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Seismic performance evaluation of PBPD designed Chevron Braced Steel Frames considering the effect of aftershocks

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ABSTRACT

The performance-based plastic design (PBPD) method is an efficient seismic design method in which the nonlinear behavior of structures is considered directly at the beginning of the design process. The structures designed following the PBPD method are expected to show a desired performance under seismic events. Experience of past earthquakes shows that structures located in seismically active regions may be exposed to one or more aftershocks following the mainshock. The aftershocks have the potential to cause the structures damaged by the mainshocks to collapse or experience additional damage. Since no seismic design code takes into account the effects of aftershocks in the design process, and aftershocks have negative effects on structures, the PBPD method was recently developed to consider the effects of aftershocks to achieve desired performance under mainshock-aftershock (MS-AS) sequences. This study aims to compare the seismic performance of the chevron-braced steel frames (CBSFs) designed based on the conventional PBPD method and the developed PBPD method in terms of inter-story drifts and the distribution of plastic hinges under mainshocks and MS-AS sequences. Furthermore, fragility curves are developed to compare the seismic vulnerability of the frames designed based on conventional and developed PBPD methods under MS-AS sequences. The results show that the CBS frames designed based on the developed PBPD method show more desired performance than the structures designed based on the conventional PBPD method.

Keywords: Aftershocks, Performance-based Plastic Design, Inter-story Drift, Chevron Braced Steel Frames, Fragility Curves.

INTRODUCTION

Structures in areas with a high probability of earthquake occurrences can be damaged by multiple quakes, such as foreshocks, mainshocks, and aftershocks. An aftershock (AS) is typically a lower magnitude earthquake that follows a mainshock (MS). Past earthquakes have shown that buildings damaged by mainshocks are further damaged and pose a threat to residents' safety when exposed to aftershocks. Recent devastating earthquake in Turkey and Syria again highlighted the damage potential of aftershocks and how mainshock damaged structures can completely collapse during an aftershock. The high damage potential of aftershocks has several causes. Firstly, aftershocks are unpredictable in terms of the time and location of occurrence, and their energy contents. Secondly, previously damaged structures have a reduced stiffness and strength capacity, making them more susceptible to further damage during aftershocks [1], [2].

Chevron braced steel frames (CBSFs) have become a popular structural system in seismically active regions due to their ability to resist earthquake forces. However, previous studies have indicated that CBSFs designed using conventional methods and current seismic design codes can experience moderate to severe damage, resulting in uncontrolled and unexpected inelastic deformation under seismic events. These findings have highlighted the need for the development of more effective and reliable seismic design methods for CBSFs. Therefore, Goel and Chao [3] developed performance-based plastic design (PBPD) as an efficient method that incorporates nonlinear structural behavior in the design process to achieve desired seismic performance without the need for a repetitive trial-and-error process that is usually performed in the performance based seismic design method. The results of time history analyses show that the frames designed based on the PBPD method exhibit a desirable performance under earthquakes.

Many studies have been conducted on the effects of multiple earthquakes on structures. Some of the studies have been carried out on the effects of mainshock-aftershock on a single degree of freedom (SDOF) structure [4], [5]. Mahin [5] was one of the pioneers in this field to investigate the effects of aftershocks on the seismic demand of SDOF elastic-plastic (EP) system and found that aftershocks increase the seismic demand of a structure. Furthermore, Zhai et al [4] investigated the performance of non-elastic SDOF systems with nonlinear hysteretic behavior under aftershocks with different intensities by scaling the intensity of aftershocks to the mainshock and obtained the response of the structure based on three seismic demand parameters, including normalized hysteretic energy, and the Park Ang damage index. Some studies have also been conducted on the effects of aftershocks on multi-degree of freedom (MDOF) structures. Li and Elingwood [6] studied the damage potential of aftershocks on steel moment frame structures and found that the level of damage caused by the mainshocks, and the frequency of aftershocks have a significant impact on the level of damage caused by aftershocks. Garcia [7], [8] investigated the effect of aftershocks on the maximum energy absorbed by the residual displacement of multi-degree of freedom (MDOF) structures. Abdollahzadeh et al [9] compared the seismic behavior of steel moment frames (SMFs) designed using the elastic method and PBPD method under mainshocks and mainshock-aftershock sequences, finding that PBPD SMFs perform better than those designed based on the elastic design method.

