0868

RESEARCH AND DEVELOPMENT OF RESPONSE-CONTROL RETROFITTING TECHNIQUES BY MEANS OF FRICTION DAMPER

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SUMMARY

The purpose of this study is to develop a seismic retrofitting method which increases earthquake-resisting capacity of the building by absorbing the energy, which is input to the building during an earthquake, with dampers which are added to the building. This paper first gives an outline of the study, analyzes the response characteristics of buildings retrofitted with dampers, and presents examples of damper retrofitting of buildings of trial design. It then describes experimental studies on unit performance test for friction dampers, on the connection between the existing building and damper-braces, and on a pseudo-dynamic test on reinforced concrete frames retrofitted with dampers.

INTRODUCTION

The Hyogoken-Nanbu Earthquake which occurred in January 1995 caused great damage to buildings having poor earthquake-resisting capacity that were designed based on the standards established before the adoption of the New Seismic Design Code (the present code of Japan). As a lesson learned from the experience, a law concerning the promotion of seismic retrofitting of buildings was implemented in December of the same year in an attempt to promote seismic diagnosis and seismic retrofit of existing buildings.

The common approach to seismic retrofitting is increasing the strength and/or ductility of buildings by retrofitting or making additions such as columns, beams and earthquake-resisting walls to main structures. That is, the strength-resistant, ductility-resistant and strength/ductility-resistant retrofitting methods have been used. These retrofitting methods have been adopted mainly for school buildings [1].

Recent developments in earthquake resisting technologies (in the broad sense of the word which covers seismic isolation and response control technologies) have made it possible to equip buildings with additional energy-absorbing devices (hereinafter called dampers) to increase their earthquake-resisting capacity [2]. The seismic retrofit technology by means of response control techniques is useful as it enables retrofitting work without suspending the use of the building. Its application to actual practice is desired.

The objective of this study is to develop a seismic retrofitting method which increases earthquake-resisting capacity of the building by absorbing the energy, which is input to the building during an earthquake, with dampers which are added to the building. More specifically, it is the objective of this development to put to practical use the retrofitting method for increasing the earthquake-resisting capacity of existing R/C buildings by building into them friction dampers which have an explicit energy-absorbing capacity. This study covers low- and mid-rise R/C buildings which are considered to have a greater need for retrofitting. The study is based on the assumption that highly rigid-plastic hysteretic friction dampers having high energy dissipation efficiency are developed and built into the core of steel pipe brace (hereinafter referred to as a damper-brace). This paper first gives an outline of the study, analyzes the response characteristics of buildings retrofitted with dampers, and presents examples of damper retrofitting of buildings of trial design. It then describes experimental studies on unit performance test for friction dampers, on the connection between the existing building and damper-braces, and on a pseudo-dynamic test on reinforced concrete frames retrofitted with dampers.

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OUTLINE OF THE STUDY

A flowchart of the study is shown in Figure 1. As the first step in this study, the earthquake-resisting capacities of original and damper-retrofitted buildings were examined, using the existing seismic diagnosis method and the response analysis method which is used for designing high-rise or base-isolated buildings. As a result, it was confirmed that incorporation of damper-braces into the existing buildings reduced response displacement, and thus the effectiveness of damper retrofitting was verified [3].

Then, in order to establish a retrofitting design method by means of damper, the relationship between response displacement of the building retrofitted with dampers and damper strength, and the relationship between response displacement and stiffness of damper-braces were analyzed. Here a response prediction equation was formulated based on the balance between the energy input into the building during an earthquake, and that dissipated by the building, in order to identify the response characteristics of buildings retrofitted with dampers.

For a more practical implementation of damper retrofitting, trial designed buildings were retrofitted with dampers in the case studies. Damper-braces were applied making minimum changes to interior finishing. In addition, examinations were made of anchorage methods which could make the best use of damper capacity, and of specific details.

