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Experimental and numerical developing of reduced length buckling-restrained braces

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ABSTRACT

Buckling-restrained braced frames (BRBFs) have been widely used as an efficient seismic load resisting system in recent years mostly due to their symmetric and stable hysteretic behavior and significant energy dissipation capacity. However, buckling-restrained braces (BRBs) are heavier and more expensive in comparison to other concentric bracing systems. In order to facilitate the use of BRBs, the idea of reducing the length of the core and the encasings which can result in lighter and more replaceable BRBs is proposed and experimentally investigated in this paper. Two relatively similar all-steel reduced length BRBs (RLBRBs) are designed, detailed and constructed using a special debonding and stopper mechanism. The design and construction procedure is accomplished by paying special attention to low-cycle fatigue (LCF). The specimens were tested under the quasi static loading protocol, and withstood high axial strains of 4–5% without any global or local failure. The hysteretic responses of the specimens were stable and symmetric. Moreover, numerical models were developed and nonlinear cyclic analyses were performed to provide better insight into the core and encasing performance as well as application of the RLBRB in the brace configuration.

1. Introduction

1.1. Background and research motivation

In comparison to other lateral resisting systems, buckling-restrained braced frames (BRBFs) have both high stiffness and ductility. To reach an optimum seismic design in which most of the energy dissipating potential is utilized, different elements with various strengths and stiffnesses are required. The strength and stiffness of a buckling-restrained brace (BRB) can be increased independently by selecting a larger cross section and reducing the BRB length. Reducing the length of BRB and placing it in series with an elastic brace has several advantages. The length of BRB directly effects the amount of material used in BRB, including core, encasing, filler, and the debonding material, as well as the capacity of the facilities utilized in the production and handling of the BRB. Hence, producing BRBs can be assumed as a function of their length. Although reducing the length of BRB might increase its stiffness, some studies comparing buildings designed with reduced length BRBs (RLBRBs) and conventional BRB show that reducing the length of BRB does not change the required core cross section majorly [1,2]. In such cases a shorter BRB could naturally be more economical than a longer one. Moreover, the replaceability and handling of a fuse-type BRB located in a limited space of the frame after an earthquake is simpler than a full-length heavy BRB occupying the whole frame. From the analytical point of view, the comparison of the performance of structures equipped with conventional BRBs and RLBRBs shows that the RLBRB systems have better seismic performance in terms of uniform plasticity through the height of the structure as well as less residual and maximum drifts [1–3].

The core strain demand of BRB (ε_c) is dependent upon the maximum story drift ($\Delta_{\max}$), the BRB length (L), the ratio of yielding core to the total length of brace (L_c/L) (α), and the BRB angle (θ):

$$\varepsilon_c = \frac{\Delta_{\max}\cos\theta}{\alpha L} \tag{1}$$

The strains of the core in a long BRB are less than those of a RLBRB. Naturally, the BRBs used in very long spans are hardly capable of entering the plastic zone, and therefore, the ductility capacity of the BRB may not be used efficiently. In such cases, reducing the BRB length can effectively provide the core plasticity and energy dissipating demands of the brace. For instance, considering a long span with 10 m width and 3 m height, a

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Nomenclature

A	brace cross sectional area
A_c	core cross sectional area
$A(x)$	core cross sectional area as a function of distance (x)
b	total span of the frame
c	fatigue ductility exponent
E	Young's modulus
E'	tangent modulus
$E(\Delta)$	energy dissipated by a BRB through a complete cycle
FDI	fatigue damage index
FS	factor of safety
h	height of story
K	axial stiffness of BRB
L	total length of brace
L_b	bolt spacing
L_c	length of core
L_w	higher mode buckling wave length
N_f	number of cycles to fatigue failure
n_i	number of cycles
P_{cr}	critical buckling load of the brace
P_y	yielding load of the brace
α	the ratio of yielding core to the total length of brace (L_c/L)
β	compression strength adjustment factor of BRB
δ	total deformation of the brace
θ	BRB horizontal angle
μ	displacement ductility of BRB
Δ_{by}	brace axial displacement corresponding to yielding
Δ_{bm}	brace axial displacement corresponding to design story drift
Δ_m	frame design story drift
Δ_{max}	maximum story drift
Δ_{rby}	RLBRB axial displacement corresponding to yielding
Δ_{rbm}	RLBRB axial displacement corresponding to design story drift
Δ_{pl}	RLBRB plastic axial displacement
$\Delta\varepsilon$	strain amplitude of the core
ε_c	average axial strain of the core
ε'_f	fatigue ductility coefficient
ε_L	local axial strain of the core along the length
ε_T	local strain of the core along the thickness
ε_V	volumetric strain
ε_W	local strain of the core along the width
η	ratio of cumulative plastic displacement to yield displacement
ω	strain hardening adjustment factor of BRB

