OVERALL BUCKLING PREVENTION CONDITION OF BUCKLING-RESTRAINED BRACES AS A STRUCTURAL CONTROL DAMPER

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ABSTRACT :

One of the required performances in buckling-restrained braces as a structural control damper under severe earthquakes is to prevent its overall buckling, i.e., Euler-type buckling of both the brace and restraining members as a whole. This paper deals with an examination into the adequacy of the commonly used buckling prevention condition with a series of well-controlled experiments. Moreover, a design guideline for the buckling prevention condition is discussed.

KEYWORDS: Damage control design, structural control damper, steel structures, buckling restrained brace, cyclic loading

1. INTRODUCTION

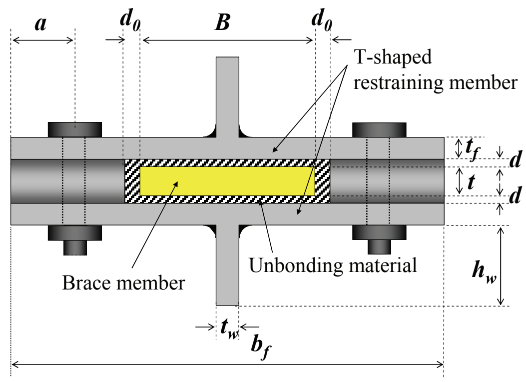
In recent years, the steel hysteretic damper that controls the damage of the main structure has attracted attention, and examples of practical application have also been reported (JSSC 1998; Usami et al. 2006). The steel hysteretic dampers, which absorb and disperse earthquake energy by plastic deformation of steel material, are divided into the axial-yielding type, shear-yielding type, and bending-yielding type by the yielding form. The buckling-restrained brace (hereafter, it is called BRB) is enumerated as the axial yielding type of the structural control damper. The BRB is composed of the unbonding steel member (hereafter, it is called the brace member) that takes charge of the axial force, and buckling restraining member (hereafter, it is called the restraining member) that used mortar or steel section, etc. (Fig. 1).

The experimental and analytical researches on the deformation performance and dynamic response of BRB have already been done by authors (e.g., Kato wt al. 2002; Watanabe et al. 2003; Usami et al. 2004; Seda et al. 2006) and other researchers (e.g., Hoda et al. 2004; Kanaji et al. 2005; Maeno et al. 20059). The restraining member proposed previously, was mortar-filled steel section which is considerably rigid member. In such kind of BRBs, the brace member and restraining member have been integrated and overall buckling did not happen (the Euler-type flexural buckling, as shown later in Photo 1). However, when BRB is applied to the bridge structure, it inevitably becomes large-scale compared with the frame structure of buildings, accordingly the influence of the deflection by the dead weight of BRB grows and the construction becomes difficult. Therefore the development of light-weight BRBs is needed. In that case, however, the examination of overall buckling becomes indispensable.

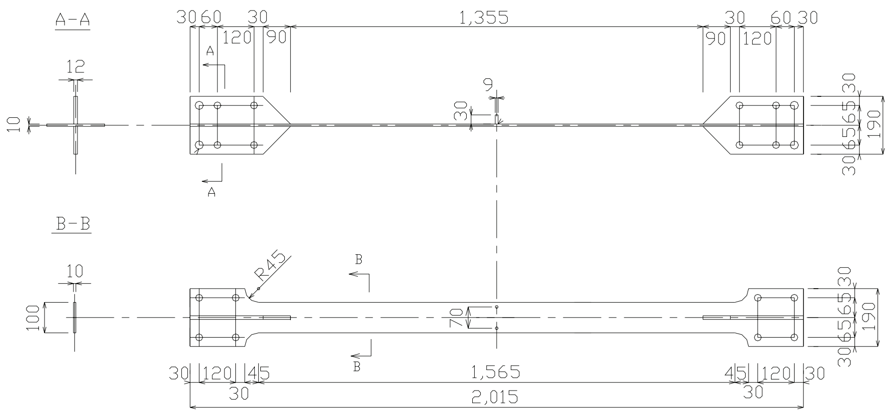
In this paper, a kind of lightened BRBs composed of only steel member without filling mortar is proposed, and its performance experiment is conducted. And then, the prevention condition of overall buckling of BRB is examined in detail.

