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PSEUDO-DYNAMIC TEST ON AN EXISTING R/C SCHOOL BUILDING RETROFITTED WITH FRICTION DAMPERS

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SUMMARY

The authors have been researching and developing methods of retrofitting existing reinforced concrete buildings with friction dampers. Using an existing school building which will be demolished in the future, the authors conducted full-scale seismic tests to verify the effects of response control retrofit on actual buildings. It was found, through the pseudo dynamic tests, that the effects of response control retrofit on buildings rehabilitated in the same way as actual retrofit constructions is similar to that predicted in design. In addition, elasto-plastic behaviors of the building retrofitted with friction dampers were examined by comparing the test results with analysis results. The analysis confirmed that applying braces with friction dampers could produce a similar effect to that verified by the test, and was found to reproduce the behaviors of the actual building accurately. The damage mitigation effect of retrofit was identified from the absorbed hysteretic energy of each member and the viewpoint of the energy balance.

INTRODUCTION

Research and development on seismic response control technologies, which can improve the seismic performance of existing reinforced concrete buildings (hereafter called RC buildings) by providing them with dampers whose energy absorption performance is accurately known, has been active in recent years. Such technologies have already been used in some projects, and receiving attention as one of the new methods which allow buildings in use to be retrofitted without the interruption of use. [1]

The authors, too, have developed several seismic retrofit technologies using friction dampers [2]-[6] and conducted studies to apply such technologies to actual retrofit projects. This time, the authors were given an opportunity to use a 3-story school building, which is scheduled to be demolished, for tests to verify the effect of seismic retrofit methods.

The purpose of this study is to confirm whether the same results as design calculation can be obtained from pseudo dynamic tests using an actual building rehabilitated in the same way as actual retrofit constr uctions, i.e. installing braces with friction dampers (hereafter called damper braces) on the exterior walls of the building without removing its sashes and interior/exterior finishings.

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In addition, the damage to structural members, side walls, spandrel walls, partition walls, and interior/exterior finishings of the test building was investigated to use such information for estimating the extent of damage to other seismically retrofitted buildings caused by major earthquake forces.

TEST BUILDING

Profiles of The Test Building

Photograph 1 and Figure 1 show the full-view and the plan view of the building used as the test model, respectively. The building is a three-story RC school building located in a city in Saitama Prefecture, and has ten spans in the X-direction and three spans in the Y-direction, with the section between grids X7 and X11 completed in 1969 and the section between grids X1 and X7 in 1973.

Photo.1 Full view of the test building

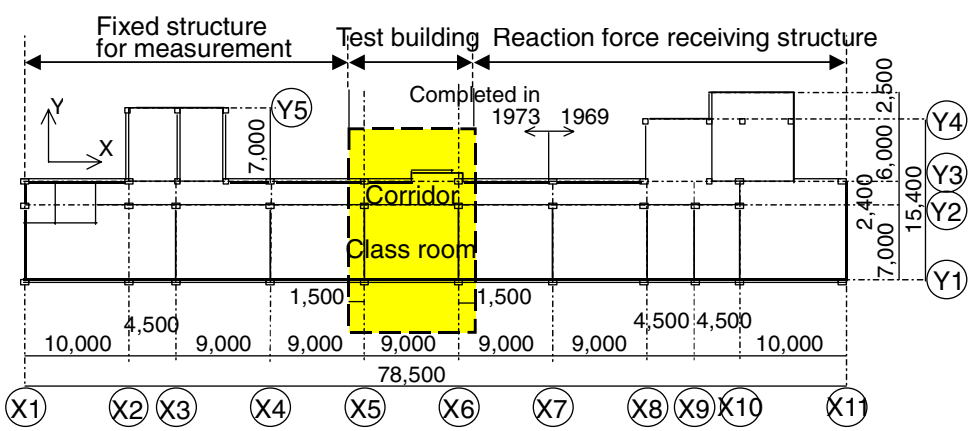


Fig.1 Plan view of the test building

The section surrounded by grids X5, X6, Y1 and Y3 (1x2 spans) was selected as the test building, since this section allowed damper braces to be easily installed and its neighboring spans were able to be used as the reaction force receiving structure. Prior to the tests, the slabs of the second, third and roof floors were saw-cut along the lines 1.5 m from the grids X5 and X6 at a width of 50 cm. The three spans between grids X1 and X4 were used as the fixed structure for measurement and the four spans between grids X7 and X11 as the reaction force receiving structure. Figure 2 shows the framework of the test building and Figure 3 the cross section of each structural member.

