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PERFORMANCE-BASED PLASTIC DESIGN (PBPD) OF RC SPECIAL MOMENT FRAME STRUCTURES

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ABSTRACT

Performance-Based Plastic Design (PBPD) method has been recently developed to achieve enhanced performance of earthquake resistant structures. The design concept uses pre-selected target drift and yield mechanism as performance criteria. The design base shear for selected hazard level is determined by equating the work needed to push the structure monotonically up to the target drift to the corresponding energy demand of an equivalent SDOF oscillator. The design of frame members is then carried out by plastic method. This paper presents development of the PBPD approach as applied to reinforced concrete special moment frame (RC SMF) structures. RC structures present special challenge because of their complex and degrading ("pinched") hysteretic behavior. In order to account for the degrading hysteretic behavior the FEMA 440 C_2 factor approach was used in the process of determining the design base shear. Four baseline RC SMF (4, 8, 12 and 20-story) as used in the FEMA P695/ATC-63 Project and designed to comply with the requirements of ACI 318-05 and ASCE/SEI 7-05 were selected for this study. Those frames were then redesigned by the PBPD approach. For response evaluation purposes, the baseline code compliant frames and the PBPD frames were subjected to extensive inelastic pushover and time-history analyses. The results showed that the PBPD approach can be successfully applied to RC structures as well, and that the responses of the example moment frames were much improved over those of the corresponding baseline frames.

Introduction

Reinforced concrete special moment frames (RC SMF) comprise of horizontal framing components (beams and/or slabs), vertical framing components (columns) and joints connecting horizontal and vertical framing components and deemed to satisfy the special requirements in seismic provisions (ASCE/SEI 41-06, ACI 318). In seismic provisions, certain special requirements such as special proportioning and detailing requirements result in a frame capable of resisting strong earthquake shaking without significant loss of stiffness or strength. Since RC SMF have been widely applied as part of seismic force-resisting systems, design methodologies and

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systematic procedures are needed which require no or little iteration after initial design in order to meet the targeted design objectives.

In order to achieve more predictable structural performance under strong earthquake ground motions, knowledge of the ultimate structural behavior, such as nonlinear relations between force and deformation, and yield mechanism of the overall structure are essential. Consequently, design factors such as, determination of appropriate design lateral forces and member strength hierarchy, selection of desirable yield mechanism, and structure strength and drift etc., for given hazard levels should become part of the design process right from the beginning. Therefore, a complete seismic design method should include not only determination of proper design base shear, but also a systematic procedure for proportioning members by considering inelastic characteristics of the overall structure. One such complete design methodology, which accounts for inelastic structural behavior directly, and practically eliminates the need for assessment or iteration after initial design, has been developed in the recent past for practical design work (Goel at el., 1999~2009). It is called Performance-Based Plastic Design (PBPD) method.

The PBPD method uses pre-selected target drift and yield mechanism as key performance limit states. These two limit states are directly related to the degree and distribution of structural damage, respectively. The design base shear for a specified hazard level is calculated by equating the work needed to push the structure monotonically up to the target drift to the energy required by an equivalent EP-SDOF to achieve the same state (Fig. 1). Also, a new distribution of lateral design forces is used (Chao at el, 2007), which is based on relative distribution of maximum story shears consistent with inelastic dynamic response results. The higher mode effects are also well represented in this distribution. It is also worth mentioning that the PBPD method has been successfully applied to steel MF, CBF, BRBF, EBF and STMF (Goel et al, 2008).