Unit performance tests of friction dampers and experiments with the connection of damper-braces were conducted to verify performance estimated in retrofitting designs. Also, a 1/3-scale model of a two-span two-story R/C frame, where the shear failure of the columns was prevalent, was retrofitted with dampers, and the seismic performance of the entire retrofitted system was examined in a pseudo-dynamic test. It was confirmed in the test that response displacement could be reduced to the level at which columns withstand the input ground motion equivalent to Level 2 obtained by normalizing at the maximum velocity of 50cm/sec. Thus the effects of damper retrofitting were proved to be satisfactory.

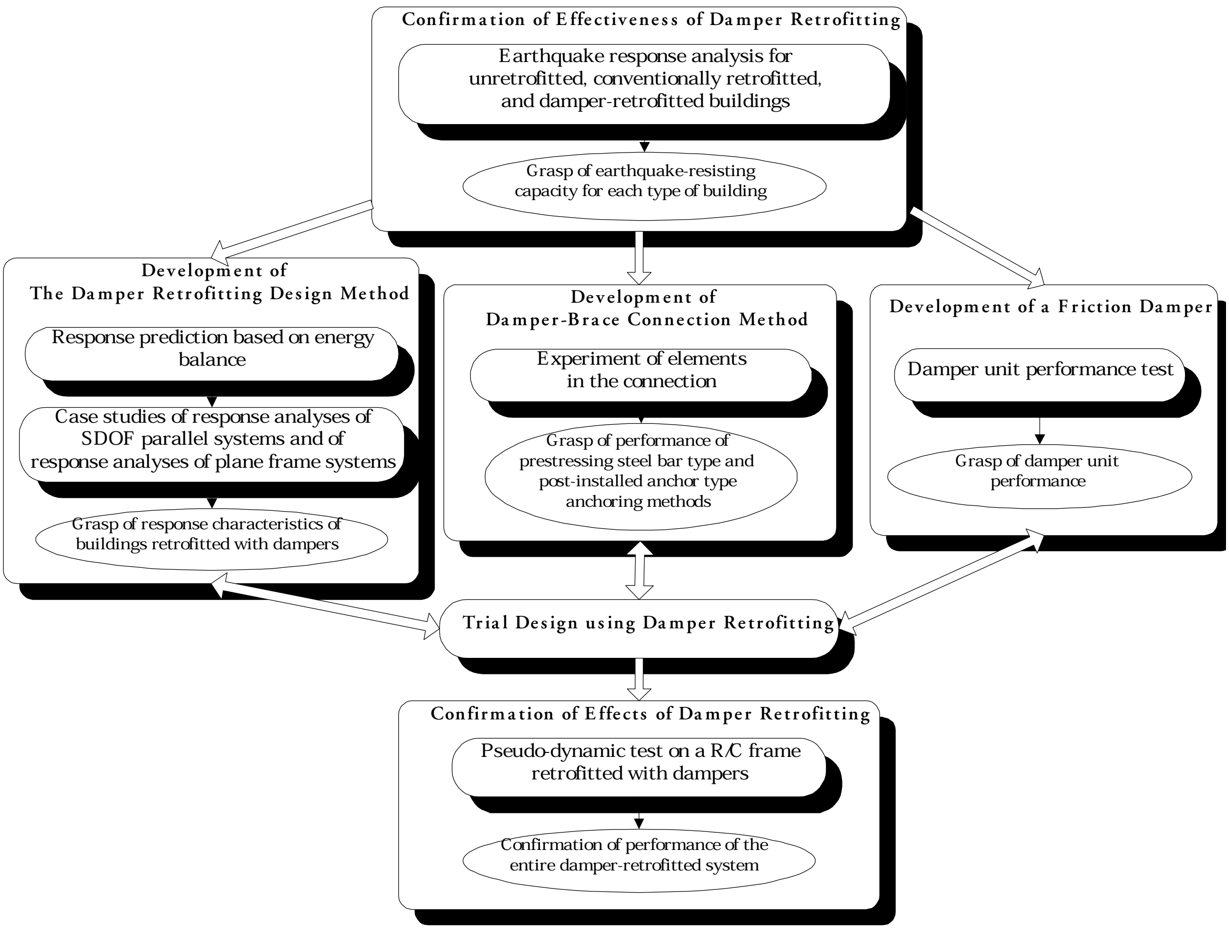


Figure 1: Flowchart of the study

RESPONSE CHARACTERISTICS OF DAMPER-RETROFITTED BUILDINGS

In the development of damper retrofitting design, the relationship between response displacement of the building retrofitted with dampers and damper strength needs to be grasped. Here the relationship between response displacement and damper strength is formulated based on the balance between energy input and dissipation during an earthquake, and the validity of the equation is examined through response analyses of single-degree-of-freedom (SDOF) parallel systems. Applicability of the response prediction formula to buildings of trial design is also confirmed by response analyses of frame systems.

