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Energy-based seismic strengthening design of non-ductile reinforced concrete frames using buckling-restrained braces

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ABSTRACT

This paper presents the application of an energy-based seismic design procedure to strengthen non-ductile reinforced concrete frames using buckling-restrained braces. An experimental study was conducted to examine the seismic behavior of a large-scale non-ductile RC specimen strengthened with BRBs. For the analytical study, a large number of dynamic analyses of non-ductile systems that were strengthened using ductile elements with varying strength were conducted to investigate the overall response behavior. Finally, a practical strengthening design method was presented. The method was based on the modified performance-based plastic design approach. A design example was presented. Nonlinear pushover and nonlinear time history analyses were conducted to evaluate the performance of a non-ductile RC frame strengthened with BRBs. Both the test and analysis results indicated that BRBs significantly increased the stiffness, lateral force capacity and energy dissipation. The analysis results of the strengthened frame exhibited significant response improvement in terms of structural performance and story drifts. The results were used to verify the effectiveness of the presented design approach.

1. Introduction

Non-ductile RC frames present a significant hazard to safety due to high risks of collapse during an earthquake. This type of structural system is commonly found in many areas around the world, especially in old reinforced concrete buildings. These structures were primarily designed for gravity load effects without ductile detailing. As such, they have limited lateral load resistance and deformability and have a tendency to develop excessive sideways or soft-story mechanisms under earthquake ground motions [1,2].

Over the past 10–15 years, a number of retrofitting schemes for these non-ductile frames have been investigated, such as providing RC infilled walls [3–5], column and beam jacketing [6–11] and adding new steel braces [12–14]. In recent years, the use of energy dissipating elements, such as buckling restrained braces (BRBs), has gained popularity as an alternative way to retrofit an existing structure [15–18]. This is due to the stable hysteretic behavior of these braces that results in large energy dissipation.

One of the main issues of using BRBs to strengthen a structure is how the sizes of the BRBs can be selected to match the required performance targets of the retrofitted structure. The conventional elastic design shears modified by a response reduction factor may be inappropriate because the overall ductility of the structure is difficult to quantify due to the hybrid nature of the frame. The approach based on equivalent damping also requires the designer to pre-define the strength of the BRBs to calculate the damping [19,20].

This study focuses on an application of the performance-based plastic design approach (PBPD) for the direct design of BRBs to strengthen a non-ductile reinforced concrete frame with a soft-story mechanism. The PBPD method is a performance-based design approach that is based on the energy balance concept [21]. The PBPD approach has been successfully applied for the design and evaluation of structures [22–24]. It has also been applied for the retrofitting design of existing soft-story structures using shear yielding devices [25].

This research consists of two main parts, experimental and analytical studies. The main objective of the experimental study is to examine the cyclic behavior of large-scale RC frame specimens. Cyclic tests of non-ductile RC frames with and without BRBs were conducted. The cyclic behaviors of the test specimens were used for the development of accurate analytical models. For the analytical study, a large number of dynamic analyses of non-ductile systems strengthened using ductile elements with varying strength were conducted to investigate the overall response behavior. The