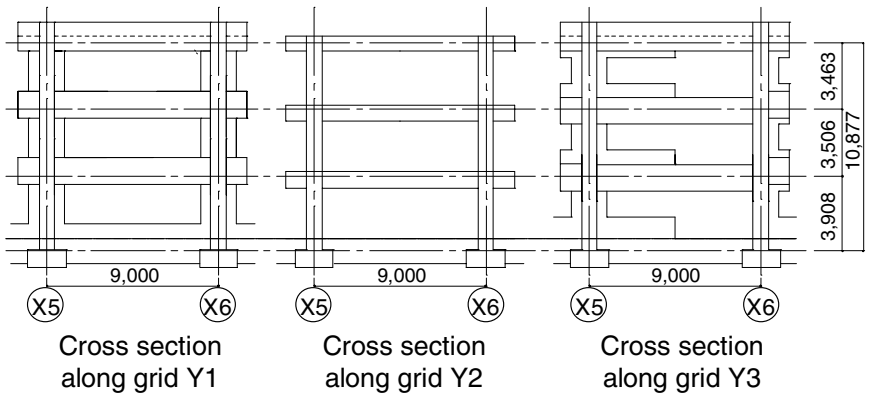


Fig.2 Framework of the test building

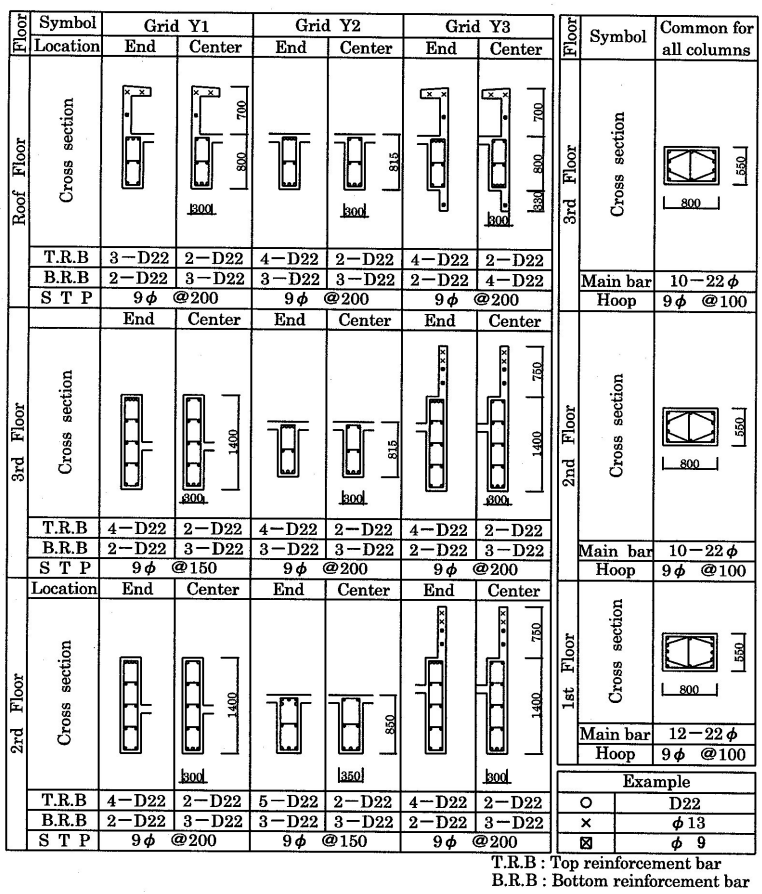


Fig.3 Cross sectional details of each member

Material Strength

The results of the strength tests for concrete and reinforcement bars are shown in Tables 1 and 2. Concrete specimens of column were taken from the columns along grid X4. Concrete and reinforcement bar specimens of beam were sampled from the cut face of beams. Although the compressive strength of the specimen cored from the second floor column was lower than the design strength (17.6MPa), the other specimens showed strengths higher than the design strength. The yield strength and elongation rate of each reinforcement bar specimen met the specifications of Japanese Industrial Standards.

Table 1 Concrete test results

	Floor	Unit weight [kN/m^3]	Number of specimens	Compressive strength [MPa]	Variation coefficient [%]	Young's modulus [GPa]	Poisson's ratio	Splitting strength [MPa]
Columns	3	21.95	6	18.4	9.3	15.19	0.22	-
	2	21.85	3	14.5	3.6	15.68	0.19	-
	1	21.66	4	20.0	18.1	16.27	0.15	-
	Average	21.82	-	17.6	16.7	15.71	0.19	-
Beam	R	22.05	7	21.8	26.4	17.93	0.20	1.6
	3	21.85	7	21.7	29.0	18.23	0.19	2.0
	2	22.05	7	21.6	17.6	19.01	0.20	1.7
	Average	21.98	-	21.7	23.6	18.39	0.20	1.8

Table 2 Reinforcement bar test results

	Floor	Number of specimens	Yield strength [MPa]	Variation coefficient [%]	Tensile strength [MPa]	Variation coefficient [%]	Young's modulus [GPa]	Elongation [%]	Yield strain [%]
Beam main bar D-22	R	4	339	3.0	523.3	6.2	193.06	20.3	0.20
	3	4	349	3.4	539.6	6.4	193.06	19.7	0.19
	2	4	337	5.7	519.1	7.5	195.02	19.5	0.21
	Average	-	342	4.1	527.3	6.7	193.71	19.8	0.20
ϕ 9		3	311	3.7	414.1	0.9	196.00	33.3	0.15
ϕ 13		3	331	3.8	451.5	3.1	205.80	30.1	0.16

Retrofit Design

Prior to retrofit design, the seismic performance of the test building was evaluated based on the static elasto-plastic analysis. Springs, whose both ends are made rigid-plastic, were provided on the surfaces of the members of the frame model for the analysis [7]: side walls, spandrel walls, and vertical walls were also included in the frame model. The analysis was carried out by the incremental external load method based on the Ai distribution that is the seismic story shear coefficient distribution for design. The story shear force-relative story displacement relationship derived from the analysis is shown in Figure 4. It was found that the test building would not be seriously damaged if the story drift angle were less than 1/200rad. Therefore, it was determined that the maximum story drift angle for retrofit design shall not exceed 1/200rad.

The damper load and the brace cross-sectional area of the damper brace were determined by the approximate calculation method [6], taking into consideration the results of the above static elasto-plastic analysis. Based on the calculation results, it was decided to install damper braces (damper load: 294kN, steel pipe outer diameter: 165.2 mm, cross sectional area: 8,324mm^2) at the first to third floors along the grid Y1. The earthquake response analysis using the two-dimensional frame showed that the test building retrofitted in such a way could meet the above requirement (i.e. maximum story drift angle < 1/200rad).

