SEISMIC STRENGTHENING OF A NON-DUCTILE REINFORCED CONCRETE FRAME WITH SOFT-STORY MECHANISM USING BUCKLING-RESTRAINED BRACES

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ABSTRACT

This paper presents an application of the performance-based plastic design approach for the design of buckling-restrained braces to strengthen a non-ductile reinforced concrete frame with a soft-story mechanism. The selected building is a 5-story school structure that was designed primarily for gravity loads. An inelastic pushover analysis was performed to study the failure mechanism of the existing structure and to guide the selection of the performance target for seismic strengthening design. The energy balance equation was used to determine the required story shear strength and the capacity of the braces in each story. Both the design basis earthquake and the maximum considered earthquake levels were considered. To evaluate seismic performance of the strengthened frame, nonlinear time history analyses were carried out using 20 ground motion records representing large-magnitude-large-range earthquakes and 20 records representing large-magnitude-short- range earthquakes. All of the ground motion records were scaled according to the seismic design standard of Thailand. The analysis results of the strengthened frame show significant response improvement in terms of structural performance and story drifts. The results show that the presented approach can be used as a tool in strengthening design of non-ductile reinforced concrete frames to meet pre-selected performance targets.

Keywords: BRBs, non-ductile RC frame, performance-based plastic design, strengthening, soft-story

1. INTRODUCTION

A large number of old reinforced concrete buildings in many seismically active areas around the world were designed primarily for gravity loads. Unlike buildings designed based on modern design codes, these existing buildings are non-ductile and are highly susceptible to collapse under seismic events. Some deficiencies that may be found in these existing buildings include; limited lateral load resistance, lack of ductile detailing, and the presence of inappropriate building configurations (Celik and Ellingwood 2009). Extensive experimental studies and the analytical studies to strengthen these non-ductile RC frames have been carried out. Several of these studies involved strengthening the RC frames using conventional steel braces (Badoux 1990; Bush 1989; Jain 1984). Although these studies

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indicated that the steel braces may be utilized to improve the seismic resistance of a non-ductile frame, these conventional braces may exhibit limited ductility and energy dissipation under cyclic yielding and buckling. Consequently, energy dissipating elements such buckling-restrained braces (BRBs) have recently gained popularity as an alternative way to retrofit and strengthen an existing structure (Bordea and Dubina 2009; Fahnestock et al. 2007; Ishii et al. 2004; Sarno and Manfridi 2009). This is due to the stable hysteretic behavior of these braces that results in large energy dissipation.

One of the main issues of using the BRBs to strengthen a structure is how the sizes of the BRBs can be selected to match with 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. Hence, a number of trial design and analysis cycles are generally needed in order to ensure that the performance of the retrofitted structure meets the target. 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 soft-story mechanism. The PBPD method is a performance-based design approach that is based on the energy balance concept (Leelataviwat 2002). The PBPD approach has been successfully applied for the design of new structures (Goel and Chaos 2008; Leelataviwat 2009). In this study, the PBPD approach was used to design BRBs to strengthen an existing 5-story structure. 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 seismic strengthening design. The PBPD procedure was used to determine the story shear strength and the capacity of the BRBs required in each story. Nonlinear time history analyses were performed to examine the performance of both existing RC frame and the strengthened RC frame.

2. EXAMPLE STRUCTURE

The example building for this study is a 5-story elementary school building commonly found in Thailand. The building was designed primarily for gravity loads according to the existing code at the time. The structure was a conventional reinforced concrete frame system without ductile detailing. The structure has 7 bays in the longitudinal direction and 2 bays in the transverse direction. The plan view of building is shown in Figure 1. In this study, only the resistance in the N-S direction will be considered. It was assumed that the structure had adequate seismic resistance in the E-W direction. The seismic resistance in the N-S direction of the frame was enhanced by strengthening the two perimeter frames using BRBs with multi-story X-bracing configuration. In subsequent analyses, each of strengthened frames was considered to be responsible for half of the total building mass and the seismic resistance was provided entirely by the strengthened frames. The elevation view of strengthened frame is shown in Figure 2.

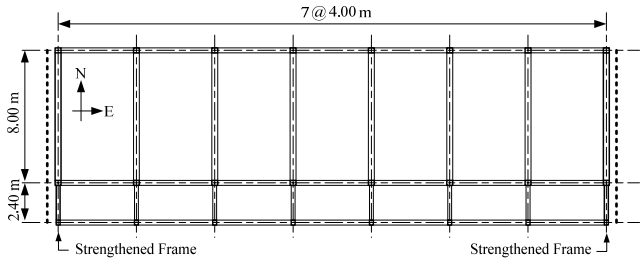


Figure 1: Plan view of the study building.