2. REQUIRED PERFORMANCE AND TARGET PERFORMANCE OF BRB

The following items are considered for the safety performance required for the BRB.
1) Prevention of overall buckling of the BRB
2) Prevention of strength deterioration by the local buckling of the brace member



(a) Section details of the tested specimen



(Unit: mm)

(b) Dimensions of brace member

Figure 1 Test specimen

3) Securing of necessary deformation performance of the brace member
4) Prevention of low cycle fatigue of the brace member
5) Strength of the restraining member
6) Strength of joint part of the BRB and the main structure

In this paper, the examination of items 1) and 5) is the main content among the above-mentioned required performances. When the brace member deflects by compression, and it comes in contact with the restraining member, the out-of-plane deformation of the entire BRB increases and strength deterioration occurs before the brace member reaches the target deformation performance if the rigidity and strength of the restraining member are not high enough. Therefore, to obtain the hysteretic characteristic on the compression side similar to the tension side, a condition of not causing overall buckling (flexural buckling) on the restraining member together with the brace member becomes necessary. In this study, the target maximum deformation of the brace member (ratio of axial displacement and yield displacement, δ/δ_y) is set to be 20.0 (almost 3% of strain in the case of a mild steel SS400), and the condition of not causing overall buckling before the target maximum deformation is examined.

3. DERIVATION OF OVERALL BUCKLING PREVENTION CONDITIONAL EQUATION

At present, the common used conditional expression of buckling prevention of the BRB simply supported on

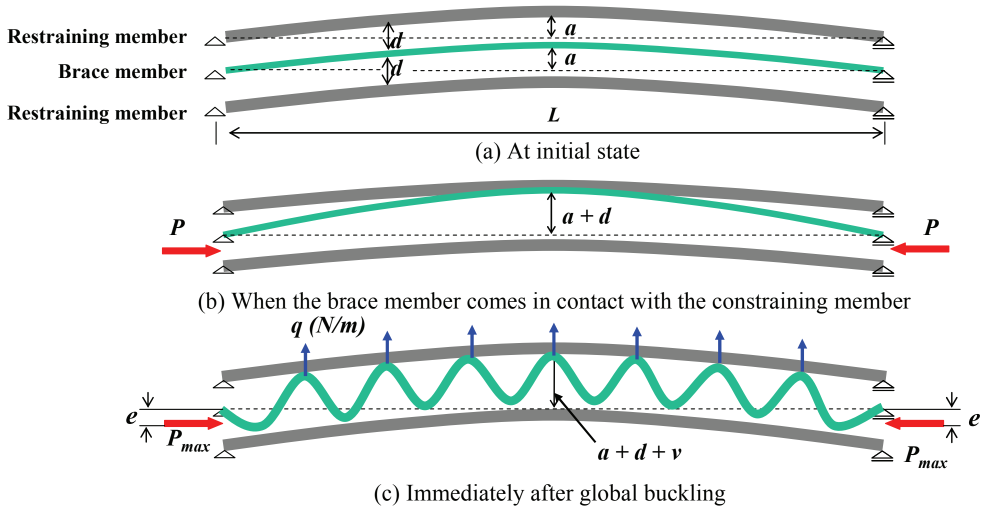


Figure 2 Behaviour of BRB up to occurrence of global buckling

both ends is given by (JSSC 1998; Usami et al. 2004)

$$\frac{P_{\max}(a+d+e)}{1-\dfrac{P_{\max}}{P_E^R}} \le M_y^R \tag{3.1}$$

Here, M_y^R = yield moment of the restraining member, $P_{\max}$ = maximum axial compression force acting on the brace member, P_E^R = the Euler buckling load of the restraining member, a = initial deflection at the center of the restraining member, d = amount of space between the brace member and the restraining member, e = eccentricity of axial compression force (equal in both ends). The left side of this equation is the bending moment (demand) at the center of the restraining member where the P-Δ effect is considered, and the right side is the yield bending strength (capacity) of the restraining member, and it is shown in the equation that the initial yielding is assumed to be the limit state. Based on the findings obtained from the authors' past researches (Kato et al. 2002; Usami et al. 2004), the derivation of the above equation is shown below.

