increment. The primary vibration direction is a long span direction. We did the experiment twice, before and after the improvement in the damper friction system. The purpose of the test is to know how much we see changes in the natural frequency when the prescribed prestress force is introduced to the damper. Introduced prestress force was 2kN per one bolt before the improvement, and was 3kN per one bolt after the improvement. The damping walls both before and after the improvement have 36 bolts in total.

3.2 Test results

The result of vibration test is represented in Figure. 5. We indicate the comparison of natural frequency between before and after improvement of the damping wall in (a), and the comparison between no prestress force and maximum prestress after improvement in (b). Vertical axis shows the natural frequency for different resonance modes from first to fourth. The figure shows us that every natural frequencies rise up significantly in every resonance modes. It is apparent that the efficiency of adding stiffness is much higher for the improved friction system.

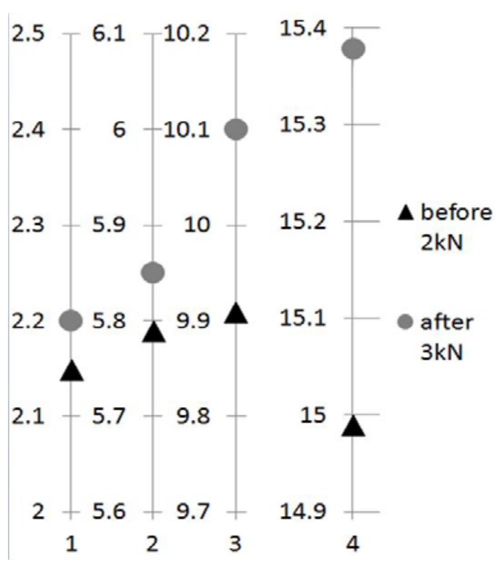


Fig. 4(a)– Comparison of natural frequency between before and after improvement

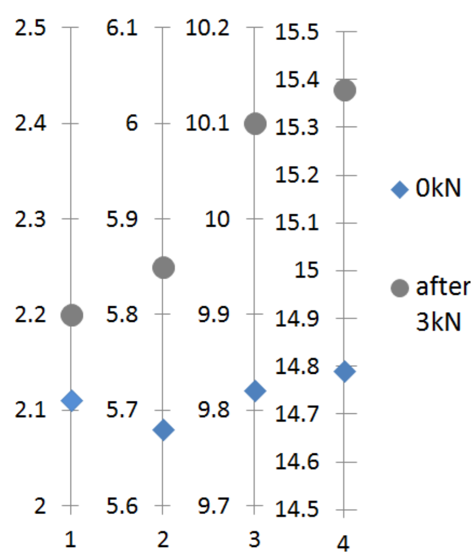


Fig. 4(b)– Comparison of natural frequency between no prestress force and after improvement

4. Static Load Test

4.1 Plan of static load test

The schematic configuration of the static load test is indicated on Figure 5. The experiment on the damping wall before improvement was completed in the preceding study [4], so in this time, only a case of a damping wall after improvement was performed.

A three-storied steel structure has been built next to the five-storied full-scale steel structure. The static load test was performed through two hydraulic pressure jacks between these two structures, and we grasp the behavior on the concrete block frictional damping wall. The experiment was performed twice by putting jacks at 3rd and 4th floors as shown in Figure 6. The two pillars on the eastern (three-storied structure's) side were loaded in a horizontal direction to the west (i.e., one-way push over experiment). The maximum adding power of hydraulic pressure jack is 50 ton per one jack, so the total maximum force applied is 100 ton. The introduced prestress force is 4kN per one bolt. The total prestress force is changed by the number of bolt used, and on this experiment, the patterns of the total prestress forces are 0kN, 48kN, 96kN, and 144kN.