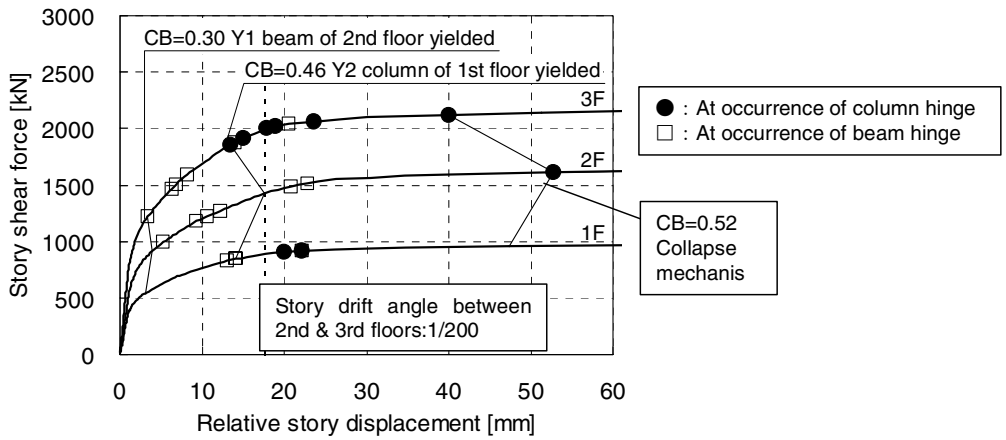


Fig.4 Story shear force-relative story displacement

Damper Brace Installation Method

Figure 5 shows the installation arrangement of damper braces. As shown in the figure, the braces were fixed to the anchor plates installed on the center and the both ends of each beam to form V-shape. The anchor plates for the beams of the second to the roof floors were pressure-fixed using prestressing steel bars. The axial force applied on one bar was 303.8 kN for the plates on the second and third floor beams, and 352.8 kN for the plates on the 1st floor beam. The anchor plate on the center of the base floor beam was indirect-fixed using post-installation anchors. The details of fixing of the anchor plates are shown in Figure 6.

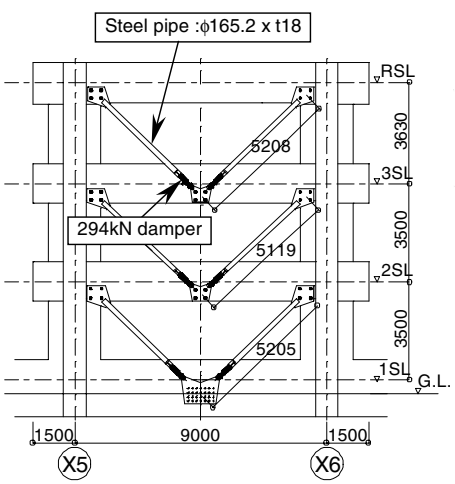
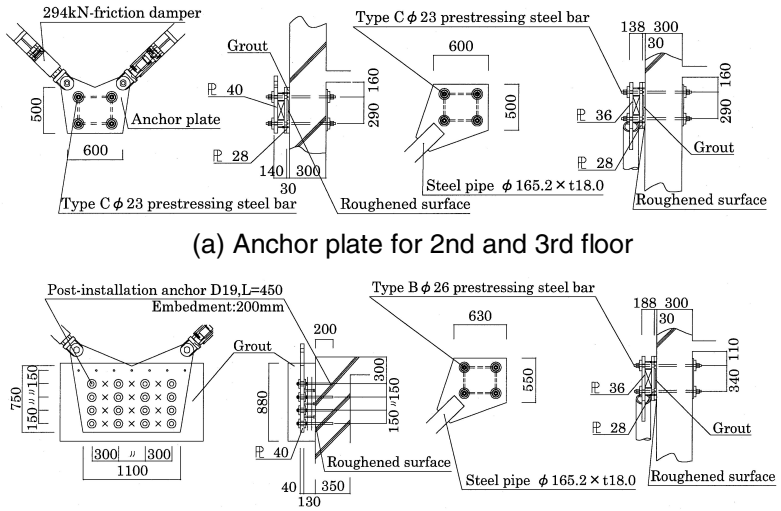


Fig.5 Installation arrangement of damper braces



(a) Anchor plate for 2nd and 3rd floor

(b) Anchor plate for 1st floor

Fig.6 Details of anchor plates

Mechanism of Friction Damper

The mechanism of a friction damper is shown in Figure 7. A friction damper consisting of a die and a rod converts seismic energy into frictional heat by being displaced under certain friction load during an earthquake, and dissipates energy until the end of the earthquake. As components of a damper, the rod is made of copper alloy, die of alloy tool steel, and inner and outer cylinders of carbon steel pipe for ordinary

structures. On the faying surface between the die and the rod, lubricant was applied to provide stable friction load.

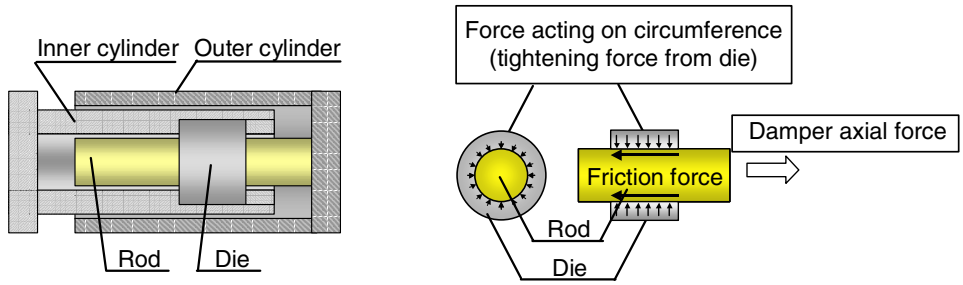


Fig.7 Configuration and mechanism of friction damper (conceptual)

OUTLINE OF TESTS

Test Schedule

Table 3 shows the schedule of the tests. Following the damper retrofit tests (1) and (2) using the test building with damper braces, non-retrofit test using the test building without damper braces were carried out to verify the retrofit effect of damper braces. Failure test was also conducted to verify the strength, the deformation capacity and the extent of damage of the test building. Before and after each test, vibration tests were performed to clarify the vibration characteristics of the test building.

Table 3 Test Schedule

Test date	Test name	Remarks
1999/4/30	Vibration test (1)	
＜Saw-cutting of test building＞		
5/22	Vibration test (2)	
＜Installation of damper baraces＞		
6/3	Vibration test (3)	
6/10	**Damper retrofit test (1)**	**1940 El Centro 50kine**
6/11	Vibration test (4)	
6/15	**Damper retrofit test (2)**	**1940 El Centro 65kine**
6/17	Vibration test (5)	
＜Removal of damper braces＞		
6/23	Vibration test (6)	
6/26	**Non-retrofit test**	**1940 El Centro 65kine**
6/28	Vibration test (7)	
7/4	**Failure test**	
7/5	Vibration test (8)	

Loading Method and Test Method

The loading method is shown in Figure 8. Along grids Ya and Y2 (corresponding to the location of the beam and girder), steel-H-beams were installed as loading beams on the roof of the test building and the reaction force receiving structure. Two actuators were installed between the H-beams on the test building and those on the reaction force receiving structure, so that concentrated loads could be applied on the top

of the test building. The actuators were controlled in such a way that their displacements while loading would be the same.