Formulation of Response Prediction Equation Based on Energy Balance

The equation of the balance between the energy input into the building by an earthquake and that dissipated by the building is represented by the following Eq. (1), which is obtained by multiplying both sides of the vibration equation by small deformations dx(= $\dot{x}$ dt) and integrating them to the total earthquake duration time t_0.

$$\int_0^{t_0}\{\dot{x}\}^T[M]\{\ddot{x}\}dt + \int_0^{t_0}\{\dot{x}\}^T[C]\{\dot{x}\}dt + \int_0^{t_0}\{\dot{x}\}^T\{Q(x)\}dt = -\int_0^{t_0}\{\dot{x}\}^T[M]\{\ddot{x}_0\}dt \quad (1)$$

(Kinetic energy:EE) + (Damping ene.dissip.:EH) + (Hyst. ene.dissip.:EK) = (Total energy input:EI)

where, [M], and [C] indicate mass and damping matrix, {Q(x)} indicates restoring force, { $\ddot{x}$ }, { $\dot{x}$ } and { $\ddot{x}_0$ } indicate response acceleration, response velocity and ground motion acceleration vector, and dt indicates time increment.

Hysteretic energy dissipation (EK) is divided into energy dissipation for the main structure (EKstr) and that for the device (EKdev) as shown in Eq.(2).

$$EK = EKstr + EKdev \quad (2)$$

The response prediction equation is formulated by Eqs.(1) and (2). Here it is formulated as a response prediction equation for single-degree-of-freedom (SDOF) systems. It is first assumed that the energy dissipation for the main structure (EKstr) and that for the device (EKdev) can be represented by the product of the maximum carried shear force of each energy dissipation (Qstr and Qdev), the maximum response displacement (δmax) and indexes showing energy dissipation efficiency of the main structure and the device (A and B), as shown in Eq.(3).

$$EK = EKstr + EKdev = A \cdot Qstr \cdot \delta max + B \cdot Qdev \cdot \delta max = \{ A \cdot Qstr + B \cdot Qdev \} \cdot \delta max \quad (3)$$

If the hysteretic energy dissipation (EK) is represented in terms of velocity as shown in Eq.(4) and both sides of Eq.(3) are divided by the weight of the building (W=Mg), the response prediction equation can be represented as shown in Eq.(5).

$$EK = \frac{1}{2} M \times V_{EK}^2 \quad (4)$$

$$\delta max = \frac{V_{EK}^2}{2 \times g \times (A \times \alpha str + B \times \alpha dev)} \quad (5)$$

where, αstr=Qstr/Mg and αdev=Qdev/Mg show carried shear coefficients for the main structure and for the device, respectively.

The proposed prediction equation corresponds to the equation for base-isolated buildings in reference [9], extended for the case in which the parallel resistance mechanism of base-isolator and damper is replaced by the resistance mechanism of the main structure and the device.

Verification of Response Prediction Equation

Case study for single-degree-of-freedom (SDOF) parallel systems

Input ground motion El Centro-NS (534cm/sec^2,50cm/sec)
Analytical model : Main structure + damper
Hysteretic model : Takeda model + bi-linear model
Weight : W=980kgf

Analytical variables :
Main structure natural period
0.25, 0.5, 1.0, 2.0[sec]
Main-structure-carried shear coefficient
αstr=0.3
Damper-carried shear coefficient
0.0, 0.05, 0.1, 0.2, 0.3, 0.4
Damper stiffness ratio(Kdev/Kstr)
0.0→4.72 7 in seven increments

