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Development of reinforced concrete encased steel brace with high ductility capacity

T. Nagao
Nihon Sekkei Inc., Tokyo, Japan

S. Takahashi
Tobishima Corporation, Tokyo, Japan

ABSTRACT: A new type of composite brace member with high ductility capacity under axial cyclic loading has been developed for practical applications where the high level of axial stress is anticipated, especially in high-rise buildings on earthquake prone areas. It is experimentally confirmed that an overall buckling can be prevented efficiently, and 1.5% of the strain level can be retained under the applied axial cyclic loading when the core steel is confined by RC.

1 INTRODUCTION

A new type of composite bracing with high ductility capacity is developed as an earthquake resistant element for high-rise buildings.

A box steel section brace is encased by reinforced concrete(RC), inserting in between a polyetylene-film-sheet in order to reduce the bond stress, as shown in Fig.1. The RC part is intended to solely prevent overall and local buckling of the core box steel section, and not to sustain the axial load. Therefore, the same stiffness and strength are expected in this type of composite brace, for both the externally applied tensile and compressive loads.

This paper discusses experimentally and analytically the required conditions necessary for a ductile behavior of the RC encased steel brace member, and also attempts to develop a practical design method.

2 EXPERIMENT

2.1 Test specimen and apparatus

The specimens used consist of:
the core member which is a box steel section made by welding (size: □-100x100x6x6mm), the encasing member which is reinforced concrete with 32mm thickness(external diameter: 164x164mm), and the unbonding material which is a polyetylene-film-sheet with 0.2mm thickness.

The parameters considered for the encasing RC are: concrete strength(Fc), quantity of axial reinforcement(p_t) and shear reinforcement(p_w); and for the core steel is the buckling length(L). In total 15 tests were performed, Table 1 includes the data for some of the specimens tested.

Table 1 Data for some of specimens tested

speci-men	Fc (MPa)	p_t (%)	p_w (%)	P_E/P_y	Fy/Py (%)
A0	steel brace: □-100x100x6x6(mm)				
A1	11.8	0.235	0.984	1.26	0.59
A2	11.8	0.706		1.50	1.76
A3	30.4	0.235		1.95	0.56
A4	34.4	0.706		2.31	1.76

σ_y=307(MPa)
$_r\sigma_y$=429(MPa)
$_w\sigma_y$=542(MPa)
L =3080(mm)
Fy=4My/L
$P_E=(\pi^2/L^2)\cdot E_cI_c$

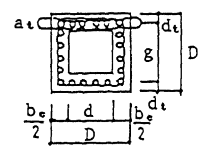


Fig.2 shows the test apparatus used to apply axial cyclic load. The in-plane supports are both pins, and the out-of-plane supports are fixed.

2.2 Experimental results

Fig.3 shows some of the experimental results in terms of axial load to axial deformation relationship for a slederness ratio of the core steel of about 80.

It is possible to observe that the elastic stiffness of the composite brace, in compression and tension, is almost the same as for the case of the steel brace; this indicates that the unbonding process is enough. Whereas the stiffness is a little different in the tension side from the compression side for a larger deformation zone(plastic zone).

The stiffness in the compression side is slightly larger than in the tension side, as RC sustains part of the compression load