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Nomenclature

A_{brb}	cross-section area of the BRB
C_2	modification factor that takes into account the effects of the pinched hysteresis shape, cyclic stiffness degradation, and strength deterioration on the maximum displacement response
C_e	normalized design pseudo acceleration
E_e	elastic energy
E_p	plastic energy
f'_c	compressive strength of concrete
f_y	yield strength of steel reinforcement
F_{ysc}	yield strength of BRB
f_u	ultimate strength of steel reinforcement
g	acceleration due to gravity
h_i	height from the ground to floor level i
I_{eff}	effective moment of inertia
I_g	gross moment of inertia
K_{brb}	spring properties of BRB
K_f	spring properties of non-ductile concrete frame
M	seismic mass of the system
P_{yc}	axial compressive strength of the BRB
P_{yt}	axial tensile strength of the BRB
r_s	strength of BRBs divided that of the concrete frame
R	reduction factor for the combined BRB and RC frame system
R_y	material over-strength factor
R_μ	yield force reduction factor for EPP system
R^*_μ	modified force reduction factor for non-EPP system
S_1	spectral acceleration at 1 s
S_a	spectral acceleration
S_s	spectral acceleration at 0.2 s
S_v	design spectral velocity
T	vibration period of structure
V_0	strength required for the system to remain elastic under ground motion
V_{brb}	lateral strength of the BRB at each story level
V_c	lateral strength of the concrete frame at each story level
V_i	lateral strength of the frame at each story level
$V_{y,brb}$	strength of BRB system
$V_{y,c}$	strength of concrete frame system
$V_{y,f}$	yield strength of the combined BRB and RC frame system
W	seismic weight of the structure
β	compression over-strength factor
Δ_{SSD}	displacement demand of the combined BRB and RC frame system
Δ_{EPP}	maximum lateral displacement demand of the corresponding elastic-perfectly-plastic system
ϕ	resistance factor
γ	energy factor
γ^*	modified energy modification factor
φ	angle of BRBs with the horizontal
λ_i	lateral force distribution factor
μ	ductility ratio
μ^*_s	modified ductility taking into account the non-EPP behavior of the strengthened frame
θ_p	target plastic story drift equal to the target drift minus the yield drift of the system
θ^*_u	equivalent EPP target drift
θ_T	target drift
ω	factor accounting for strain hardening

results from the parametric study were incorporated into the PBPD approach for seismic retrofitting applications. The modified PBPD approach was then used to design BRBs to strengthen an existing five-story structure as a case study. An inelastic pushover analysis was performed to study the failure mechanism of the existing structure and to guide the selection of the performance targets for the seismic strengthening design. Finally, nonlinear time history analyses were performed to examine the performance of both the existing RC frame and the strengthened RC frame and to verify the effectiveness of the PBPD approach.

2. Experimental study

Cyclic tests of two non-ductile RC frames were conducted, one with and one without BRBs. The test specimens were designed to represent the RC frame in the first story of a typical school building in Thailand. The test specimens were designed such that key structural indices were similar to those of the prototype frame. Structural indices are numerical indicators, such as flexural-to-shear-strength ratio, longitudinal and shear reinforcement ratios, shear-span-to-depth ratio, and average axial and shear stresses, which can be used to assess the behavior of structural members. Based on the structural indices of the prototype frame, the size and amount of reinforcement of the test specimens could be selected. The final specimens were approximately half-scale. Each test specimen consisted of 0.15×0.15 m columns, 1.6 m high and 0.30×0.15 m beams, and 4.0 m long. The material properties of the test specimens are given in Table 1. The test set-up and the details of the test specimens with the BRBs are shown in Fig. 1. The steel-only BRBs in this study were specifically designed for seismic retrofitting applications. The casings of the BRB were made of hot-rolled channel sections, and the core of the BRB was made with a rectangular steel plate with a Teflon coating. The details of the BRBs are given in Fig. 2. This type of BRB is suitable for low to moderate seismic hazards where deformation demand is not significantly large. Commercial BRBs can also be used.

Both the frames with and without the BRBs were subjected to quasi-static loading using a hydraulic actuator with the loading history shown in Fig. 3. In addition to the lateral load, vertical loads were also applied at the top of the columns using hydraulic jacks to represent the gravity loads. These axial loads were kept constant at 150 kN by manually maintaining the pressure of the hydraulic jacks. The specimens were instrumented with strain gauges and linear displacement transducers at pre-selected locations. The key readings included load, lateral deformation of the frame and uniaxial strain values in the longitudinal bars and stirrups.

2.1. RC bare frame

In the first test, the bare RC frame specimen was tested. The hysteretic loops from the first test are shown in Fig. 4.

Overall, the frame showed moderate ductility with significant pinching in the response. Flexural cracks in the columns were first observed at 0.50% drift, whereas diagonal cracks appeared at 0.75% drift. The peak strength of this specimen was 54.35 kN at 3% drift. The failure of the columns was primarily governed by bond-slip, followed by concrete crushing at the plastic hinge regions. The cracking tended to propagate along the length of the rebar, indicating a lap-splice problem. The recorded strain values at the splice location remained at only approximately half of the yield strain value, even with drift as large as 3%. This indicated that the