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Earthquake-resistant design of buckling-restrained braced RC moment frames using performance-based plastic design method

Jiulin Bai [*], Jinping Ou

School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
Key Lab of Structures Dynamic Behavior and Control (Harbin Institute of Technology), Ministry of Education, Harbin 150090, China

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ABSTRACT

In this study, a performance-based plastic design (PBPD) method for dual system of buckling-restrained braced reinforced concrete moment-resisting frames (RC-BRBFs) is developed. Trilinear force–deformation relationship of the dual RC-BRBF system was approximated as the bilinear capacity curve to derive the yield displacement. The design base shear was determined based on the energy balance equation which accounted for the energy dissipation capacity quantified by Large Takeda model. Plastic design procedure were presented to derive the section internal forces. The proposed methodology was verified through a 5- and 10-story RC frame structures with chevron-configured BRBs. Numerical model was established and validated to assess the seismic performance through nonlinear static pushover analysis and time history analyses using FEMA P695 recommended ground motions. The analytical results show both RC-BRBFs can achieve the intended performance levels in terms of capacity curves, yield mechanism, story drift ratio distribution, residual drift, maximum ductility and cumulative ductility demands. Furthermore, the developed design procedure can be easily extended to other BRB configurated dual structural systems to achieve the desired seismic performance.

1. Introduction

Buckling-restrained braces (BRBs) have served as a stable energy dissipating device due to the inelastic axial deformation of steel core, and an effective lateral load-resisting component without overall buckling in engineering structures under strong seismic loads for decades [1–4]. BRBs can achieve approximately equal behaviors both in tension as well as in compression. Previous experiment tests and analytical results have demonstrated that BRBs can exhibit excellent hysteretic performance without any strength and stiffness degradation [1–14]. Furthermore, when adding BRBs to a structural system, the economic benefits in material cost, construction and operation management are obvious and attractive, which makes the BRB system widely used in engineering practice [5].

Currently, BRB steel frames (BRBFs) have been widely analyzed and tested in terms of cyclic tests [6,7], full scale pseudo dynamic tests under bi-directional earthquake loads [8], column demands in frames [9], maximum ductility demands and cumulative ductility demands [7], replaceable property [10], and so on. These investigations provides more insights of this system to resist the seismic actions more reliably. Due to the remarkable hysteretic behavior, BRBs are increasingly used in the seismic retrofitting of existed reinforced concrete (RC) structures [11,12], and new RC frame systems [13,14].

To properly determine the height-wise BRB distributions to achieve the desired performance, many design methods have been developed. For instance, Sabelli et al. illustrated a design procedure for BRBFs using the ASCE 7 and AISC 341 standards [15]. The displacement-based design method was separately adopted by Kim and Seo [16] and Teran-Gilmorea and Virto-Cambray [17] to perform the design of BRB hinge-connected steel frames and preliminary design of RC frame systems with BRBs, respectively. Choi and Kim [18] proposed an energy-based design method for BRBF using hysteretic energy spectra and accumulated ductility spectra to decide the required sizes of BRBs. Sahoo and Chao [19] presented the performance-based plastic design (PBPD) method developed by Goel and Chao [20] for the BRBF design, where the design base shear was obtained through energy-work balance using desired yield mechanism and pre-selected target drift. Bosco and Marino [21] proposed a design procedure for steel frames equipped with BRBs and proper values of behavior factor was developed through numerical investigation. Note that most of these design approaches are based on premises that beam–column–brace connections are

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[*] Corresponding author at: School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China. Tel.: +86 18645075631.

E-mail address: baijiulin@gmail.com (J. Bai).