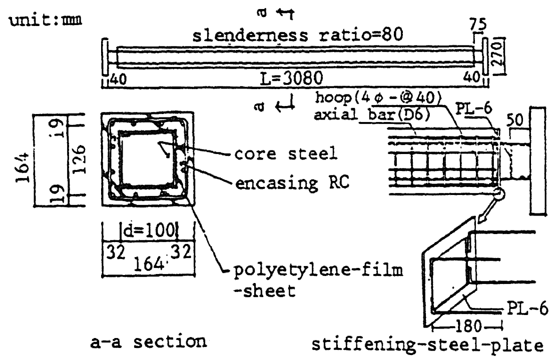


Fig.1 Specimen of RC encased steel brace

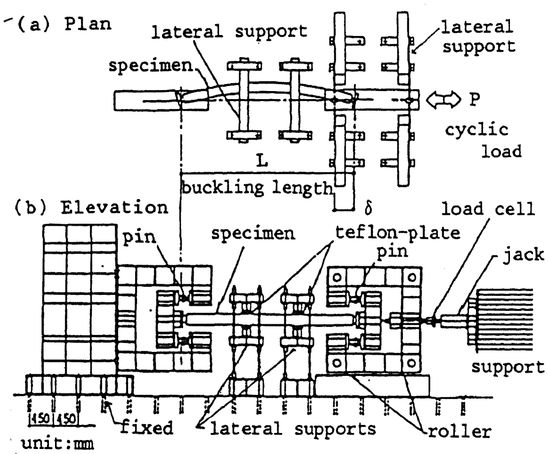


Fig.2 Cyclic load application method

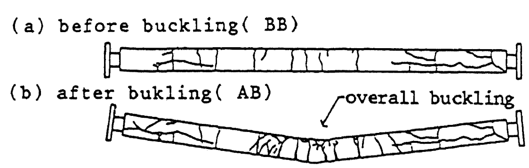


Fig.4 Cracking pattern in encasing RC (A3 specimen)

applied externally through friction.

The composite brace with sufficient stiffness and strength in the encasing RC (A4 specimen) showed an excellent ductile behavior in comparison to the conventional steel brace(A0 specimen) that indicated a brittle behavior. The plastic deformation capacity of A4 was limited by a local buckling of the core steel, however,an overall buckling was prevented efficiently, and 1.5% of strain level could be retained under the applied axial cyclic loading when the core steel was confined by RC. This strain level is equivalent to 1/50 of the inter-storey drift.

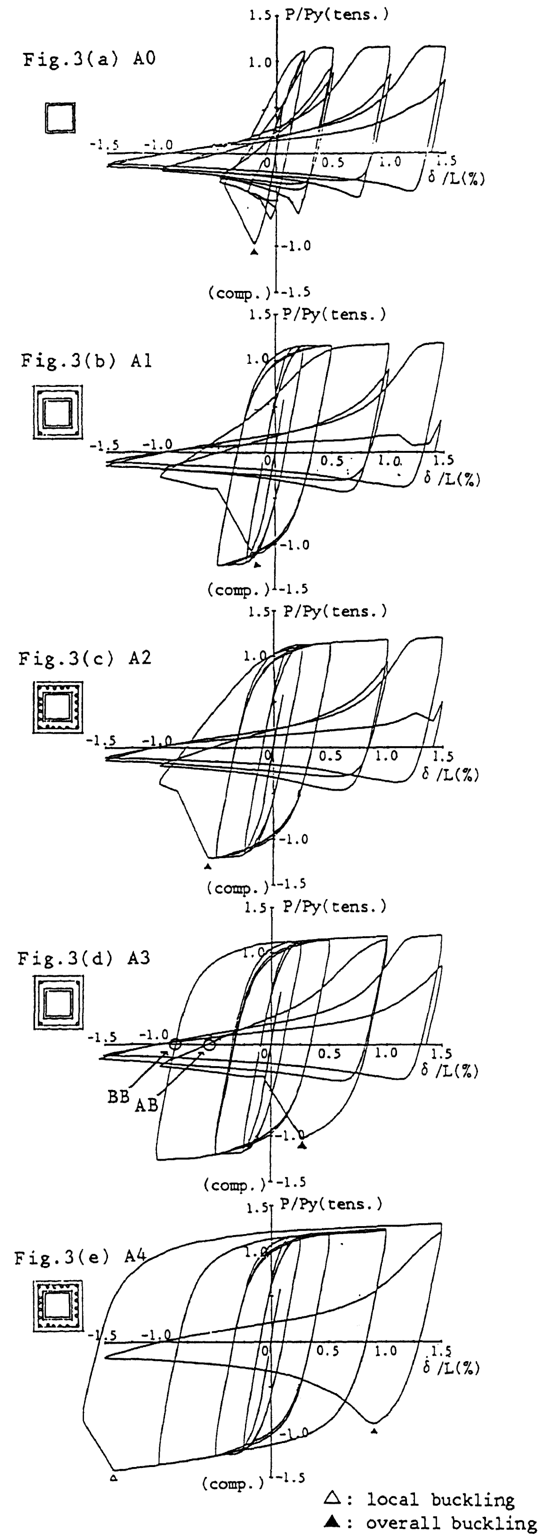


Fig.3 (P/Py) vs (δ /L) curve

A1 specimen, in which both stiffness and strength of RC were insufficient, showed a rather brittle behavior, and the plastic deformation capacity was limited by an overall buckling.

A2 and A3 specimens, in which either the stiffness or strength of RC was insufficient, showed deformation capacity to a certain degree. However, an overall buckling occured after the development of cracks in RC. Fig.4 shows the cracking pattern before and after buckling of A3 specimen that are corresponding to the states indicated as (BB) and (AB) in Fig.3(d).
The stiffness deterioration of RC due to cracking is estimated to be the main origin of an overall buckling initiation.