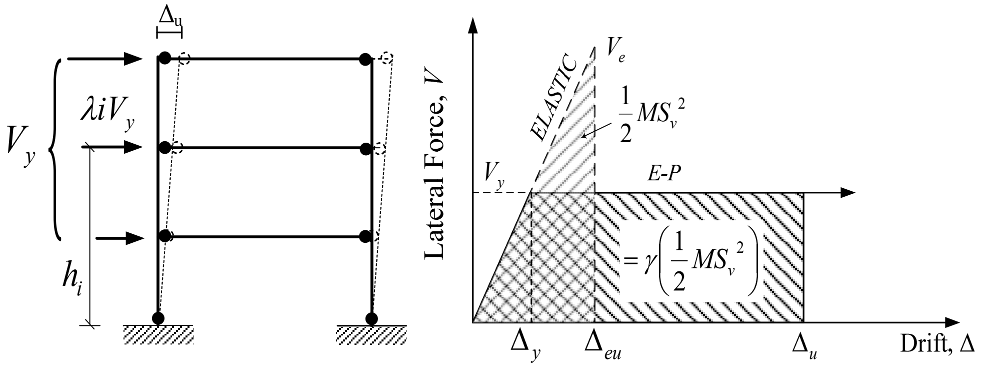


Figure 1. PBPD concept

Comparison of PBPD and Current Code Design Method

The design requirements for RC SMF are presented in the American Concrete Institute (ACI) Committee 318 Building Code Requirements for Structural Concrete (ACI 318). The special requirements relate to inspection, materials, framing members (beams, columns, and beam-column joints), and construction procedures. In addition, the pertinent seismic load requirements are specified in the American Society of Civil Engineers (ASCE) publication ASCE/SEI 7-05 Minimum Design Loads for Buildings and Other Structures (ASCE 2006). The International Building Code, or IBC, (ICC 2006), which is the code generally adopted throughout the United States, refers to ASCE 7 for the determination of seismic design loads. The ACI Building Code classifies design requirements according to the Seismic Design Categories designated by the IBC and ASCE 7 and contains latest information on design of special moment frames as well. The design base shear equations of current building codes (e.g., IBC and ASCE 7) incorporate a seismic force-reduction factor R that reflects the degree of inelastic response expected for design-level ground motions, as well as the ductility capacity of the framing system. The R factor for special moment frames is 8. Therefore, a special moment frame should be able to sustain multiple cycles of inelastic deformation under design-level ground motions.

As mentioned earlier, the PBPD method uses pre-selected target drift and yield mechanism as key performance objectives. These two design parameters are directly related to the degree and distribution of structural damage, respectively. It should be noted that in this design approach the designer selects the target drifts consistent with acceptable ductility and damage, and a yield mechanism for desirable response and ease of post-earthquake damage inspection and reparability. The design lateral forces are determined for the given seismic hazard (design spectrum) and selected target drift. Thus, there is no need for factors, such as R, I, C_d, etc. (Fig. 2), as are required in the current design codes and over which plenty of debate already exists. Those factors are known to be based on a number of considerations including engineering judgment (Miranda, 2004). It is also noted that by following PBPD design method, iteration after initial design can be practically eliminated.

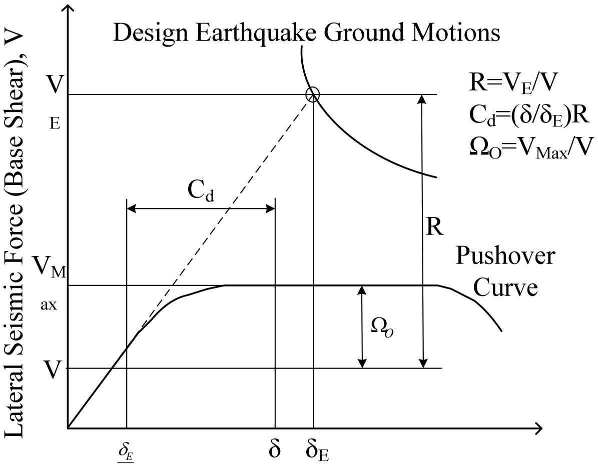


Figure 2. Illustration of seismic performance factors (R, Ωo and C_d) as defined by the commentary to the NEHRP recommended provisions (FEMA, 2004b)