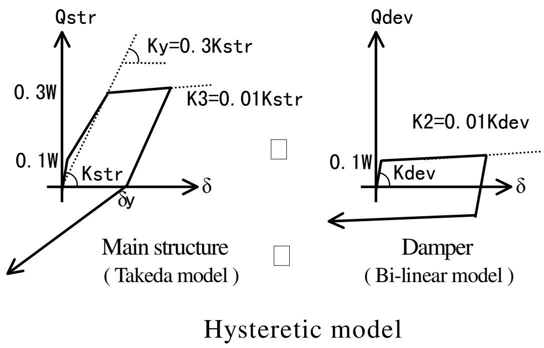


Figure 2: Specifications and hysteretic model for analysis

Response of single-degree-of-freedom (SDOF) parallel systems was analyzed, using damper strength and damper stiffness as parameters, and response characteristics of buildings retrofitted with dampers were grasped, and the validity of the response prediction equation represented by Eq.(5) was examined. The specifications for the analysis and the analytical model are shown in Figure 2. Figure 3 shows the analytical results when the elastic period of the main structure was 0.25 sec. The maximum response displacement decreased with increase in damper-carried shear coefficient (αdev). Damper stiffness ratio (Kdev/Kstr) had no remarkable impact in the range beyond 0.4 applicable to this analysis. The validity of the response prediction equation was examined for a case in which it was assumed that V_{EK}=130, A=1.8 and B=12 when αdev was 0.1. From a comparison between the analytical results and the response prediction curves, it was found out that the response prediction curve was good agree with the analytical results.

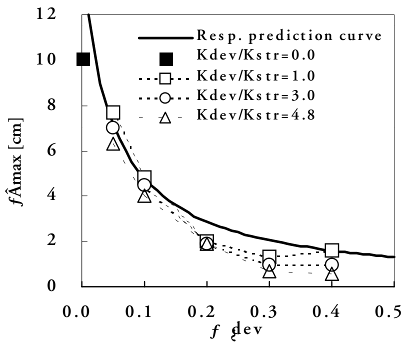


Figure 3: Comparison of response prediction curves

Case study for frame systems analyses

The response characteristics and the validity of the response prediction equation for buildings of trial design, which was retrofitted with dampers, were confirmed through response analyses of plane frame systems. A typical school building was assumed for the analyses. That is, four-story R/C buildings that were designed on a trial basis according to the old standards were used. Damper-braces were arranged in the ridge direction on both sides of the structure facing each other, which had smaller wall section. Plan and frame of the building are shown in Fig.4. Analyses were conducted in the ridge direction, using the elasto-plasticity analysis program for plane frames which had bending rigid plastic spring at the ends of members such as columns, beam ends and feet of walls. The damper-brace model was a bi-linear hysteretic truss model (substituted frame model in which damper and brace were combined). In case studies, seismic response was analyzed in eleven cases, using damper strength and axial stiffness of the brace as parameters (input ground motion: N-S component of El Centro(1940) of 50cm/sec). Damper strength per unit (N) had six different values from 33 to 250kN (damper-carried shear coefficient for the first floor: αdev=0.016 through 0.121) where the axial stiffness of the brace remained unchanged (sectional area=35.1cm^2). The axial stiffness of the brace represented in terms of sectional area varied from 14.0 to 70.1cm^2 in other five cases where damper strength remained unchanged at 100kN.

Results of the analysis using damper strength as a parameter are shown in Table 1 and Figure 5. The thick broken line indicates the response prediction curve calculated by Eq. (5). It was assumed that the results of the frame analysis could be represented by equivalent single-degree-of-freedom systems, using the first-floor shear and the displacement on the third floor (floor of the fourth floor) where the centroid of the horizontal external force was located. The relative first-floor displacement prediction curve (thin broken line) was obtained as one-