In order to verify the retrofit effect of dampers, tests were carried out based on the pseudo dynamic test method which is capable of duplicating the movement during earthquakes. Since concentrated loads were applied on the top of test building, it was necessary to transform the test building into a one-mass model. The test building (3 stories in the vertical direction and 1x2 spans in the horizontal direction) was transformed in two steps; first, the equivalent height and equivalent mass were calculated using the participation vector; and the modified equivalent mass was then derived by dividing the overturning moment for the first step, which was calculated by multiplying the equivalent height by the equivalent mass, by the loading height. The modified equivalent mass was calculated to be 276.8 t. The procedure of this transformation is shown in Figure 9.

50-kine waves and 65-kine waves (kine means cm/sec), both of which were produced by amplifying the 1940El Centro N-S waves, were used as the input ground motions. The duration of input ground motion and the time interval was set to 7.0 and 0.02 seconds, respectively. The damping model considered was in proportion to the initial stiffness and had a damping factor of 3%. The natural period of the test building before and after installation of damper braces was calculated to be 0.20 sec and 0.18 sec, respectively.

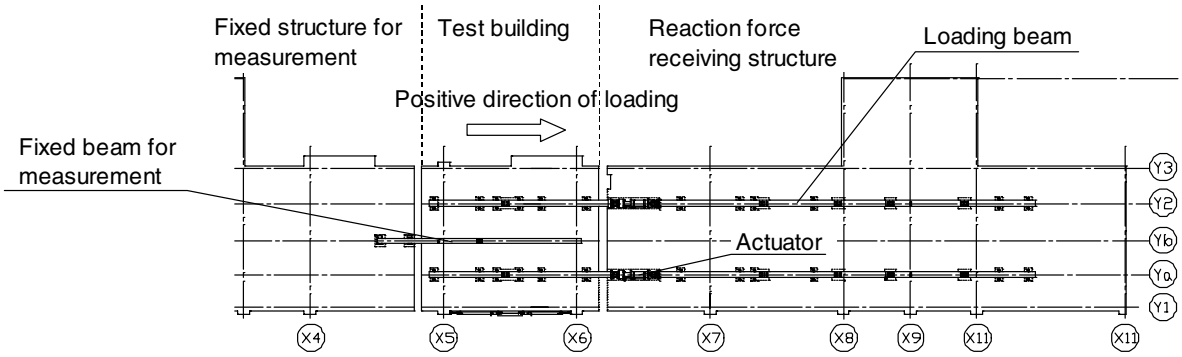


Fig.8 Loading method

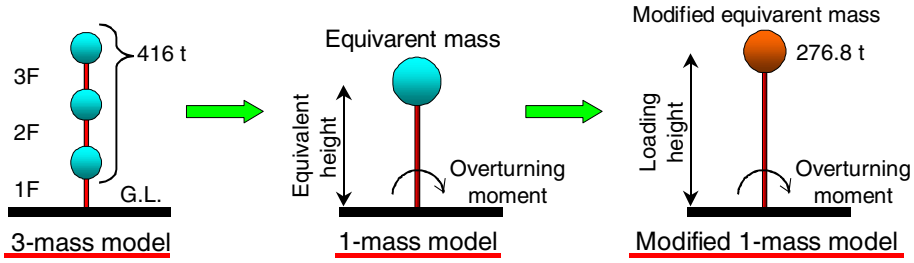


Fig.9 Transformation of test building model

Measurement Method

The restoring force, which was obtained from the loading test for sequential calculation of response, and the horizontal displacement, which was controlled as response displacement, were measured with the load cells provided at the ends of the actuators and the digital displacement meters attached to the beams (along grids Ya and Y2) of the roof floor, respectively. Other measurement items were horizontal and vertical displacements of each story; damper displacement; damper brace displacement; upward

displacement and strain of anchor plates; and upward displacement of the footing. In addition, strain gauges were placed on damper braces to measure the axial forces acting on them.

TEST RESULTS

In this report, the results of damper retrofit test (2), in which 65-kine ground motion was used, and those of non-retrofit test are compared to evaluate the retrofit effect of damper braces.

Figure 10 shows the time history of the response displacement at the top of the test building for both the damper retrofit test and the non-retrofit test. The maximum response displacements and the response hysteresis (load-displacement relationship at the top of the test building) obtained from the tests are shown in Figure 11 and Table 4, respectively. It can be seen from Figure 10 that the response displacements obtained from the damper retrofit test are smaller than those obtained from the non-retrofit test. Table 4 shows that the maximum response displacement obtained from the damper retrofit test is less than half that obtained from non-retrofit test, while there is no significant difference in terms of the maximum response shear force between the two test cases. In the response hysteresis curve shown in Figure 11 (a), which was obtained from the damper retrofit test, slight bi-linear type swelling is observed even for small amplitudes, which indicates that dampers effectively worked for absorption of vibration energy. On the other hand, for the case of the non-retrofit test, considerable swelling of the hysteresis area is observed for large amplitudes, as shown in Figure 11 (b). Figure 12 shows the comparison of the maximum story drift angle for each floor obtained from the tests. The maximum story drift angle appeared at the third story for both test cases, with the damper retrofit test showing 0.42% (story drift angle R=1/238rad) and the non-retrofit test 0.88% (story drift angle R=1/113rad).