In addition, the proportioning and detailing requirements for special moment frames are intended to ensure that inelastic response is ductile. In order to achieve satisfactory performance of RC SMF, Moehle (2008) proposed three main goals for design of RC SMF; they are (1) to achieve a strong-column/ weak-beam design that distributes inelastic activity over the height of the structure; (2) to avoid shear failure; and (3) to provide details that enable ductile flexural response in yielding regions. All these goals can simultaneously reached by following the PBPD method since the yield mechanism is preselected and all non designated yielding members (columns) are designed by capacity-design approach by considering equilibrium of the entire "column tree" instead of single joints. The theoretical background and detailed design procedures of the PBPD method can be found in several publications (Goel et al 2008).

Special Considerations for RC SMF in PBPD Method

RC structures present special challenge due to their complex and degrading (pinched) hysteretic behavior. While development of the PBPD method for RC structures is currently in progress, results from the study so far have been most promising. Design of RC SMF with PBPD method basically follows the same procedure as that of steel frames with the following two modifications for determination of design base shear to account for pinched hysteretic behavior and P-Delta effect.

Pinched Hysteretic Behavior

Investigators have studied the effect of degrading hysteretic behavior of SDOF systems on resulting peak displacements. The results show that the peak displacements are larger than those of systems with non-degrading hysteretic behavior in the short period range, but are about equal for longer periods. Approximate expressions have been proposed for modification factors to account for this effect, e.g., C_2 factor in FEMA 440 (2006), Figure 3. Thus, the target design drift for a given structural system with degrading hysteretic behavior can be divided by the C_2 factor that would give design target drift for an equivalent non-degrading system. The design base shear can then be calculated by using this modified target drift.

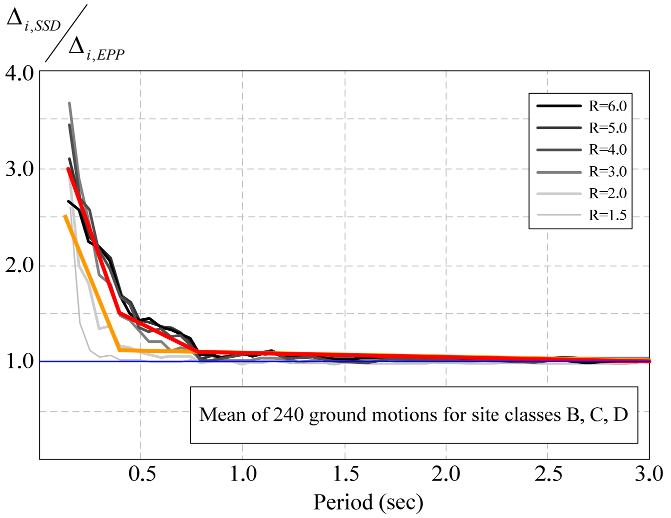


Figure 3. Mean displacement ratio of SSD to EPP models (C_2) computed with ground motions recorded on site classes B, C, and D. (FEMA 440, 2006)

P-Delta Consideration

Due to stiffness and strength degradation at beam plastic hinges it was found necessary to include P-Delta effect in the determination of required moment capacity of beams for the RC SMF. That was accomplished by adding “P-Delta lateral force”, F_{i-PD}, to the basic design force, F_i. The force F_{i-PD} can be taken equal to $P_i\,\theta_u$, where P_i represents the tributary gravity load at floor level i and θ_u the target design drift ratio which is assumed constant over height of the structure for design purposes. The values of F_{i-PD} for the frame are shown in Table 1. Their influence on the total lateral design force can be clearly noticed as it has significant effect on the required frame strength.