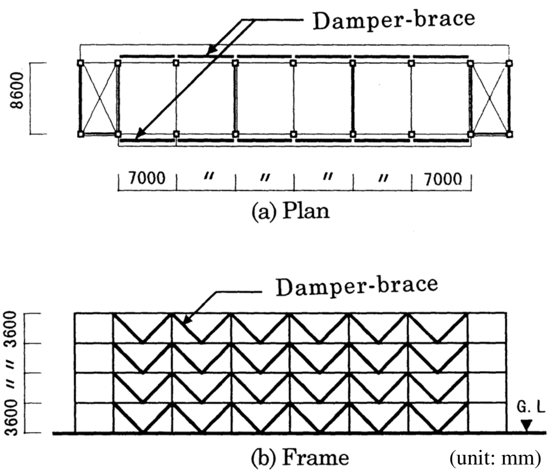


Figure 4: Building outline

Table 1: Impact of damper strength

N (kN)	αdev	C_B	D3f (cm)	D1f (cm)
0	0.00	0.39	10.41	3.52
33	0.02	0.48	8.29	3.36
67	0.03	0.50	5.91	2.26
100	0.05	0.51	4.58	1.81
133	0.07	0.51	3.69	1.68
167	0.08	0.51	3.31	1.45
250	0.12	0.61	2.79	1.25

N : Damper strength per damper
αdev : Damper-carried first-floor shear
C_B : First-floor shear coefficient
D3f : Third-floor displacement
(displacement of the floor of the fourth floor)
D1f : Relative first-floor displacement

Table 2: Impact of axial stiffness of the brace

A (cm^2)	T (sec)	Kdev/Kstr	D3f (cm)	D1f (cm)
0.0	0.34	0.00	10.41	3.52
14.0	0.30	0.33	5.66	2.22
28.0	0.27	0.63	4.70	2.01
35.1	0.26	0.77	4.58	1.81
42.1	0.25	0.91	4.51	1.77
70.1	0.22	1.41	4.38	1.75

A : Brace sectional area
T : Elastic primary period
Kdev/Kstr: Stiffness ratio as compared with the case of unretrofit
D3f : Third-floor displacement
(displacement of the floor of the fourth floor)
D1f : Relative first-floor displacement

third of the third-floor displacement prediction. Variables in the response prediction equation were fixed at the values when αdev=0.05 (V_{EK}=110, A=1.0, B=18.0). It was found from the figure that with increase in damper strength the maximum response displacement (δmax) decreased along the response prediction curve. That is, response characteristics for frame systems were similar to those for SDOF parallel systems. This may be because the four-story building of trial design was relatively low, damper retrofitting eliminated displacement concentration on specific floors, and the natural period was dominant among frame vibration systems.

Results of an analysis using the axial stiffness of the brace (sectional area) as a parameter are shown in Table 2 and Figure 6. It was found that the maximum response displacement was reduced to about half of that without retrofitting if the brace had a sectional area of more than $28cm^2$. The brace size exceeding the value had no significant impact on reduction of the maximum response displacement. The damper stiffness ratio (Kdev/Kstr) at the point was 0.63. The same tendency was also confirmed in the case study of SDOF parallel systems.

DAMPER RETROFITTING DESIGN SAMPLES

This section describes samples of retrofitting design made to implement the damper retrofitting method in a more practical manner. The buildings to be retrofitted are those of trial design, for which frame analyses were introduced in the preceding section. Retrofitting principles are as listed below.

□ The damper strength and the brace sectional area are determined so that response displacement on each floor can be reduced to the level where no columns experience shear failure due to input ground motions equivalent to Level 2. Here, damper strength and brace sectional area are set at 196kN and $28cm^2$ or more, respectively based on the results of the case studies given above. Only one seismic wave, input ground motion of the N-S component of El Centro(1940) of 50cm/sec, is used in this study. In actual design, however, other types of input ground motion will also be studied.