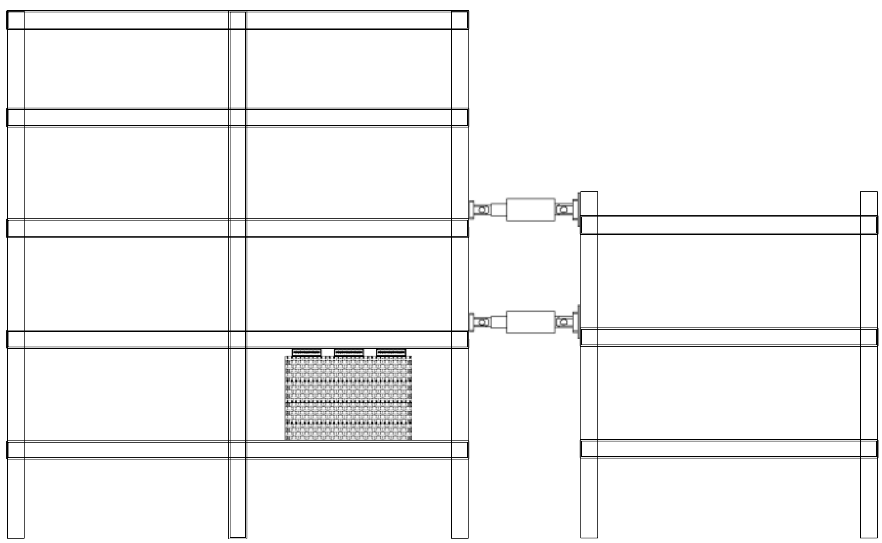


Fig. 5– Schematic vertical view of the static load test from the long span side

4.2 Result of static load test and comparison between before and after improvement

We made a bi-linear model of the motion of the damping wall as a result of this experiment (Figure 6, Table1).

In order to compare the concrete block frictional damping wall before and after improvement, the friction force and the energy absorption per cycle are represented in Figure 7 and Figure 8. The sliding friction of the damping wall, loading 3rd and 4th floor at 800kN in before and after improvement for each introduced total prestress force is shown to (a), (b) of Figure 7. The horizontal axis shows the total prestress force, and the vertical axis shows the sliding friction. The energy absorption amount of the damping wall in one cycle, loading 3rd and 4th floor at 800kN in before and after improvement for each introduced total prestress force is shown to (a), (b) of Figure 8. The horizontal axis shows the total prestress force, and vertical axis shows the energy absorption amount.

These results show that after improvement, in proportion to the introduced prestress force both the frictional force and the energy absorption amount are getting larger. We also found that after improvement the wall can absorb the energy more than before improvement even after repeated experiments.

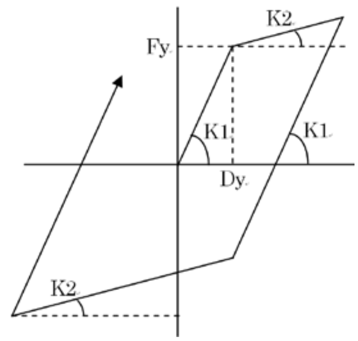


Fig. 6– Bi-linear model

Table.1–Result of the static load test

Loading floor	Load [kN]	Prestress force[kN]	Dy[mm]	Fy[kN]	K1 [kN/mm]	K2 [kN/mm]
3	600	0	2.75	32.21	11.71	-2.31
3	600	48	1.6	69.47	43.42	-1.47
3	800	48	1.5	66.89	44.6	-1.46
3	600	96	1.85	90.5	48.92	0.079
3	800	96	1.85	95.47	51.61	-0.78
3	800	144	2.1	117	55.7	0.16
4	600	0	1.65	22.74	13.78	-2.84
4	600	48	1.65	52.16	31.61	-1.48
4	800	48	1.75	52.32	29.9	-1.38
4	600	96	1.85	70.77	38.25	-0.43
4	800	96	2	82.71	41.35	-0.87
4	800	144	1.8	98.24	54.58	-0.13