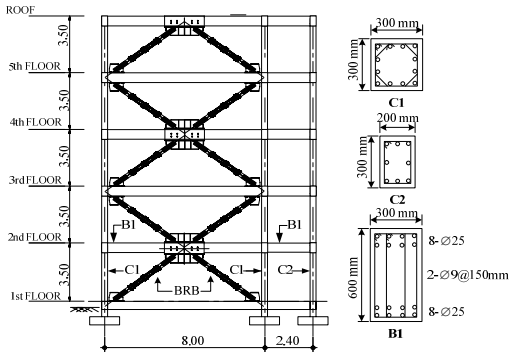


Figure 2: Elevation view of strengthened frame.

2.1 Seismic Evaluation of Existing Structure

The existing structure was first evaluated to determine the failure mechanism and to guide the selection of the performance targets for seismic strengthening design. An analytical model of the existing structure was created using a computer software PERFORM 3D (CSI 2007). A two-dimensional model was used to represent one moment frame in the N-S direction of the example structure. The analytical model was calibrated with experimental results from a past study (Khampanit et al. 2010).

The analytical model (Figure 3) consisted of a combination of fiber and lump plasticity elements. The beam-to-column joints were assumed to be rigid. Fiber and lumped plasticity elements were used in zone where significant inelastic activities took place. The column bases were modeled with rotational springs to simulate the effects of rotation due to insufficient lap-splice length (Sezen and Moehle 2003) present in this existing structure. Shear springs were also included in the analytical model of the columns to detect any shear failure. The shear strength of the columns were calculated using an expression proposed by Sezen and Moehle (2004). For this study, the effective stiffness ratio (I_{eff} / I_g) was taken as 0.60 for the columns 0.50 for the beams.

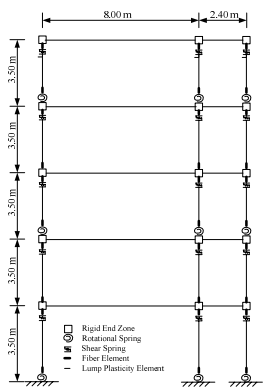


Figure 3: Analytical models of existing RC frame.

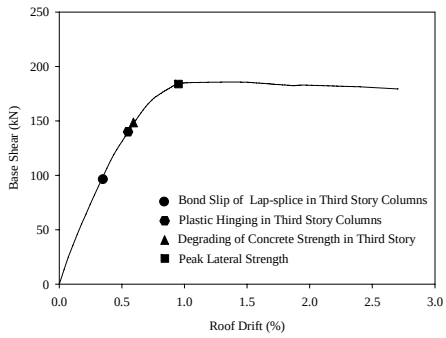


Figure 4: Base shear versus roof drift plot.

An inelastic pushover analysis was carried out to examine the performance and failure mechanism of the existing RC frame. The plot of base shear versus roof displacement is shown in Figure 4. The response of the frame was elastic up to 0.75% of roof drift. The first set of the plastic hinges was

formed at the bottom ends of the columns in the third story because of the abrupt change in the column reinforcement. The formation of these plastic hinges led to a soft-story mechanism resulting in a significant reduction of lateral stiffness and strength of the frame. The peak strength occurs at the roof drift about 1%.

3. THE DESIGN OF BRBs

3.1. Performance-based plastic design

The PBPD approach has been developed based on the energy balance concept which accounts for the structural inelastic behavior directly (Goel and Chaos 2008). To derive the required base shear strength, the energy balance concept of elastic-plastic single-degree-of-freedom (EP-SDOF) as presented in Figure 5a is assumed. The design base shear was derived by equating the work needed to push the structure monotonically up to the target drift. The drift can be chosen according to the pre-selected target performance. From energy balance concept as shown in Figure 5a, the required base shear strength can be obtained

$$\gamma \frac{1}{2} M S_v^2 = E_e + E_p \tag{1}$$

where E_e and E_p are the elastic and plastic energy needed to push the structure up to the chosen target drift respectively, S_v is the design pseudo-spectral velocity, M is the seismic mass of the system, and γ is an energy factor (Goel and Chaos 2008), which is defined as the ratio of the energy absorbed by the inelastic system to that of the equivalent elastic system. By assuming an appropriate lateral force distribution along the height of the frame and using the selected mechanism shown in Figure 5b, the E_e and E_p components in Eq. (1) can be evaluated. The details of the PBPD procedure can be found elsewhere (Goel and Chaos 2008; Leelataviwat 2002; Leelataviwat 2009).

