13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2498

EARTHQUAKE RESISTANT PERFORMANCE OF REINFORCED CONCRETE FRAME WITH ENERGY DISSIPATION DEVICES

Nobuyuki IZUMI[1], Osamu CHIBA[2], Kohji TAKAHASHI[3] and Shinichi IIZUKA[4]

SUMMARY

The paper presents that energy dissipation devices (damage fuses) in its reinforced concrete (RC) frame can upgrade the ability to dissipate the energy created by earthquake excitations. It also presents that those analysis models of RC frame with damage fuses effectively demonstrate the restoring force characteristics obtained from experimental results of horizontal loading.

In case damage fuses are applied to RC frame, it should be taken into consideration that the behavior such as cracking of attachment members and flexural yielding of reinforcing bars can reduce the effect of seismic response control. Therefore, the validity of performance evaluations of its frame with damage fuses and analysis models should be thoroughly examined.

The frame contains two different types of damage fuses such as a stud (control-column) and a brace (control-brace). The control-column is an RC stud, which contains a low-yield-point-steel panel. The control-brace is either an oil-damper brace or an unbonded (buckling-restrained) low-yield-point-steel brace.

Static and dynamic loading tests of a one-storey RC frame model with damage fuses are conducted. Next, an analysis model of an RC frame with damage fuses is formulated. Subsequently, non-linear displacement analyses are conducted. The findings from testing and analyses are as follows:

(1) In the region of assumed deformations under small to large earthquake intensity, applying damage fuses is substantially able to improve the energy dissipation ability of an RC frame.
(2) Prior to flexural yielding of reinforcing bars, the restoring force characteristics of an RC frame with damage fuses display a great ability of energy dissipation showing spindle-shape loops.

---

[1] Senior Structural Engineer, Dr. Eng., Dept. of Structural Engineering, Toda Corporation, Tokyo, Japan. Email: nobuyuki.izumi@toda.co.jp
[2] Director, Technical Research Institute, Toda Corporation, Tokyo, Japan. Email: osamu.chiba@toda.co.jp
[3] Dr. Eng., Technical Research Institute, Nishimatsu Construction, Kanagawa, Japan. Email: koji_takahashi@nishimatsu.co.jp
[4] Manager, Dr. Eng., Technical Research Institute, Nishimatsu Construction, Kanagawa, Japan. Email: shinichi_iizuka@nishimatsu.co.jp

(3) The analysis models of RC frame with damage fuses can effectively demonstrate the restoring force characteristics obtained from experimental results of horizontal loading.

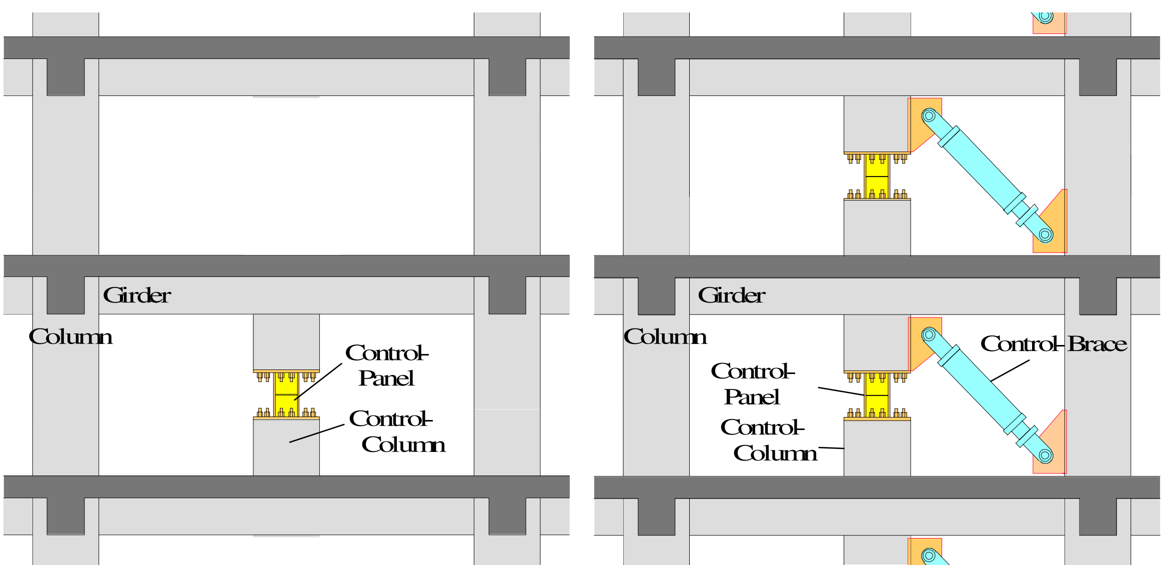
INTRODUCTION

The authors (Izumi [1], [2]) of this paper have studied the application of "damage fuses" known as energy dissipation devices that can control serious damage to reinforced concrete (RC) structures subjected to strong earthquakes.

