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Seismic Retrofitting for Existing R/C Buildings Using Buckling-Restrained Tube-in-Tube Energy Dissipative Braces†

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Abstract:

A New method of seismic retrofitting for existing R/C buildings is proposed by which energy dissipative braces are attached to the building exterior. Followings are results of the experiment; (1) The method shows better damping effect. The torsional deformation at the beam end has a large effect on the seismic performance. (2) An effective factor for local torsional deformation is specified by identifying failure mode at the beam end. An evaluation formula for the connecting beam is verified by the experimental result. Finally, prediction model the required strength of the braces is proposed.

1. Introduction

The necessity for earthquake-proofing existing buildings has been pointed out in Japan since the 1995 Southern Hyogo Prefecture Earthquake (the Great Hanshin Awaji Earthquake). Antiseismic diagnoses and reinforcement of existing reinforced concrete (RC) structures have been carried out from long ago. In recent years, seismic retrofitting, which involves using hysteretic damping-type energy dissipative members for energy absorption, has been proposed and carried out. When seismic retrofitting is applied to buildings for which many structure surfaces to be reinforced can be accessed as in school buildings, reinforcement can be performed simply by adding energy dissipative members to the periphery of the buildings. In such a case, seismic retrofitting has the advantage that the reinforcement work can be executed while the buildings are being used, resulting in lowered construction costs and shortened construction periods[1,2].

Considering that inexpensive and rapid execution of work is possible if energy dissipative members can be easily attached and replaced, the authors have proposed a new method of seismic retrofitting as shown in **Fig. 1**. Unlike conventional seismic retrofitting methods in which strength resistance is considered and which involve installing steel frame members and seismic braces within a frame, under this new method, through holes are made on a beam's side surface of an RC frame, and then buckling-restrained hysteretic damping-type energy dissipative braces (hereafter referred to as energy dissipative braces) are directly attached to the surface of a structure via anchor plates.

Because energy dissipative braces are eccentrically attached directly to an RC frame member, problems of this method include an evaluation of the effect of an axial force of an energy dissipative brace on the yield strength of an RC frame. Therefore; the following evaluations are needed: the effect of torsional moment and added axial forces by eccentric attachment on the strength of beam members, the efficiency of conversion of the inter-story deformation of RC frames into the axial deformation of energy dissipative braces, and

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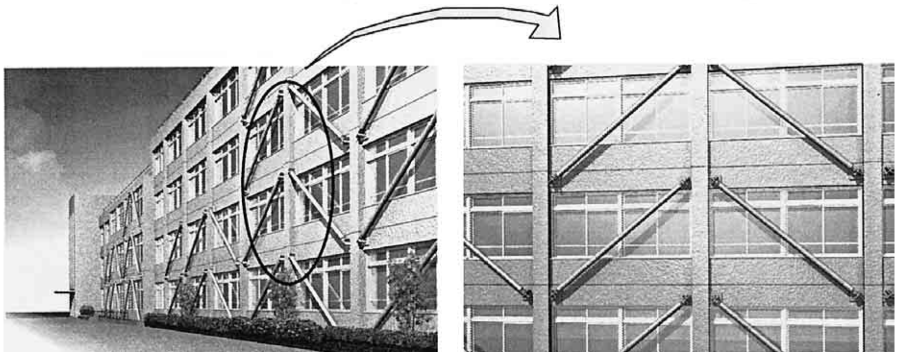


Fig. 1 Proposed method

finally, the relationship between the extent of damage to RC frames, with energy dissipative braces added, and a story drift angle.

The purpose of this paper is to propose a design policy of energy dissipative brace connections in a seismic retrofitting method. First, a static cyclic loading experiment of an RC frame to which energy dissipative braces are attached is conducted and the fracture behavior of the whole frame and the seismic retrofitting effect are verified. Next, with attention directed toward energy dissipative brace connections, a cyclic diagonal loading element experiment is conducted on the energy dissipative brace connections to understand the torsional failure characteristics and ultimate torsional yield strength of the beam end where the energy dissipative braces are attached and verify the existing evaluation formula of torsional yield strength. On the basis of these examinations, an investigation is made into the validity of the evaluation of the local torsional yield strength of the beam member within the RC frame.