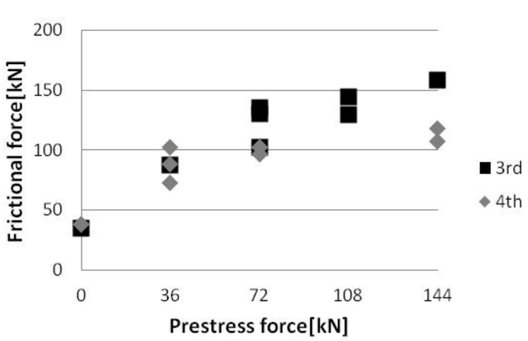


Fig. 7(a)– Sliding friction of before improvement

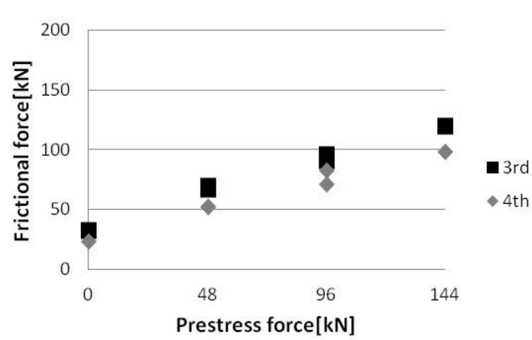


Fig. 7(b)– Sliding friction of after improvement

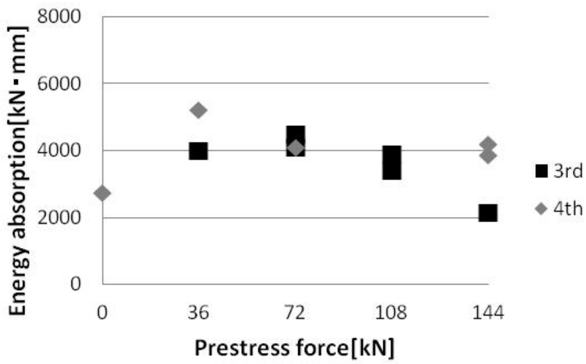


Fig. 8(a)– Enegy absorption of before improvement

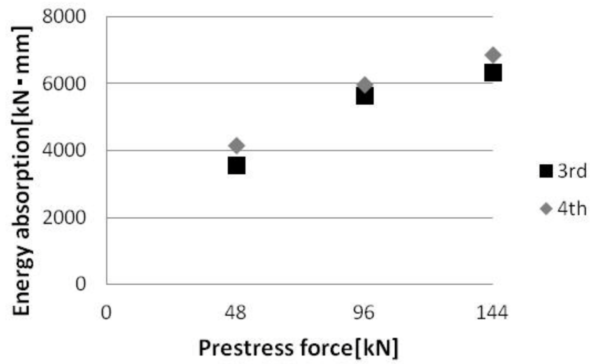


Fig. 8(b)– Enegy absorption of after improvement

5. Seismic Response Analysis Using The Damping Wall After Improvement

5.1 Building model

Based on the preceding study, we made a simple simulation model (Figure.9), whose parameters are shown in Table.2. When two pieces of the damping walls are set, the increased properties would be those shown in Table.3. We made the tri-linear restoring model of the damping wall as a result of the forced vibration test and the static load test (Figure.10). The value of F_c is set to be 2[kN/mm] according to preceding study.

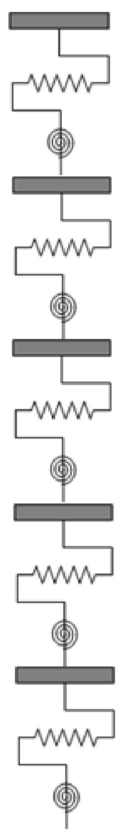


Fig. 9– Building model

Table.2–Parameter of the structure

layer	**Bending stiffness [N.m/rad]**	**Shear stiffness [kN/mm]**	**Mass [ton]**	**Rotary inertia [ton.m^2]**
5	2.66×10^9	62.0	23.3	22.6
4	2.84×10^9	80.9	27.2	26.4
3	3.47×10^9	75.1	26.8	26.0
2	5.87×10^9	158	28.6	27.7
1	7.29×10^9	88.6	27.2	26.4