3 ANALYSIS

3.1 Required condition for ductile behavior

A ductile behavior will depend on the stiffness and strength of the encasing RC, when a width to thickness ratio of the core steel is small enough to prevent a premature local buckling. Fig.5 shows the interaction between the encasing member and the core member. Buckling deformation may occur, if an axial compressive force is applied to the core member. However, lateral stiffening forces(f(x)) will generate once the core member touches to the encasing member, increasing in this way the compressive load capacity. The overall buckling load capacity of the composite brace member(Pcr) increases above the axial yield load of the core steel (Py), then a general axial yielding occurs in the core steel without an overall buckling. The condition described in Eq.(1) is required to get a ductile behavior of the member.

$$P_{cr} \geqq P_y \tag{1}$$

Pcr depends on the stiffness of the encasing RC. Besides, it is required that the encasing RC has enough strength to bear the stress caused by the lateral stiffening forces in order to get a ductile behavior. This condition is described as Eqs.(2) and (3).

$$M_y \geqq M_0 \tag{2}$$
$$Q_y \geqq Q_0 \tag{3}$$

where,
My, Qy :bending and shear strength of RC
M_0, Q_0 :maximum bending and shear stress occured in RC.

3.2 Overall buckling load(Pcr)

The lateral stiffening force is assumed to be a centrally concentrated load(f(x)=F) as a simplification. Let us consider the state where an axial compressive load P is equal to Py and the core steel is in a general yielding state. The core steel can be assumed to have a zero bending stiffness and zero bending strength, as the steel material can be assumed to have a perfect elasto-plastic stress-strain relationship. Eq.(4) indicates the equilibrium equation for this state at the maximum bending stress point(x=L/2 in Fig.6), and Eq.(5) indicates its incremental form.

$$P \cdot \delta = M_{RC} \tag{4}$$
$$(P+\Delta P)\cdot(\delta+\Delta\delta) = M_{RC}+\Delta M_{RC} \tag{5}$$

$\Delta\delta > 0$ and $\Delta P > 0$ correspond to a stable condition, whereas $\Delta\delta > 0$ and $\Delta P < 0$ will indicate an unstable condition. Therefore, the buckling load of the composite brace(Pcr) can be derived substituting $\Delta P=0$ in Eq.5:

$$P_{cr} = \Delta M_{RC} / \Delta\delta \tag{6}$$

From Eq.(6), Pcr corresponds to the tangential stiffness of the M_{RC}-δ curve. Pcr is equal to Eq.(7) when the lateral stiffening force is a centrally concentrated load and the encasing RC is in the elastic state.

$$P_{cr} = P_e = \frac{12}{L^2} E_c I_c \tag{7}$$

where,
Pe:overall buckling load of a composite brace when the encasing RC is in the elastic state
Ec:initial elastic modulus of concrete
Ic:moment of inertia of the encasing RC

3.3 A maximum bending stress M_0

There are some initial imperfections in the RC encased brace member, such as an unavoidable load eccentricity, an initial crookedness or a gap between the encasing RC and the core steel. δe is introduced in order to express those initial imperfections. In the model shown in Fig.7, the lateral stiffening force generates only after $\delta_{RC} > 0$, where $\delta = \delta_{RC} + \delta e$. Substituting this relation in Eq.(4), the maximum bending moment that occurs in the encasing RC(M_0) can be calculated as follows:

$$M_0 = \frac{1}{(1-P_y/P_e)} \delta e \cdot P_y \tag{8}$$

where,
1/(1-Py/Pe) :moment amplification factor
$\delta e \cdot P_y$:eccentric moment

3.4 Nonlinear effect of the encasing RC

The bending stiffness of RC decreases as cracks develop in the encasing RC during the process of a cyclic loading.