2. Examination by Experiment on RC Frame with Braces

2.1 Experiment Plan

The RC frame portion of a 1/2 size model of a one-story one-span rigid frame is shown in **Fig. 2**. Two specimens having different collapsing types, i.e., a girder bending yielding specimen and a column bending yielding specimen were prepared. Each of the specimens was designed so that an RC frame obtains a story shear yield strength of 400 kN or so[3,4]. A list of the member sections is shown in **Table 1**. The energy dissipative brace chosen is a buckling restrained tube-in-tube dissipative brace by inner tube stiffening using low-yield-point steel tubes "RIVER FLEX100-S." The configuration of the energy dissipative brace is shown in **Fig. 3**. The V shaped energy dissipative braces have a yield strength of 80 kN per brace when converted to a story shear load, and the yield strength ratio (the ratio of the shear

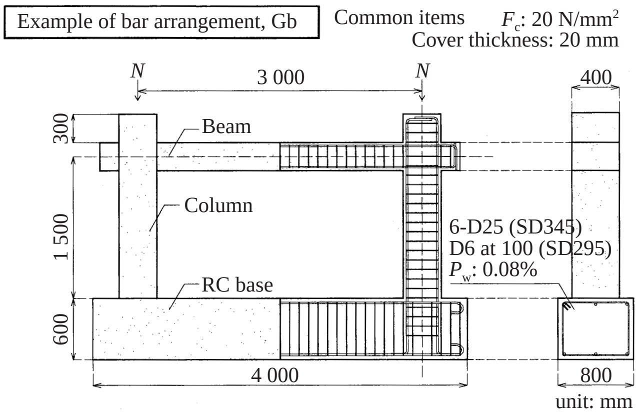
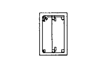
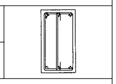
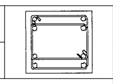
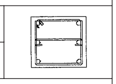


Fig. 2 Example of arrangement of reinforcing bars in specimen

Table 1 List of member sections

Specimen	Girder bending yielding, Gb		Column bending yielding, Cb	
Initial axial tensioning (kN)	320		245	
	Beam section			
M_u (kN · m)	69.6		224	
Q_u (kN · m)	97.6		249	
$b \times D$	200 × 300		250 × 500	
Top/bottom side reinforcement	6-D19 (SD295)		6-D25 (SD345)	
Rib reinforcement	D6 at 100 (SD295)		D6 at 100 (SD345)	
P_w (%)	0.48		0.38	
	Column section			
M_u (kN · m)	217		139	
Q_u (kN)	250		246	
$b \times D$	400 × 400		350 × 350	
Main reinforcement	8-D22 (SD345)		6-D22 (SD345)	
Hoop reinforcement	D6 at 100 (SD295)		D6 at 50 (SD295)	
P_w (%)	0.32		0.55	

M_u: Ultimate bending strength, Q_u: Ultimate shear strength,
$b \times D$: Width × height

strength of the energy dissipative brace to the strength in the RC frame) is 0.4 or so.

Anchor bolts are used to attach the brace. The brace is attached to a side surface of an RC frame with four PC

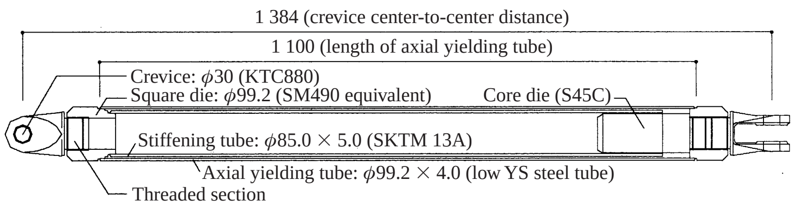
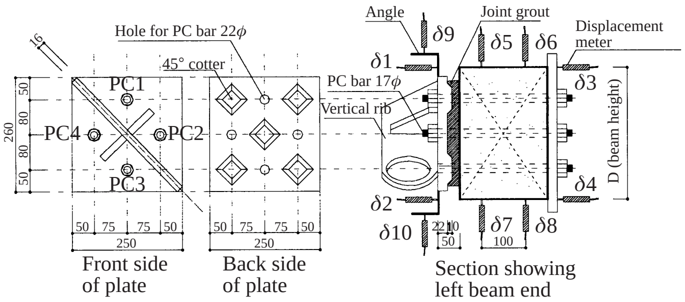


Fig. 3 Configuration of energy dissipative brace

steel bars in which an initial axial tensioning of 150 kN per PC bar is introduced. **Figure 4** shows a detail view of an anchor plate and PC bar positions.

The loading device used in the experiment is shown in **Fig. 5**. Loading was controlled by the story drift angle (R), which was calculated by use of a displacement meter δ_R at the center of the RC frame. After the confirmation of crack initiation, two cycles of incrementally increasing positive and negative alternating loading were applied in each stage, with loading increased in steps of R = 5/1 000 rad. A constant vertical load was introduced in each column by use of an oil jack so that the axial force ratio became 0.1. The torsional rotation angle (θ_c) at the beam end and the rotation angle (θ_s) of the anchor plate were measured by using the displacement meters shown in Fig. 4. The elastic deformation in the energy dissipative brace was measured.