Table.3–Rise of the parameter with the damping wall instration

Shear stiffness rise in upper layer[kN/mm]	147
Bending stiffness rise in setting layer[$\times10^9$N.m/rad]	8.53
Bending stiffness rise in upper layer[$\times10^9$N.m/rad]	18.1

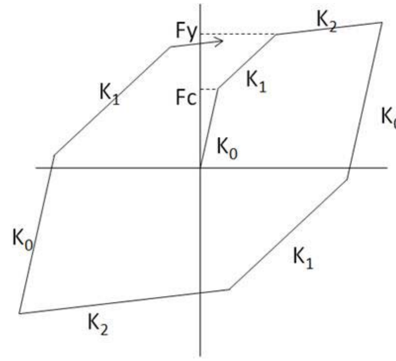


Fig. 10– Tri-linear model

5.2 Seismic response analysis

In this study, when we do seismic response analysis, we use SNAP, which is the commercial software of elasto-plastic analysis of arbitrary shaped three-dimensional frames. Using the EW component acceleration of KiK-net IWASE, which is the main shock of Tohoku earthquake, we performed a simple seismic response analysis.

According to the preceding study, it is said that when the damping wall is set on the weakest stiffness floor, the damping effect is highest, therefore we have verified the model of setting four piece of the damping wall at the 3rd layer which has the weakest stiffness. Comparison before and after improvement is shown inFigure.11, while comparison with and without walls after improvement is shown in Figure12. The blue accelerograms in both figures are for the case of the wall after improvement. The red ones in Figure 11 are for the case of the wall before improvement. Each one has the maximum prestress force. The green ones in Figure 12 are for the case of no wall. From these result, the performance of the damping wall during the earthquake can be confirmed sufficiently.

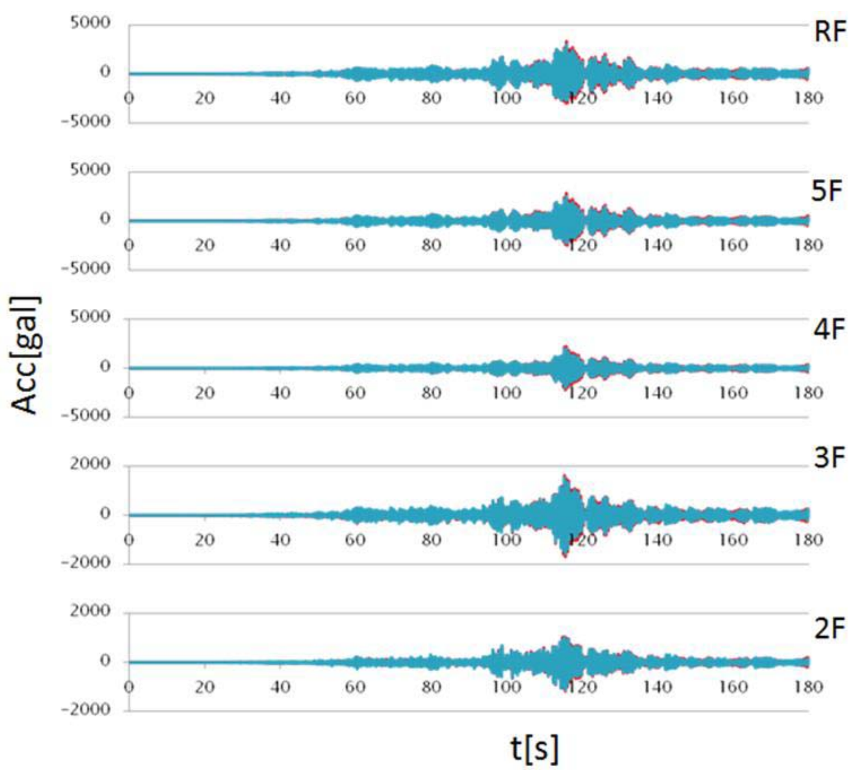


Fig. 11– Comparison of seismic response analysis between the case of before and after improvement