Even though aftershocks can damage buildings and put people's safety at risk, current seismic design codes don't take them into account when designing structures. However, recent studies focused on the development of PBPD for considering the effects of aftershocks in the structural design process. Since aftershocks have the potential to increase damage levels, Abdollahzadeh et al. [10] developed PBPD for SMFs that incorporates the effects of aftershocks to achieve a desired performance of the structure under mainshock-aftershock sequences. The results indicate that the SMFs designed using the developed PBPD method perform well under MS-AS sequences. Mohammadgholipour and Billah [11] also developed PBPD method for CBSFs considering the effects of aftershocks in the structural design process.

Due to the importance of aftershocks, and their negative impacts on structures, and since CBSFs have become common in seismic prone regions, in this study, two 6- and 9-story frames designed based on conventional PBPD and developed PBPD methods. A comparison of the seismic performance of CBSFs designed based on developed PBPD method and conventional PBPD method under MS only and MS-AS is provided. Furthermore, the study develops seismic fragility curves for the CBSFs designed via both methods to assess and compare the seismic vulnerability of the frames under MS-AS seismic events.

DESIGN OF CBSFS BASED ON CONVENTIONAL AND DEVELOPED PBPD METHODS

This study aims to compare the seismic response of chevron braced steel frames designed based on conventional and developed PBPD methods under MS and MS-AS sequences. To achieve this objective, two 6- and 9- story CBS frames consisting of three bays with heights of 3.2m and lengths of 6m were designed. The conventional PBPD frames are designed based on the method presented by Goel and Chao [3] and the developed PBPD frames are designed based on the developed PBPD method for considering the effects of aftershocks, presented by [11]. The flowchart of developed PBPD method is shown in Figure 1. The columns and beams were designed using W sections (ASTM A992), while the brace sections were designed using HSS sections (ASTM A500). Figure 4 shows the elements' number and the elevation of the CBSFs and Table 1 depicts the dimensions of the steel sections utilized in the design. The dead and live loads distributed on the beams were calculated to be 30 kN/m and 10 kN/m, respectively. The frames were considered to be in San Francisco on soil type D (V_s=180-360 m⁄s), and the seismic design acceleration was determined according to ASCE7-16 [12]. The target drift ratio was predetermined based on FEMA-356 [13]. For 2/3MCE and MCE earthquakes, the predetermined target drift ratios were 1.5% and 2%, respectively, [13] and the yield drift ratio was 0.3% [12]. The predetermined yield mechanism is considered to be the formation of plastic hinges at the braces and the first story column bases.

SELECTED MAINSHOCK AND AFTERSHOCK GROUND MOTIONS

To evaluate the seismic performance of CBSFs designed using PBPD subjected to mainshocks and MS-AS sequences, it is necessary to conduct nonlinear dynamic analyses. ASCE 7-16 [12] recommends utilizing at least 11 earthquake records for such analyses to have a reliable results. To meet this requirement, a total of twelve MSs with their corresponding ASs were chosen from various earthquakes. All ground motions used in this research were obtained from the Pacific Earthquake Engineering Research database (PEER)[14]. The seismic accelerograms were recorded in soil type D (V_s=180-360 m / s), and no forward directivity effect was observed in the ground motions. Details of the selected MS and AS characteristics can be found in Table 2. The mainshocks were scaled to the MCE and 2/3MCE hazard spectrum presented in the ASCE7-16 [26] for the seismic design of a building and the aftershocks were scaled to hazard spectrum for aftershocks presented by Abdollahzadeh et al. [9]. The seismic design spectrum of mainshock and aftershock for the hazard level of 10% in 50 years (2/3MCE) and 2% in 50 years (MCE) are shown in Figure 3. A 30 second time gap of zero acceleration is considered between the mainshock and the aftershock. This causes the structure to reach a rest state following the mainshocks [9], [10].