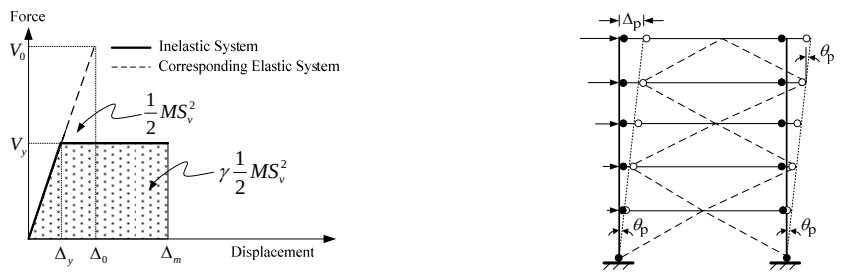


Figure 5: a) Energy balance concept. b) Yield mechanism of a strengthened frame.

3.2. Target Drift and Required Strength for the Example Structure

The PBPD approach was applied for the design of BRBs to strengthen the example RC frame. The goal of the strengthening was to mitigate the soft-story mechanism of the RC frame and to keep the ductility demands in the non-ductile frame to an acceptable level. For this purpose, the displacement targets of the frame were first selected. The targets were chosen based on the drifts and failure

mechanism according to the overall behavior of the strengthened frame as shown in Figure 4. The retrofitting objective of this study frame conformed to a life safety level in which the building may experience damage to structural and nonstructural component under the design earthquake. For a non-ductile RC frame, the target drifts must be sufficiently small to prevent the failure in the RC frame. For this study frame, the target drifts were selected at 1.0% for the design basis earthquake level (DBE) and 1.5% of roof drift for the maximum considered earthquake level (MCE). The idealized response of the RC frame, BRB system, and the retrofitted frame is shown in Figure 6. The yielding of the non-ductile RC frame was assumed at 1.0% roof drift, and the yielding of the BRB system was calculated to be 0.25% according to the configuration of the BRBs. The overall yield drift was approximately 0.35%. This resulted in target plastic drifts of 0.65% and 1.15% for the DBE and MCE levels respectively.

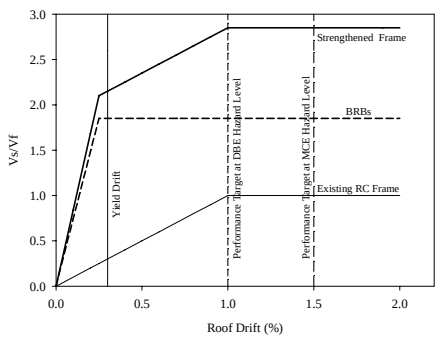
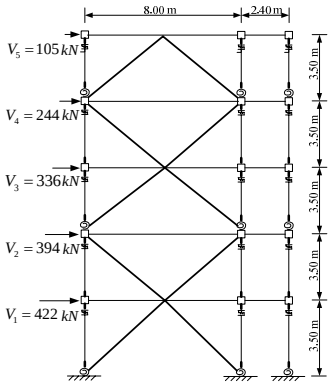


Figure 6: Idealized response of the RC frame and the BRB system.



Design Parameters	DBE Hazard Level	MCE Hazard Level
S_a	$0.499g$	$0.749g$
T	0.70 sec	0.70 sec
θ_y	0.35%	0.35%
θ_u	1.00%	1.50%
θ_p	0.65%	1.15%
V/W	0.10	0.094

Figure 7: Calculated design base shear of strengthened frame using PBPD approach.

To design the BRBs, a design spectrum was chosen in accordance with the seismic design standard of Thailand (DPT 1302-52). The building was assumed to be located in a moderate-to-high seismic region in the northern part of Thailand. Important parameters used to calculate the design spectrum were S_1 = 0.28g, S_s = 0.702g, Seismic Used Group I, and Soil Type D. The required shear strength for each story was calculated using the PBPD procedure at DBE and MCE hazard levels (Figure 7). For this structure, the governing design base shear used to design the BRBs was the one which was calculated from the DBE hazard level as shown in Figure 7.

The base shear was calculated by assuming that each braced bay carried half of the building total mass. The required story shear strength was compared with the strength of the existing frame assuming a story mechanism for each story. The BRBs were used to provide the additional shear strength as required. The total lateral strength of the strengthened frame (V_s) in each story was taken as the combination of concrete frame strength (V_f) at the considered target drift and the BRBs strength (V_{brb}). The BRBs were also provided in such a way that there would be no abrupt change in the story strength to avoid structural irregularity. The required strength of BRBs in each story is shown in Table 1.

