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Global buckling prevention of end collared buckling-restrained braces: Theoretical, numerical analyses and design recommendations

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ABSTRACT

In recent years, buckling-restrained braces (BRBs) have been widely utilized in engineering structures. Generally, BRBs are diagonally installed in frame structures to serve as lateral-resistance and energy-dissipation members. To prevent the local buckling of the unrestrained portion of a pin-ended BRB, an end collared BRB (EC-BRB) was proposed by prior researchers by installing end collars at both ends of an ordinary BRB. By using this approach, the enhancement construction of the unrestrained portion could be remarkably simplified, and the end collars can provide lateral restraints to the restraining member, thus improving the global stability of the BRB member. In this paper, a design method for global buckling prevention of pin-ended EC-BRBs based on the restraining ratio requirements is provided via theoretical and numerical analyses. The equation of elastic buckling loads of EC-BRBs is firstly derived and validated by the eigenvalue buckling analyses via ANSYS, and the restraining ratios of EC-BRBs could be further calculated. Then, the restraining ratio requirements of EC-BRBs are theoretically proposed based on the magnification factor of the mid-span lateral deformation, and accordingly a recommended design procedure is provided. The design procedure is further validated by numerous finite element (FE) models subjected to hysteretic and monotonic loadings, indicating that this procedure can conservatively ensure the global stability of EC-BRBs and it is suitable for practical engineering applications.

1. Introduction

1.1. Prior BRB researches

In recent years, buckling-restrained braces (BRBs) have been increasingly used in engineering structures [1]. Different from common braces, the axial force of a BRB is fully carried by its inner steel core and the lateral deformation of the core is restrained by the outer restraining member. Consequently, a BRB member can exhibit full-sectional yielding of the core without global buckling, leading to a symmetric response under both tension and compression. Therefore, BRBs could be adopted in frame structures to work as lateral-resistance and energy-dissipation members [2–5].

The concept of BRB was firstly proposed by Kimura et al. [6] in the year of 1976, and it was well known after the investigations conducted by Fujimoto et al. [7,8]. In the past several decades, numerous researches, including theoretical, numerical and test investigations, have been conducted about BRBs to study their load-carrying mechanism and hysteretic behavior [2–5,9–16]. In addition, numerous different types of BRBs were proposed by changing the forms of the restraining members. At the beginning of the BRB research, BRBs encased by mortar infilled steel tubes were studied [2–4,6–8,17]. In order to eliminate the use of unbonding material along the core/restraining member interface, all-steel BRBs were proposed [18–20] in which the use of mortar was avoided and the gap size between the core and restraining member could be precisely controlled. Then, some assembled BRBs were proposed [21–24] with their restraining members assembled by bolts to enable the disassembly of the BRBs with convenience. By using this type of BRB, the damaged steel core could be easily replaced with recycle of the restraining member after severe earthquake. Furthermore, several new types of BRBs were proposed [25–32] in recent years to obtain higher performances and more economic designs.

1.2. Objective of EC-BRBs

BRBs are commonly used in frame structures and they are diagonally installed. Consequently, the lateral force applied to the frame structure would be transmitted, by means of the storey drift, to the diagonally installed BRBs. It is expected by the engineers that the BRBs could be subjected to pure-axially tensile and

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Nomenclature

A_c	cross-sectional area of the core
d_c, d_e, d_r	diameter of the tubes of the core, end collar and restraining member
E	Young's modulus of steel
f_{yc}, f_{yr}	yield stress of the core and restraining member
I_c, I_e, I_r	moment of inertia values of the core, end collar and restraining member
k	elastic buckling coefficient
L	length of EC-BRB
$M_{\max}$	maximum bending moment at mid-span of EC-BRB
M_{mid}	capacity of bending moment of EC-BRB
N	axial force of EC-BRB
$N_{cr,0}$	Euler buckling load of an ordinary BRB
N_{cr}	elastic buckling load of EC-BRB
$N_{\max}$	maximum compressive load of the core
N_y	initial yield load of the core
r_N	axial force ratio
R_y	enhancement factor of the core material
t_c, t_e, t_r	thickness of the tubes of the core, end collar and restraining member
v_0	amplitude of the initial imperfection
$v_{\max}$	maximum lateral deformation at mid-span
W_r	sectional modulus of the restraining member about its outmost fiber
α	end collar length factor
β	magnification factor of mid-span lateral deformation
$[\beta]$	upper limit of the magnification factor
ε	axial strain of the core
ζ	restraining ratio
$[\zeta]$	restraining ratio requirement
η	moment of inertia coefficient of EC-BRB

compressive loadings to produce their maximum energy-dissipating abilities. However, when the frame structure suffers lateral forces, the loading condition of a diagonally installed BRB would be closely related to its end connection type.

