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Experimental and numerical studies of hysteretic response of triple-truss-confined buckling-restrained braces

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ABSTRACT

A new type of BRBs, namely a triple-truss-confined BRB (TTC-BRB) is proposed, and its hysteretic response is investigated experimentally and numerically in this paper. The TTC-BRB is formed through introducing an additional structural system of rigid trusses to the outside of a common BRB to effectively increase its external restraining flexural stiffness and its overall load-carrying capacity, especially when it is utilized as a long-span and a heavily axially loaded brace. The TTC-BRB may be adopted innovatively as diagonal braces in mega-frame structures of high-rise buildings and in long-span spatial structures. A total number of two TTC-BRB specimens have been designed and the hysteretic responses of the two TTC-BRB specimens are experimentally investigated under a combination of standard and fatigue loading protocols. The obtained experimental results indicate that both the TTC-BRB specimens have excellent hysteretic responses as well as being able to attain stable and ample hysteretic curves under cyclic loads, with both cumulative ductility and total accumulated cycles of loading, being well above the requirements specified respectively in the AISC seismic provisions and the Chinese code GB50010 for seismic design of buildings. The experimental results obtained are compared with those obtained by numerical analysis from a simplified FE model consisting of BEAM188 element, indicating that the FE model provides good correlations with the experimental results. Moreover, relevant failure mechanism and design suggestions of the TTC-BRB specimens are discussed and provided based upon the FE results. At last, as a mega brace, the influence of its self-weight, length and imperfection are investigated numerically to reveal the performance of the TTC-BRBs under cyclic loads.

1. Introduction

Energy dissipation devices have been increasingly popular and accepted in structures to achieve stable cyclic behavior as well as excellent energy dissipation capability in seismic-prone regions [1]. A buckling-restrained brace (BRB) is one of the most widespread and applicable energy dissipation devices being utilized in frame structures, long-span spatial structures and bridge structures for enhancing seismic load resistance and ductility in recent years [2–5]. A common BRB generally consists of an inner core member and an external restraining system [6–7], where the inner core sustains only the axial load and the external restraining system provides a lateral restraining action to the inner core to prevent the inner core from deforming laterally when subjected to compression. This leads to the inner core to be fully yielded to dissipate energy, thus effectively achieving higher lateral stiffness and overcoming global buckling or instability of the inner core, and obtaining stable hysteretic behavior under cyclic loads [8–9]. In comparison to the conventional braces, the axial yield force in tension and compression provided by the BRBs are almost equal in its magnitude. In addition, the BRBs exhibit stable hysteretic behavior, thus providing adequate energy dissipation capability and sufficient ductility. Hence, the BRBs can also be considered as yielding metallic hysteretic dampers during a moderate to severe earthquake [7].

Numerous studies and research work have been conducted in the last few decades for the development of the BRBs. Xie reported a summary of the studies on the seismic behavior and practical applications of the BRBs in building structures in Asia [10]. Uang et al. provided a review of past research on the BRB frame system at the component, subassemblage and frame levels [11]. Clark et al. suggested a design procedure for buildings incorporating the BRBs [12]. Takeuchi et al. investigated local buckling behavior of the BRBs both experimentally and numerically [13]. According to previous researches and studies, the development of the BRBs can be