The paper describes the behaviors of RC frames with damage fuses, as shown in Fig.1. The types of damage fuses are as follows: an RC stud (control-column) that contains a low-yield-point-steel panel (control-panel) of which deformations are dependent on its relative storey displacement (hysteresis system), an oil-damper brace (viscous damping system) that is dependent on its relative storey velocity and an unbonded low-yield-point-steel brace (hysteresis system); those braces will be hereinafter called control-braces. Combining a control-panel with a control-brace (using different damping characteristics: hysteresis system and viscous damping system) can demonstrate outstanding damping effects on wide-ranging excitation. Furthermore, more space can be effectively allocated by using those control-panel and control-braces.

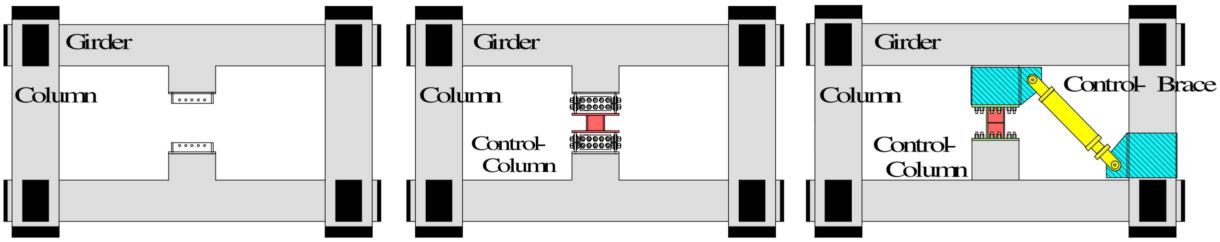
The damping effect of the damage fuses reduces the damage to the RC frame resulting from earthquakes that range from small to middle intensities. Moreover, the damping effect above-mentioned and the energy absorption capacity of the RC frame secure itself from serious damage resulting from strong earthquakes. The performance evaluations of its frame with the damage fuses and the validity of appropriate analysis models should be examined in order to apply the devices. In case more than one type of the devices is applied, it is important to evaluate the complex behaviors of the frame as a whole.

The paper presents static and dynamic loading tests of a one-storey RC frame model with the damage fuses. The test results show the damping-added performance of the damage fuses on RC frames. Furthermore, the paper proposes the analysis models and the validity of the restoring force characteristics of its frame with the damage fuses.



(a) RC Frame with Control-Column (b) RC Frame with Control-Column and Control-Brace

Fig.1. RC Frame with Energy Dissipation Devices



(a) Frame-based (b) Frame-based with Control-Column (c) Frame-based with Control-Column and Control-Brace

Fig.2. RC Frame Models

EXPERIMENTAL PROGRAM

Procedure

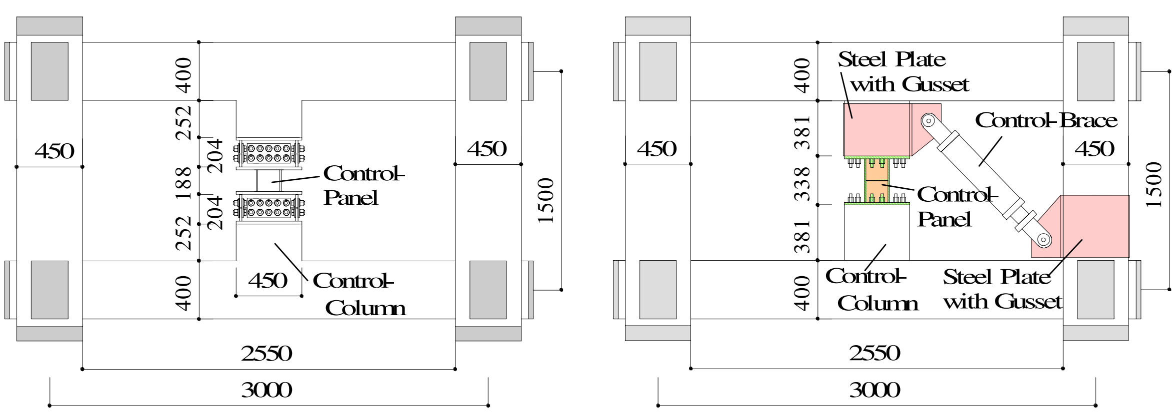
The following types of RC frame models are tested (see Fig.2):

1. Loading test of an RC frame (frame-based test),
2. Loading test of an RC frame with a control-column (control-column test) and
3. Loading test of an RC frame with a control-column and a control-brace (control-column and control-brace test).

First, the frame-based test is performed prior to installing the control-panel within an RC stud. Second, the control-panel is installed, and the control-column test is performed. Third, the control-column and control-brace test (dynamic loading test) is performed on another frame with a control-column and an oil-damper brace. Then, the oil-damper is replaced with an unbonded low-yield-point-steel brace (unbonded brace), and the static loading test is performed. The tests use the two different frames, and each frame is identical whereas connecting members of the damping devices differ.