Table 1. Design parameters for PBPD RC SMF

Design Parameters	**4-story**		**8-story**		**12-story**		**20-story**	
	2/3MCE	MCE	2/3MCE	MCE	2/3MCE	MCE	2/3MCE	MCE
Sa	0.74g	1.11g	0.40g	0.60g	0.30 g	0.45 g	0.30 g	0.45 g
T (sec.)	0.81	0.81	1.49	1.49	2.13	2.13	3.36	3.36
C_2	1.1	1.1	1.07	1.07	1.04	1.04	1	1
Yield Drift Ratio	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Target Drift Ratio	2%	3%	2%	3%	2%	3%	2%	3%
Modified Target Drift Ratio	1.82%	2.73%	1.87%	2.81%	1.92%	2.89%	2%	3%
Inelastic Drift Ratio	1.32%	2.23%	1.37%	2.31%	1.42%	2.39%	1.5%	2.5%
μ	3.64	5.46	3.74	5.61	3.85	5.77	4	6
R_μ	3.64	5.46	3.74	5.61	3.85	5.77	4	6
γ	0.47	0.33	0.46	0.32	0.45	0.32	0.44	0.31
α	2.103	3.552	1.243	2.092	0.937	1.570	0.662	1.103
V/W	001167	0.1117	0.0577	0.0552	0.0416	0.0398	0.055	0.054
V w/o PD (kips)	242.2 (governs)	231.8	107.1 (governs)	102.5	116.3 (governs)	111.3	255 (governs)	248
ΣF_{i-PD} (kips)	41.5		36.9		55.9		92	
Design Base Shear V^*	283.7		144		172.2		347	

Redesign of RC SMF in FEMA P695/ ATC-63 Project by PBPD Method

Four examples of 4, 8, 12 and 20-story RC special moment frame structures are briefly presented in this section. All of them were space frames. The baseline space frames were designed to comply with the requirements of ASCE 7-05 and ACI 318-05 in FEMA P695 (2009) by Haselton (2007). The frames were then redesigned by the modified PBPD method by using the FEMA 440 (2006) C_2 factor approach and considering P-Delta effect as discussed earlier. Typical floor plan is shown in Figure 4, and important design parameters are given in Table 1. For response evaluation purposes the baseline code compliant frames and the PBPD frames were subjected to inelastic pushover and time-history analyses.

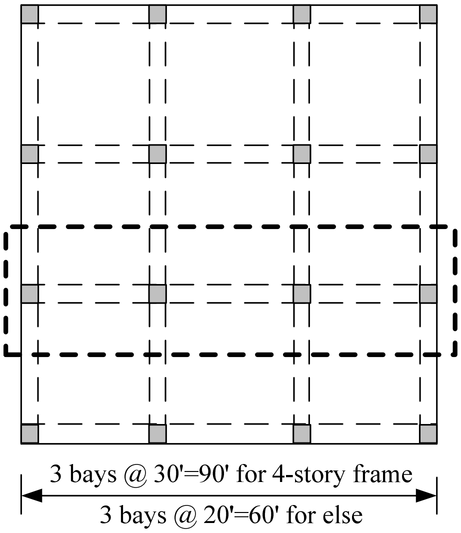


Figure 4. Floor plan of RC space moment frame building

Comparison of Performances of the Code Compliant and PBPD SMF

Nonlinear static (pushover) and dynamic (time-history) analyses were carried out for the code compliant and PBPD frames by using Perform-3D program (CSI, 2007). A lumped "P-Delta column" with pin connections at the floor levels was added which enables the model to capture the P-Delta effect. Stiffness, strength and cyclic degradation of moment-rotation behavior of plastic hinges were also modeled to account for the pinched hysteretic behavior.

The pushover curves for the eight frames in Figure 5 show that, even though the design base shear for the baseline frame is smaller than that of the corresponding PBPD frame, the ultimate strength of the baseline frame is higher than that of the corresponding PBPD frame. That is mainly due to the fact that the design of the baseline frame was governed by drift which required major revision of the member sizes after having been designed for strength. That iteration step is not needed in the PBPD method. Calculated values of R_{max} for the baseline and PBPD frames according to the recommended equation in FEMA P440A (2009) are 12.5/15.4, 5.0/17.5, 3.2/14.6 and 5.3/10.8, for the 4, 8, 12, 20-story frames respectively. That reflects much enhanced margin against dynamic instability (collapse) of the PBPD frame over that of the baseline frames.