Table 1: Summary of design strength at DBE hazard level

Floor Level	Design Story Shear, V (kN)	Strength of RC Frame, V_f (kN)	Strength of BRBs, V_{brb} (kN)
5	105	52	130
4	244	97	186
3	336	134	255
2	394	158	297
1	422	171	317

4. PERFORMANCE ASSESSMENT

Performance assessment was carried out using inelastic pushover analyses and nonlinear time history analyses. The pushover analyses were performed to investigate the overall response, the sequence of inelastic activity leading to collapse and the failure mechanism of the strengthened frame. The base shear versus roof drift plots of the existing and strengthened frames are shown in Figure 8 for comparison. The result shows that, because of the BRBs, the stiffness and lateral strength of the strengthened RC frame are much higher than those of the existing RC frame. Figure 9 shows the failure mechanism of the two frames. As can be seen, the yielding of the existing frame is concentrated in only one story whereas the failure of mechanism of the strengthened frame involved yielding of the columns and BRBs in a number of stories.

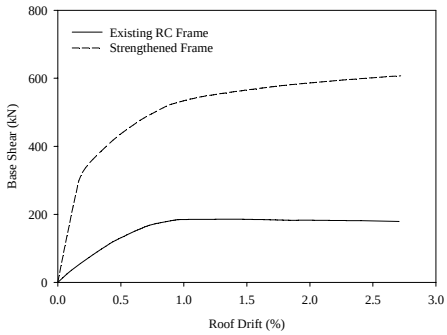


Figure 8: Base shear versus roof drift.

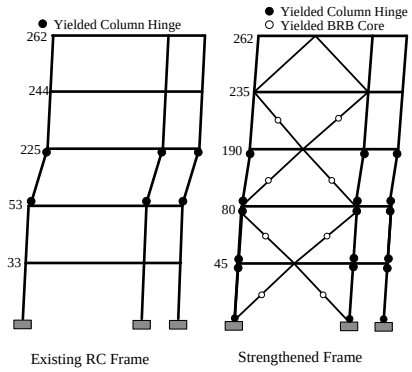


Figure 9: Floor displacement (mm) and location of inelastic activities at 1.5% of roof drift.

For the nonlinear time history analysis, two sets of ground motion records were used to examine the behavior of the existing and strengthened frames. A total of 40 ground motions were used. The first set consisted of 20 ground motion records representing large-magnitude-large-range (LMLR) earthquakes, and the second set also consisted of 20 records but with the characteristics representing large-magnitude-short-range (LMSR) earthquakes (Chopra and Chintanapakdee 2003). The records were scaled such that the median spectral acceleration value matched with those of the design spectra at DBE and MCE levels at the fundamental vibration period of the frame. The scaled response spectra of LMSR and LMLR earthquake records are shown in Figure 10.

The analysis results in terms of peak inter-story drifts under the earthquake excitations are shown in Figures 11 and 12. The inter-story drift values of the existing RC frame were very high particularly for

the third story indicating a soft story mechanism. The existing RC frame had high probability of collapse under the excitations particularly under LMSR ground motions.