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

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

D : Girder depth

Fig. 4 Detail of anchor plate and positions of displacement meters

2.2 Experimental Results

2.2.1 Damage behavior of each specimen and their load-deformation relationship

Figure 6 shows the relationship between the story shear force Q and story drift angle R of each specimen.

In the girder bending yielding specimen (hereinafter called the Gb specimen), the beam end was twisted while loading was continued, and the damage to the beam end by the torsion became great when R reached 15/1 000 rad. Therefore, the energy dissipative braces were removed. Due to the loading after the removal of the energy dissipative braces, the main reinforcements

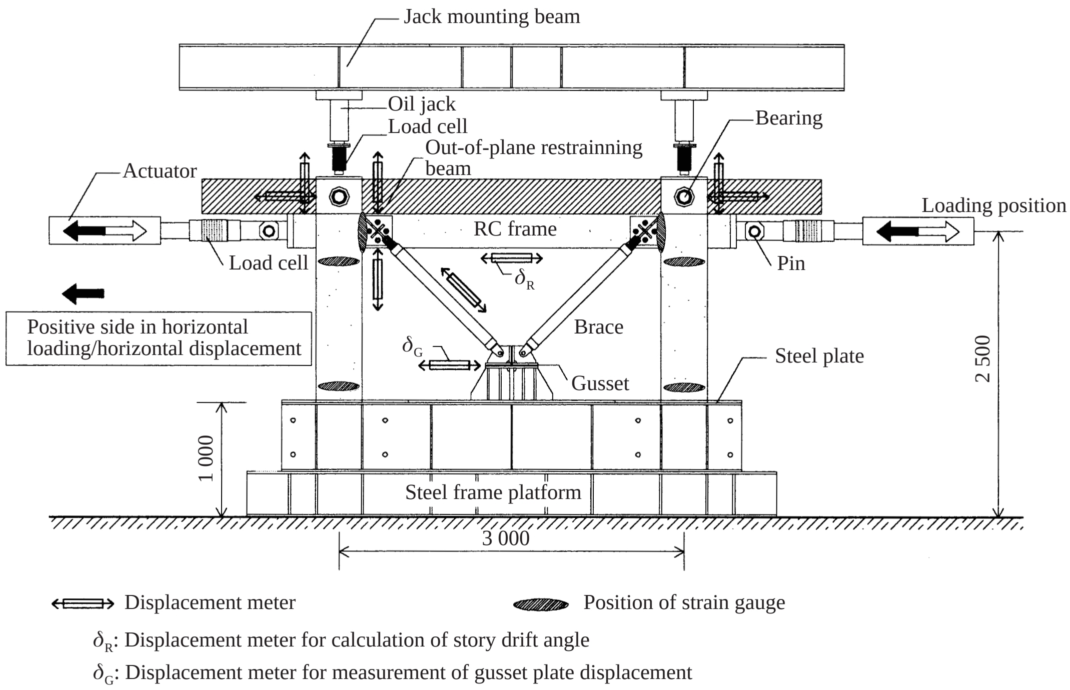
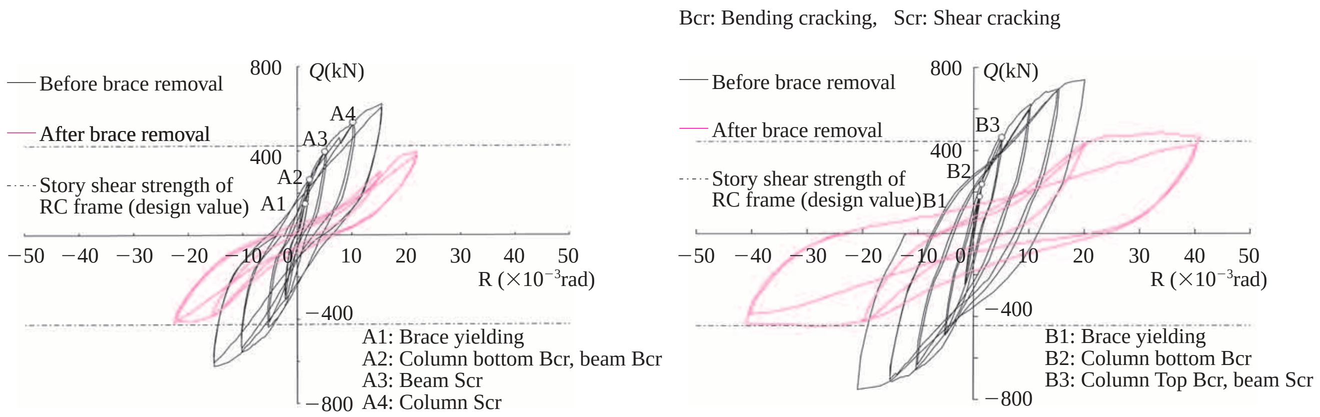
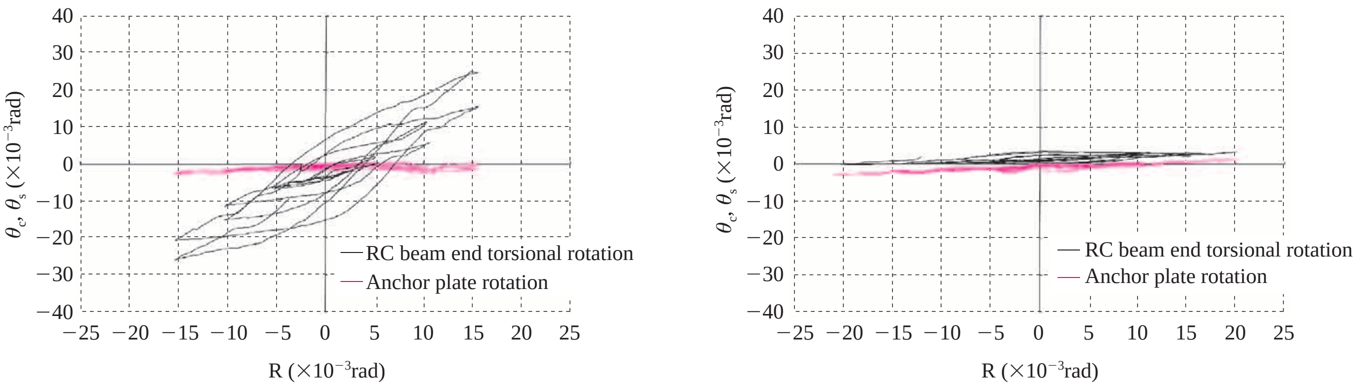


