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SEISMIC RETROFIT FOR EXISTING R/C BUILDING USING ENERGY DISSIPATIVE BRACES

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SUMMARY

The authors propose the method of attaching the energy dissipative brace in the building exterior for purpose of the seismic retrofitting for existing R/C buildings. It is a simple method to attach a bracing just on the building facade by means of the steel plates fixed to the facade with steel bars for prestressed concrete. This method is economically feasibly , since it requires no steel frames to attach the bracing.

However, considering the bracing to stick out of building facade, it is necessary to take into consideration not only the strength and the rigidity of the brace-end connection but also a torsion introduced into the beam end.

In this paper, the vibration control effect is discussed according to the amount of story drift angle as well as the collapse type of the R/C frame under the cyclic loading; the loading tests of the bracing installed into R/C frame were conducted, and horizontal cyclic load was applied to the frame.

INTRODUCTION

The purpose of this research is to develop an evaluation method which makes it possible to verify the dynamic seismic performance of a seismic retrofitting system which can be installed more simply than external framing. In the proposed method, buckling-restrained hysteretic damping-type energy dissipative braces (hereinafter referred to as energy dissipative brace) are attached externally to the facade of an existing reinforced concrete (RC) building by clamping with prestressing steel bars (PC bars) by way of anchor plates and grout **[1]**. As a seismic retrofitting method for existing RC buildings, Kitajima et al. have shown in pseudo-dynamic experiments that a strengthening effect can be obtained by externally attaching members called damper-brace devices, which consist of a steel brace and a friction damper and have a low upper limit value of yield strength, to a structure where column shear failure is the prevalent failure mode **[2]**.

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However, when using energy dissipative braces which are strengthened by strain hardening under seismic loading, such as those in the present research, the vibration control effect is greatly influenced by local stresses generated by the braces and by differences in the collapse type of the RC frame. In view of such factors, there is room for further study. In past research **[1]**, the authors investigated the failure characteristics of the RC beam end and energy dissipative brace connection and verified the existing design methods for energy dissipative brace connections and the RC beam end based on cyclic diagonal loading element experiments with brace connections.

Considering the fact that the slabs in actual buildings do not bear the component force in the beam axial direction of energy dissipative braces, in this paper, we conducted static horizontal positive and negative alternating loading (reversed cyclic loading) experiments in which hysteretic damping-type energy dissipative braces were attached to RC frames of different collapse types, ignoring the slab in order to make a conservative evaluation of design safety, and identified the process of frame damage with each collapse type. We then clarified the effect of differences in collapse type on the vibration control effect of the energy dissipative braces by evaluating seismic performance with particular attention to energy absorption characteristics.

EXPERIMENTAL PROCEDURE

Specimens

As specimens, 1/2 scale models of one-story one-span RC frames of three different collapse types were fabricated. All of the RC frames were designed with a target story shear strength of approximately 400 kN. An example of the reinforcing bar arrangement is shown in **Fig.1**. A list of member sections is given in **Table 1**. The ultimate bending strength, M_u, and ultimate shear strength, Q_u of the columns and beams were obtained from references **[3]** and **[4]** using the material properties shown in **Table 2**.

The girder bending (Gb) yielding specimen was a weak-beam and strong-column type in which the bending strength of the beam was set at 1/3 that of the columns so that the beam would yield before the columns. The design shear strength of the beam was set with a margin of 2 times the shear strength in the collapse mechanism; a margin of 1.2 was set for the columns. In the column bending (Cb) yielding specimen, a column bending strength 1/3 that of the beam was assumed, so that the columns yield before the beam. In this case, the margin relative to shear strength during collapse is 2 for the beam and 1.1 for the columns. In the column shear failure (Cs) specimen, a margin of 1.6 times relative to the bending strength of the columns during shear failure is set for the columns; for the beam, a margin of 2.5 times is assumed for shear strength and 1.6 times for bending strength. The strength of the energy dissipative braces assumes a yield strength of 80 kN per brace when converted to story shear load. In the preliminary analysis, the rigidity ratio (ratio of rigidity of energy dissipative brace/rigidity during yielding of RC main structure) was assumed to be 3.96 for Gb, 4.17 for Cb, and 2.22 for Cs, and the yield strength ratio (ratio of yield strength of energy dissipative