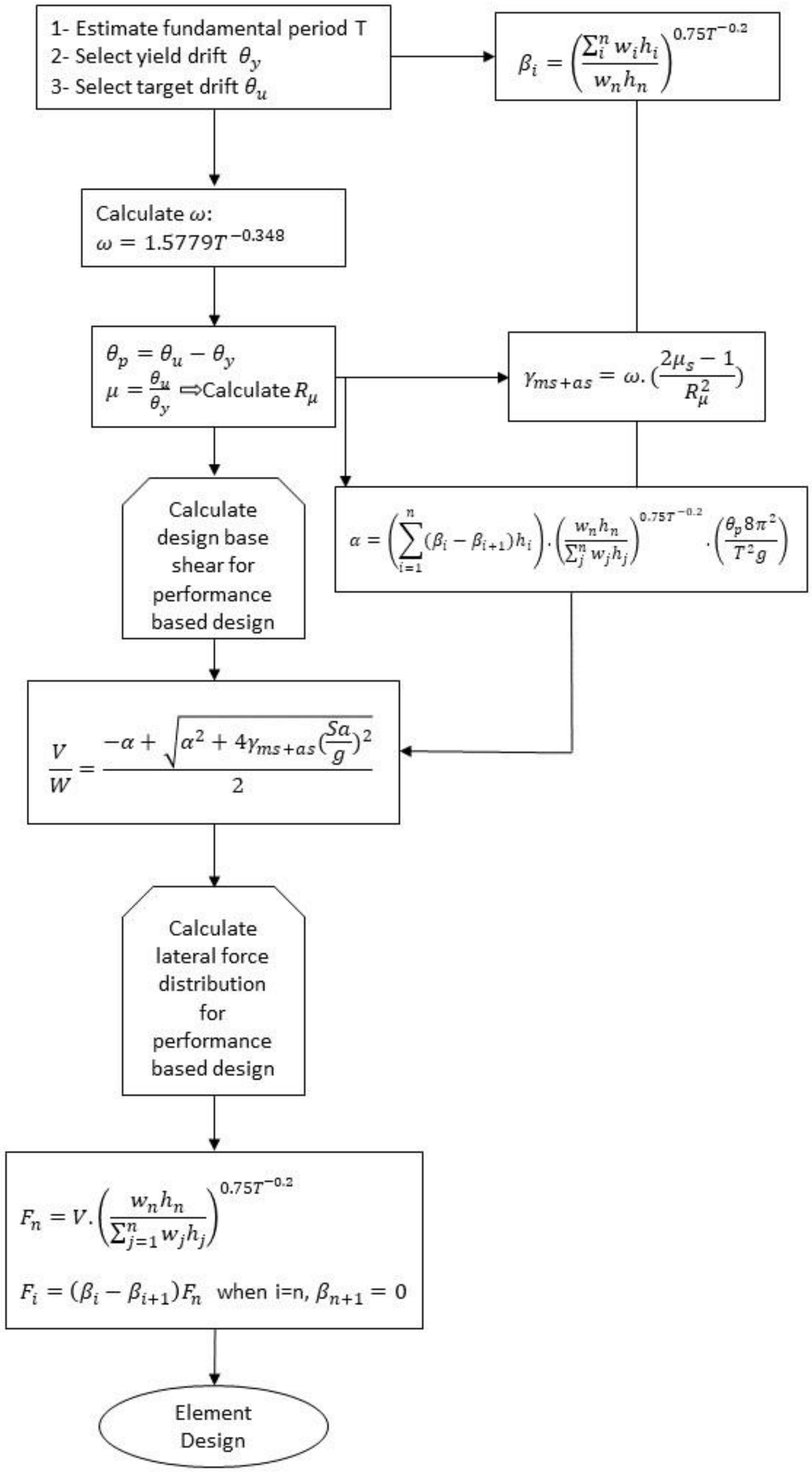

Figure 1. Flowchart for developed Performance based Plastic Design of CBSFs [11]