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Nomenclature

Symbol	Description, unit
D_c	diameter of a steel core, mm
D_{ch}	diameter of a chord, mm
D_e	diameter of an external tube, mm
D_{ed}	diameter of an external diagonal web, mm
D_{id}	diameter of an internal diagonal web, mm
D_t	diameter of a transverse tube, mm
D_v	diameter of a vertical web, mm
d_{ch}	horizontal distance between two adjacent chords, mm
E	Young's modulus of steel components, GPa
f_{u}	tensile strength of steel components, MPa
f_y	yield strength of steel components, MPa
h	center-to-center distance between the core and the chord, mm
h_{cs}	height of a core stiffener, mm
h_{es}	height of an external tube stiffener, mm
L	total length of the TTC-BRB specimen between the two pin connections, m
l_y	length of plastic zone of core, mm
n_s	number of segments of the truss confining system, dimensionless
P_e	elastic buckling load of the external restraining system of a BRB, N
$P_{\mathrm{c,max}}$	maximum compressive load, kN
$P_{\mathrm{t,max}}$	maximum tensile load, kN
$P_{y,c}$	axial yield load of the steel core, N
t_c	thickness of a steel core, mm
t_{ch}	thickness of a chord, mm
t_{cs}	thickness of a core stiffener, mm
t_{es}	thickness of an external tube stiffener, mm
t_e	thickness of an external tube, mm
t_{ed}	thickness of an external diagonal web, mm
t_{id}	thickness of an internal diagonal web, mm
t_t	thickness of a transverse tube, mm
t_v	thickness of a vertical web, mm
v_0	initial central geometric imperfection amplitude of the TTC-BRB, mm
β	compression strength adjustment factor, dimensionless
δ	axial displacement of core, mm
ε_c	axial strain amplitude in the plastic zone of the core, dimensionless
ζ	restraining ratio of the TTC-BRB, dimensionless
$[\zeta]$	lower limit of restraining ratio, dimensionless
ζ_0	restraining ratio without the truss confining system, dimensionless
μ_{max}	maximum ductility, dimensionless
μ_{c}	cumulative ductility, dimensionless
ω	strain hardening adjustment factor, dimensionless

generally categorized into two types depending on the external restraining system [14]: (1) core buckling inhibited by steel tube filled with concrete or mortar, in which the steel tube is usually a rectangular or circular hollow structural section; (2) core buckling inhibited by all-steel components, namely all-steel BRBs.

In a common BRB (Fig. 1), the external restraining system was often made out of concrete or a concrete-infilled tube [15–16]. Those BRBs have been practically applied in many high-rise buildings and such analyses and corresponding design methods have been investigated and established thoroughly [17–19]. However, due to the complexities involved with the pouring and curing of concrete or mortar, the concrete or mortar filled tubes were found to have problems concerning the quality control in the fabrication process as it was difficult to control the accurate configuration of the steel core and the gap between the concrete/mortar and the steel core. In order to resolve the abovementioned problems, the all-steel BRBs have been developed. All-steel assembled BRB was a type of light-weight BRB being developed in recent years, and the external restraining system of the assembled BRBs is composed of several profiled steels connected together by high strength bolts [20–24]. It has several advantages over the common BRBs including much lighter self-weight; easier fabrication and on-site assembling; and yielded core could be easily replaced after an earthquake. Recently, Guo et al. proposed a new type of all-steel BRBs namely a core-separated buckling restrained brace (CSBRB) [25]. The CSBRB increases its sectional second moment of area and overall flexural stiffness, hence significantly increasing its load-carrying efficiency by separating the inner core members in a distance.

The development of the BRBs has been trending towards a more light-weight as well as large-capacity design over the last few decades. This is to reduce the extra loads brought from the BRBs themselves and to fulfil the requirement of lateral stiffness as well as energy dissipation capacity of the high-rise buildings or the long-span structures. In order to achieve a more light-weight, long-span as well as large-capacity design of the BRBs simultaneously by overcoming the limitations of the current BRBs, Guo et al. proposed a new type of BRBs namely a pre-tensioned cable stayed buckling-restrained brace (PCS-BRB) [26] where an additional structural system of pre-tensioned cables and a number of cross-arms are introduced to the outside of a common BRB. This new system significantly improves the BRB's overall external restraining stiffness, hence increasing the load-carrying efficiency in its structural design. Due to its aesthetically appealing structure, it can be utilized in stadiums and so forth as a laterally resistant brace. Recently, a mega-PCS-BRB with 5 cross-arms along its length was investigated and applied in a practical engineering case, located

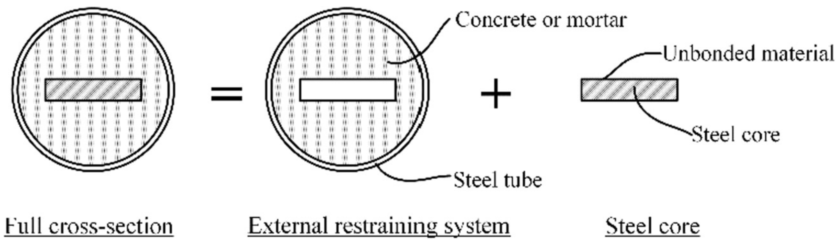

Fig. 1. Sectional composition of a common concrete in-filled tube BRB.