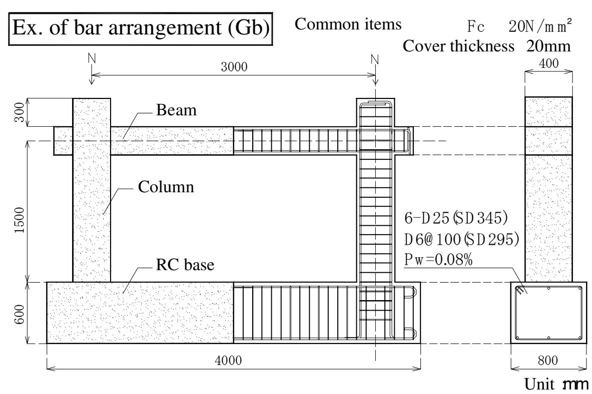


Fig.1: Example of arrangement of reinforcing bars in specimen

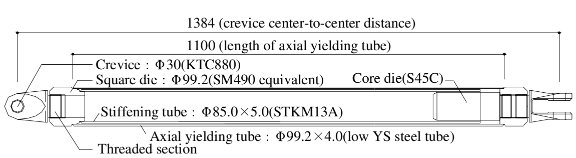


Fig.2: Configuration of energy dissipative brace

brace/strength in RC collapse mechanism) was assumed to be approximately 0.3 in all cases.

The hysteretic damping-type energy dissipative brace is a buckling-restrained tube-in-tube energy dissipative brace, in which low yield point steel (steel with low yield stress) is used in the axial yielding member, and buckling is restrained by an inner steel tube which acts as a stiffener. The brace comprises an outer axial member tube, which forms the core material that transmits axial force, and the inner stiffening tube, which restrains overall buckling of the axial member during compression without transmitting axial force. The configuration of the energy dissipative brace is shown in **Fig.2** The mechanical properties of the axial member (low YS steel tube) are shown in **Table 3**. Anchor plates are used to attach the brace. The brace is clamped with 4 PC bars in which initial axial tensioning of 150 kN is introduced. Axial tension is controlled by strain gauge values. **Fig.3** shows the detail of the anchor plate and the clamping position of the PC bars.

Table 1: List of member sections

Specimen	Girder bending yielding (Gb)	Column bending yielding (Cb)	Column shear yielding (Cs)
Initial axial tensioning (kN)	320	245	320
	Beam section		
Mu (kN·m)	69.6	224	119
Qu (kN)	97.6	249	124
b×D	200×300	250×500	200×300
Top/bottom side reinforcement	6-D19(SD345)	6-D25(SD345)	6-D25(SD345)
Rib reinforcement	D6 @100(SD295)	D6 @100(SD345)	D6 @100(SD295)
Pw(%)	0.48	0.38	0.48
	Column section		
Mu (kN·m)	217	139	329
Qu (kN)	250	246	199
b×D	400×400	350×350	400×400
Main reinforcement	8-D22(SD345)	6-D22(SD345)	8-D29(SD345)
Hoop reinforcement	D6 @100(SD295)	D6 @50(SD295)	D6 @100(SD295)
Pw(%)	0.32	0.55	0.16

Mu: Ultimate bending strength Qu: Ultimate shear strength
b ×D: Width × height

Table 2: Material properties of concrete and grout

Specimen	Concrete			Grout
	Tensile strength (N/mm^2)	Compressive strength (N/mm^2)	Young's modulus ($\times 10^4 N/mm^2$)	Compressive strength (N/mm^2)
Gb	1.50	15.6	1.58	45.2
Cb	1.42	15.5	1.85	35.9
Cs	1.72	17.1	1.85	39.8