First of all, the mechanism of overall buckling of BRB is discussed to better understand the overall buckling condition. Fig. 2 shows the initial state, the state that the brace member comes in contact with the restraining member and the state immediately after overall buckling of BRB subjected to monotonic eccentric loading respectively. The initial deflection is assumed to be the same with the restraining member and the brace member. The brace member causes the lateral deflection as the compressive load increases from the initial deflection state (Fig.2(a)), and comes in contact with the restraining member (Fig.2(b)). The lateral deflection grows up to the deformation mode of higher-order as long as the load increases further. The contact force acting in the restraining member from the brace member becomes a hoop stress. However, before overall buckling occurs, the total contact force acting on the upper and lower restraining members is balanced, and the lateral deflection of the restraining member is small. In the case of the restraining member with low rigidity, when the load increases furthermore, the lateral deflection of the restraining member will be caused together with occurrence of the overall buckling, and accordingly the contact force becomes to act only on the upper restraining member (in the deformed direction), as can be seen from Fig.2(c). Though the magnitude of the contact force is not easy to be calculated, as described in the previous paper (Usami et al. 2004), it can be considered that almost the same contact force at the contact point of the brace member and the restraining member is acting in the longitudinal direction (length direction) of the restraining member. The lateral deflection of the restraining member grows as long as the axial compressive force increases, and the yielding at the center of the restraining member is considered the ultimate state of BRB.

The bending moment, M_c, generated at the center of BRB after the occurrence of overall buckling is expressed by

$$M_c = P_{\max}\left(a+d+e+v\right) \tag{3.2}$$

Here, v= lateral deflection of the restraining member after the overall buckling. At the point of overall buckling, the contact force of unit length q (N/m) acting on the restraining member from the brace member is assumed to be uniformly distributed, and if it is further assumed that the contact force q and the bending moment M_c caused by the contact force are resisted by the restraining member only, we have

$$v = \frac{5qL^4}{384E^R I^R} = \frac{5M_c L^2}{48E^R I^R} \tag{3.3}$$

Here, $E^R I^R =$ flexural rigidity of the restraining member. By substituting Eq.(3.3) into Eq.(3.2), the following equation is obtained.

$$M_c = \frac{P_{\max}\left(a+d+e\right)}{1-\dfrac{5P_{\max}L^2}{48E^R I^R}} \cong \frac{P_{\max}\left(a+d+e\right)}{1-1.03\dfrac{P_{\max}}{P_E^R}} \tag{3.4}$$

in which, $P_E^R = \pi^2 E^R I^R / L^2 =$the Euler buckling load of the restraining member. As for the overall buckling prevention conditional equation (Eq.(3.1)), a coefficient 1.03 in Eq.(3.4) is taken to be 1.0, and the resistant moment M_y^R of the restraining member is obtained from the condition to exceed the external moment given by Eq.(3.4).

The above derivation is appropriate when the strength and rigidity of the restraining member are considerably large, and the overall buckling will occur after the brace member deforms in the higher-order mode. However, when the strength and rigidity of restraining member are not so large, the overall buckling might occur before the brace member deforms in the higher-order mode. In extreme cases, as shown in Fig.2(b), the overall buckling might occur at the moment that the center part of the brace member comes in contact with the restraining member. At this time, the contact force is not uniformly distributed, and it is appropriate to consider it as a concentrated load applied at the centre of the restraining member. In this case, by a derivation similar to the above, the coefficient 1.03 of the denominator of the final part of Eq.(3.4) becomes 0.82. This result indicates that if the contact force is assumed to be uniformly distributed, the evaluation equation on the safety side can be obtained.