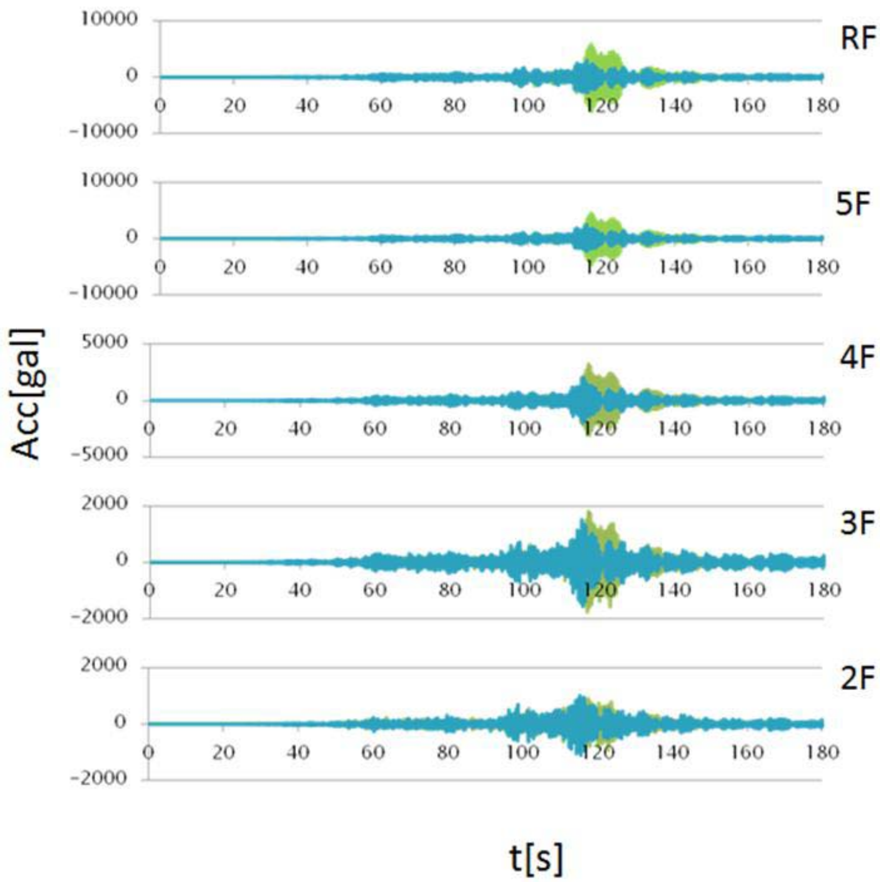


Fig. 12– Comparison of seismic response analysis between the case of after improvement and no wall

6. Conclusion

In this report, in order to assess efficiency of the concrete block frictional damping wall before and after improvement, the vibration test and the static loading test were performed. The full scale steel structure in Kyoto University Uji campus with five stories was used as the target structure of this research. The experimental result shows that a large and stable energy absorption is possible when we install this concrete block frictional damping wall. Considering the experimental result, the defect that the frictional force and amount of energy absoption tend to saturate asthe prestress force is getting high has been improved. Bychanging the damping jig, the defect that its maximum strength is falling down as the damper is loaded repeatedly has also been improved. By the seismic response analysis, we found that the wall performed well. We would like to perform further experimental studies for practical implementations in the future based on these results, and we wish this damping wall, which is low cost and easy to set, would save lives when huge disasterous erathquakes occure.

7. Acknowledgements

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8. References

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