Table 3: Mechanical properties of low yield point steel

Tube diameter (mm)	Tube thickness ave(mm)	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Yield ratio (%)
99.2	3.95	96.4	240	53.8	40.2

Loading Device

The loading device, including an RC specimen, is shown in **Fig.4**. The specimen was placed on a steel frame platform and secured with PC bars. Two steel plates were embedded in the beam-to-column connections of the RC frame, pins for use in loading were set, and panel zone strengthening was performed. In horizontal loading, the actuators on both sides were operated simultaneously in the same direction so that axial forces would not act on the beam. A constant vertical load was introduced in all columns using oil jacks to obtain an axial force ratio of 0.1. To restrain out-of-plane deformation during horizontal loading, bearings were mounted on steel plates on the column side faces, and restraining beams were aligned parallel to the RC frame beam.

Loading Method and Measurement Items

Fig.3 shows the detailed positions of the displacement gauges attached around the left beam end (left end of beam in **Fig.4**, **Fig.4** shows the positions of the main displacement gauges used in measurements, and **Fig.5** shows the positions of the strain gauges on the main reinforcements and hoop reinforcements in members.

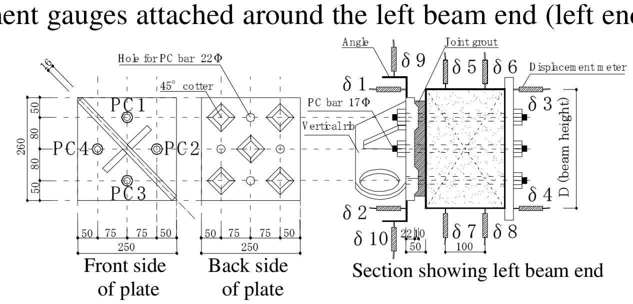


Fig.3: Detail of anchor plate and positions of displacement meters

Loading was controlled by the story drift angle R, which was calculated from the displacement gauge δ_R at the center of the RC frame. After confirming crack initiation, 2 cycles of

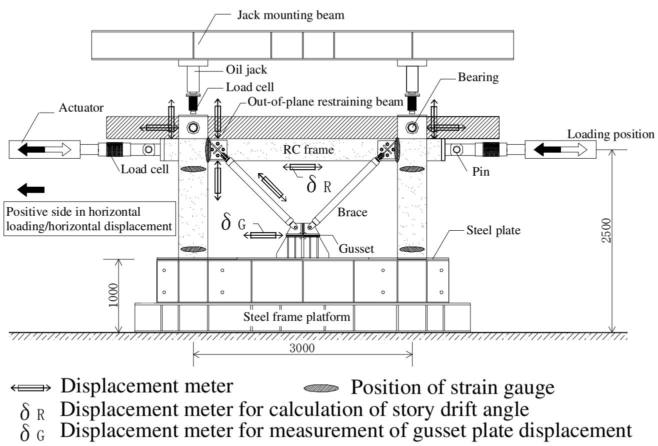


Fig.4: Loading device and positions of value measurements

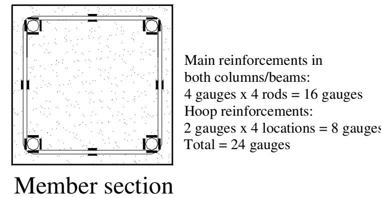


Fig.5: Gauge position

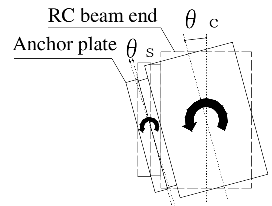


Fig.6: Concept of rotation angle

incrementally increasing positive and negative alternating loading were applied in each stage, with loading increased in steps of R = 5/1000 rad. To confirm residual seismic performance, the energy dissipative braces were removed and 1 cycle of positive and negative loading was performed to the story drift angle experienced immediately previously or to a larger angle. The rotational displacement of the anchor plate was measured by δ1, δ2, torsional deformation of the RC beam was measured by δ3 through δ8, and lateral displacement of the anchor plate was measured by δ9, δ10. In the energy dissipative brace, elastic displacement was measured. Strain in the main reinforcements and shear reinforcing bars of the RC main structure, PC bars, and energy dissipative brace was measured with gauges. Loads due to horizontal and vertical loading were measured with load cells. The torsional rotation angle of the beam end θ_c and rotation angle of the anchor plate θ_s were calculated by eq. (1) and (2). The concept of θ_c and θ_s is shown in **Fig.6**. Here, D is girder depth.