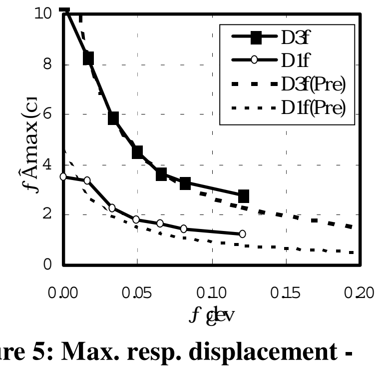


Figure 5: Max. resp. displacement - damper carried shear relationship

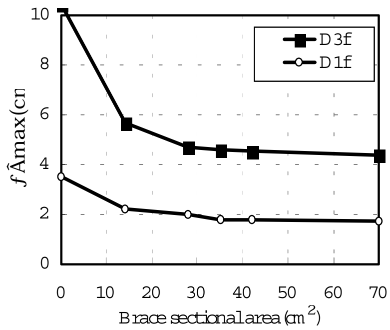


Figure 6: Max. response displacement – brace axial stiffness relationship

□ The design axial force acting on the damper-brace is set 1.5times larger than the damper strength, and the brace and anchorage zone are designed so as to provide allowable stress against the design axial force. As a result of calculation of sectional area, carbon steel tubes for general structural purposes (SS400) having a sectional area of 28cm^2 or more with the smallest diameter of 165.2 x 7.0 (A=34.8cm^2) was used as a brace.

The gusset on the steel tube side, the splice plate at the joint, and the gusset on the anchor bearing side are designed to have a thickness larger than the brace sectional area so as to produce adequate axial stiffness of the brace.

Damper-braces are anchored to the existing frame by creating through holes on the beam of the frame, and by fastening anchor bearings at both ends of the damper-brace with prestressing steel bars. Shear keys are created on the top surface of the anchor bearing, on which deformed bars D10 are welded. Grout is injected between the frame and the anchor bearing, and then post-tension is introduced [8]. The tensioning force introduced and the anchor bearing size are fixed based on the results of experiments with the anchorage zone so that a friction coefficient may be 1.0 and a bearing stress of 2.0MPa may work on the grout.

□ It was confirmed that axial force and shear generated by the force transferred from the anchor bearing caused no failure of the ends of the beam, by using the punching shear strength calculation referred to in reference [1].

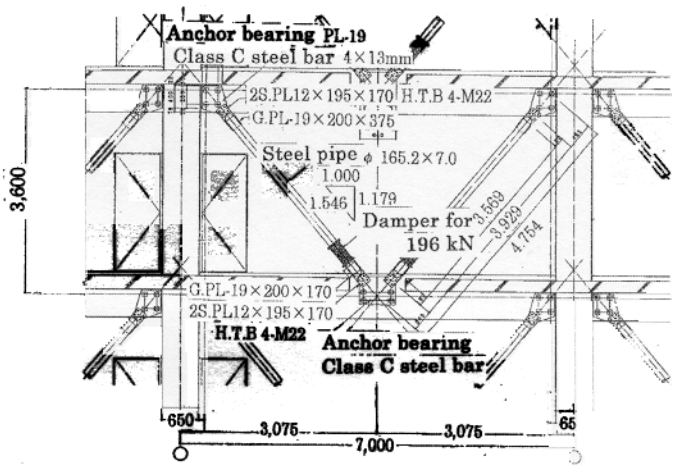


Figure 7: The details of damper retrofitting design

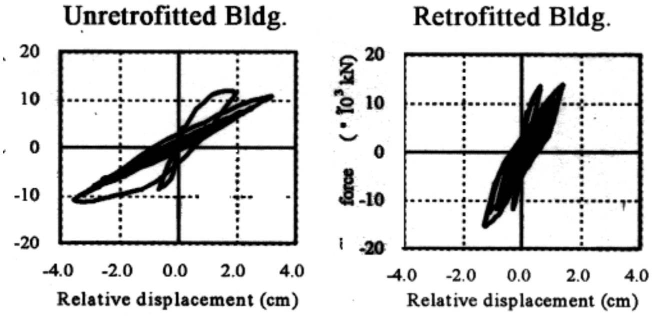


Figure 8: Hysteresis curves on the first floor

The details of damper-braces designed based on the above principles are shown in Figure 7. The response hysteretic curves on the first floor of original and damper-retrofitted buildings are shown in Figure 8. The figure indicates that damper retrofitting reduces the response displacement to about one-third.