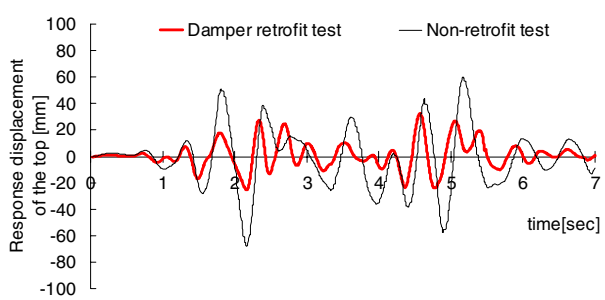
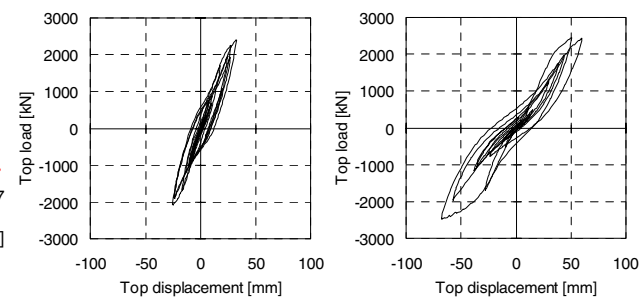


Fig. 10 Time history of response disp.



(a) Damper retrofit test (b) Non-retrofit test

Fig.11 Load-disp. relationship at the top of the test building

Table 4 Maximum response values

Test name	Maximum response shear force [kN]		Maximum response displacement at the top	
	Positive	Negative	Positive	Negative
Damper retrofit	2404	2082	32.0	25.5
Non-retrofit	2452	2466	59.1	67.9

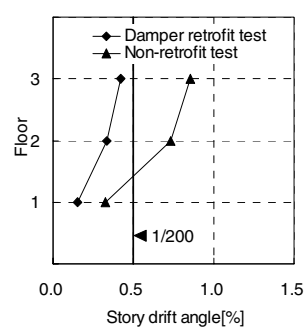
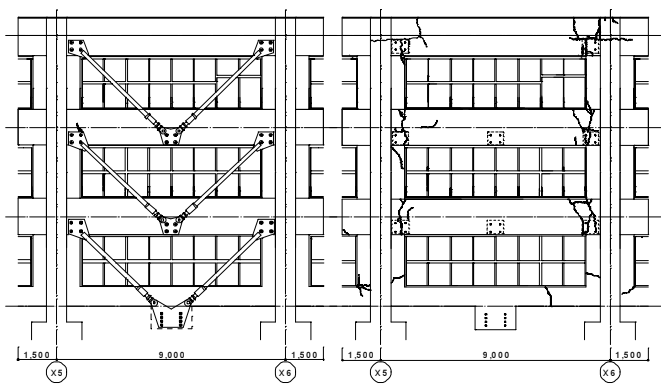


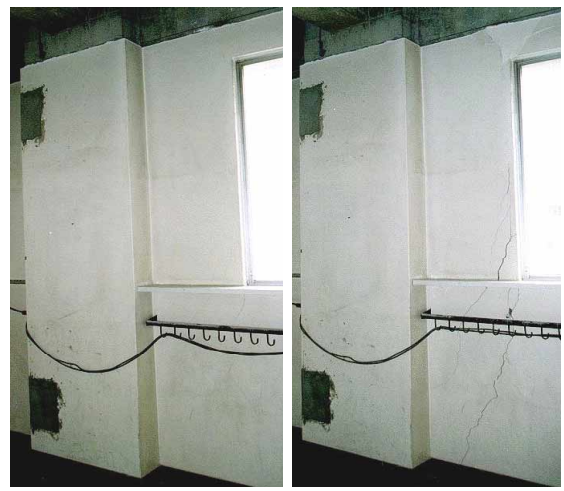
Fig.12 Maximum story drift angle

Condition of cracks (wider than 0.3 mm) after each test is shown in Figure 13. While no major cracks were found after the damper retrofit test, many cracks, which were identifiable with the naked eye, were observed after the non-retrofit test. Photograph 2 shows the damage to the second floor column on the intersecting point of grids Y3 and X5 (extra short column). Although the cracks that appeared during the damper retrofit test were detectable only at very close range, the cracks that appeared during the non-retrofit test were easy to detect. Furthermore, while the damage to the building after the non-retrofit test was such that it was difficult to open and close windows, no serious damage to sashes and interior/exterior finishings was observed after the damper retrofit test. These findings indicate that the retrofit method used in the damper retrofit test provided the same retrofit effect as assumed in the retrofit design.



(a) Damper retrofit test (b) Non-retrofit test

Fig.13 Condition of cracks (after test)



(a) Damper retrofit test (b) Non-retrofit test

Photo.2 Damage to the column on the intersecting point of gridsY3 and X5 (2nd floor)

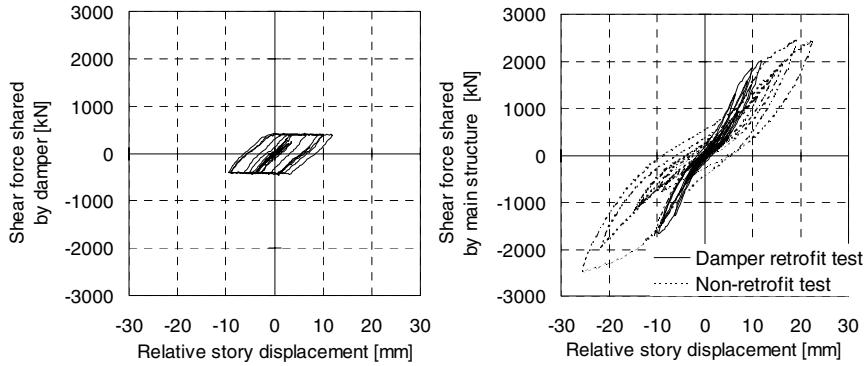
DISCUSSION OF THE TEST RESULTS

Shear Force Shared by Damper and Main Structure

In order to better evaluate the retrofit effect of dampers, the story shear force and energy absorption shared by dampers and the main structure were calculated, and their hysteresis curves were drawn: Figure 14 gives the results for the second story which were obtained from the damper retrofit test and the non-retrofit test. As shown in Figure 14 (a), the hysteresis of the shear force shared by dampers exhibits bi-linear shape, which indicates that dampers effectively worked. On the other hand, with respect to the shear force shared by the main structure, the skeleton for the hysteresis for the damper retrofit test is in good agreement with that for the non-retrofit test (dot line in Figure 14 (b)). This means that the hysteresis curve for a building retrofitted with dampers can be shown with the sum of the hysteresis curves for dampers and the main structure.