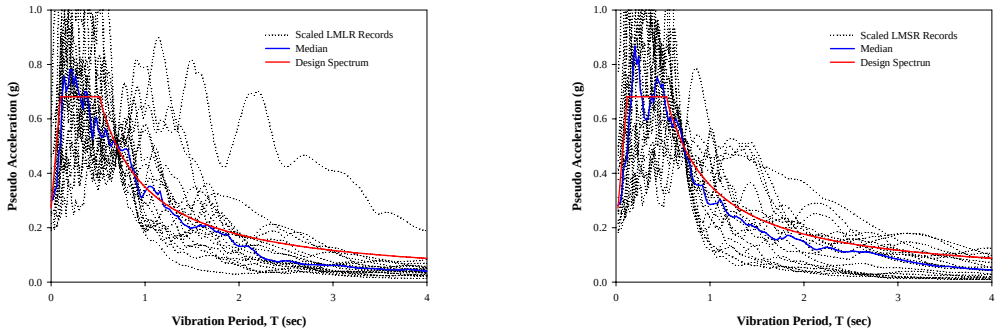
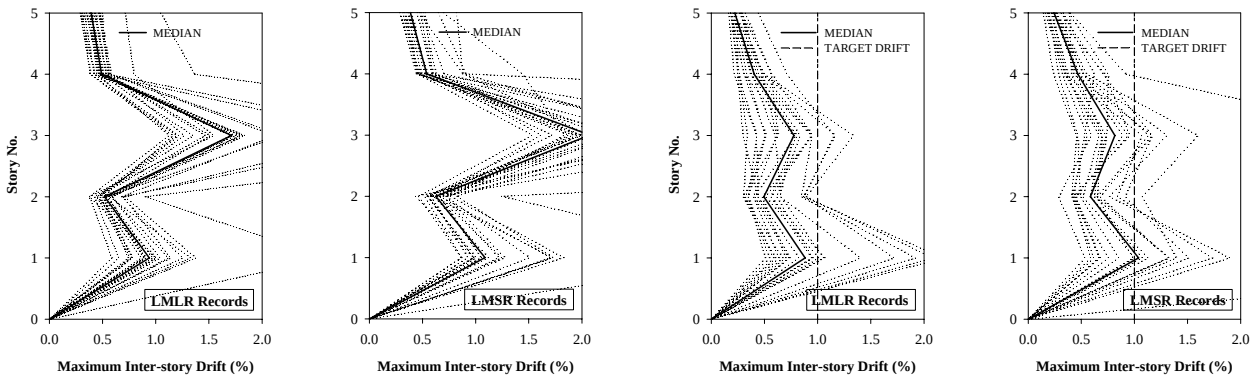


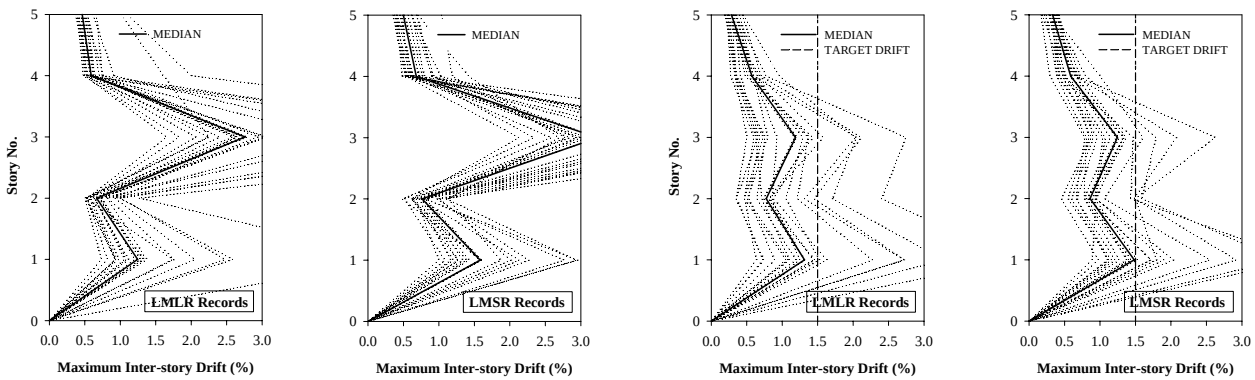
Figure 10: Response spectra of LMLR and LMSR earthquake records (DBE Level).

For the strengthened frame, the median values of the maximum story drifts were within the target drifts at both the DBE (1.0%) and MCE (1.50%) levels. The story drifts of the strengthened frame were more uniform along the height of the frame which indicated that the possibility of having a soft-story mechanism was significantly reduced. The plastic hinge rotation demands in the column were also reduced. The characteristics of the ground motions (LMLR and LMSR) had minor effects on the strengthened frame with regards to the peak and distribution of the story drifts.



(a) Existing RC frame (b) Strengthened frame

Figure 11: Comparison of inter-story drifts at the DBE hazard level.



(a) Existing RC frame (b) Strengthened frame

Figure 12: Comparison of inter-story drifts at the MCE hazard level.

5. CONCLUSIONS

An application of the PBPD methodology for the design of BRBs to strengthen a non-ductile RC frame with soft-story mechanism is presented in this study. The example structure is a 5-story school structure that was designed primarily for gravity loads. The main findings of this study are as follows:

1. The PBPD procedure can be used to design BRBs for strengthening a non-ductile RC frame to achieve preselected performance targets. The BRBs that were designed by the PBPD approach limited the maximum inter-story drifts of the strengthened frames to within the target drifts at both DBE and MCE hazard levels. More importantly, the BRBs significantly reduced the possibility of having the soft-story mechanism present in the existing frame.

2. The performance of the strengthened frame designed by the PBPD method was rather insensitive with regards to the characteristics of the ground motions involved in the study.

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