EXPERIMENTAL STUDY ON DAMPER RETROFITTING

The damper-retrofitting system consists of friction dampers which absorb seismic energy, damper-braces having friction dampers built in the core of the axis of the steel brace, and the anchorage zone where the damper-brace is anchored to the frame. This section reports an outline of the experimental studies, which are the unit performance test on friction dampers and the experiments with the anchorage zone for verifying performance estimated in the damper retrofitting design, and the pseudo-dynamic test on damper-retrofitted frames conducted to verify retrofitting effects on the entire system. These experimental studies are described in detail in reference [6] and [7].

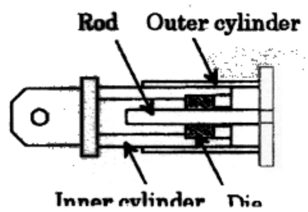


Figure 9: Configurations of the damper

Unit Performance Test on Friction Dampers

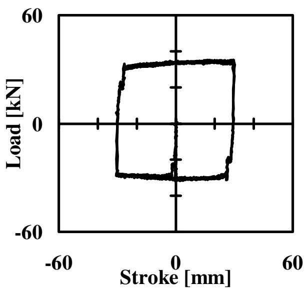


Figure 10: Results of performance testing on the damper

The configuration of friction damper is shown in Figure 9. The damper consists of a die and an inner cylinder, and a rod and an outer cylinder. Friction force is adjusted by the rod outer diameter, and the inner diameter and the length of the die. In the unit performance test, impacts of the number of repetitions, speed, frequency, amplitude and temperature affected by surroundings, which affect damper capacity, were examined. Practicable capacity of the damper was verified. Shown here are test results where friction load was in the range between minus 30kN and plus 30kN. These values are used in the pseudo-dynamic test on damper-retrofitted frames which is described later. Figure 10 shows the load displacement curve when static excitation was applied with an amplitude from minus 30mm to plus 30mm. The hysteretic characteristics of damper was rigid perfectly plastic, which means high energy absorption efficiency. It was confirmed that the characteristics were in agreement to those of the bi-linear model estimated in retrofitting design.

Experiments with Damper-Brace Connection

For anchoring damper-braces to existing frames, the prestressing steel bar is used in which the anchor bearing is fastened to the side of the main structure with prestressing steel bars, as described for the retrofitting design samples. The connection in damper retrofitting is required to have sufficient stiffness and prevent slipping under repeated load acting from the damper-brace. In this experiment, the tensile force (friction coefficient) of prestressing steel bars and the size of anchor bearing (bearing stress acting on the grout) that would meet the above requirements were examined, and ultimate strength and ductility of the connection were also reviewed. Experiments were also conducted with the indirect connection using post-installed anchors (hereinafter referred to as the post-installed anchor type) for fear that no through holes could be driven for prestressing steel bars. In the post-installed anchor type, adhesive post-installed anchors were driven into the frame, then they were connected by grouting with the anchor bearing having headed studs on the bottom surface. Ladder bars were arranged in the grout to distribute shrinkage crack. Figure 11 shows a conceptual diagram of the prestressing steel bar and post-installed anchor methods. The relationship between load and relative anchor bearing-frame displacement, which were obtained in the tests, are shown in Figure 12. For the prestressing steel bar method, the load which could be applied repeatedly without increasing deformation matched the load which caused no slipping between the grout and the concrete frame. The friction coefficient for the tensile force of the prestressing steel bar was 1.0. The repeatedly applicable load for the post-tension anchor method was that which caused no separation between the frame and the grout.

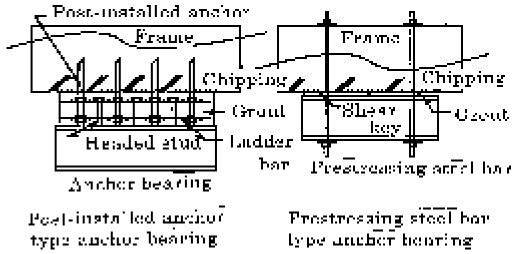
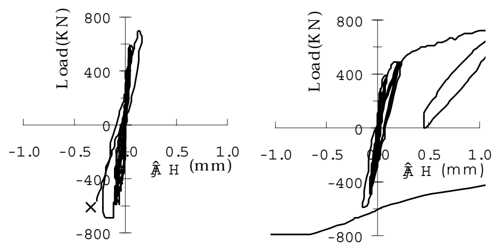


