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Effect of brace end rotation on the global buckling behavior of pin-connected buckling-restrained braces with end collars

Junxian Zhao [a], Bin Wu [a,*], Jinping Ou [a,b]

[a] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, People's Republic of China
[b] School of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian 116024, People's Republic of China

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ABSTRACT

The effect of brace end rotation on the global stability of buckling-restrained braces (BRBs) is a common but unaddressed issue in design. To further investigate this issue, component tests of nine pin-connected BRBs with end collars were conducted, in which the effects of brace end rotation, the gap between the core and the casing, the gap between the collar and the casing and the stiffness and strength of the casing were considered. The test results show that premature global buckling still occurred even though the capacities of the specimens met the current stiffening requirement to prevent global buckling. It indicates that the commonly used global stability design criterion is not conservative. Additional end bending moments in the casing, induced by brace end rotation, would be developed if rotational gap fully developed to cause two-point contact near the casing ends. A simplified procedure to estimate the magnitudes of end bending moments is proposed. It shows that such end bending moment exceeded the yield moment of the casing when the specimens failed by global buckling, indicating a significant negative effect on global stability of BRBs. C-mode brace end rotation configuration was found to be more unfavorable than S-mode configuration for the global stability of BRBs. Several design implications and future research needs for global stability design of BRBs with pinned and bolted end connections are presented. It is suggested that the effect of end bending moment should be considered into global stability design of BRBs.

1. Introduction

Buckling-restrained braces (BRBs) are now gaining wide acceptance in seismic-prone areas due to their ductile performance and stable cyclic behavior under seismic loading. BRBs have recently been implemented mainly in buildings and bridges [1] as energy dissipation members, mostly in Japan and in the United States. The global stability is one of the most concerned issues in BRB design, and this topic has been widely studied by numerous researchers [2–11]. Based on their findings, the initial deflection of the steel core, the gap between the core and the casing and the stiffness and strength of the casing are four governing parameters for the global stability of BRBs. These studies, however, mainly focused on the interaction between the constrained steel core and the casing and ignored the effect of brace end rotation on the global stability of BRBs.

Either pinned or bolted end connections can be used to connect the BRBs to the frame gussets in actual applications. It is expected that the brace ends of bolt-connected BRBs will be forced to rotate due to the frame action during a seismic event. To consider such effect, subassemblage testing is required in the AISC Seismic Provisions [12] to verify the ability of BRB to accommodate the combined axial and rotational deformation demands. The subassemblage tests by Saeki et al. [13] and Uemura et al. [14] showed that brace end rotation would induce additional in-plane bending moment at the core extension and connection portion, which caused premature buckling of these parts. Merritt et al. [15] and Tremblay et al. [16] found that such rotation would also induce additional in-plane bending effect in the casing, and its magnitude could be up to 30% of the yield moment of the casing [15]. The frame test by Tsai and Hsiao [17] showed that the BRBs with significant brace end rotational demands exhibited low cumulative plastic ductility (CPD) capacities and experienced premature out-of-plane buckling. But Aiken et al. [18] and Tremblay et al. [16] found that such additional bending moment did not seem to affect the axial response of BRB. These studies, however, focused on the effect of brace end rotation on the connection performance and axial response of BRB only and ignored potential negative effect on the global stability of BRBs. A more detailed investigation was conducted by Takeuchi et al. [19]. In their study, the evaluation formulas for the rotational stiffness and bending strength of

* Corresponding author. Address: School of Civil Engineering, Harbin Institute of Technology, 202 Haihe Road, Nangang District, Harbin 150090, People's Republic of China. Tel.: +86 451 86283765; fax: +86 451 86282704.
E-mail address: bin.wu@hit.edu.cn (B. Wu).