The curves in Figure 15, which were obtained by integrating the above hysteresis curves, show the energy absorbed by dampers and that absorbed by the main structure. With respect to the energy absorbed by the relative displacement of the second story (results of the damper retrofit test), the following findings were obtained. The ratio of the energy absorbed by dampers to the total energy absorbed is large, indicating that dampers supplement the energy absorption capacity of the main structure. The ratio of the energy

absorbed by dampers (42.5 kN・m) to the total energy absorbed (67.2 kN・m), when the test was completed, was about 64%.



(a) Damper (b) Main structure

Fig.14 Shear force shared by damper and main structure

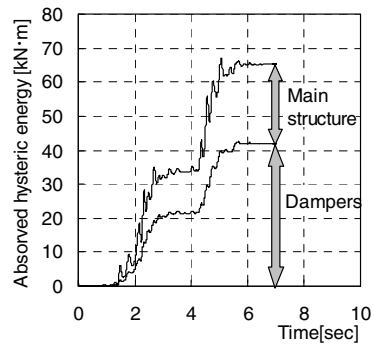
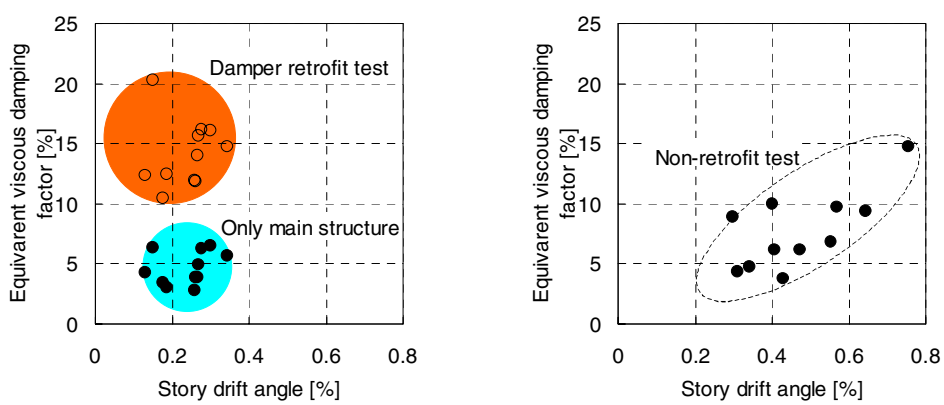


Fig.15 Absorbed hysteretic energy

Equivalent Viscous Damping Factor

The equivalent viscous damping factor was calculated for both the damper retrofit test case and the non-retrofit test case, in order to evaluate the improvement of seismic performance by dampers. The equivalent viscous damping factors derived using the test results are shown in Figure 16. The equivalent viscous damping factor of the whole test building, obtained from the damper retrofit test, show large values ranging from 10 to 20% even for small deformation. The equivalent viscous damping factor given only by the main structure is only 3 to 7%, indicating that most of the improvement in seismic performance is dependent on the energy absorption by dampers. The equivalent viscous damping factor for non-retrofit test case ranged between 4 and 15%.



(a) Damper retrofit test (b) Non-retrofit test

Fig.16 Equivalent viscous damping factor

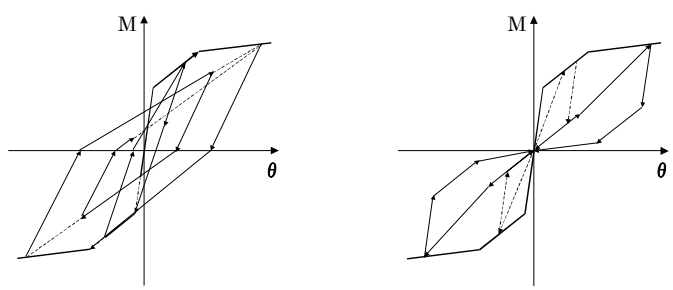
ANALYTICAL STUDY OF FULL-SCALE TEST RESULTS

Reproducibility of Pseudo Dynamic Test Results

For the analysis, substituted skeleton members were evaluated as shown in Table 5 and a three-dimensional elasto-plastic analysis program [11] was used. The restoring force models used were the Takeda model (Figure 17 (a)) and a slip model (Figure17 (b)) that considered slip represented in the hysteresis loop of the test result. An earthquake response analysis was made in model where slip models were used only for the beams with vertical or waist walls. The results were compared with the results of a pseudo dynamic test conducted while controlling the displacements of two actuators to verify the accuracy of reproduction of test results by the analysis. The specifications for the earthquake response analysis are listed in Table 6. A bilinear model was used to represent the restoring force of the damper brace. The design strength and stiffness were adopted.

Table 5 Evaluation of each members for the analysis

Cross section	Based on the measurements of the test building
Member stiffness	Columns and beams: Side, waist or vertical walls are considered. Width of slabs participating in resisting bending moment: Based on the reinforced concrete standards
Rigid zone	Members with side, waist or vertical walls: A half of the member depth. Other members: One-fourth of the member depth.
Material strength	Result of a material test using test pieces sampled from the test building
Member strength	Columns and beams: Side, waist or vertical walls are considered. Effective width of slab reinforcement: Total slab width Formula for calculating strength: Architectural Institute of Japan 1999 [8], 1990[9], 1987[10]