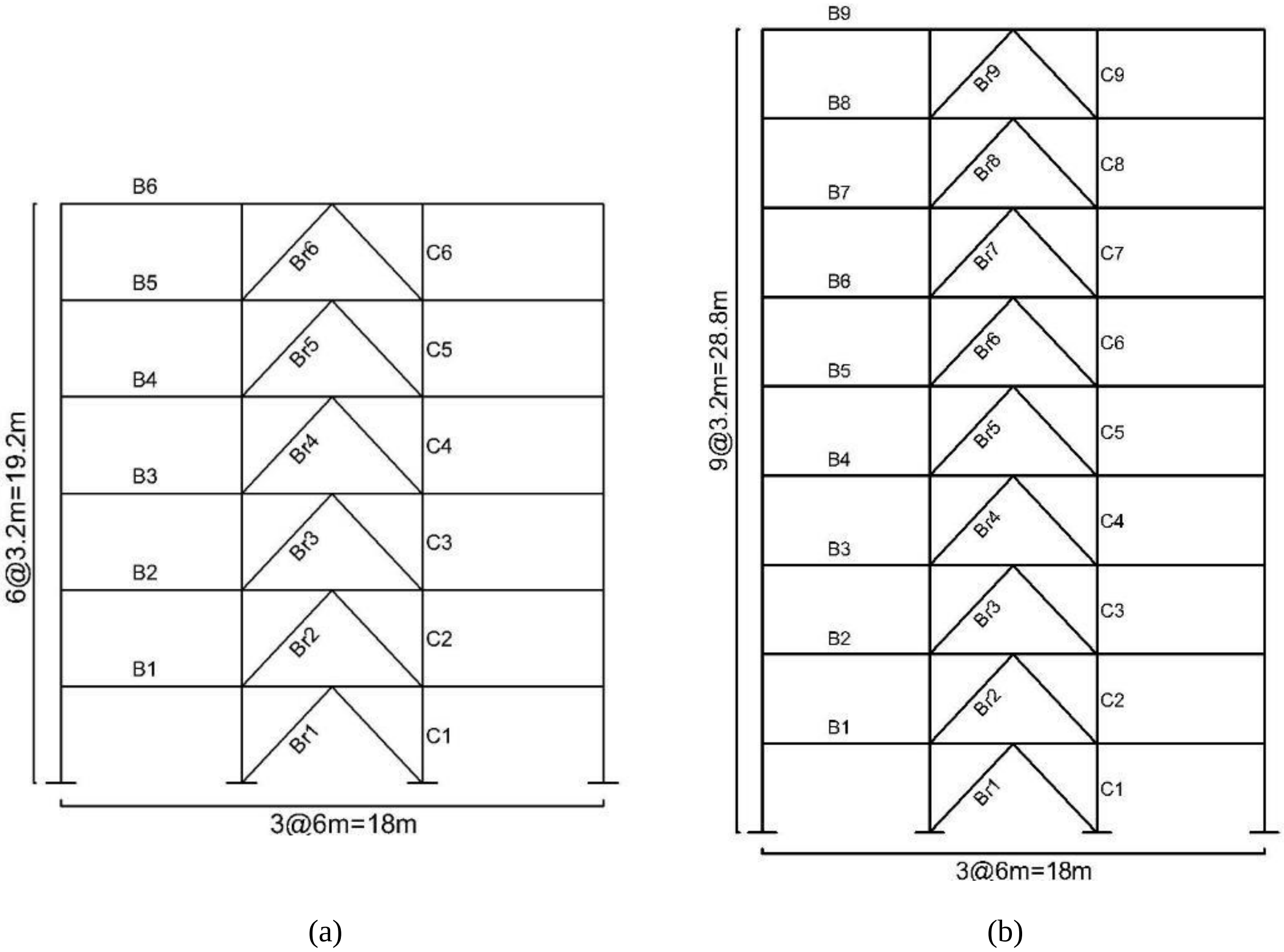

Figure 2. The elevation of PBPD frames a) 6 story b) 9 story

Table 1. Sections of the PBPD frames

Conventional PBPD	**Six Story Frame**					
	Column		Beam		Brace	
	C6	W250X73	B6	W610X101	Br6	HSS64X64X6.4
	C5	W250X80	B5	W610X113	Br5	HSS89X89X6.4
	C4	W250X80	B4	W610X125	Br4	HSS102X102X6.4
	C3	W310X129	B3	W610X140	Br3	HSS102X102X7.9
	C2	W310X129	B2	W610X140	Br2	HSS127X127X6.4
	C1	W310X129	B1	W610X140	Br1	HSS127X127X6.4
	Nine Story Frame					
	Column		Beam		Brace	
	C9	W310X79	B9	W690X125	Br9	HSS76X76X4.8
	C8	W310X79	B8	W690X125	Br8	HSS89X89X6.4
	C7	W310X79	B7	W690X152	Br7	HSS102X102X6.4
	C6	W310X107	B6	W690X152	Br6	HSS102X102X7.9
	C5	W310X107	B5	W690X170	Br5	HSS127X127X7.9
	C4	W360X162	B4	W690X170	Br4	HSS127X127X7.9
	C3	W360X162	B3	W690X170	Br3	HSS127X127X7.9
	C2	W360X196	B2	W690X192	Br2	HSS127X127X9.5
	C1	W360X196	B1	W690X192	Br1	HSS127X127X9.5
Developed PBPD	**Six Story Frame**					
	Column		Beam		Brace	
	C6	W250X80	B6	W610X101	Br6	HSS102X102X6.4
	C5	W250X80	B5	W610X113	Br5	HSS127X127X7.9
	C4	W310X97	B4	W690X170	Br4	HSS127X127X9.5
	C3	W310X97	B3	W690X192	Br3	HSS152X152X9.5
	C2	W310X202	B2	W690X192	Br2	HSS152X152X13.5
	C1	W310X202	B1	W690X192	Br1	HSS152X152X13.5