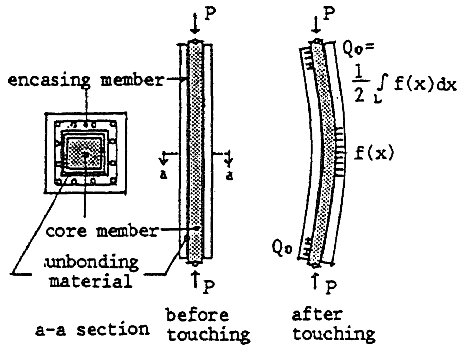


Fig.5 Interaction between core and encasing members

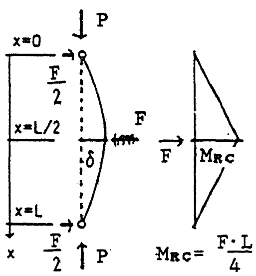


Fig.6 Equilibrium condition of core member

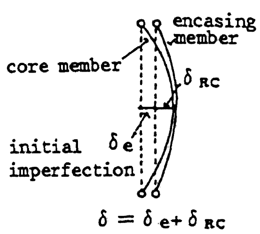


Fig.7 Deformation compatibility between core and encasing members

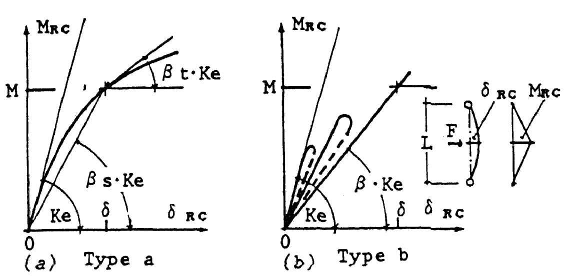


Fig.8 Non-linear M_{RC} vs δ_{RC} curve

Two types of nonlinear moment-deformation (M_{RC}-δ_{RC}) relationships are shown in Fig.8 (a) and (b). The former is a general non-linear relationship, and the latter is often observed from a cyclic axial or bending load test of a RC member.
Pcr and Mo for these two types are calculated using Eqs.(7) and (8) as follows:

Type a ($\Delta M_{RC}/\Delta\delta_{RC}=\beta t, M_{RC}/\delta_{RC}=\beta s$);

$$Pcr=\beta t\cdot Pe \tag{7a}$$

$$M_0=\frac{1}{(1-Py/\beta s\cdot Pe)}\delta e\cdot Py \tag{8a}$$

Type b ($\Delta M_{RC}/\Delta\delta_{RC}=\beta, M_{RC}/\delta_{RC}=\beta$);

$$Pcr=\beta\cdot Pe \tag{7b}$$

$$M_0=\frac{1}{(1-Py/\beta\cdot Pe)}\delta e\cdot Py \tag{8b}$$

where,
βt :tangential stiffness reduction factor
βs :secant stiffness reduction factor
β :stiffness reduction factor

3.5 Shape of lateral stiffening force

Eq.(9) corresponds to the lateral stiffening force shape assumed for discussion, and it is a sine wave distribution that includes higher orders(Fig.9).
Pe can be written as Eq.(10) following the same process as for Eqs. (4) to(7):

$$f(x)=f_0\cdot\sin\left\{\frac{\pi}{(1-\alpha)}(x/L-\alpha/2)\right\} \tag{9}$$

$$Pe=\zeta\cdot\frac{\pi^2}{L^2}\cdot EcIc \tag{10}$$

where, ζ depends on α (Fig.10).
when $0\leqq\alpha\leqq 2/3$;

$$\zeta=\frac{1}{(1-\alpha)^2+\dfrac{\pi^2\cdot\sin A}{8\cdot(\sin A+1)}}$$

when $2/3\leqq\alpha\leqq 4/5$;

$$\zeta=\frac{1}{(1-\alpha)^2+\dfrac{\pi^2\cdot\sin A\ \{(\alpha-1/2)-(\alpha-1/2)^2\}}{2\cdot(\sin A-1)}}$$

And so on.
where,

$$A=\frac{\alpha}{2(1-\alpha)}\pi$$

It is possible to observe that the shape of the stiffening force will correspond to a higher order sine wave when the force distribution factor(α) increases. Consequently, the deformation shape of the core steel will also be of a higher order. The local minimum values of Pe, for example the points A,B and C in Fig.10, are considered to have a higher probability to occur and some of them are shown in Table 2. The minimum value of Pe (point A) indicates the Euler buckling load

(P_E) of the encasing RC which is important from an engineering point of view.

3.6 Effects of shear stress

One of the effects is the decrease of an overall buckling load, and the other is the decrease of shear strength in the encasing RC caused by a particular shear resistant mechanism due to an unbonding process.

1. The overall buckling load of the composite brace(Pcr) decreases when considering the shear deformation of the encasing RC. The calculated Pcr for 1/2 length of A4 specimen decreases about 5% when RC is in the elastic state. The decreasing rate of Pcr is larger, if the cracking effect of RC is considered.