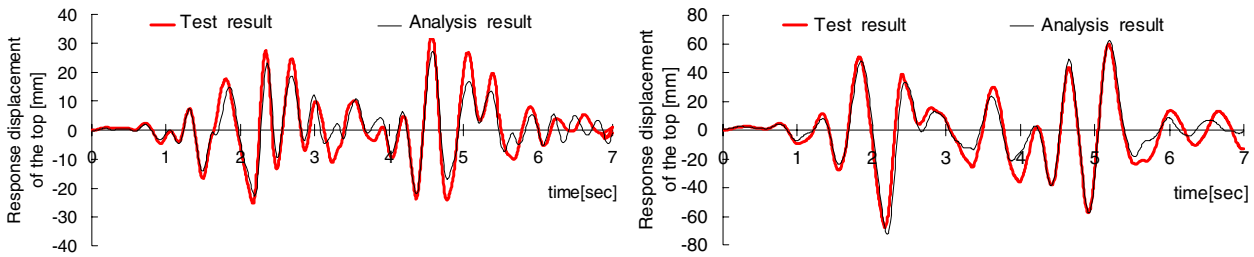
(a) Takeda model (b) Slip model

Fig.17 Hysteresis models

Table 6 Specifications for earthquake response analysis

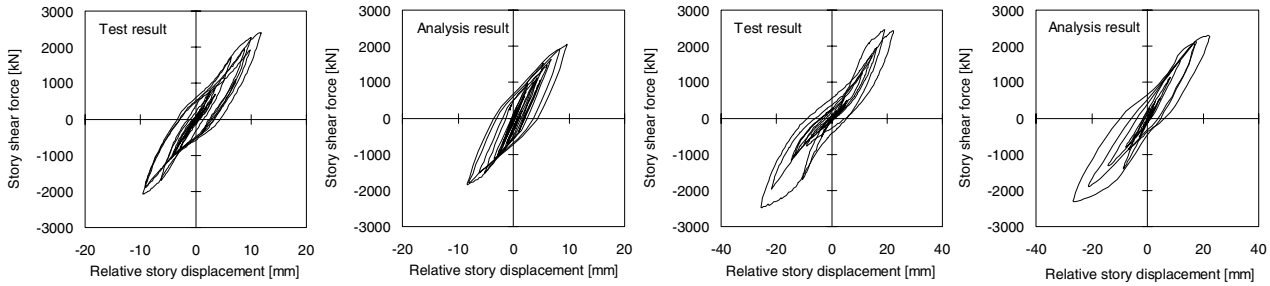
Analysis model	Beams with vertical or waist walls: Slip model Others: Takeda model
Mass of the test building	Mass concentrated at the top of the test building: 276.8 t
Numerical integration, time interval	Newmark-β method (β=0), dt=0.005 sec
Damping	In proportion to initial stiffness (h=3%)
Input motions	Retrofit: El Centro 1940 N-S record 50 kine and 65 kine, 7 sec
	Non-retrofit: El Centro 1940 N-S record 65 kine, 7 sec
Rotational distortion	Restrained (corresponds to the test while controlling displacement)

The time histories of response displacement of the top when a motion of 65 kine was input to a retrofitted or non-retrofitted test building are shown in Figure 18. The relationship between the story shear force and relative story displacement of the second floor (response curves) is show in Figure 19. The test and analysis results agreed well with each other in terms of response displacement and shape of the hysteresis loop. The analysis accurately reproduced the behavior of the actual building and confirmed the effect of retrofit identified in the test. The test and analysis results for the behavior of damper braces installed on the second floor when a motion of 65 kine was input (Figure 20) agreed to each other in terms of hysteresis loop shape and damper-carried shear although there was a slight difference in relative story displacement. It was thus confirmed that the damper braces behaved in the test as expected during the retrofit design.



(a) Damper retrofit (b) Non-retrofit

Fig.18 Time history of response disp. of the top of the test building



(a) Damper retrofit (b) Non-retrofit

Fig.19 Story shear force and relative story disp.

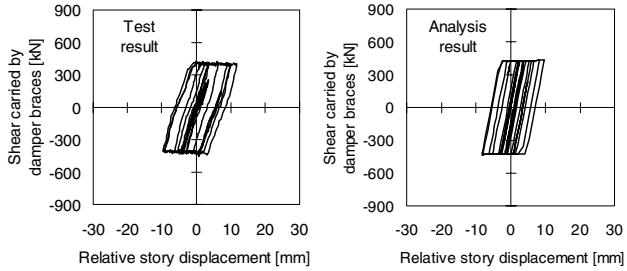


Fig.20 Hysteresis loops of damper braces

DAMAGE MITIGATION BY DAMPER RETROFIT

Comparison of Absorbed Hysteretic Energy of Each Member

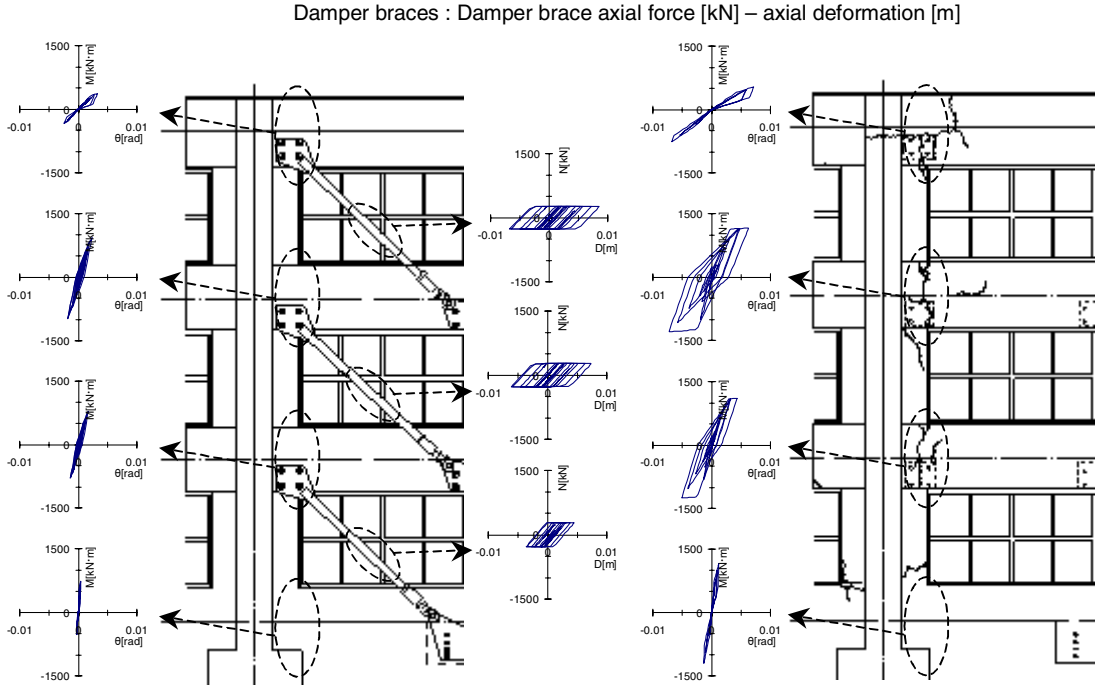
The pseudo dynamic test confirmed the effectiveness of installing damper braces in reinforcing the structure. The analysis accurately reproduced the behavior during the test. So, the focus of attention was directed toward the behavior of each member that could not be grasped by tests. How the damage was mitigated for each member of the retrofitted test building was identified based on the absorbed hysteretic energy. Table 7 shows the absorbed hysteretic energy of each member in comparison with the total absorbed hysteretic energy in retrofitted and non-retrofitted cases. In the non-retrofitted test building, the beams absorbed 76% of the total energy. In the retrofitted test building, the damper braces absorbed 66% of energy and thus held the energy absorbed by beams to 23%. The total absorbed energy of the retrofitted test building was also reduced. Figure 21 shows the hysteresis loops of beam ends and damper braces in the cross section along grid Y1 on the X5 side for retrofitted and non-retrofitted test buildings. The figure also shows cracking detected in the test. When the test building was retrofitted, friction dampers with a perfect elasto-plastic hysteresis loop absorbed energy effectively, and the beam end was hardly plasticized. When the test building was not retrofitted on the other hand, the seismic energy was absorbed by plasticizing the main structure. As a result, beams experienced larger deformation. The test confirmed outstanding cracking.