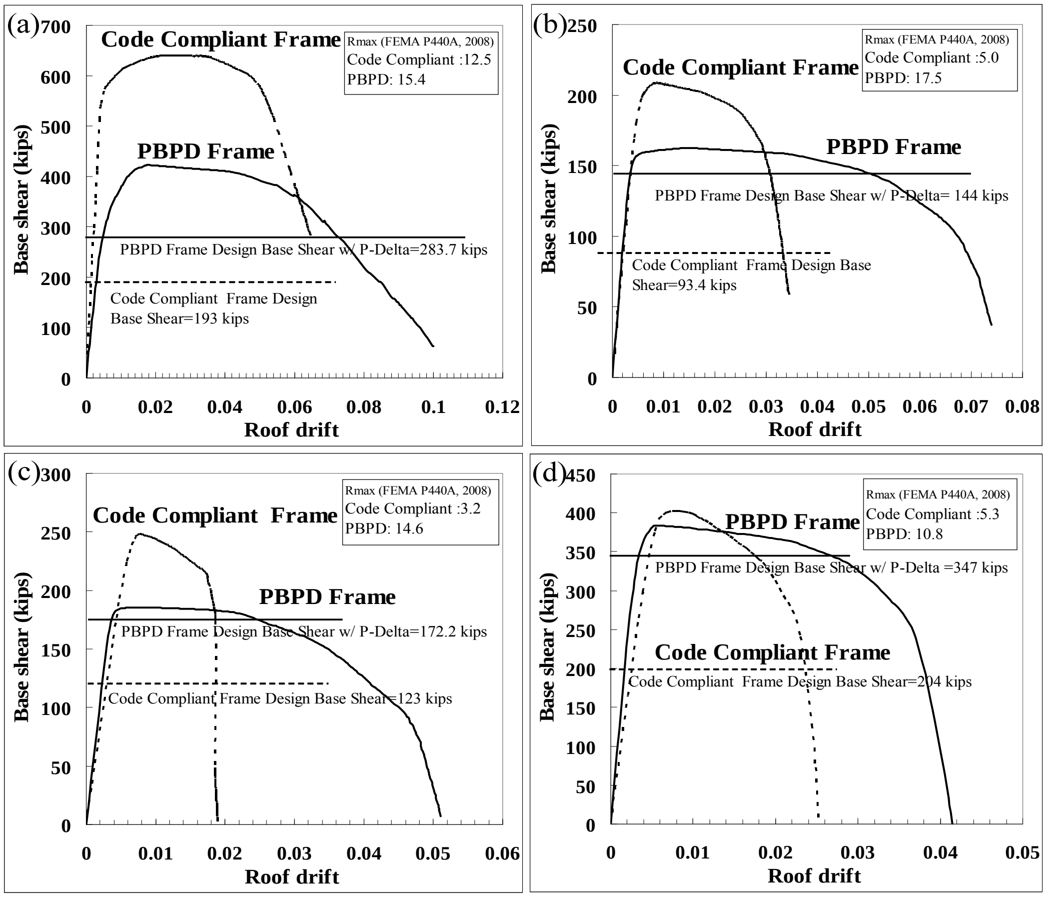
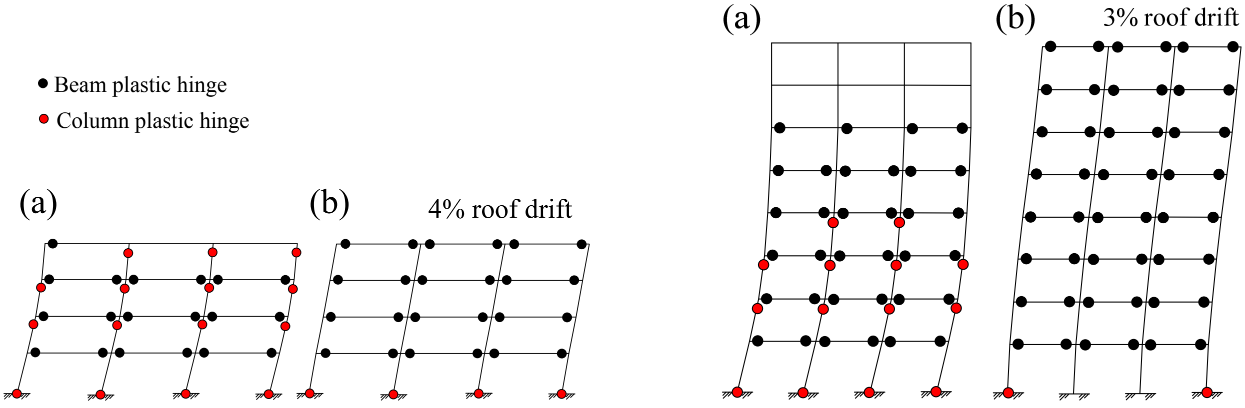