Solving Eq.(3.2) for $P_{\max}$ at the ultimate state (i.e., taking an equal sign at overall buckling), and defining the safety factor as the ratio of $P_{\max}$ and P_y, we have

$$\nu_F \equiv \frac{P_{\max}}{P_y} = \frac{1}{\dfrac{P_y}{P_E^R} + \left(\dfrac{P_y L}{M_y^R}\right)\cdot\dfrac{a+d+e}{L}} \tag{3.5}$$

This safety factor is the value that should be given in the maximum axial compression force assumed in the design.

It should be noted that the conditional equation is led on the basis of a lot of assumptions. Thus, the validity of this conditional equation should be verified by a stricter numerical analysis and/or experiment.

4. EXPERIMENTAL VERIFICATIONS

4.1 Outline of Experiments

For the BRB that had been used so far by authors, it used steel plate for the brace member, and made the restraining member by cutting ready-made deck plate, and filling it by mortar. For the easiness of the construction on site, or for the easiness of inspection of damage state of the brace member after strong earthquake, a couple of restraining member was connected by bolts. On the other hand, a new section composition was thought about as shown in Fig.1 (Kawamura et al. 2004). Such kind of BRB used steel plate for the brace member as before, and CT steel (including the flat bar by cutting the web) for the restraining member. This new restraining member can reduce weight by about 40 percent compared with the past restraining member.

In this study, cyclic loading tests are carried out on four test specimens for the verification. Of which, three specimens use flat bar type ($h_w = 0$) restraining member and one uses a T-type restraining member.

4.1.1 Test specimens

(1) Brace member

The SS400 mild steel was used for the brace member. A graph of the brace member is shown in Fig.1(b). The four brace members are made all in the same size with length L (the length of the plane section excluding the cruciform part) = 1,355mm, width B = 100mm, and thickness t = 10mm. In the cruciform part, two ribs of 12mm thickness are welded to both ends of the brace member as the ends of the brace member are exposed from the buckling restraining member. The parameter of the brace member was shown in Table 1, in which A = sectional area, λ = slenderness ratio on weak axis, P_y = yield axial force ($=\sigma_y A$), and δ_y = yield displacement in the axial direction ($=\varepsilon_y L$). Three tension test pieces were made from the same steel for the brace member, and obtained average values of material properties are shown in Table 2. Here, E = Young's modulus, σ_y = yield stress, ε_y = yield strain, E_{st} = initial strain hardening modulus, ε_{st} = strain at onset of strain-hardening, σ_u = tensile strength, and ν = Poisson ratio.

(2) Restraining member

The flat bar restraining member is made of three different kinds of thickness to change the flexural rigidity.

Table 1 Dimensions of tested BRB specimens

Specimens	Steel	L [mm]	B [mm]	t [mm]	A [mm^2]	λ	P_y [kN]	δ_y [mm]
(a)F10W0-d1-6	SS400	1,355	100	10.2	1020	462	285	1.81
(b)F12W0-d1-2			100	9.81	981	479	268	1.77
(c)F14W0-d2-2			99.8	10.2	1020	459	285	1.81
(d)F14W31-d1-2			101	10.3	1050	454	292	1.81

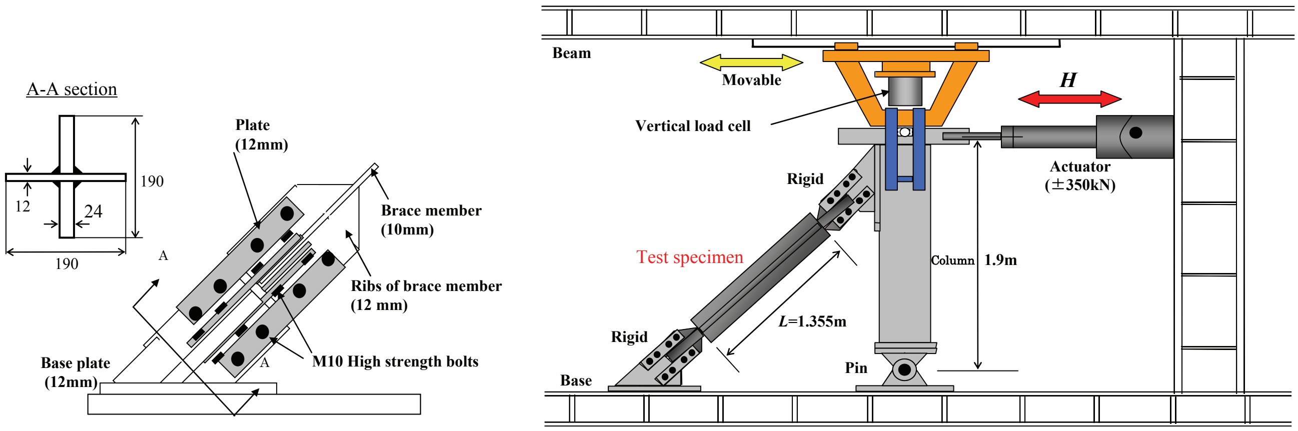
Table 2 Material properties of brace members