Fig. 5 Loading device and positions of value measurements



(a) Girder bending yielding, Gb (b) Column bending yielding, Cb

Fig. 6 *Q*-*R* relationship in respective specimens



(a) Girder bending yielding, Gb (b) Column bending yielding, Cb

Fig. 7 θ_c-R, θ_s-R relationship

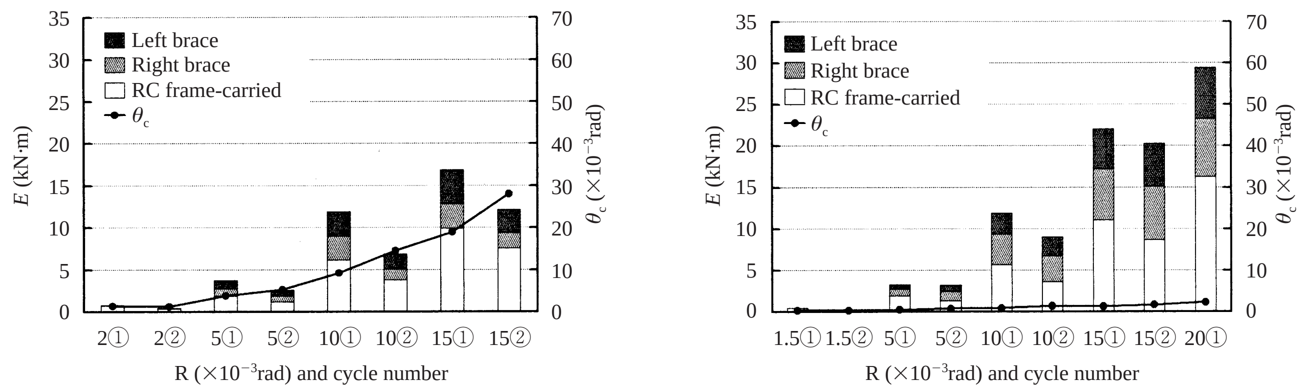
of both columns yielded at R = 20/1 000 rad and the designed yield strength was exceeded, resulting in a girder bending yielding type collapse mechanism.

In the column bending yielding specimen (hereinafter called the Cb specimen), cracks in both columns opened greatly at R = 15/1 000 rad and later and the designed yield strength was exceeded, resulting in a column bending yielding type collapse mechanism. At this stage, the energy dissipative braces were removed and after that, loading was continued until R reached 40/1 000 rad. However, the yield strength did not become lower than the designed yield strength.