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Nomenclature

L_o	connection length	M_c	bending moment at the center of casing
L_c	constrained length for core stiffening portion	M_{end}	end bending moment
L_y	core yielding length	$M_{end,1}$	end bending moment for case 1
L_r	constrained length for collar	$M_{end,2}$	end bending moment for case 2
L_e	casing length	$M_{end,tr}$	triggering end bending moment
b_h	horizontal width of steel core	$M_{end,tr,c}$	triggering end bending moment for C-mode
t_s	thickness of steel core	$M_{end,tr,s}$	triggering end bending moment for S-mode
b_v	vertical width of steel core	$M_{end,tr,L}$	triggering end bending moment for L-mode
D	width of casing	θ	brace end rotational response
T	thickness of casing	θ_{rg}	rotational gap between casing and collar
c	gap between core and casing	θ_u	brace end rotational response of upper end
d	gap between casing and collar	θ_b	brace end rotational response of lower end
a	initial deflection at the center of steel core	θ_o	vertical inclination of core axis
v_o	initial deflection at the center of casing	$\theta_{r,c}$	rigid body rotational demand of brace end for C-mode
P_y	axial yield force	$\theta_{r,s}$	rigid body rotational demand of brace end for S-mode
P_e	Euler buckling load of casing	$\theta_{r,L}$	rigid body rotational demand of brace end for L-mode
$P_{cmax,e}$	expected maximum axial force	$\theta_{r,1}$	rotational demand of brace end with one-point contact
$P_{cmax,t}$	measured maximum axial force	ε	core strain
P_{gb}	global buckling load	ε_y	yield strain of casing
n_E^B	stiffness parameter of casing	ε_{gb}	core strain when global buckling occurs
m_y^B	strength parameter of casing	ε_m	flexural strain of casing
M_y	yield moment of casing	$\varepsilon_{cmax,t}$	measured maximum compressive core strain
M_p	plastic moment of casing		

bolt-connected BRBs at the casing ends were proposed, and the effect of rotational stiffness on the overall buckling strength was also discussed. However, the corresponding negative effect of end bending moments transferred to the casing on the overall flexural buckling behavior of BRB was not reported.

One way to minimize the bending effect at the brace ends induced by frame action is to connect the BRBs to the frame gussets by pins. However, in the authors' prior cyclic tests of pin-connected BRBs [20,21], significant brace end rotational demands could still be observed due to the presence of gap between the core and the casing and the rotational deformations at the casing ends. Moreover, it was found that additional bending moment, induced by brace end rotation, could still be developed in the core extension even though the BRBs were flexurally isolated from the gussets. This resulted in premature buckling of the weaker core extension. Similar failure mode of pin-connected BRBs could also be observed in the tests by Narihara et al. [22], Usami and Kaneko [23] and Ju et al. [24]. These studies [20–24] seem to indicate that the effect of brace end rotation on the performance of pin-connected BRBs is similar to that of bolt-connected BRBs, which also raises concerns for the potential negative effect on the global stability of this type of braces. On the other hand, although several subassemblage tests and frame tests of pin-connected BRBs were conducted [25,26], the corresponding effect on the global stability has not yet been reported.

It should be noted that in actual design, the calculated margin of safety for stability against global buckling of BRBs highly exceeds the lower bound value governed by the current global stability stiffening requirement. Hence, the corresponding negative effect of brace end rotation on the global stability might be covered by the high margin of safety. So, this problem could not be easily exposed in the prior studies.

It is apparent from the above summary that the effect of brace end rotation on the global stability of BRBs is a common but unaddressed issue in BRB research regardless of the connection details (pinned or bolted end connections). In addition, the issues regarding how the additional in-plane bending moments act on the casing, how to predict their magnitudes after BRB yields and the corresponding influential factors have not yet been well understood especially for pin-connected BRBs. These problems are expected to be related to the specific brace end configuration and the interaction between the brace end and the casing end, which still needs further investigation.

2. Research objectives

Angle steel BRBs (ABRBs) as shown in Fig. 1 is a novel type of all-steel buckling-restrained brace proposed by the authors [20]. A series of cyclic tests were conducted on this type of BRBs. Test results showed that ABRB exhibited stable cyclic behavior and excellent energy dissipation capacity up to 3% core strain [20].

Based on the authors' prior researches [20,21] and the problems mentioned in Section 1, this paper aims to further investigate the effect of brace end rotation on the global buckling behavior of pin-connected ABRBs with end collars (Fig. 1). The end collars are typical brace end configuration for pin-connected BRBs [25], which are used to avoid compressive-flexural buckling at the core extension [20]. There are two main reasons to start investigating this issue with pin-connected BRBs. Firstly, brace end rotational demands of bolt-connected BRBs are mainly governed by frame action, which would make this issue more complicated. In addition, to start with pin-connected BRBs could also provide further research hints for the BRBs with bolted end connections.

In this paper, component tests were conducted on nine ABRB specimens with pin-and-collar assembly at the brace ends (Fig. 1), in which the effects of brace end rotation, the gap between the core and the casing, the gap between the collar and the casing and the stiffness and strength of the casing were considered. The hysteretic responses, failure modes, characteristics of brace end rotation and flexural responses in the casing are first presented. The effects of brace end rotational deformation and brace end rotation modes on the global stability of the specimens are discussed. Some main weaknesses of the commonly used global stability stiffening requirement are pointed out. The occurrence mechanism of in-plane end bending moment in the casing and the corresponding