Figure 5. Pushover curves for (a) 4-story, (b) 8-story, (c) 12-story and (d) 20-story code compliant and PBPD frames

Figure 6 shows the deformed shape and location of plastic hinges of the code compliant and PBPD frames at 4%, 3%, 2% and 2.5% roof drift under pushovers, for the 4, 8, 12, 20-story frames respectively. Formation of plastic hinges in the columns and story mechanism in the lower part of the baseline frame can be clearly seen. In contrast, there are no unintended plastic hinges in the columns of the PBPD frame, resulting in more favorable deformed shape and yield pattern as intended in the design process.



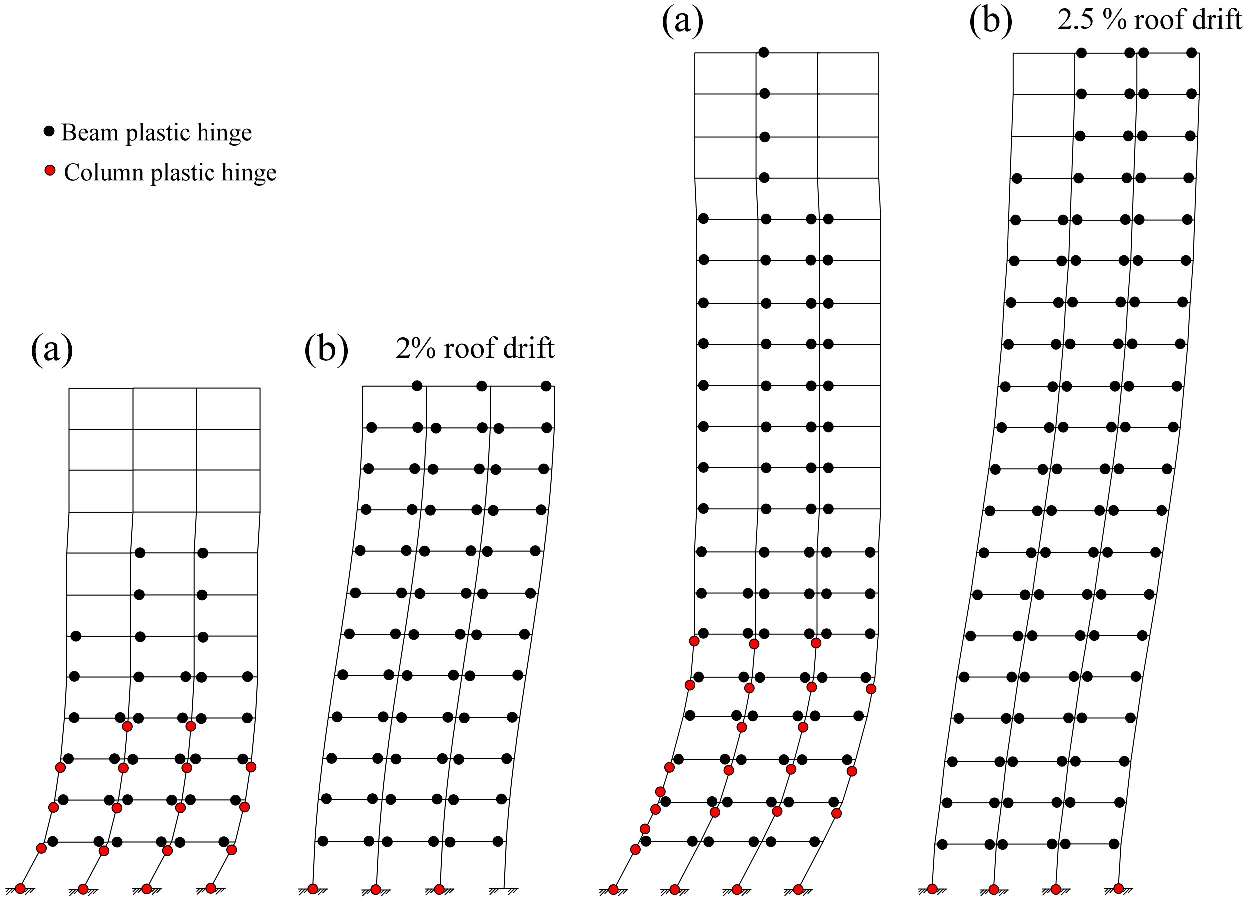


Figure 6. Deformed shape and PH locations of 4, 8, 12 and 20-story for (a) code compliant and (b) PBPD RC SMF under pushovers.

Figure 7 shows comparison of maximum interstory drifts of the baseline and PBPD frames obtained from time-history analyses using appropriately scaled ground motion records representative of 2/3 MCE and MCE hazard levels. For clarity and brevity only the mean values of maximum interstory drifts are shown here. The results show that the mean maximum interstory drifts of the PBPD frames are well within the corresponding target values, i.e., 2% for 2/3 MCE and 3% for MCE. Moreover, the story drifts of the PBPD frames are more evenly distributed over the height as compared with those of the baseline frame where undesirable "softness" in the lower stories is evident, which is caused mainly by plastic hinges in the columns. Formation of plastic hinges in the columns and story mechanism in the lower part of the baseline frames can be clearly noticed. In contrast, there are no unintended plastic hinges in the columns of the PBPD frame, resulting in more favorable deformed shape and yield pattern as intended in the design process.