	Nine Story Frame					
	Column		Beam		Brace	
	C9	W310X79	B9	W690X125	Br9	HSS102X102X6.4
	C8	W310X79	B8	W690X170	Br8	HSS127X127X7.9
	C7	W310X79	B7	W690X170	Br7	HSS127X127X9.5
	C6	W360X147	B6	W690X192	Br6	HSS152X152X9.5
	C5	W360X147	B5	W690X192	Br5	HSS152X152X9.5
	C4	W360X162	B4	W690X265	Br4	HSS152X52X13
	C3	W360X162	B3	W690X265	Br3	HSS152X52X13
	C2	W360X347	B2	W690X280	Br2	HSS178X178X13

Table 2. Selected mainshock and aftershock ground motions for nonlinear dynamic analysis

No	Earthquake	Mv	Station	PGA of Mainshock(g)	PGA of Aftershock(g)
1	**ChiChi**	7.62	Chy036	0.27	0.098
2			Chy101	0.39	0.147
3			Tcu113	0.073	0.1
4	**Northridge**	6.69	Hollywood - Willoughby Ave	0.25	0.096
5			Sun Valley - Roscoe Blvd	0.44	0.099
6			Arleta - Nordhoff Fire Sta	0.345	0.11
7			Beverly Hills - 12520 Mulhol	0.6	0.33
8	**Imperial Valley**	6.53	El Centro Array #10	0.23	0.048
9			Calexico Fire Station	0.27	0.098
10			Holtville Post Office	0.25	0.11
11	**Hollister**	5.6	Hollister City Hall	0.114	0.07
12	**Whittier Narrows**	5.99	Brea - S Flower Av	0.11	0.073

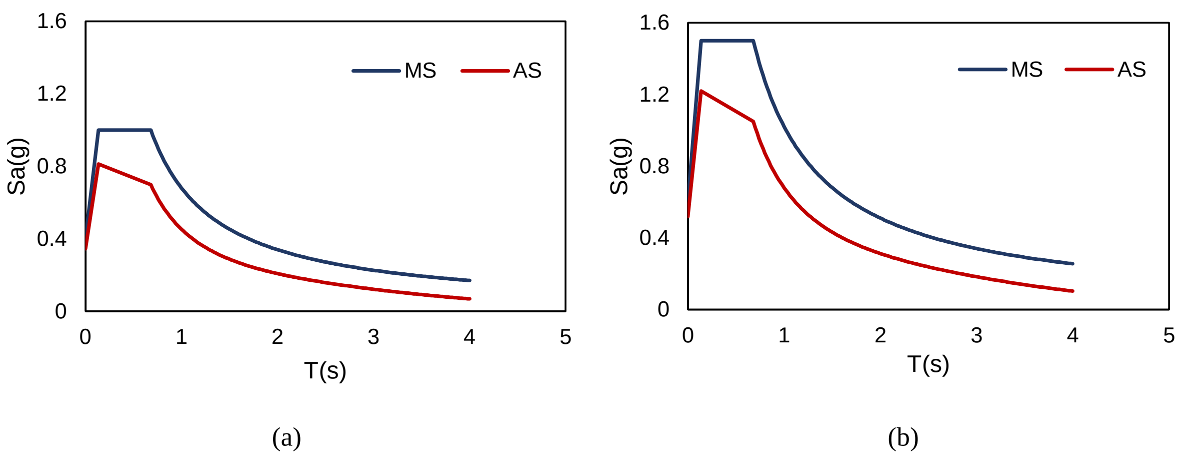

Figure 3. The seismic design spectrum for mainshocks and aftershocks a) 2/3MCE and b) MCE

