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Numerical studies of cyclic behavior and design suggestions on triple-truss-confined buckling-restrained braces

Yan-Lin Guo [a], Peng Zhou [a,*], Meng-Zheng Wang [a], Yong-Lin Pi [b], Mark Andrew Bradford [b]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, UNSW Australia, UNSW Sydney, NSW 2052, Australia

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ABSTRACT

The cyclic behavior and design of a triple-truss-confined buckling-restrained brace (TTC-BRB) is investigated, especially when it is used in mega-frame high-rise buildings and long-span spatial structures as a long-span BRB. The TTC-BRB is formed by introducing an additional structural system of rigid truss frames to the outside of a common double-tube BRB in order to achieve a higher external restraining flexural stiffness as well as a high overall load-carrying capacity. An analytical method is utilized to derive a formula of the elastic buckling load of a pin-ended TTC-BRB, which is verified and modified through FE analyses. The effect of restraining ratio of the TTC-BRB on its cyclic behavior and failure mechanism is explored. The findings indicate that the TTC-BRB may have two different failure modes, namely in-plane and out-of-plane instability failures of the chord subjected to compression at the mid-span of the TTC-BRB. In addition, the load-carrying capacity of the TTC-BRB under cyclic loading is found to be proportional to the restraining ratio, and there exists a lower limit of the restraining ratio which ensures the core could reach its full cross-sectional yield load before overall instability failure of the TTC-BRB. Furthermore, in order for the TTC-BRB to be an energy dissipation type of BRBs, the lower limit requirement of the restraining ratio should be satisfied and its end constructional and strength design should be carefully carried out to avoid its premature failure. The investigation of the elastic buckling load and cyclic behavior as well as failure mechanism of the TTC-BRB provides fundamentals to the further development of a comprehensive design method of the TTC-BRB.

1. Introduction

A buckling-restrained brace (BRB) typically consists of a steel core and an external buckling restraining system which prevents the steel core plate from overall flexural buckling [1]. The core is generally a steel tube filled with mortar or a pure steel component, which resists the entire axial load, and is able to yield both in tension and compression because its overall buckling is prevented by the external buckling restraining system having quite high lateral stiffness. Therefore, the BRBs can dissipate a significant amount of energy under cyclic loads, and achieve adequate energy dissipation capability and sufficient ductility if they are properly designed and fabricated [2–4]. In actual engineering applications, under minor earthquakes or wind loads, the BRBs are able to remain elastic and provide sufficient structural lateral stiffness in order to control horizontal drift of the main structures. Under moderate or serve earthquakes, the BRBs not only provide structural lateral stiffness but can also be utilized as metallic yielding dampers in building structures for their excellent ductile performance as well as stable hysteretic response [1,5–9].

Many researchers have conducted experiments and numerical investigations on BRBs for them to be incorporated in building structures as seismic load-resisting systems. Hoveidae and Rafezy [10] conducted a parametric study of BRBs with different amounts of gap between the core and the buckling restraining systems and initial imperfections to investigate their effects on the global buckling behavior of the brace (Fig. 1). Xie [11] reported studies on the seismic behavior and practical applications of the BRBs in building structures in Asia. Tremblay et al. [12] conducted sub-assemblage seismic tests on BRBs with different brace core segment lengths and buckling restraining systems consisting of all-steel and common bracing members. Zhao et al. [13] proposed a novel type of angle steel BRBs (Fig. 2) and investigated their cyclic behavior and failure mechanism experimentally. Guo et al. [14–15] proposed a new type of all-steel core-separated BRBs where the cores are separated in a distance to increase overall flexural stiffness and load-carrying capacity (Fig. 3). It is known that the forms of the

* Corresponding author.
E-mail address: zhou-p15@mails.tsinghua.edu.cn (P. Zhou).