maximum story drift of 2%, and yielding ratio of 80% corresponding to conventional BRBs, the core strain demand will be 0.68% which is corresponding to limited BRB ductility of 5.6 (for ST 37-2 steel). However, if the yielding length is reduced to 30% in the form of RLBRB, the strain demand easily increases to 1.81% corresponding to a reasonable BRB ductility of 15 which is a common practical value according to BRB literature [4].

In addition, from the architectural point of view, two RLBRBs can be placed in a single frame in an X-pattern configuration which is not applicable in normal BRBs.

The steel material is capable of resisting axial strains up to 20–30%; however, in most of BRBs the strain amplitudes are limited to 1–2% [5]. Considering this advantage of steel material, in this study a detailing for an all-steel RLBRB, designed to withstand axial strain of about 4.0–5.0% without fatigue failure, is presented. The all-steel BRB can be lighter than conventional concrete filled BRBs, and have higher replaceability potential. Besides, the construction of all-steel BRBs can take less time due to the elimination of concrete curing.

1.2. Relevant prior researches

As mentioned in previous section, an improvement to the detailing of BRBs is the presentation of all-steel BRBs which sandwich the BRB core. This solution helps to replace the damaged core easily using detachable encasings which might be used during several earthquakes. Several detailings have been proposed for the development of all-steel sandwiched BRBs [6–10]. D'Aniello et al. tested two detachable all-steel BRBs consisting of a rectangular steel plate and a restraining steel sleeve which formed two omega shapes bolted together. The all-steel BRB showed symmetric response up to the story drift range of ±1.5% which corresponded to core strain of 2.5% [6]. An all-steel bolted BRB was tested by Mazzolani et al. to upgrade a non-ductile two-story reinforced concrete (RC) structures. The buckling-restraining action was given by two rectangular steel tubes. The two restraining tubes were joined together by means of bolted stiffened elements. The BRB showed a good ductility of 15, though some additional improvement was required at the core to gusset plate connection [7]. In a recent attempt to develop extra light weight BRBs, Dusicka et al. proposed and investigated the behavior of a BRB made up of aluminum core and bundled glass fiber-reinforced polymer pultruded tubes for the buckling restraint which reduced the weight of the BRB remarkably [11].

Chou and Chen [12] presented a specific type of sandwiched BRBs which eliminated the use of unbonded material. The encasings were composed of a welded steel channel to a flat plate and finally filled with 48–58 MPa concrete. The encasings were connected together using A490 bolts. The authors proposed design guidelines for providing the global stability of the whole brace, as well as the local rigidity of the encasings, and the axial demand of the connecting bolts based on the higher mode buckling wavelength. The results of the tests showed that in case of providing sufficient flexural rigidity for the encasings, the proposed BRBs exhibit stable hysteretic response to a lateral design story drift of 2.4% and proper cumulative plastic ductility [12]. Moreover, a frame with the same BRB was used and safely tested to a lateral design story drift of 2.5% [13]. The stopping mechanism which is responsible for constraining the motion of the encasings to the core center, was provided by an outward projection in the core where the tensile fracture initiated. Since concrete is assumed to contribute merely in providing global stability and can be replaced by steel, eliminating concrete can be advantageous to reduce the weight of BRB and expedite the production process. The specimens tested by Chou and Chen experienced a maximum axial strain of 2.6%. If the length of BRB decreases the plastic strain demand on the BRB increases and consequently the normal force exerting on the encasings and the contact points of the core and encasing rise leading to amplification in the friction force as observed by Tremblay et al. [5]. Higher friction force is detrimental to the fatigue life of the BRB.

Most of the BRB members developed up to now have a long encasing which extends through the whole brace. The ratio of yielding core to the total length of brace (L_c/L) for common BRBs normally varies from 0.6 to 0.8 [5,14,15] and the axial strain amplitude is less than 3%. Some limited studies have assessed BRBs with