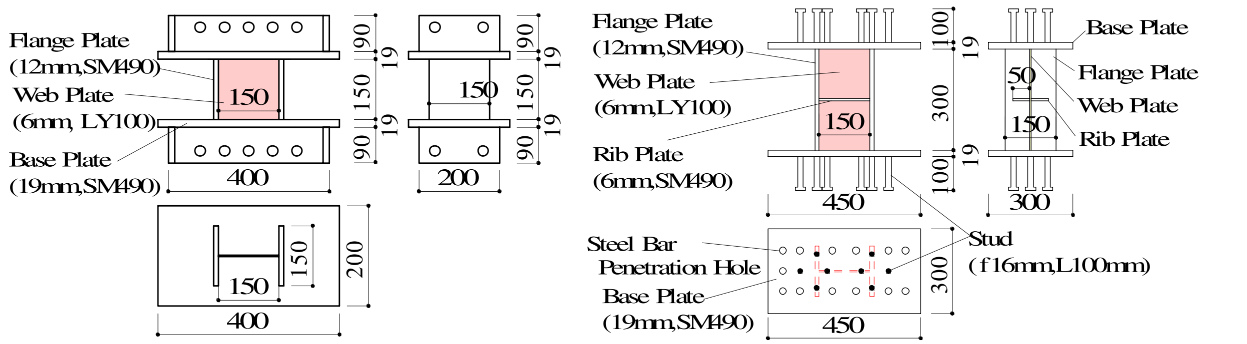
Test specimens

Each test specimen is a half scale model of a one-storied rigid RC frame that consists of columns and girders (see Fig.3). The control-column is placed in the middle of the span of its frame. The control- brace is placed in an opening between the control-column and a column of its frame.



(a) Frame-based with Control-Column (b) Frame-based with Control-Column and Control- Brace

Fig.3. Test Specimens



(a) Control-Panel in Control-Column Test (b) Control-Panel in Control-Column and Control-Brace Test

Fig.4. Dimensions of Control-Panel in Test Specimens

Each frame is designed as the flexural yielding of girders precedes the flexural yielding of columns. The control-panel consists of a low-yield-point-steel web plate (first axial-yielding stress of 100 N/mm^2), vertical flange plates of SM490 and base plates of SM490 at the top and the bottom of the panel (see Fig.4). The control-panel and the top and the bottom of RC portions are jointed through headed studs and reinforcing bars of a control-column. The maximum damping force of an oil-damper brace is approximately equivalent to the maximum strength of an unbonded brace. The properties of design characteristics (damping force-velocity curve) of an oil-damper brace are shown in Fig.5, and the details of an unbonded brace are shown in Fig.6. The core member of an unbonded brace uses a low-yield-point-steel plate (first axial-yielding stress of 100 N/mm^2) with 16mm by 60 mm (thickness by width). Each end of the control-braces is connected at the top of an RC stud and at the bottom of a column where the top of an RC stud and the bottom of a column are reinforced by steel plates (reinforcing steel plates). Hence, each of the control-braces is not directly connected to its girders. The reinforcing steel plates with a gusset plate are jointed through headed studs and U-shape reinforcing bars. Table 1 shows the details of test specimens of a frame, and Table 2 shows the results of material testing.

Test setup and loading sequence

Fig.7 shows the static-loading test setup in which both pin supports at the ends of a loading beam above columns are loaded by the actuators (the dynamic-loading test setup uses only one actuator). The loading histories are controlled by drift angles (Rf) of the frame (see Fig.8). The dynamic-loading test uses two