$$\theta_c = (\delta 5 + \delta 6) \times \frac{1}{D} \qquad (1)$$

$$\theta_s = \{(\delta 1 - \delta 3) + (\delta 2 - \delta 4)\} \times \frac{1}{D} \qquad (2)$$

EXPERIMENTAL RESULTS

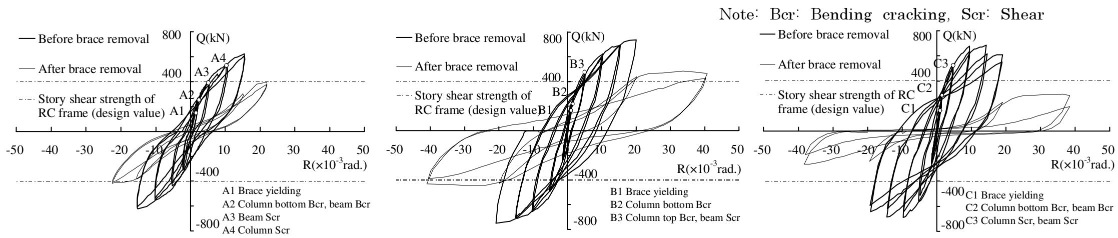
Damage Behavior of RC Frame-Brace System

Fig.7 shows the relationship Q–R between the horizontal load acting on the RC frame-brace system (Q) and the story drift angle (R) in each of the specimens.

The failure characteristics of the respective specimens are shown in **Fig.8.** In this connection, it may be noted that gusset plate displacement δ_G (**Fig.4**) was substantially zero in all the specimens.

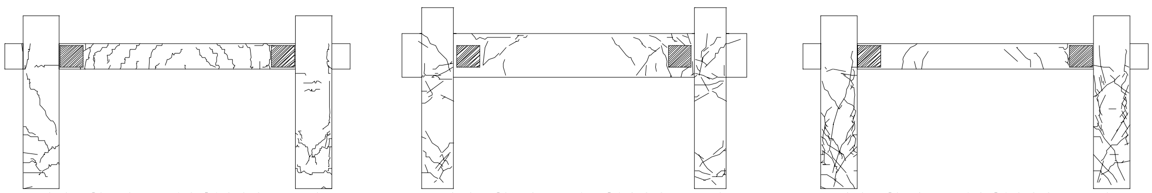
Isolation of Hysteresis Curves of RC Frame and Energy Dissipative Braces

To investigate the behavior of energy dissipative braces in RC frames, the Q–R relationship was divided into the story shear force shared by the RC structure and the story shear force shared by the brace. In the following, the former is referred to as the Q_C–R relationship, and the latter, as the Q_B–R relationship. The restoring force property of the energy dissipative brace obtained in an element test of the brace shown in **Fig.9** was modeled by the method proposed in reference **[5]** and used as the load cell of the braces in this experiment. In this connection, the yield strength of the unit braces increased due to strain hardening, and the cumulative ductility factor η before buckling reached 1073.