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Nomenclature

α	BRB inclination angle
β	compression strength adjustment factor
γ	energy modification factor
ε_y	yielding strain of beam reinforcements
μ_s	displacement ductility factor
η	hysteretic energy reduction factor
ρ	the ratio of Δ_y^B to Δ_y^F
λ	lateral force distribution factor
p	base shear ratio of BRB system to total system
θ_y	yield drift ratio
θ_y^B	yield drift of BRB system
θ_y^F	yield drift of frame system
θ_p	plastic drift ratio
θ_u	ultimate drift ratio
ϖ	story shear distribution factor
ω	tension strength adjustment factor
ϕ	mode vector
ϕ_t	resistance factor for tension
ϕ_c	resistance factor for compression
Γ	modal participation factor
h	story height
h_b	beam depth
q	uniform load
r	post-yield stiffness ratio
w	story weight
x	the location of beam maximum positive moment
f_y	specific yield strength of BRB core segment
A_c	sectional area of BRB core segment
A_j	sectional area of BRB transition segment
A_t	sectional area of BRB connection segment
C_B	beam compression force due to BRB
C_C	column compression force due to BRB
E_e	elastic vibrational energy
E_b	elastic modulus of BRB core segment
E_{eff}	effective elastic modulus
E_p	inelastic strain energy
E_I	seismic input energy
F_t	BRB yield strength for tension
F_c	BRB yield strength for compression
F_h	horizontal unbalanced forces due to BRB
F_v	vertical unbalanced forces due to BRB
F	lateral forces from PBPD method
F^{D}	total design lateral forces
F^{B}	lateral forces applied to BRB system
F^{F}	lateral forces applied to frame system
K_{eff}	effective axial stiffness of BRB
L	beam length measured from centerline to centerline of column
L_b	beam span
L_c	length of BRB core segment
L_j	length of BRB transition segment
L_t	length of BRB connection segment
L_w	total length of BRB
M	story mass
M^*	effective modal mass
$M_{\mathrm{Asn,min}}$	negative beam moment determined by minimum reinforcements
$M_{\mathrm{Asp,min}}$	positive beam moment determined by minimum reinforcements
M_c	base column moment
M_p	positive flexural moment of beam ends
M_n	negative flexural moment of beam ends
$M_{\max}$	maximum positive moment of beams
M_{sn}	beam negative moment derived by PBPD method
M_{sp}	beam positive moment derived by PBPD method
R	ratio of beam negative moment to beam positive moment
R_μ	strength reduction factor
R_y	material overstrength factor
S_a	spectral acceleration
S_v	spectral velocity
T_e	structural elastic period
T_B	beam tension force due to BRB
T_C	column tension force due to BRB
V_y	design base shear of total system
V_y^F	design base shear of RC frame system
V_y^B	design base shear of BRB system
V^B	story shear of BRB system
Δ_y^F	yield displacement of RC frame system
Δ_y^B	yield displacement of BRB system
Δ_y	yield displacement of bilinear system
ΔF	additional lateral forces due to P–Δ effects

pinned (e.g., [15,16,18,19,21]) and all the lateral seismic forces are resisted by the buckling-restrained braces (e.g., [15–19,21]). However, these assumptions completely neglect the contribution of main frame system which is not consistent with the actual condition, especially in RC structures.

When BRBs are configured into rigid frames, additional strength and stiffness will be produced to develop a dual system which can enhance the seismic performance of total system and results in potentially significant improvements in reducing residual story drifts [22]. Regarding the design of BRBF as a dual system, some attempts have been made. Kim and Choi [23] performed the parametric study of BRB sectional area and yield strength to maximize the equivalent damping ratio, and developed a straightforward design procedure using capacity spectrum method. Maley et al. [24] developed a displacement based-design (DBD) method for dual BRBFs. However, the gravity was not considered into the DBD design procedure. Oviedo et al. [25] presented the 'constant yield story-drift ratio' as a deformation-controlling scheme to define the yield deformation of BRBs and investigated the seismic response of a 10-story structure through parametric study. As can be seen, these design methods for dual systems do not consider the frame-BRB interaction (e.g., the force demands applied to the frame due to BRB yielding and strain hardening), which may underestimate the internal force demands of beams and columns intersected by braces. Furthermore, there is no investigation on the seismic design of dual frame-BRB structures to consider the yield mechanism and nonlinear drift demand for achieving the expected seismic performance, especially for RC frame-BRB system where the energy dissipating capacity of RC components degrades under large drift while BRB system keeps stable hysteretic behavior.

To achieve the desired seismic demands of RC frame-BRB (RC-BRBF) dual system, the present study is motivated in the framework of performance-based plastic design (PBPD) methodology to design such systems. The main objective of this investigation is to develop a design procedure of RC-BRBF dual system to account for the energy dissipation capacity of BRBs and RC frame system and inelastic behavior, such as yield mechanism and drift demands under severe ground motions. The proposed procedure was applied to two RC moment frames with chevron-configured