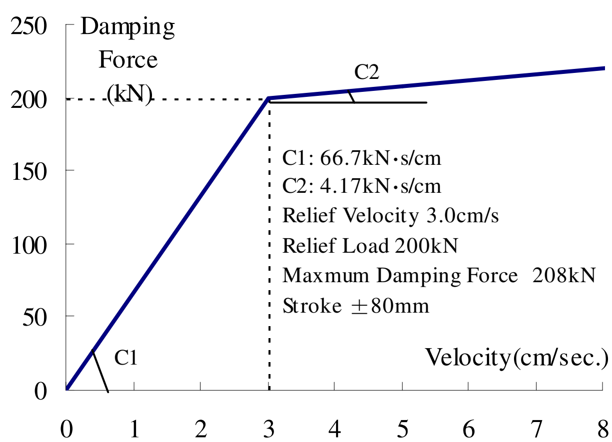


Fig.5. Properties of Design Characteristic of Oil Damper

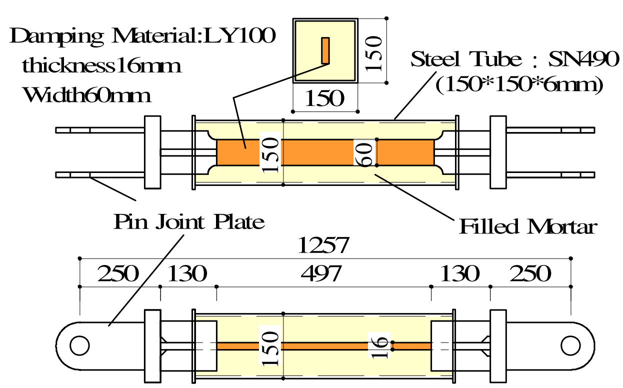


Fig.6. Unbonded Brace

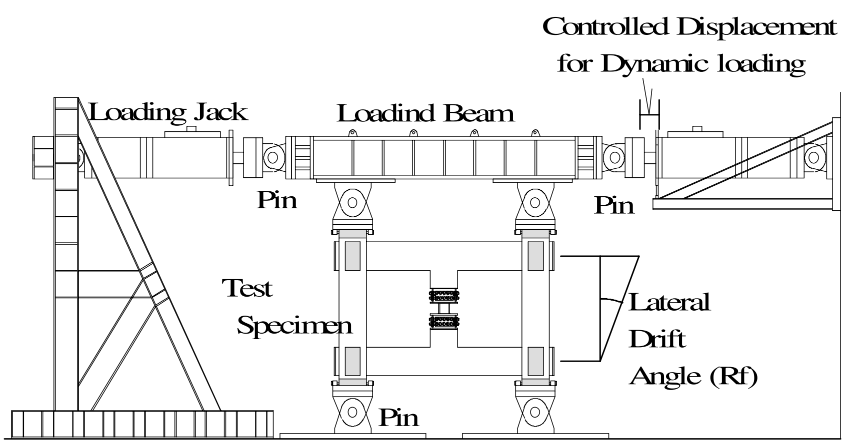
Table 1. Details of Test Specimens

	BxD (mm)	Fc (N/mm^2)	Main reinforcement Steel Bar	Shear reinforcement Steel Bar
Column	450x450	45	16-D22 (SD490)	4-φ6@50 (USD685)
Girder	200x400	35	4+2-D19 (SD490)	4-φ6@40 (USD685)
Control-Column	200x450	35	14-D19 (SD490)	4-D6(SD295) 2-D6(SD295)

Table 2. Results of Material Testing

Re-bars & Steel	Young's Modulus ($x10^5 N/mm^2$)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)
D22(SD490)	1.93	509	685
D19(SD490)	1.92	523	666
φ6(USD685)	1.80	701	846
D6(SD295A)	1.71	330	469
PL4.5(LY100)	1.69	97	248
PL6(SM490)	2.06	392	520
PL12(SM490)	2.06	384	530
PL16(SM490)	2.07	378	536
PL19(SM490)	2.11	360	517

Concrete	Secant Modulus ($x10^5 N/mm^2$)	Compressive Strength (N/mm^2)	Cleavage Strength (N/mm^2)
Girder, Control-Column (RC)	0.26	31	2.35
Column	0.35	55	4.56

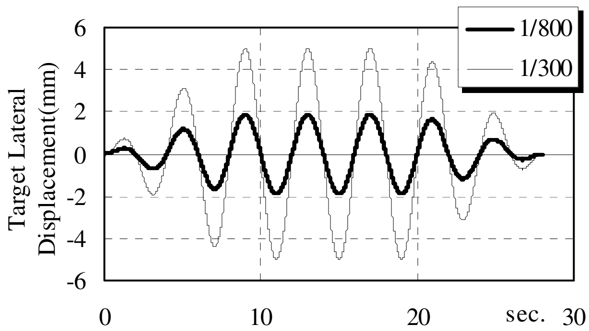


(a) Drawing

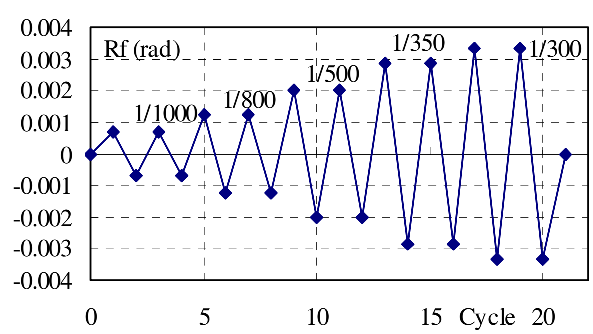
(b) Photo

Fig.7. Test Setup

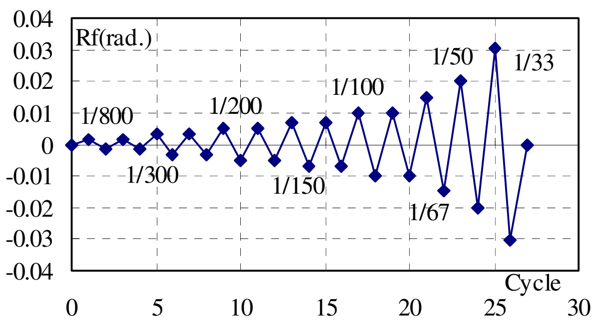
types of natural periods, 2 and 4 seconds, respectively, in consideration of the natural periods of high-rise RC structures. The target drift angles of 1/800 and 1/300 are chosen for dynamic loading. The target drift angle of 1/300 indicates the drift angle caused by earthquakes that rarely occur. It must be noted that the test-result values and the target drift displacements differ slightly since the values of Rf for dynamic loading are controlled by the horizontal displacements of a loading beam.