(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.7: Q-R relationship in respective specimens



(a) Gb(R=10/1000rad.) **(b) Cb(R=15/1000rad.)** **(c) Cs(R=10/1000rad.)**

Fig.8: Failure condition of specimens

Behavior of Energy Dissipative Braces in RC Frames

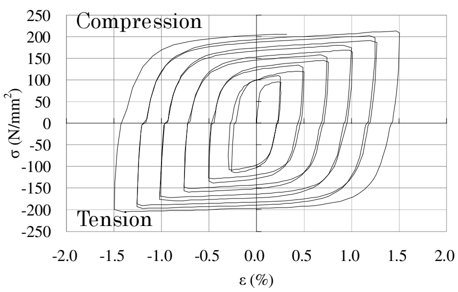


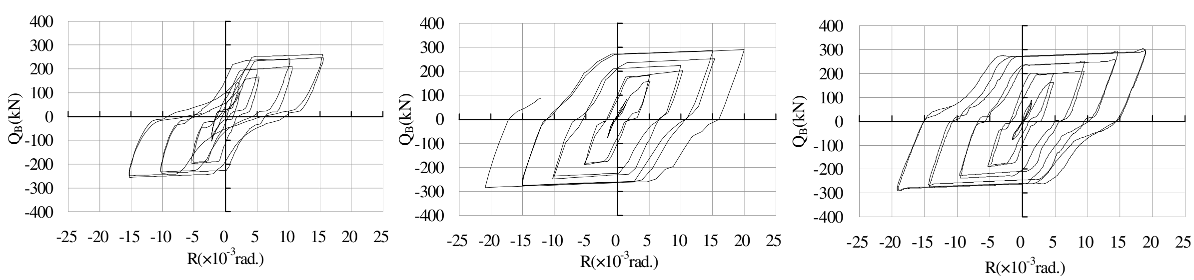
Fig.9: Results of brace element test

Hysteresis curves for the Q_B–R relationship are shown in **Fig.10**. It was found that the Q_C under small displacement obtained using the strain on the column main reinforcements (by calculating the moments acting on the column top and bottom ends and dividing by the gap between the base and beam face) and the Q_C under large displacement obtained from the Q–R relationship after removal of the braces roughly agrees with the Q_C obtained by subtracting Q_B from Q. **Fig.11** shows the θ_c–R and θ_s–R relationships. The respective rotation angles have been determined so as to be positive when the braces are in tension.

From **Fig.10(a)**, in Gb, after loading is removed, the brace axial force does not increase, even with progressive story displacement under negative loading, indicating that story drift is adequately transmitted in the form of brace axial deformation. In comparison with Gb, Cb and Cs show large hysteresis curves.

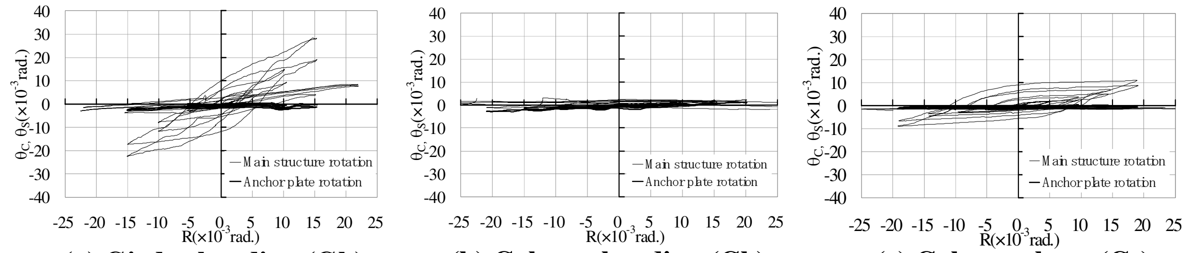
With Gb in **Fig.11(a)**, θ_c is large in comparison with that of the Cb frame in **(b)** and Cs frame in **(c)**, and furthermore, torsion is larger when the tensile force caused by the braces acts on the beam ends. This suggest that brace axial force influences torsional deformation. The same result was also obtained in reference **[2]**.