Table 7 Absorbed hysteretic energy of each member

	Total absorbed hysteretic energy	Columns	Beams	Braces
Retrofit	137.9 (100%)	14.6 (11%)	32.1 (23%)	91.2 (66%)
Non-retrofit	221.8 (100%)	52.2 (24%)	169.5 (76%)	

[kN・m]

Beam ends : Bending moment at the end of the member [kNm] – rotation angle [rad]
Damper braces : Damper brace axial force [kN] – axial deformation [m]



(a) Retrofitted (b) Non-retrofitted

Fig.21 Hysteresis loops of beam ends and damper braces

Input Energy and Deformation

Damper retrofit aims at mitigating damage by reducing input energy and deformation. The concept is shown by spectra in Figure 22. The figure shows the elastic spectra of the total energy input (VE) spectrum (h=10%), pseudo-velocity response (pSv) spectrum (h=10%) and displacement response (SD) spectrum (h=20%) because damper retrofit and non-retrofit tests had found that the equivalent viscous damping factor of the test building was 10 to 20% near the maximum response displacement. The total energy input equivalent velocity, maximum response displacement and absorbed hysteretic energy equivalent velocity for a loop at the maximum response displacement that were obtained from the test and analysis results are plotted in relation to the equivalent period (which was obtained from the apparent stiffness represented by the gradient of the line connecting the points of maximum positive and negative responses before the maximum response displacement occurred). The figure shows fairly good agreement between the test and analysis results, which represents a similar tendency to that of the elastic spectra. As a result, the following findings were obtained. When the building was not retrofitted, input energy from an earthquake increased because the building had a longer period due to damage. When the building was retrofitted, the balance of energy was maintained while deformation was kept at a low level. This indicates that retrofitting had a synergistic effect and controlled the increase of the period of the building due to damage.

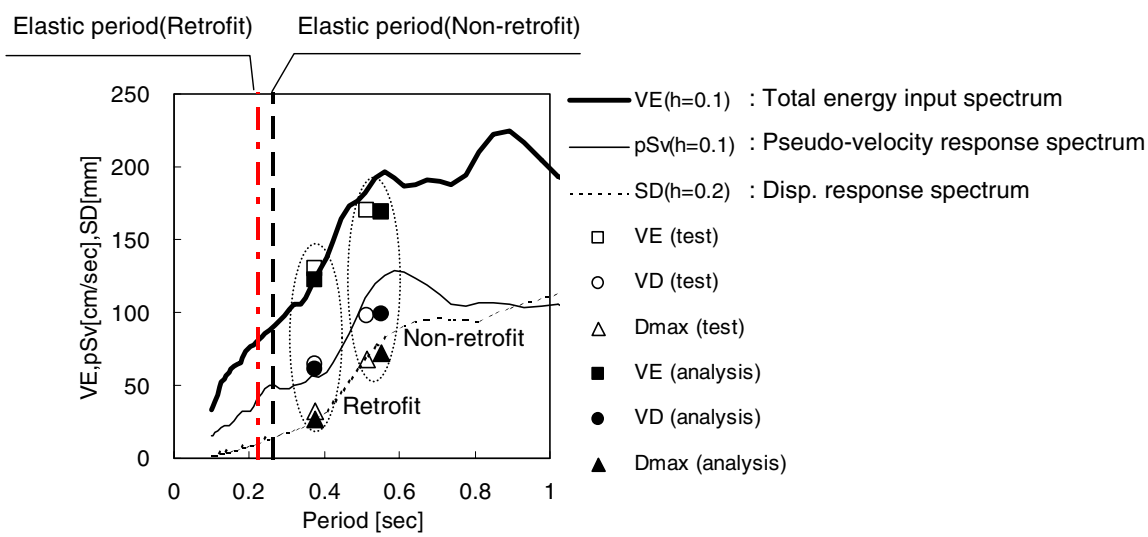


Fig.22 Relationship between test, analysis result, and various elastic response spectra

CONCLUSIONS

Although the results presented in this paper cover limited cases, it was found, through full-scale seismic tests using an existing school building, that the installation of braces fitted with friction dampers on the exterior walls of buildings provides the same retrofit effect as assumed in the retrofit design. In addition, useful data which allow the extent of damage to seismically retrofitted buildings caused by large earthquake forces to be assumed, were obtained through investigation of damage on major structural members, nonstructural walls, sashes and interior/exterior finishings.

An analytical study was made of the result of a full-scale seismic test of a seismically retrofitted existing school building. It was confirmed that installing damper braces on the outer wall of the actual building

could produce similar effects to those in the test, and the effectiveness of retrofit in reducing damage was identified based on the absorbed hysteretic energy and energy spectra.

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