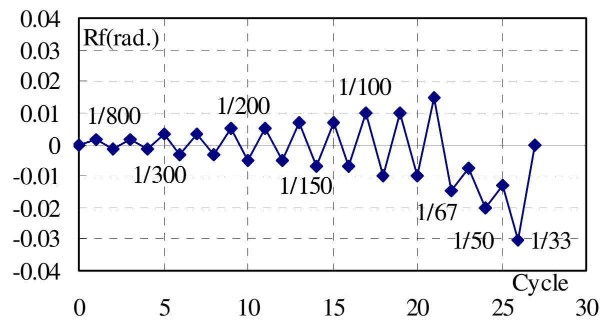
(a) Dynamic Loading of Control-Column and Oil-Damper Brace Test



(b) Static Loading of Frame-Based Test



(c) Static Loading of Control-Column Test



(d) Static Loading of Control-Column and Unbonded Brace Test

Fig.8. Loading Histories

EXPERIMENTAL RESULTS

Results of dynamic loading test

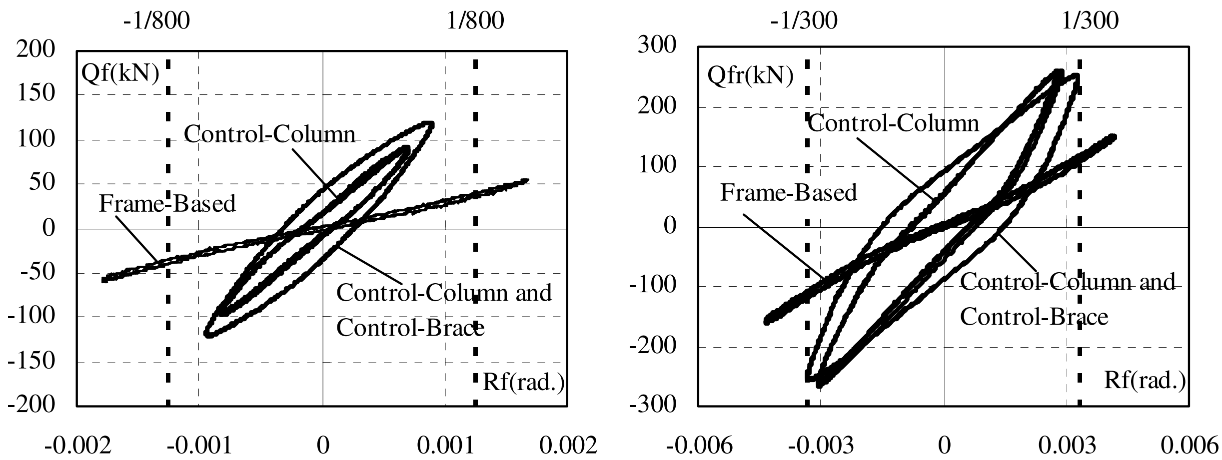
Not so many cracks develop in columns. The maximum size of residual crack width is approximately 0.06mm at the end of girders while most of the crack widths are smaller than 0.04mm. The stresses of longitudinal reinforcing bars of both girders and columns are still within elastic limit after the test.

The load-displacement relationships for dynamic loading are shown in Fig.9. Prior to the first yielding of reinforcing bars, the damage fuses can upgrade damping performance of an RC frame as compared with the curves from the frame-based test (without damage fuses).