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Notations

Symbol	Unit, description
A_{ch}	m^2, cross-sectional area of each chord
A_d	m^2, cross-sectional area of each diagonal web
A_v	m^2, cross-sectional area of each vertical web
D_c	m, diameter of a steel core
D_{ch}	m, diameter of a chord
D_e	m, diameter of an external tube
D_d	m, diameter of a diagonal web
D_t	m, diameter of a transverse tube
D_v	m, diameter of a vertical web
E	GPa, Young's modulus of each steel component
F	N, concentrated force acting at the ends of the core or the external restraining system
h	m, center-to-center distance between the core and the chord
I_{chs}	m^4, sectional second moment of area of all chords
I_{ch}	m^4, sectional second moment of area of each individual chord about its own neutral axis
I_c	m^4, sectional second moment of area of the core
I_d	m^4, sectional second moment of area of the diagonal web
I_e	m^4, sectional second moment of area of the external tube
I_{tr}	m^4, sectional second moment of area of the truss confining system
K_v	N, shear stiffness of the truss confining system
L	m, total length of a TTC-BRB
l_y	m, length of plastic zone of core
l_1	m, length of each segment of chord
n_s	dimensionless, number of segments along the external tube divided by the truss confining system
P	kN, a concentrated force (axial force) applied at one end of the core
P_{cr}	N, elastic buckling load of a TTC-BRB
P_e	N, elastic buckling load of the external restraining system
$P_{cr,0}$	N, elastic buckling load of a common double-tube BRB
$P_{cr,c}$	N, elastic buckling load of the core
$P_{cr,e}$	N, elastic buckling load of the external tube
$P_{cr,tr}$	N, elastic buckling load of the truss confining system
$P_{y,c}$	N, axial yield load of a steel core
$P_{c,max}$	kN, maximum compressive load
$P_{t,max}$	kN, maximum tensile load
$q(z)$	N/mm, interaction force between the core and the external restraining system
t_c	m, thickness of a steel core
t_{ch}	m, thickness of a chord
t_e	m, thickness of an external tube
t_d	m, thickness of a diagonal web
t_t	m, thickness of a transverse tube
t_v	m, thickness of a vertical web
V	N, shear force actions at the segment of the truss confining system
$V_i, i = 1, 2, 3$	N, shear force sustained by each truss frame
α	° (degree), angle between the *x*-axis and the line of buckling direction
λ	dimensionless, modification factor of elastic buckling load of TTC-BRB
γ_1	dimensionless, unit shear angle for a TC-BRB with a single frame
φ	° (degree), angle between one of the truss frames and the direction of the shear force actions V
ρ	m^{-1}, curvature of a segment of the external tube
θ	° (degree), angle between the diagonal web and a segment of the external tube
Δ_f	m, axial deformation of the chord due to its flexural deformation
Δ_s	m, displacement at the node of the segment of the external restraining system due to shear force actions V
$\Delta_s i, i = 1, 2, 3$	m, displacement of each truss frame due to shear force actions V
σ_y	MPa, yield stress of core
ε_c	dimensionless, axial strain amplitude in the plastic zone of the core
ε_y	dimensionless, yield strain of core
δ	mm, axial displacement of core
ζ	dimensionless, restraining ratio of a TTC-BRB/common BRB
$[\zeta]$	dimensionless, lower limit of restraining ratio of a TTC-BRB without considering cyclic strain hardening
$[\zeta]_\eta$	dimensionless, lower limit of restraining ratio of a TTC-BRB with consideration of cyclic strain hardening
η	dimensionless, cyclic strain hardening factor
μ_{max}	dimensionless, maximum ductility
μ_c	dimensionless, cumulative ductility

BRBs can be categorized into two types depending on the external restraining system: (1) core buckling restrained by a steel tube filled with concrete or mortar; (2) core buckling restrained by all-steel components known as all-steel BRBs. In addition, the forms of the BRBs can also be categorized into two types depending on the number of cores: (1) single-core BRB; (2) dual-core or multiple-core BRB (known as latticed type of BRBs).

Due to the increasing demand for more complex high-rise buildings and mega-spatial structures, the scope of engineering applications of the BRBs have expanded enormously over the years. To meet the engineering requirements, attentions in investigations of the BRBs has been paid to the development of light-weight as well as large-capacity BRBs. In order to achieve a light-weight BRB design, the buckling restraining systems in BRBs have been gradually transformed from concrete or a concrete-infilled tube to all-steel components. All-steel BRBs exclude the complexities associated with pouring and curing of concrete or mortar, thus eliminating possible fabrication errors. In addition, the self-weight of all-steel BRBs are smaller than that of common BRBs. All-steel assembled BRB is an important type of light-weight BRB being developed in recent years, and its external restraining system is composed of several profiled steels connected together by high strength bolts [10,16–18]. The assembled all-steel BRBs have several advantages over the common BRBs including much light self-weight; convenient fabrication and on-site assembling; and their yielded core can be easily replaced after an earthquake. It is commonly recognized that the flexural stiffness provided by the external restraining system is the determining factor of the load-carrying capacity of a BRB. Therefore, in order to achieve a large-capacity BRB design, a conventional approach is to enlarge the cross-sectional dimensions of the external restraining system thus increasing its flexural stiffness. However, this would significantly increase the self-weight of the BRB itself and is not aesthetically appealing. Hence, this approach is not suitable for actual engineering applications. In order to overcome the limitations of the current BRBs and to achieve a light-weight, long-span and high-capacity design of the BRBs, Guo et al. [19] proposed a new type of BRBs namely a pre-tensioned cable stayed buckling-