Figure 11: Outline of anchoring method



Post-installed anchor type Prestressing steel bar type

Figure 12: Relationship between load and relative lateral displacement

Pseudo-Dynamic Test on Frames Retrofitted with Dampers

A two-span two-story reinforced concrete frame where the shear failure of the columns was the prevalent failure was retrofitted in the same manner as in the sample retrofitting design, and performance of the damper-retrofitted system was confirmed by a pseudo-dynamic test. Figure 13 shows the configuration of retrofitted test specimen. The specimen was 1/3-scale model.

A positive and negative alternating loading test was conducted on the unretrofitted specimen before the pseudo-dynamic test on the retrofitted specimen in order to study the basic properties of the unretrofitted one. The maximum strength of 179kN was observed at R (overall rotation angle, which was obtained by dividing displacement on the top of the specimen by its testing height) =1.0%. Then strength decreased at R=1.1%. Finally, the top of the second floor column went into shear failure.

The damper-retrofitted specimen was made by retrofitting a specimen having the same shape and bar arrangement as the unretrofitted specimen, with the friction dampers described in 5.1 above. The pseudo-dynamic test used input ground motion of the N-S component of El Centro(1940) of 50cm/sec. The response hysteresis curves obtained in the

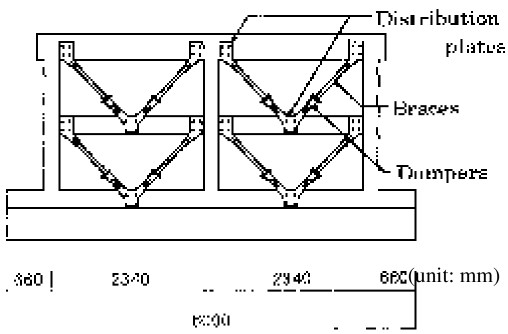


Figure 13: Configuration of test specimen

pseudo-dynamic test on the retrofitted specimen are compared with the test result on the unretrofitted specimen in Figure 14. The maximum response rotation angle was R=0.6% on the negative side. The horizontal load at the time was 238kN. At this point, shear cracks were observed in columns and in column-beam connections, but no decrease either in horizontal resistance or in axial holding strength of the frame was found. No slipping occurred in damper-brace connections. Thus retrofitting effects on the entire system were confirmed.

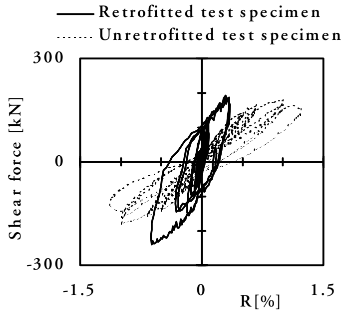


Figure 14: Response hysteresis curves

CONCLUSIONS

Discussed above are an outline of the study, response characteristics of damper-retrofitted buildings, samples of retrofitting design, and an outline of experimental studies, related to a study on the technology for retrofitting existing R/C buildings with dampers. The following points were learned from the discussion although the conclusions have only a limited range of application as only a few cases were studied.

1. Retrofitting of existing reinforced concrete buildings with dampers reduces seismic response displacement, and increases earthquake-resisting capacity of the buildings.
2. The relationship between response displacement and damper strength can be grasped almost completely by a response prediction equation based on the energy balance.
3. As shown in samples of damper-retrofitting design, the retrofitting method is practicable, enabling retrofitting work while keeping the interior finishing unchanged as much as possible.
4. The hysteretic characteristics of friction dampers was rigid perfectly plastic, which meant high energy absorption efficiency, and were in agreement with those for the bi-linear model assumed in retrofitting design.
5. Experiments with damper-brace connections confirmed that either the prestressing steel bar method or post-installed anchor method met requirements for the connections.
6. As a result of a pseudo-dynamic test on damper-retrofitted frames, it was confirmed that response displacements could be reduced to the level at which columns withstand Level 2 input ground motion equivalent to the maximum velocity of 50cm/sec, and retrofitting effects on the entire system could be obtained.

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