Results of static loading test

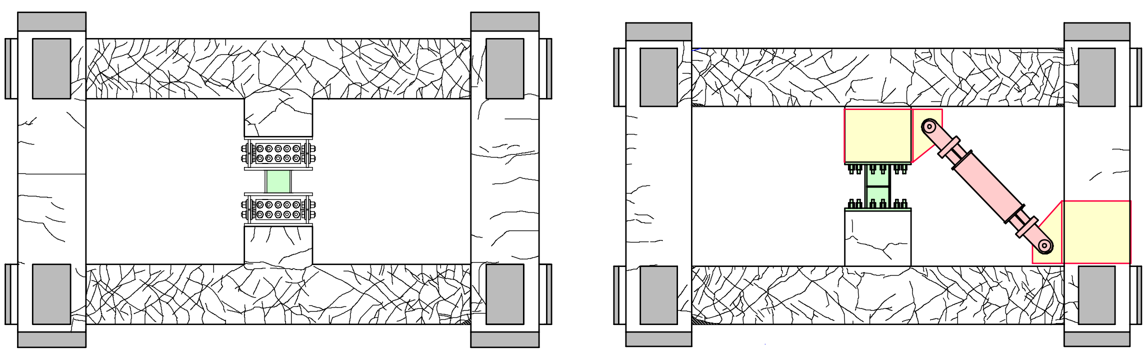
Fig.10 shows the crack patterns after testing. The maximum size of residual crack width is approximately 0.06mm when Rf reaches to 1/150. Part of reinforcing bars of girders starts to yield when Rf reaches to 1/100. When Rf reaches to 1/67, all longitudinal reinforcing bars in girders yield with the maximum size of residual crack width of 0.15mm. The flexural cracks of columns, meanwhile, start to develop when Rf reaches to 1/200. The numbers of flexural cracks of columns increase with Rf, whereas the most of the residual cracks of columns are closed after testing. The frame demonstrates that the flexural yielding of girders precedes the flexural yielding of columns. The web-plate of control-panel deforms out of plane of the web-plate when Rf reaches to 1/150 for the control-column test whereas the web-plate deforms out of plane when Rf reaches to 1/100 for the control-column and control-brace test. The out-plane deformations increase with Rf, whereas no tear of the web-plate develops at Rf of 1/33.

The out-plane deformation starts to develop adjacent to the pinned-joint of unbonded brace after the sequential loading of Rf of 1/100. After the sequential loading of Rf of 1/67, the out-plane deformations adjacent to the pinned-joints become markedly. Therefore, the direction of loading is set to move only in the direction in which the unbonded brace shows the characteristics of tensile stress.



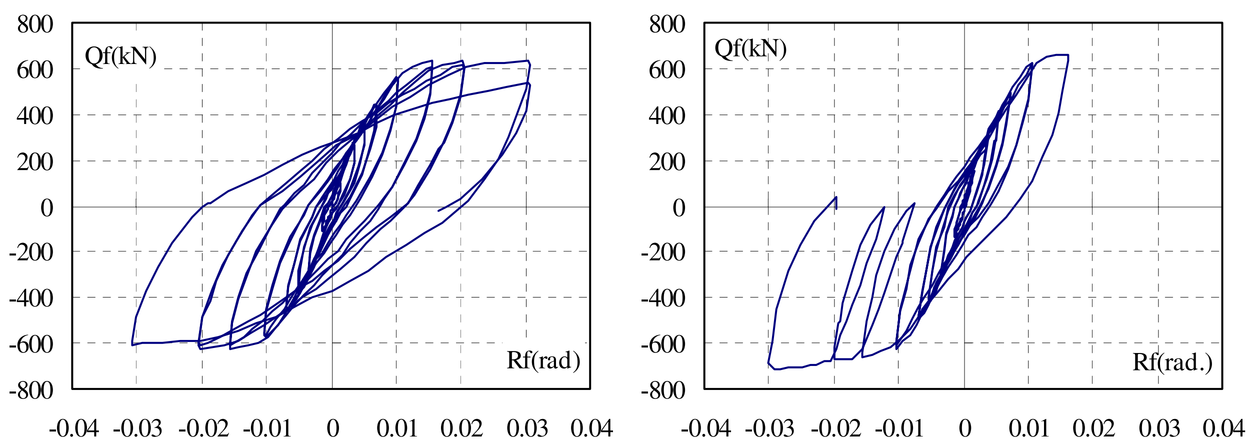
(a) Taget Rf of 1/800 (b) Target Rf of 1/300

Fig.9. Load-Lateral Drift Angle Relationships for Dynamic Loading



(a) Control-Column Test (b) Control-Column and Control-Brace Test

Fig.10. Crack Patterns after Testing



(a) Control-Column Test (b) Control-Column and Unbonded Brace Test

Fig.11. Load-Lateral Drift Angle Relationships of Static Loading Tests

Fig.11 shows the load-displacement relationships of the static loading tests. Prior to the flexural yielding of longitudinal reinforcing bars of girders at Rf of 1/67, the restoring force characteristics demonstrate a great ability of energy dissipation showing spindle-shape loops. The weld cracking causes the strength degradation after Rf reaches to 1/33 for the control-column test (see Fig.11(a)). No sign of the strength degradation is seen when Rf reaches to 1/33 for the control-column and control-Brace test only in the direction mentioned above (see Fig.11(b)).

EVALUATION OF EXPERIMENTAL RESULTS

Amounts of energy absorption

The comparison of the amounts of energy absorption is shown in Fig.12. The amounts of energy absorption are calculated by averaging the energy absorption values of three sequential loops. It is seen that installing the damage fuses can greatly increase the amount of energy absorption (The damage fuse dissipates the energy created by earthquake excitations.).