2. Tension zones are formed in the encasing RC due to the unbonding process as shown in Fig.11. Therefore, shear strength in the concrete part of the encasing RC is unexpectable,especially after cracking. The shear strength of RC members is calculated generally as in Eq.11. However,it is recommendable to consider Qc=0 in the design.

$$Qy=Qc+Qr \qquad (11)$$

where,
Qc,Qr :shear strength by concrete and shear reinfocement(hoop), respectively

4 COMPARISON BETWEEN EXPERIMENT AND ANALYSIS

Two failure modes can be considered for the encasing RC: bending and shear failure modes. From the experimental studies, it is possible to say that the latter occurs seldomly except for the case of a short brace with poor shear reinforcement. Therefore, the required conditions for a ductile behavior of the RC encased steel brace will be efficiently predicted by Eqs.(1) and (2).

Fig.12 shows Eqs.(1) and (2) in terms of stiffness to strength relationship for the encasing RC.
The strength is defined as a maximum bearing capacity against a centrally concentrated lateral force(Fy). The stiffness is defined as an Euler buckling load of the encasig RC (P_E) that is the minimum value of Pe obtained from Eq.(10). A point above these curves indicates that Eqs.(1) and (2) satisfy the stiffening criteria and therefore a ductile behavior can be predicted.
It is also possible to observe that Eq.(2) is always above Eq.(1), and that the curve corresponding to Eq.(2) will change upwards when the value of initial imperfections(δe) is increased. Therefore, δe is an important

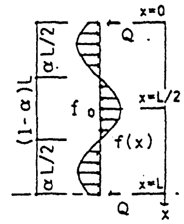


Fig.9 Lateral stiffening force distribution

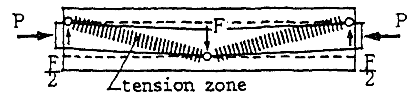
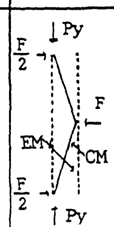
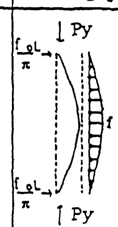
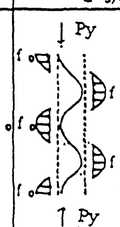
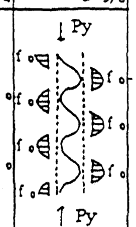


Fig.11 Shear resistant mechanism due to unbonding process

Table 2 Overall buckling load(Pe) due to lateral stiffening force distribution(f(x))

f(x) Shape	f(x)=F	f(x):Eq.(9)		
		Point A α=0	Point B α=3/4	Point C α=5/6
				
Pe=	$\frac{12}{L^2}E_cI_c$	$\frac{\pi^2}{L^2}E_cI_c$	$\frac{1.90\pi^2}{L^2}E_cI_c$	$\frac{1.55\pi^2}{L^2}E_cI_c$

EM:encasing member
CM:core member

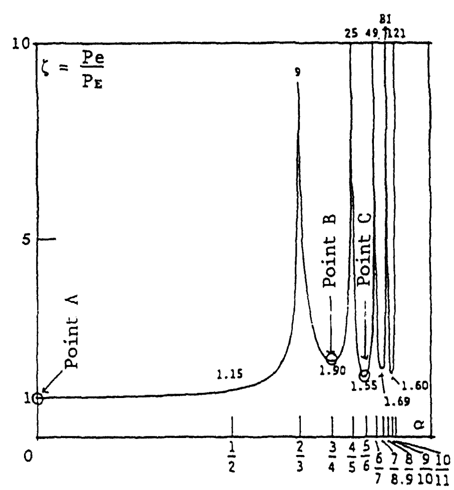


Fig.10 Pe/P_E vs α curve

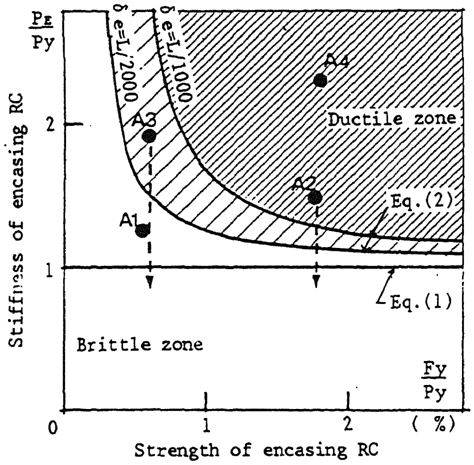


Fig.12 Stiffening criteria for RC encased steel brace

value to judge the experimental results. The curves in Fig.12 correspond to $\delta e=L/1000$ and L/2000, which are considered to be adequate for the specimens.