In **Fig. 7**, R is plotted as the abscissa, and the torsional rotation angle θ_c at the beam end of each specimen and the rotation angle (θ_s) of the anchor plate are plotted as the ordinate. From Fig. 7(a) it is apparent that in the Gb specimen, θ_c is large and that damage to the beam end by torsion is great. On the other hand, from Fig. 7(b) it can be seen that θ_c is large and that the beam end is hardly damaged. Both specimens have small values of θ_s and in the energy dissipative brace connections, the anchor plates function well without rising. Thus, the validity of the design formula shown in Ref. 5) was verified. No fracture of the grout portion was observed and, this also shows that the design formula shown in Ref. 6) is valid.

2.2.2 Strengthening effect of energy dissipative braces

To grasp the effect of the degree of torsional damage to the beam end on the damping effect of the energy dissipative braces, the story shear yield strength Q was divided into the shear strength of the braces and shear strength of the RC frame, and changes in the absorbed energy of the braces and the RC frame were determined. The results are shown in **Fig. 8**. From the figure it is apparent that in all models, the braces absorbed as much as 50% of the total absorbed energy. From this fact, it became evident that the energy dissipative braces provide sufficient dampening in this retrofitting method. A change in θ_c is also shown in Fig. 8 (right axis). From this figure, it can be seen that in the Gb specimen, θ_c continues to increase after the second cycle at R = 10/1 000 rad and that the quantity of absorbed energy of the braces is small compared to that of the Cb specimen. From this fact, it becomes evident that the torsional deformation at the beam end to which the braces are attached increases and inter-story deformation is not directly transmitted to the braces, with the result that the energy absorption capacity of the braces



(a) Girder bending yielding, Gb

(b) Column bending yielding, Cb

Fig.8 Absolute energy absorption, *E*-*R* relationship

decreases. On the other hand, as shown in the figure, in the Cb specimen, θ_c is as small as 5/1 000 rad even at R = 15/1 000 rad and the torsional little deformation occurred at the beam end. Therefore, much energy is absorbed in a stable manner at each story drift angle.

As is apparent from the above results, the torsional deformation at the beam end results in not only a decrease in the quantity of absorbed energy of the braces, but also in the percentage. Therefore, in performing simplified attachment of energy dissipative braces, determining the ultimate torsional yield strength for suppressing the torsional deformation at the beam end is very important for establishing a seismic retrofitting technique.

3. Examination of Energy Dissipative Brace Connections by Elemental Experiments

In this chapter, to verify the torsion behavior and ultimate torsional yield strength of the parts around the beam ends of the RC frame specimens, a static cyclic loading experiment is conducted on elemental experiment specimens.

3.1 Experiment Plan

The specimen (**Fig. 9**) is a 1/2 size model of an energy dissipative brace connection, of which two specimens were prepared. A list of member sections is shown in **Table 2**. Experimental variables are those of the loading program, and the purpose of the experiment was to examine the effect of damage during positive loading (during axial tensioning of the brace) on the ultimate yield strength during negative loading (during axial compression of the brace). In fixing anchor plates to the RC portion, the anchor plates were always attached by use of PC bars and in order to prevent the anchor plates from rising, the initially introduced axial force of the PC bars (ϕ17 mm) was set at 100 kN by using the design

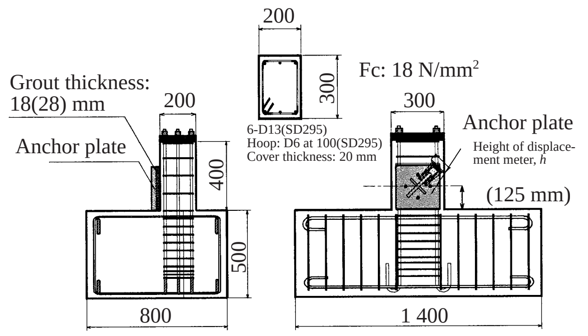


Fig.9 Configuration of specimen

Table 2 List of member specimens

Specimen	PC18-45	PC18-D10
RC Section	200 mm × 300 mm	
Arrangement of reinforcing bars	6-D13(SD295) Hoop: D6 at 100(SD295)	
Concrete strength	F_c = 18 N/mm^2	
Diameter of PC bar	ϕ17 mm	
Initial axial tensioning	100 kN	
Cotter type	45	D10
Grout thickness	28 mm	18 mm

formula shown in Ref. 5) so that the anchor plates would not rise. The grout thickness was 18 mm or 28 mm and the grout strength was determined by using the formula shown in Ref. 6) so that the grout portion does not undergo shear failure. Incidentally, it is ensured that the braces attached to the anchor plates will not yield until the failure characteristics of the anchor plates are sufficiently understood. In this experiment, the objective is a fundamental examination in which attention is paid to the effect of the axial force carried by the braces on the energy dissipative brace connections, no consideration is given to in-plane bending moments which occur within the RC frame.