Although Cs and Gb have beams with the same sectional profile, because θ_c is smaller in Cs, it can be



(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.10: Q_B-R relationship



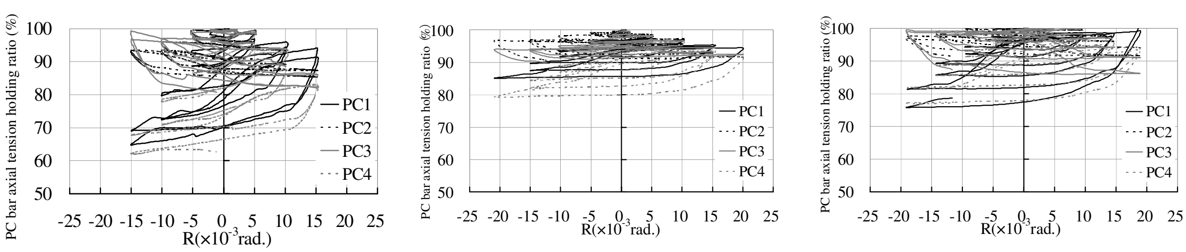
(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.11: θ_c-R, θ_s-R relationship

inferred that the main reinforcement capacity is effective against torsional deformation. On the other hand, Cb has a large cross-sectional area, and the energy absorbing capacity of the energy dissipative brace is consistently satisfactory.

Damage Behavior at Anchor Plate Attachment

Fig.12 shows the PC bar axial tension holding ratio (axial tension on PC bar/initial axial tension introduced in PC bar). With Gb, axial tension on the PC bars decreases by a maximum of approximately 40%. As mentioned previously, with Cs, damage to the beam ends was slight, and as a result, the reduction in axial tension on the PC bars was also smaller than in Gb, at a maximum of approximately 25%. Similarly, due to its large beam section, Cb suffered virtually no beam end damage and maintained a PC bar axial tension ratio of roughly 80% or more. When the anchor plates were removed after the experiment, virtually no cracking was observed in the grout surface of any of the specimens. Thus, as shown in **Fig.11**, because almost no rotation occurred in the anchor plates with any of the specimens, the torsional deformation of the beam ends is thought to have had a large influence on the reduction in PC bar axial tension.



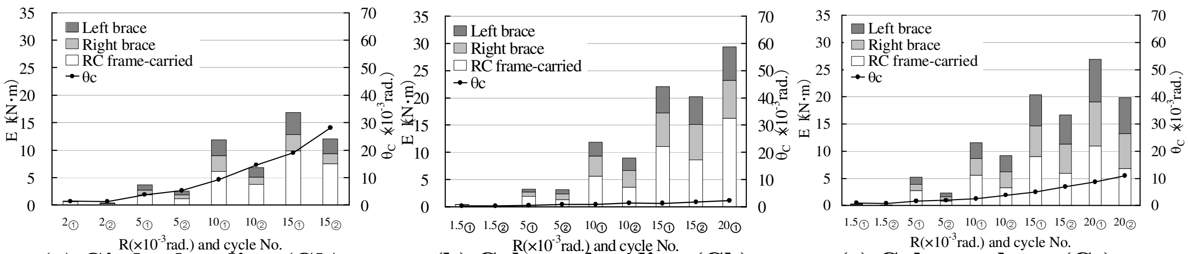
(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.12: PC bar axial tension holding ratio-R relationship

DISCUSSION

Analysis of Seismic Performance in Terms of Energy Absorption Capacity

Fig.13 shows the hysteretic damping energy absorption of the RC frame and energy dissipative braces calculated as the area of the hysteresis curve in each loading cycle, together with the rotation angle θ_c of the beam ends where the energy dissipative braces were attached. Up to R = 15/1000rad., the energy absorption of the RC frame was substantially the same with all specimens. Comparing the 1st and 2nd cycles at each story drift angle, the energy absorption of the RC frame was smaller in the 2nd cycle with all specimens. In comparison with Cs, which went into shear failure at R = 15/1000rad., with Cb, the energy absorption of the RC frame increased at R = 20/1000rad. The energy absorption of the energy dissipative braces was stable in Cb and Cs at all story drift angles. In contrast to this, with Gb, the absolute value of energy absorption by the braces was small, and furthermore, in the 2nd cycle at each story drift angle, energy absorption decreased to approximately 50% that in the 1st cycle. In the 2nd cycle at R = 15/1000rad., Gb showed a value of nearly θ_c = 30/1000rad., and extremely severe torsional damage