Specimens	E [GPa]	σ_y [MPa]	ε_y [%]	E_{st} [GPa]	ε_{st} [%]	σ_u [MPa]	ν
(a), (c), (d)	210	279	0.133	4.19	1.58	428	0.287
(b)	209	273	0.133	3.70	1.73	422	0.288

Table 3 Dimensions of restraining members

Specimens	$b_f = b^R$ [mm]	$t_f = t^R$ [mm]	h_w	t_w	σ_y^R [MPa]	E^R [GPa]	$\frac{M_y^R}{P_y L}$	$\frac{P_E^R}{P_y}$	Space amount [mm]	
									d	d_o
(a)F10W0-d1-6	200	10.2	0	0	279	210	0.0241	2.10	1	6
(b)F12W0-d1-2	200	12.3	0	0			0.0333	3.34	1	2
(c)F14W0-d2-2	201	13.7	0	0			0.0401	4.46	2	2
(d)F14W31-d1-2	201	13.7	33	9.1			0.0246	6.89	2	2

Note: notations refer to Figure 1.



Connection details

Figure 3 Test setup

Parameters of the test specimens are shown in Table 3. Some of notations in Table-3 are defined in Fig.1, and other notations are: σ_y^R =yield stress of the restraining member and E^R = Young modulus of the restraining member. Moreover, for the name of the test specimen, the number after F is the thickness of flange part of the restraining member, the number after W is the height of web part of the restraining member, the number after d sequentially means the space amount between the brace member and the restraining member in out-of-plane direction and in-plane direction. According to circumstances, the name of the test specimen will be abbreviated in (a)~(d) ahead of that because it is too long. A couple of restraining members is connected by 29 bolts along the length at intervals of 50mm, using high strength bolts of 8.8-Grade M10 (insurance load=33.7KN).

(3) Unbonding material

The unbonding material is a kind of material bonded to the brace member to let the brace member deform freely in axial direction in the space between the restraining members. In this experiment, the Santac sealer of 1mm thickness made by Hayakawa rubber Ltd. is used. This material is a kind of tape sealing material which is made mainly of the butyl rubber, and it is cohesive in solid rubber, so it is possible to put it on the brace member like the seal.

4.1.2 Test setup

Figure 3 shows the test setup. The test specimen is connected by bolts with an angle of 45° between the perpendicular pillar of the pin support (height =1.9m from the pin) and the plinth without causing the eccentric axial force as much as possible. Details of the connection to the plinth at the bottom end of the test specimen are shown in Fig.3. The connection to the perpendicular pillar at the top end is also the same. The horizontal force is applied by the actuator of ±350kN in capacity. Under the horizontal loading by the actuator, an axial load $\sqrt{2}H$ (H = the horizontal force) and an axial displacement $\delta_H/\sqrt{2}$ (δ_H =the horizontal displacement) are given to the test specimen. A minimal vertical load is also applied with the jack in the upper part of rigid pillar so that the rotation might slip well for the pillar. In this jack, the horizontal beam is supported by roller, and it is possible to move freely in horizontal direction.