The equivalent viscous damping coefficient of the frame itself is approximately 0.02 (at Rf of 1/230) whereas the frame with the control-column and the control-brace is 0.16 (at Rf of 1/298). Therefore, installing the damage fuses can greatly improve the effect of damping on an RC frame.

Analysis model

The analysis model of the frame is based on the elasto-plastic characteristics of each RC member, as shown in Fig.13. In the analysis model, the flexural deformations of columns and girders behave nonlinearly whereas the shear and axial deformations behave elastically. The shear deformation of the control-panel is modeled by using a shear spring while the flexural deformations of the top and bottom of the control-column are modeled by using flexural springs of RC column. A Maxwell model with a linear axle spring of the brace describes the analysis model of an oil-damper brace whereas a bi-linear axle spring describes the analysis model of an unbonded brace. Pinned joints at each end, where steel plates reinforce the top of an RC stud and the bottom of a column, connect each of the braces. Rigid zones are set for the column-girder joints while shear panels are set for the joints between the control-column and the girders. Another rigid zones are also placed in each end of the control-brace in order to consider the eccentricity of the brace that acts on the columns.

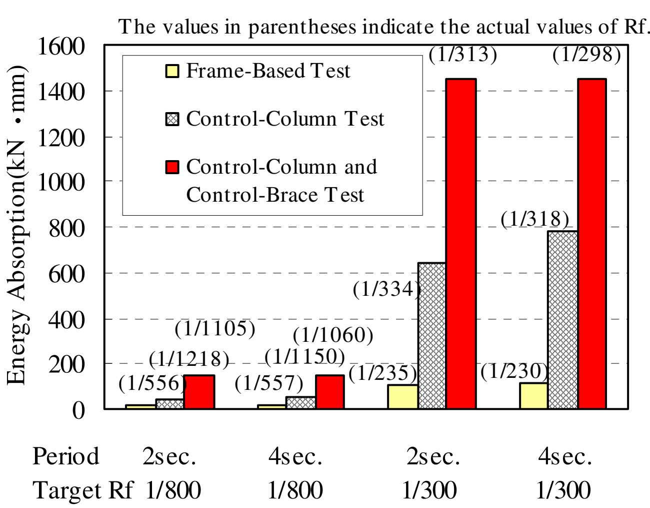


Fig.12. Comparison of Energy Absorption

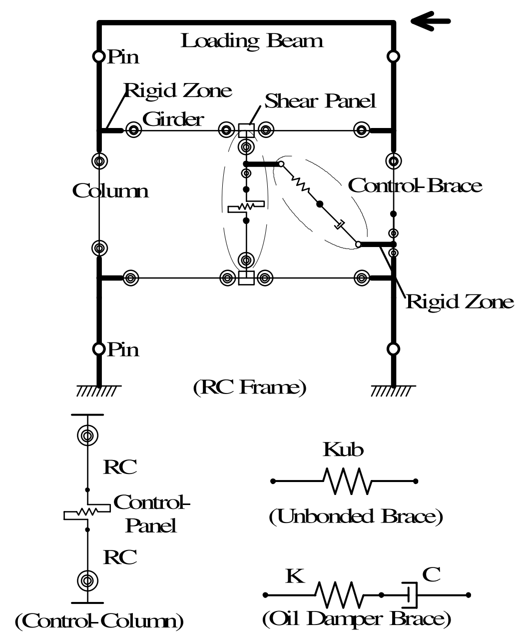


Fig.13. Analysis Model

Table 3 Restoring Force Characteristics of Analysis Model

(a) Control-Panel and Unbonded Brace

	Control-Panel	Unbonded Brace
Initial Stiffness (kN/mm)	99.0	397.8
First Breaking Point Load (kN)	59.4	96.0
Second Breaking Point Load (kN)	153.2	192.0
Second Gradient Ratio	0.0625	0.2
Third Gradient Ratio	0.0195	0.001

(b) Oil Damper Brace

Spring Stiffness (kN/mm)	137
C1(kN・s/mm)	667
C2(kN・s/mm)	41.7
Breaking Point Velocity (mm/s)	30
Breaking Point Damping Force (kN)	200