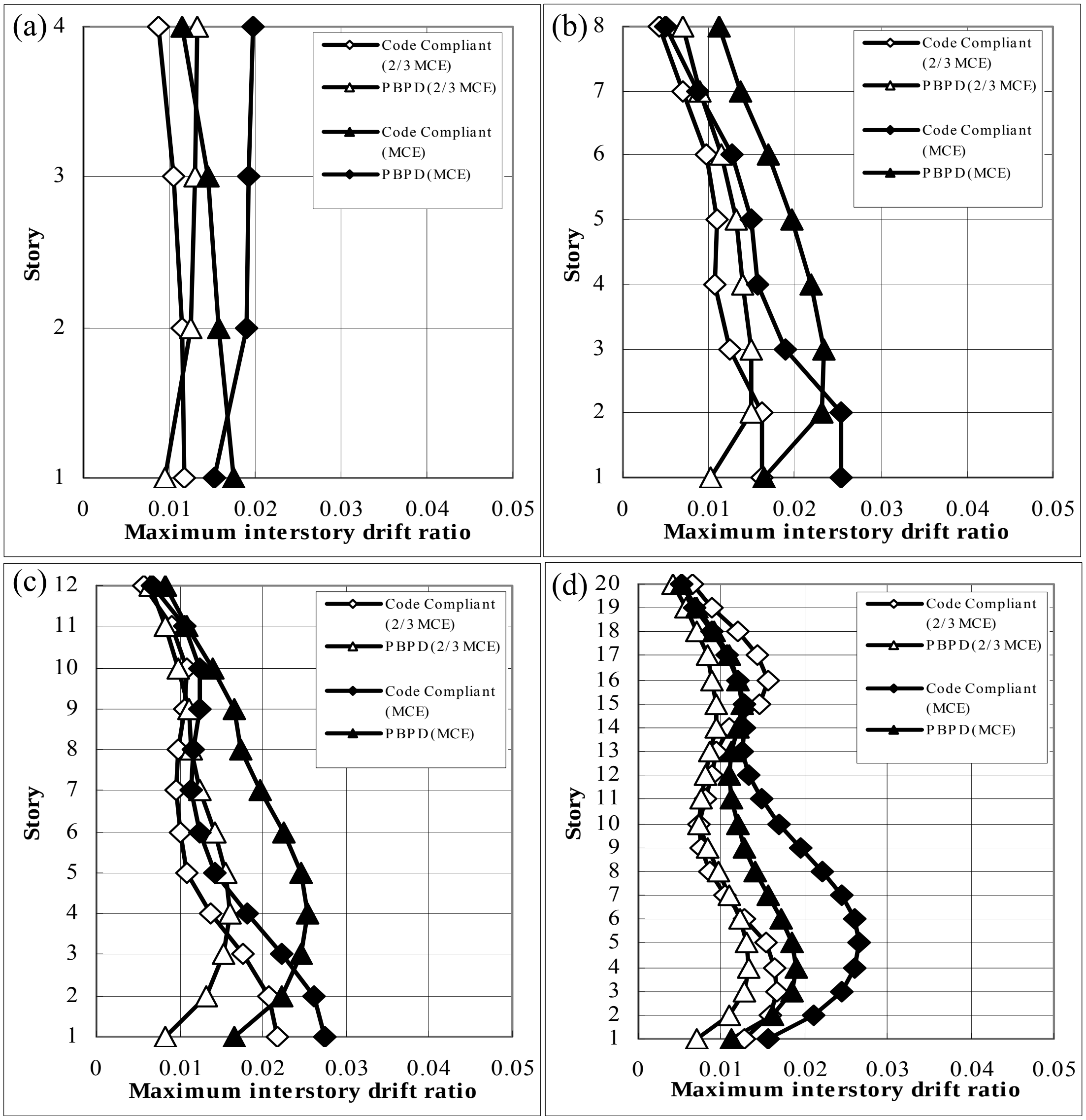


Figure 7. Comparison of maximum interstory drifts by time-history analyses of code complaint and PBPD frames for 2/3 MCE and MCE hazard levels (a) 4-story, (b) 8-story, (c) 12-story and (d) 20-story.

Summary and Conclusions

The PBPD method is a direct design method which uses pre-selected target drift and yield mechanism as key performance objectives, which determine the degree and distribution of expected structural damage. The design base shear for a specified hazard level is calculated by equating the work needed to push the structure monotonically up to the target drift to the energy required by an equivalent EP-SDOF to achieve the same state. Plastic design is performed to detail the frame members in order to achieve the intended yield mechanism and behavior.

By modifying the determination of design base shear due to pinched hysteretic behavior and P-Delta effect, the PBPD method was successfully applied to the design of RC moment frames. The 4, 8, 12 and 20-story code compliant frames used in ATC 63 Project were redesigned by the modified PBPD method. The PBPD frames responded as intended in design with dramatic improvement in their performances over those of the corresponding code compliant frames.

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