4.1.3 Loading pattern

In this experiment, the actuator is controlled by the axial displacement δ of the test specimen, and the gradually increasing cyclic loading of tension and compression alternating is performed. The loading pattern began from $0.5\delta_y$, and increased evenly by displacement increment $1\delta_y$ from $1\delta_y$ to $6\delta_y$, $2\delta_y$ from $6\delta_y$ to $12\delta_y$, and $3\delta_y$ after $12\delta_y$, and for each amplitude one time of cyclic loading on both sides was performed. Moreover, the experiment was terminated at $21\delta_y$ because of the limitation of the capacity of the experimental apparatus.

4.2 Experimental Results

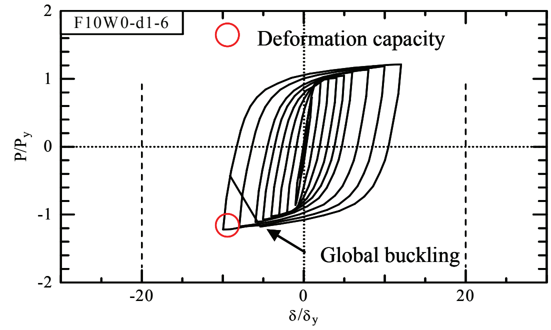
4.21 Initial deflection of the restraining member

For the test specimens of (c) F14W0-d2-2 and (d) F14W31-d1-2, after setting up BRB in the experimental apparatus, the initial deflection of the restraining member is measured. The maximum initial deflection of the test pieces are about $L/333$ and $L/500$ respectively, and the shape is in half wave of sine curve. The maximum initial deflection of the restraining member is important in the design of BRB, because of its influence on the conditional equation (3.1) of overall buckling prevention of BRB.

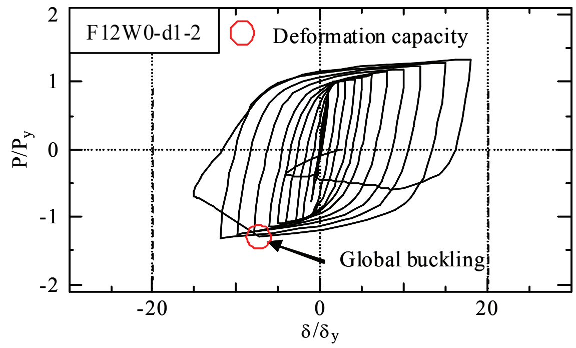
4.2.2 Deformation behaviour

In Fig.4, the relation of the axial loading (P/P_y) and axial displacement (δ/δ_y) of each test specimen obtained from this experiment is shown. In the figure, the tensile side is shown as positive. In the loading process after the cycle of $\delta = 10\delta_y$ in (a)F10W0-d1-6(t^R =10.2mm), and $\delta = 12\delta_y$ in (b)F12W0-d1-2(t^R =12.3mm), the strength decreased rapidly, it became impossible for the loading beyond that (the deformation limit in the figure). This is because overall buckling of restraining member together with brace member occurs as shown in Photo 1.

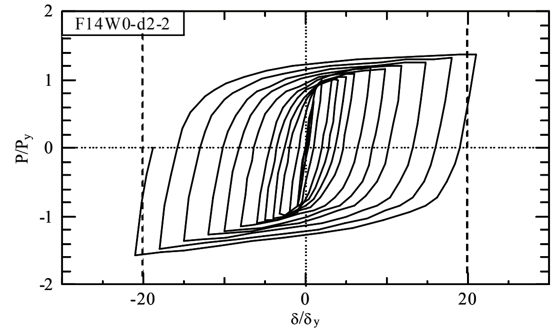
On the other hand, for the test specimen of (c)F14W0-d2-2(t^R =13.7mm) and (d)F14W31-d1-2 (T-type restraining member), the overall buckling did not happen, and the hysteretic curve of the spindle type with large hysteretic absorption energy is obtained, as seen in the past experiment (e.g., Watanabe et al. 2003). For the test specimens (c) and (d) in which the overall buckling was not observed, the relation of P/P_y - δ/δ_y is almost the same. From the experimental result of the plane restraining member, it is understood that the thickness limit of restraining member causing overall buckling is within t^R =12～14mm.