For a fix-ended BRB with its both ends welded to the gussets, as depicted in Fig. 1(a), an end rotation of the gusset region would be transmitted through the welded connection to the unrestrained core portion of the BRB member. Since sectional flexural rigidity of the BRB exhibits a sudden change at the joint section between the unrestrained and restrained portions (i.e. the easily failure location presented in Fig. 1(a)), a plastic hinge might occur at the joint section when the end rotation gets larger. This would aggravate the possibility of local buckling or local strength failure of the unrestrained portion at BRB ends. In consideration of the disadvantage of welded connections, some engineers prefer to choose the pin-ended BRBs with hinged connections at their ends. As shown in Fig. 1(b), when the pin-ended BRB is adopted in the frame structure, the end rotation of the gusset region is isolated by the hinge section and the BRB appears to achieve pure axial loading. Based on some prior researches [33–35], in a pin-ended BRB the local enhancement construction of the unrestrained portion of the core should be carefully considered. Otherwise, local buckling or local strength failure of the unrestrained portion would easily occur, which was observed in several subassemblage test results provided by prior researchers. For instance, Fig. 2 depicts the failure mode observed from a test of a pin-ended core-separated BRB conducted recently by the authors [32], in which local strength failure of the unrestrained portion of the BRB occurred. This indicates that an inevitable eccentric load or bending moment caused by end rotation of framing easily results in a local failure at the unrestrained portion of the core although it is a pin-ended BRB.

In order to prevent the local buckling or local strength failure of the unrestrained portion and to simplify the local enhancement construction of a pin-ended BRB, the end collared BRBs (EC-BRBs) with end collars at their both ends were proposed and studied [35–37]. Taking the BRBs composed of steel tubes as an example, the comparison of ordinary BRB and EC-BRB is performed in Fig. 3(a) and (b). It can be seen that the end collars in an EC-BRB is installed at its both ends and directly welded to the end plates, indicating that the rotational and translational DOFs of the end collar equal to that of the core at BRB ends. The dimension of the end collars in diameter is slightly larger than the restraining member to ensure an air gap between them, hence the end collar can move freely in the longitudinal direction of the EC-BRB. Additionally, the end collar can provide lateral restraints to the restraining member via the contact effect along their interface. For convenience of the following discussion, the length of EC-BRBs is denoted by L, and an end collar length factor α is defined by the ratio between the length of a single end collared region and the total length of an EC-BRB.

In consideration of the differences between ordinary BRBs and EC-BRBs in their construction and load-carrying mechanism, several advantages of EC-BRBs over ordinary BRBs are listed as follows:

(1) Based on the investigations performed by Zhao et al. [36,37], local buckling of the unrestrained portion could be efficiently prevented in an EC-BRB, due to the enhancement effect of the end collars to the unrestrained core portion.
(2) The construction of unrestrained core portion is remarkably simplified.
(3) The end collars can provide lateral restraints to the restraining member via the contact effect along their interface, leading to a better restraining effect of the BRB member, thus the end collars are helpful in improving the global stability behavior of the BRB member.

1.3. Research plan

In order to propose a comprehensive method for EC-BRB design, the following aspects should be considered:

(1) The strength design of the EC-BRB member considering local and global buckling failures: this aspect requires numerous theoretical and FE numerical investigations and it is of major concern in this paper.
(2) The construction details and strength design of pin connections at EC-BRB ends to the frame structure: the details of end connections are shown in Fig. 3(c) and the hinge joints at both ends of the EC-BRB should be designed to make sure that their resistance is greater than the required axial load of the EC-BRB member, including additional axial load induced from the strain hardening of the core under cyclic loadings.
(3) Material properties and energy-dissipating behavior: the material with high-ductility performance should be chosen for the yield core, and the restraining system should provide