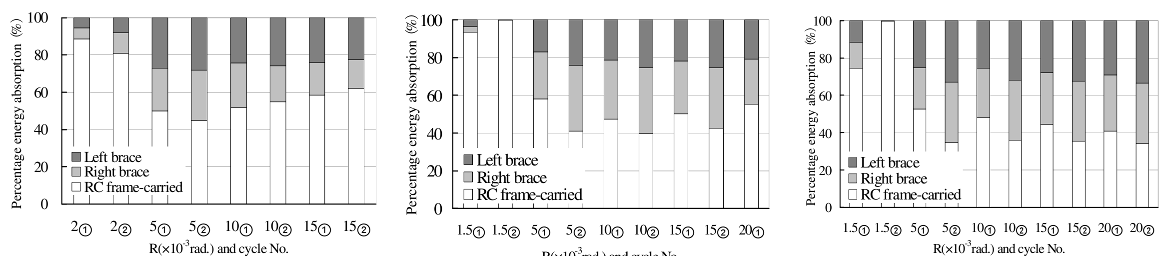
(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.13: Absolute energy absorption (E)-R relationship

had occurred in the beam ends. It can therefore be understood that the energy absorption performance of the energy dissipative braces is strongly influenced by local torsion.

Strengthening Effect of Energy Dissipative Braces

Fig.14 shows the relative amounts of hysteretic damping energy absorption of the RC frame and energy dissipative braces calculated for each loading cycle in **Fig.13**. Considered in percentage terms, even at R = 5/1000rad., where absolute energy absorption is small, the energy dissipative braces absorb approximately 50% of total absorbed energy in all of the specimens. Comparing the 1st and 2nd cycles, the amount of energy absorption shared by the RC frame decreases, and in the 2nd cycle, percentage energy absorption by the braces tends to show a relative increase. However, with Gb, as the story drift angle increases, percentage energy absorption by the braces begins to decrease at R = 10/1000rad. due to the influence of torsion, and thereafter, percentage energy absorption by the braces decreases even when story displacement increases. With Cb, the energy dissipative braces show high percentage energy absorption at all story drift angles, while with Cs, the percentage energy absorption by the braces shows a relative increase as the story drift angle increases due to progressive shear failure of the columns.



(a) Girder bending (Gb) **(b) Column bending (Cb)** **(c) Column shear (Cs)**

Fig.14: Percentage energy absorption (%)-R relationship

CONCLUSION

The following knowledge was obtained in these experiments.

1. The following can be said with regard to frames of the respective collapse types.

   With the girder bending (Gb) yielding type frame, when energy dissipative bracing is installed by eccentric external attachment, torsion causes damage to the beam ends, which have relatively low strength, and the effect of the energy dissipative braces tends to decrease as the story drift angle increases. However, this type of frame showed high residual seismic performance after the energy dissipative braces were removed.

   With the column bending (Cb) yielding type frame, stable energy absorption by the braces could be confirmed because the beams possessed adequate strength, indicating that energy dissipative braces are suitable for seismic retrofitting in structures of this type.

With the column shear (Cs) failure type frame, the beam main reinforcement functioned effectively in suppressing torsion, which has a negative effect on energy dissipative brace performance. As a result, the seismic retrofitting effect of the energy dissipative braces was high. However, a reduction in residual seismic performance was noted.

2. The axial tension on the prestressed steel bars (PC bars) was reduced due to the effect of torsion at the beam ends, which resulted from eccentric attachment of the energy dissipative braces, but because anchor plate rotation was extremely small, adequate performance could be secured in the brace connections. However, in retrofitting with energy dissipative braces where increased strength is expected from strain hardening, adequate consideration must be given to the forces generated in the beam ends by the braces and torsional deformation.

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