Restoring force characteristics

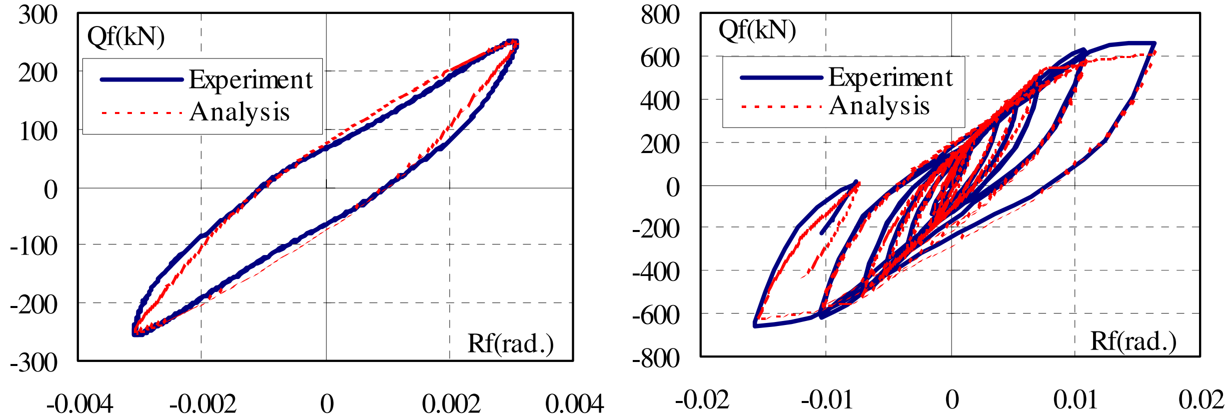
A Takeda model (Takeda [3]) that describes a crack point and a yield point is used for the restoring force characteristics of flexural deformations of columns and girders. A bi-linear curve model that exhibits a yield point describes the analysis model of the only column that is strengthened by the reinforcing steel plates. A Normal Tri-linear curve model describes the restoring force characteristics of shear deformations of the control-panel. The low-yield-point of the control-panel that has the first yielding stress of approximately 100kN/mm^2 doesn't demonstrate the exact value of a shear yield point. Therefore, the properties of a first and second yield points are referred to the test results of the control-panel itself (Izumi [4]), as shown in Table.3. The criterion point of low-yield-point panel is chosen to be the Rf of 1/100. And finally, a Normal Tri-linear curve of an axle spring describes the restoring force of an unbonded brace (see Tabel.3).

Restoring force characteristics of RC frame

The analysis model of restoring force characteristics of an RC frame with a control-column and a control-brace is compared with the test results of those. Fig.14(a) shows the comparisons of restoring force characteristics between the dynamic loading test results and the analysis model of the frame with the control-column and the oil-damper brace (natural period of 4 seconds at Rf of 1/298). The analysis value of the amount of energy absorption of the frame is approximately 95% of the test result while the analysis value of the equivalent viscous damping coefficient is approximately 93% of the test result.

Next, the analysis model of restoring force characteristics is compared with the static loading test results of those. Fig.14(b) shows the comparison of restoring force characteristics between the static loading test results and the analysis model of the frame with the control-column and the unbonded brace. The analysis values of the energy absorption of the frame range from 92 to 109% of the test results under the displacements ranging from Rf=1/150 to Rf=1/100. Therefore the analysis model appropriately expresses the characteristics of the RC frame obtained from the test results. However, the analysis values are somewhat larger than the test results as the analysis values range from 101 to 131% of the test results under the displacements ranging from Rf=1/300 to Rf=1/200. Furthermore, the analysis values of the equivalent viscous damping coefficient are nearly identical to the test results.

Therefore, the analysis models satisfactorily predict the load-displacement relationships of all test specimens with acceptable accuracy.



(a) Control-Column and Oil-Damper Brace in Dynamic Loading

(b) Control-Column and Unbonded Brace in Static Loading

Fig.14. Comparisons of Restoring Force Characteristics (Static & Dynamic)

CONCLUSIONS

Based on the studies presented in this paper, the following conclusions can be made:

1. In the region of assumed deformations under small to large earthquake intensity, applying damage fuses is substantially able to improve the energy dissipation ability of an RC frame.
2. Prior to flexural yielding of reinforcing bars, the restoring force characteristics of an RC frame with damage fuses display a great ability of energy dissipation showing spindle-shape loops.
3. The analysis models of RC frame with damage fuses predict the load-displacement relationships obtained from the test results with acceptable accuracy.

ACKNOWLEDGMENTS

The research in this paper was conducted as a part of Toda Corporation-Nishimatsu Construction Cooperative Research Program. The assistance of Mr. Takahiro Watabe and Mr. Hiroyuki Takenaka of Toda Corporation in preparing the paper was acknowledged. The writers also wish to express sincere gratitude to the members of the program for their support on the experimental investigation.

REFERENCES

1. Izumi N, Takenaka H, Ooi T, Chiba O. "Experimental Study on Seismic Performance of RC Column with Low Yield Point Strength Steel Panel." Proceedings of Japan Concrete Institute, 2000. 22(3), 1099-1104.
2. Izumi N, Takenaka H, Chiba O, Asega H. "A Study on Seismic Performance of RC Frame with Damping Member." Proceedings of Japan Concrete Institute, 2002. 24(2), 1057-1062
3. Takeda, Sozen, Nielsen, "Reinforced Concrete Response to Simulated Earthquake." Journal, Structural Division, ASCE, 96(ST12), 1970: 2257-2573.
4. Izumi N, Takenaka H, Chiba O. "Experimental Study on Damping Member with Low Yield Strength Steel." Summary of Technical Papers of Annual Meeting of Architectural Institute of Japan, Fukuoka, 1998. Vol.C-1, 785-790