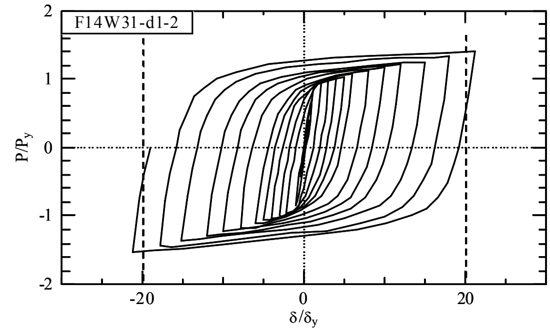
(a) F10W0-d1-6 (t^R = 10.2mm)



(b)F12W0-d1-2(t^R = 12.3mm)



(c)F14W0-d2-2(t^R = 13.7mm)



(d)F14W31-d1-2(T-shaped)

Figure 4 Experimental results

Table 4 is a comparison of the safety factor obtained from equation (3.5) and the maximum load and ductility obtained from the experiment. The ductility is an inelastic deformation capacity on the compressive side at the ultimate deformation. Taking (b)F12W0-d1-2 test specimen as an example, though the strength deterioration was not observed up to -12 δ_y, when further loading to -15 δ_y, the overall buckling occurred. Therefore the ductility is 12. But for the test specimens (c) and (d), though the experiment was ended in the limitation of loading by -21 δ_y for the capacity of experimental apparatus, the ductility shown in the table is denoted to be >21 because there is a possibility to have a bigger deformation performance. Moreover, in the

Table 4 Summary of Experimental results and safety factors

Specimens	Restraining Plate thickness $t_f = t^R$	Tests			Prediction by Eq.(3.5)
		Maximum Load $(P_{max}/P_y)_{exp}$	Ductility δ_m / δ_y	Occurrence of global buckling	Safety factor $\nu_F = P_{max}/P_y$
(a) F10W0-d1-6	10.2	1.21	10	Yes	1.59
(b) F12W0-d1-2	12.3	1.29	12	Yes	2.65
(c) F14W0-d2-2	13.7	>1.60	>21	No	2.97
(d) F14W31-d1-2	13.7	>1.60	>21	No	3.90

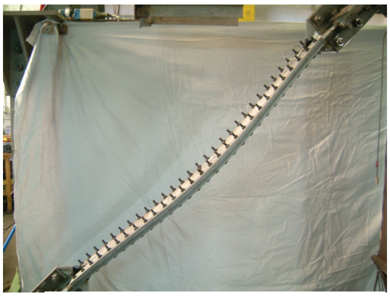


Photo 1 Global buckling

prediction by Eq.(3.5), the parameters, material constants and initial deflections of BRB used are measured values, and the eccentricity is assumed to be 0.

It can be found from the table that there is a remarkable difference between the safety factor obtained from equation (3.5) and the maximum load from experiments of the test specimens (a) and (b). That is, for these test specimens, though predictions by equation (3.5) indicate that the overall buckling was expected to occur at axial compressive load of $1.59P_y$ and 2.65 P_y, respectively, the overall buckling occurred in the experiment at a load considerably smaller than the predicted load. This main reason might be effect of possible eccentricity of axial load although the load was applied concentrically as much as possible.

5. CONCLUSIONS

One of the required performances of the buckling restrained brace (BRB) is the performance of not causing overall buckling until the brace member reaches enough plastic deformation. This required performance becomes important as BRB is lightened, and the strength and rigidity of the restraining member become lower. In this paper, this required performance was experimentally examined by using steel BRB model under cyclic loading. Among four test specimens, two of the flat bar restraining member (plate thickness = 10.2, 12.3mm) with low strength and rigidity has caused overall buckling failure under compression. Other test specimens have not caused overall buckling until reaching the target ductility (δ / δ y= 20.0). The strength and energy absorption ability decreased rapidly by overall buckling, and the deformation performance under tensile load was also influenced.

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