SEISMIC EVALUATION OF THE FRAMES

To evaluate the seismic behavior of the structures designed based on conventional and developed PBPD under MSs and MS-ASs and compare their response, nonlinear time history analyses were performed using SeismoStruct [15]. Material nonlinearity was modeled using the Giuffre-Menegotto-Pinto steel model with isotropic strain hardening, and braces were divided into two fiber elements with an initial imperfection of 0.1% of the brace length. The numerical model accounted for full strength and rigid beam-to-column joints, but modeled braces as perfectly pinned. The seismic performance of the frames is evaluated in terms of inter-story drifts and plastic hinge distribution. As mentioned, according to the PBPD method, the structure designed based on this method is expected to meet the preselected target drift and yield mechanism. The target drifts for CBSFs under 2/3 MCE and MCE are 1.5% and 2%, respectively, and the desired yield mechanism is the formation of plastic hinges in braces the basis of columns in first floor. In this section, the seismic performance of the CBSFs designed based on conventional and developed PBPD methods under MSs and MS-ASs are evaluated and compared.

Inter-story drift

As mentioned, in PBPD method it is expected that the mean inter-story drifts do not exceed the target drift when the building is subjected to the seismic events. Figure 4 shows the distribution of inter-story drifts for the 6- story frame designed based on conventional PBPD and developed PBPD under MS and MS-AS sequences. According to Figure 4.a, it can be observed that the 6-story conventional PBPD frame shows a desirable performance under mainshock as the inter-story drift did not exceed 1.5%, which is the target drift for the hazard level of 2/3MCE. However, when the damaged structure was exposed to an aftershock, the inter-story drift in the 6th and 7th stories exceeded the target drift and the structure showed undesirable performance. Figure 4.b represents the inter-story drifts for the 6-story frame designed based on the developed PBPD. As shown, the inter-story drifts of the developed PBPD frame are below the target drift under MS and MS-AS sequences, and the frame shows a desired performance after being exposed to the aftershocks.

Figure 5 compares the inter-story drifts of the frames designed based on conventional PBPD and developed PBPD methods under MS and MS-AS sequences with the hazard level of MCE. As can be seen, the aftershocks considerably increased the inter-story drift of the frame designed based on the conventional PBPD method. For example, the mean inter-story drift of the frame is about 2.1% under MS and aftershocks increased the inter-story drift by 71%. However, the frame designed based on the developed PBPD method shows a desirable performance when under MS-AS sequences, as the value of inter-story drifts is below the allowable drift. Figures 6 and 7 also show the inter-story drift distribution for a 9-story building designed based on conventional PBPD and developed PBPD under 2/3MCE and MCE, respectively. As can be seen, the developed PBPD 9-story frame shows more desirable performance under MS and MS-AS sequences than the frame designed based on conventional PBPD.

Furthermore, it is interesting to note that the aftershocks increase the inter-story drift of the building damaged highly under MS more than the building experienced less damage under MS. For example, according to Figure 6a the inter-story drift of the 9th story of the conventional PBPD frame is about 1.55% under MS, and this value increased by 67%, reaching 2.7%. However, the value of inter-story drifts for the frame designed based on the developed PBPD method increase negligibly after being exposed to the aftershocks.