A4 showed an excellent ductility in the experiment, whereas A1 showed a brittle behavior. These behaviors can be clearly predicted from Fig.12.

A3 and A2 showed, to a certain extent, deformation capacity in the experiment. However, an overall buckling occured after cracks developed in the encasing RC. The points corresponding to A3 and A2, at an initial stage, are close to the limit values of Eq.(2) as can be seen in Fig.12. The stiffness decreases sharply when cracking occurs, however the strength is rather insensible to it. This is possible to observe in the same figure where these points move downwards along the dashed lines after cracking occurs, thus violating the stiffening criteria.

All these results indicated a good correlation between analyses and experiments.

5 DESIGN FORMULA FOR RC ENCASED STEEL BRACE

The design formula for the RC encased steel brace with unbonding material is proposed as follows:

1. The initial bending stiffness(EcIc), bending strength(My), and shear strength (Qy) of the encasing RC shall be determined from Eqs.(12) to (14).

$$Pcr \geqq f1 \cdot Py \qquad (12)$$
$$My \geqq f2 \cdot M_0 \qquad (13)$$
$$Qy \geqq f3 \cdot Q_0 \qquad (14)$$

where,

f1,f2,f3:safety factors,that shall be introduced properly to use this formula.

$Pcr=\beta 1 \cdot P_E$:buckling load of composite brace considering the cracking effect of the encasing RC

$P_E=(\pi^2/L^2)\cdot EcIc$:Euler buckling load of the encasing RC

L :effective buckling length of the brace

Ic :moment of inertia of the encasing RC

Ec :initial elastic modulus of concrete,that may be taken as $Ec=2.06\times10^4\times\sqrt{Fc/19.6}$ (MPa)

Fc :concrete strength (MPa)

Py :axial yield load of the core steel

$M_0=\dfrac{1}{(1-Py/\beta 2\cdot P_E)}\delta e\cdot Py$: maximum moment in the encasing RC including its cracking effect

δe:initial imperfection,that may be taken as $\delta e=L/1000$

$\beta 1,\beta 2$:stiffness reduction factor, that may be taken as $\beta 1=\beta 2=1/5$. This value(1/5) is widely used in the design formula (current AIJ,ACI,or Euro codes) for a long composite column: $Pcr=(\pi^2/L^2)\cdot\{EsIs+(1/5)\cdot EcIc\}$ Where EsIs(bending stiffness of steel member)=0 is considered for the case of RC encased braces.

$Q_0=\pi\cdot M_0/L$:maximum shear stress in the encasing RC, for the case when the lateral stiffening force is a half sine wave, i.e. $\alpha=0$ in Eq.(9), which corresponds to the minimum buckling load Pe.

My :yield moment of the encasing RC,according to the current AIJ code,that may be taken as; $My=a_t\cdot{}_r\sigma_y\cdot g$

Qy :shear strength by shear reinforcement, according to the current AIJ code that may be taken as; $Qy=b_e\cdot g\cdot{}_w\sigma_y\cdot p_w/2$

a_t,a_w :sectional area of axial tension reinforcement and shear reinforcement

$p_t=a_t/D^2$:quantity of axial reinforcement

$p_w=a_w/b_e\cdot s$:quantity of shear reinforcement

$\sigma y,{}_r\sigma_y,{}_w\sigma_y$:yield stress of core steel, axial and shear reinforcement,respectively

s :shear reinforcement pitch

g,b_e,d,D :dimensions of RC encased steel brace shown in Table 1.

2. The width(d) to thickness(t) ratio (d/t) of the core steel has to be small enough to prevent a premature local buckling, when using a box steel section made by welding for the core member. This is recommended as;

$$d/t \leqq 0.85/\sqrt{\varepsilon_y}$$

ε_y:yield strain of the core steel

3. The shear stress concentrates in the end of the encasing RC. Therefore, it is recommended to use stiffening-steel-plate as shown in Fig.1.

6 CONCLUSIONS

It was experimentally confirmed that the RC encased brace member has an excellent ductility under applied axial cyclic loading when the encasing RC has sufficient stiffness and strength.
The required conditions for a ductile behavior of the encasing RC are summarized in Eqs.(1) to (3).
It is possible to judge the stiffening conditions using Fig.12.
Practical design formulas, Eqs.(12) to (14), are proposed in the present study.

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