The loading device used is shown in **Fig. 10**. In loading, two cycles of incrementally increasing positive and negative alternating loads were applied by using an

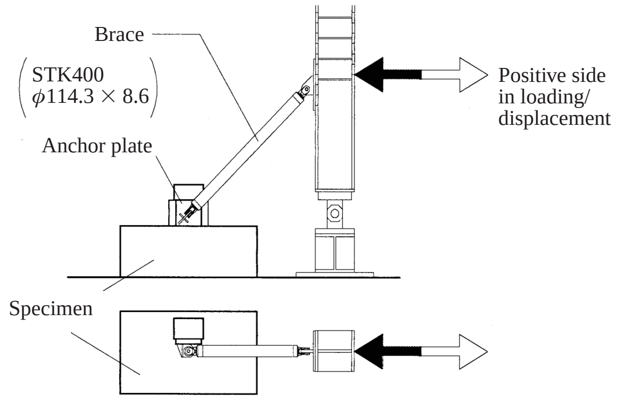


Fig. 10 Specimen and loading device

actuator at pitches of 10 to 20 kN until a maximum yield strength was reached. After the maximum yield strength was reached or after a change occurred in the failure characteristics of the specimens, a shift to displacement control was made on the side where the strength peaked out and loading was continued by load control on the side where the strength was still sufficient. It should be noted that a loading in which the braces are under axial tensile stress is regarded as a positive loading.

3.2 Experiment Results

3.2.1 Failure characteristics of specimens

Table 3 shows the results of the experiment. The failure characteristics of the specimens were as follows. During positive loading, first, a crack was formed at the RC beam end and almost simultaneously the main reinforcement, which is the most highly tensioned, yielded. After that, even when the load increased, the cracking of the RC frame proceeded and no change was observed at the boundaries between the anchor plates and the grout portion and between the grout portion and the RC frame.

Table 3 Test results

Specimen	Experimental value		
	Yield strength of main reinforcement (kN)	Maximum strength	
		Positive side (kN)	Negative side (kN)
PC18-45	66.5	88.7	332.6
PC18-D10	65.2	97.0	178.8

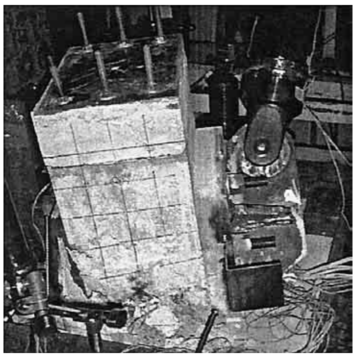


Photo 1 Torsional deformation at beam end

Eventually, during positive loading, the RC frame underwent torsional failure and a maximum load was reached. It was noted that the anchor plates showed scarcely any rise or displacement (**Photo 1**).

Figure 11 shows the relationship between the brace load NB and the torsional rotation angle θ_c at the beam end in each specimen. In each specimen, the ultimate torsional yield strength when the beam end is axially tensioned is small compared to the ultimate yield strength during axial compression. Therefore, it can be said that in the designing of energy dissipative brace connections, it is necessary only to examine safety by calculating the ultimate torsional yield strength at the RC beam end when the beam end carries the tensile stress from the braces, i.e., in a condition in which the

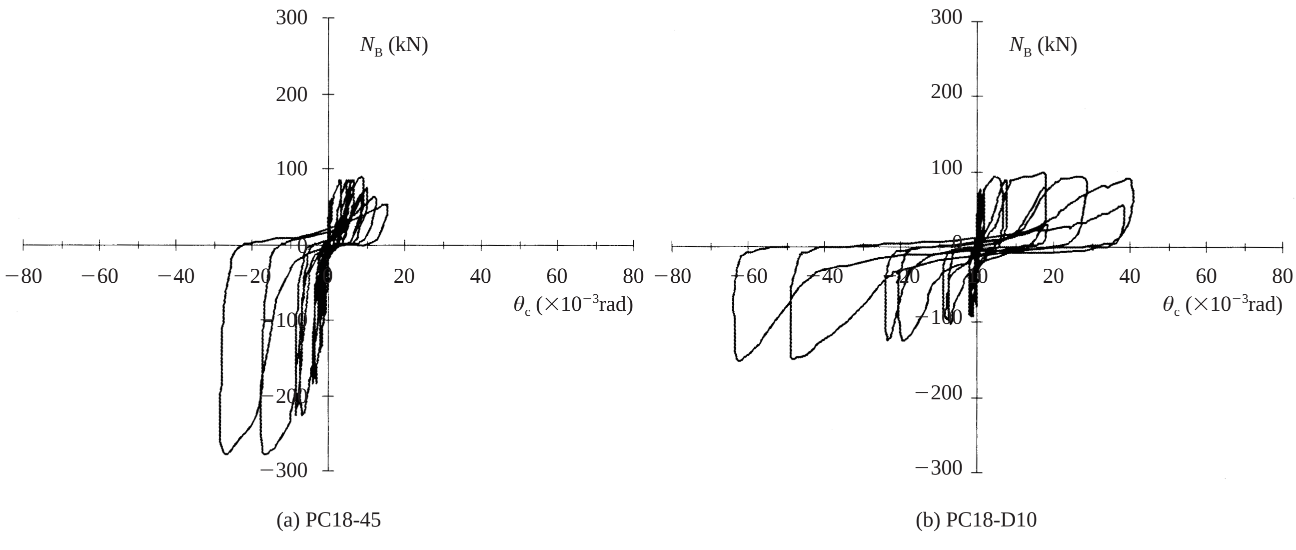


Fig. 11 N_B-θ_c relationship in respective specimens braces are under an axial tensile stress.

3.2.2 Verification of formula of torsional yield strength and proposal

A brace load ${}_{G}Q_{U}$ which acts when an existing RC beam member undergoes torsional failure due to the tensile axial force of an energy dissipative brace is found from Eq. (1):

$$ {}_{G}Q_{U} = T_{uo} / L_{e} \quad \cdots\cdots (1)$$

where L_e: Eccentric distance.

The ultimate torsional moment T_{uo} of a reinforced concrete beam which is subjected to pure torsion can be generally expressed by Eq. (2):

$$T_{uo} = {}_{c}T + {}_{s}T \quad \cdots\cdots (2)$$

${}_{c}T$: Contribution of unreinforced concrete to torsional resistance

${}_{s}T$: Contribution of shear reinforcing bars to torsional resistance

$$ {}_{s}T = \Omega \cdot b_o \cdot d_o \cdot \frac{a_v \cdot \sigma_{vy}}{s}$$

where Ω: Coefficient, b_o: Short side length of shear reinforcing bars in shear section (center-to-center distance), d_o: Long side length of shear reinforcing bars in shear section (Center-to-center distance), a_v: Area of one shear reinforcing bar, σ_{vy}: Yield strength of shear reinforcing bars, s: Spacing of shear reinforcing bars.

Hsu determined ${}_{c}T$ and Ω in the above equation by using Eq. (1) on the basis of results of many experiments conducted by himself, and proposed Eq. (3) as a practical formula[7]. Concretely, ${}_{c}T$ is expressed by a formula in which the sectional shape and the compressive strength of concrete F_c are variables, and Ω is expressed by a formula in which the ratio m of the amount of axial reinforcing bars to the amount of shear reinforcing bars, and the ratio of b_o to d_o, d_o/b_o, are variables.

$$T_{uo} = 1.01\frac{B^2 \cdot D}{\sqrt{B}}\sqrt{F_c} + \left(0.66m + 0.33\frac{d_0}{b_0}\right)\frac{A_0 \cdot a_v \cdot \sigma_{vy}}{s} \quad \cdots (3)$$

Scope of application:

$$0.7 < m \leqq 1.5 \text{ and } p_v + p_1 \leqq p_{1b} = 6.36\frac{\sqrt{F_c}}{\sigma_{vy}}$$

Where A_o: Area of core concrete enclosed by shear reinforcing bars, m: Ratio of the amount of axial reinforcing bars to the amount of shear reinforcing bars $(= p_1 \cdot \sigma_{1y}/p_v \cdot \sigma_{vy})$, a_1: Total sectional area of axial reinforcing bars, p_1: Ratio of axial reinforcing bars $(= a_1/B \cdot D)$, p_v: Ratio of shear reinforcing bars $(= a_v \cdot l_{po}/B \cdot D \cdot s)$, l_{po}: Circumference enclosed by shear reinforcing bar.

It is impossible to apply the Hsu's calculating formula of yield strength to the local ultimate torsional yield strength at the beam end which is discussed in this paper if this formula is not modified. Therefore, modification of this formula was necessary. This is because the scope of application of the coefficient m in the term ${}_{s}T$, which is the contribution of shear reinforcing bars to resistance, poses a problem. Beams of long span (about 1 830 mm) were used in Hsu's experiments, whereas in the present experiment beams of short span (about 400 mm) are used. For this reason, it is necessary to consider the torsional resistance at short spans and, therefore, the effect of shear reinforcing bars cannot be much expected. It might be thought that on the contrary, the effect of main reinforcements becomes great. In this paper, therefore, the formula was applied by expanding the scope of application of m. **Table 4** shows the values of T_{uo}' calculated as a result of this and of the ultimate torsional moment $T_{uo,exp}$ obtained in the element experiment. Results obtained in these RC frame specimens with braces are also shown in this table. From the table it is apparent that the PC18-45, PC10-D10, and the Gb specimen which underwent torsional failure have a high correlation to the modified Hsu's calculating formula of yield strength (T_{uo}' in the table). On the other hand, for the Cb specimen which did not undergo torsional failure, the calculation results show an ultimate torsional yield strength which is larger than the torsional stress which was applied during the experiment. For the Gb specimen, this formula can be substantially applied in spite of the fact that compared to the specimen of the beam RC portion, in-plane bending and shear forces are present. This fact suggests that the ultimate yield strength of a beam within an RC frame could be calculated by using the modified Hsu's calculating formula. In order to generalize this formula, clarifying the scope of application of the ratio m, particularly a maximum value, is a prob-

Table 4 Comparison of torsion strength

Specimen	Estimated value				Experimental value	
	m	T_{uo} (kN·m)	T_{uo}' (kN·m)	${}_{G}Q_{U}$ (kN)	$T_{uo,exp}$ (kN·m)	N_B (kN)
PC18-45	2.9	9.3	12.8	83.2	13.6	88.7
PC18-D10	2.9	9.2	12.6	82.3	14.9	97.0
Gb	7.7	9.1	24.2	157.7	30.2	196.6
Cb	7.2	25.5	64.1	417.8	31.7	206.5

T_{uo}: $m = 1.5$
T_{uo}': $m = p_1 \cdot \sigma_{1y} / p_v \cdot \sigma_{vy}$

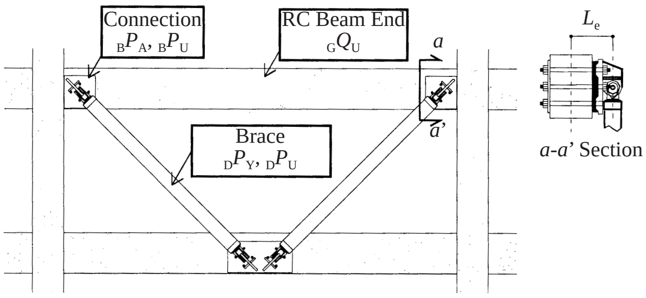


Fig. 12 Concept of design

lem to be solved in the future.

4. Method of Calculating Required Yield Strength of Energy Dissipative Brace Connections for Retrofitting

Figure 12 shows a conceptual diagram of a method of calculating the required yield strength. In designing energy dissipative brace connections, it is necessary to find the yield load $_DP_Y$ and ultimate load $_DP_U$ of an energy dissipative brace, the brace load $_GQ_U$ which acts when an existing RC beam member undergoes torsional failure due to the tensile axial force of the energy dissipative brace, the rise load $_BP_A$ of an anchor plate, and the shear failure load $_BP_U$ of a grout portion.

In order to increase the damping effect, it is necessary that beyond the yield of the energy dissipative braces, the anchor plates and beam members maintain sufficient rigidity without damage and that rises and shifts of the anchor plates scarcely occur. In order to ensure safety against excessive disturbances, it is necessary that the ultimate yield strength be determined by a member having a high deformability.

Therefore, it is required that these values satisfy the following conditional expressions:

$$_DP_Y < {}_BP_A \quad (4)$$

$$_DP_U < {}_BP_U < {}_GQ_U \quad (5)$$

Incidentally, $_DP_Y$ and $_DP_U$ are based on the mechanical properties of energy dissipative braces, and the yield strength values of other parts ($_BP_A$ and $_BP_U$) are based on the design shown in Refs. 5, 6).

5. Conclusions

The following knowledge was obtained in this paper:

(1) From the experimenst on RC frames with braces it became apparent that a good damping effect can be obtained from the proposed seismic retrofitting method.
(2) For the girder bending yielding specimen, it became apparent that the torsional deformation which occurs in the RC beam end increases and that the quantity of absorbed energy of the brace decreases, thereby effecting the damping effect.
(3) From the results of the element experiments it became apparent that by expanding the scope of application of the calculating formula of yield strength proposed by Hsu, the ultimate torsional yield strength of the beam end under a tensile stress in the retrofitting method can be roughly estimated. The applicability of the proposed calculating formula of torsional yield strength was suggested by applying this formula to the RC beam end within the frame.
(4) On the basis of the results of these two experiments, the calculating method of required yield strength of the energy dissipative braces necessary for the seismic retrofitting design method discussed in this paper was proposed.

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