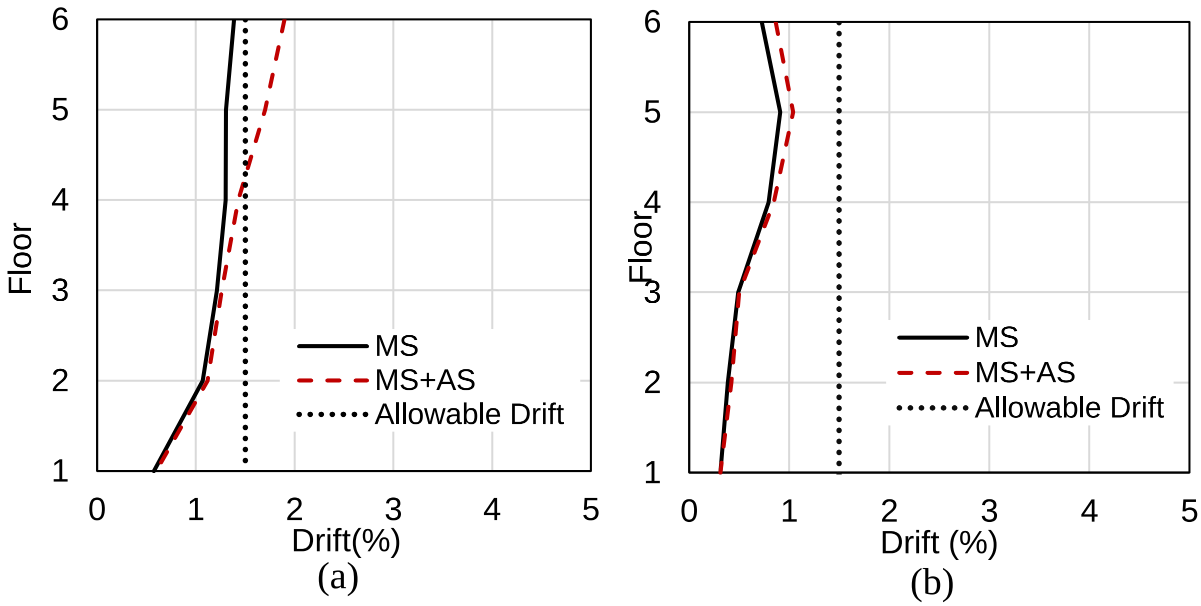

Figure 4. Mean values of maximum inter-story drifts for the 6-story frame designed based on a) conventional PBPD b) developed PBPD under 2/3MCE mainshocks and mainshock-aftershock sequences

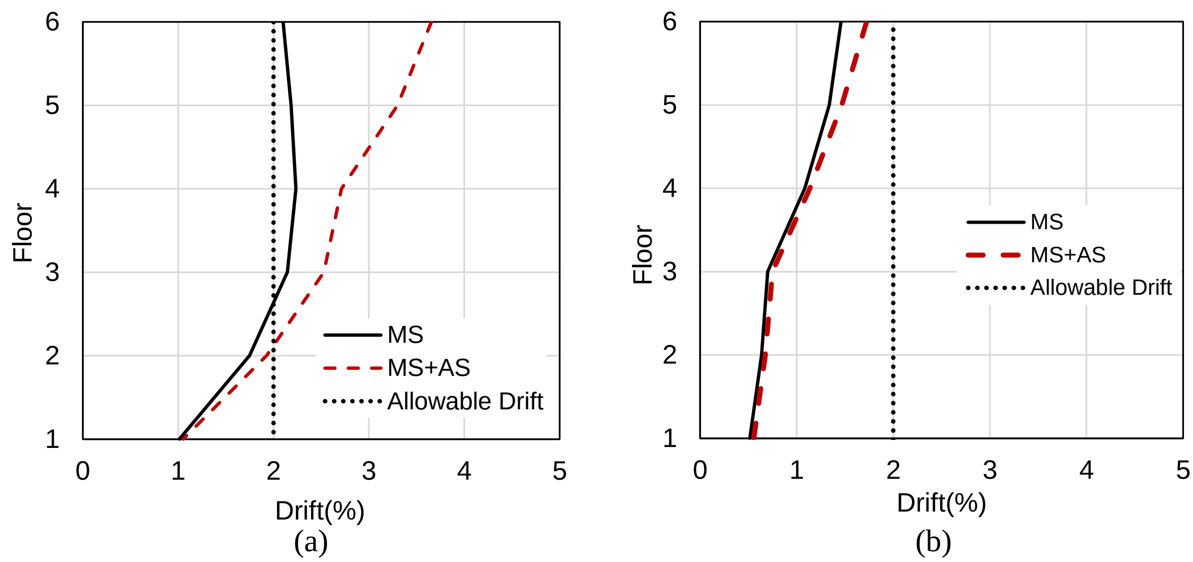

Figure 5. Mean values of maximum inter-story drifts for the 6-story frame designed based on a) conventional PBPD b) developed PBPD under MCE mainshocks and mainshock-aftershock sequences

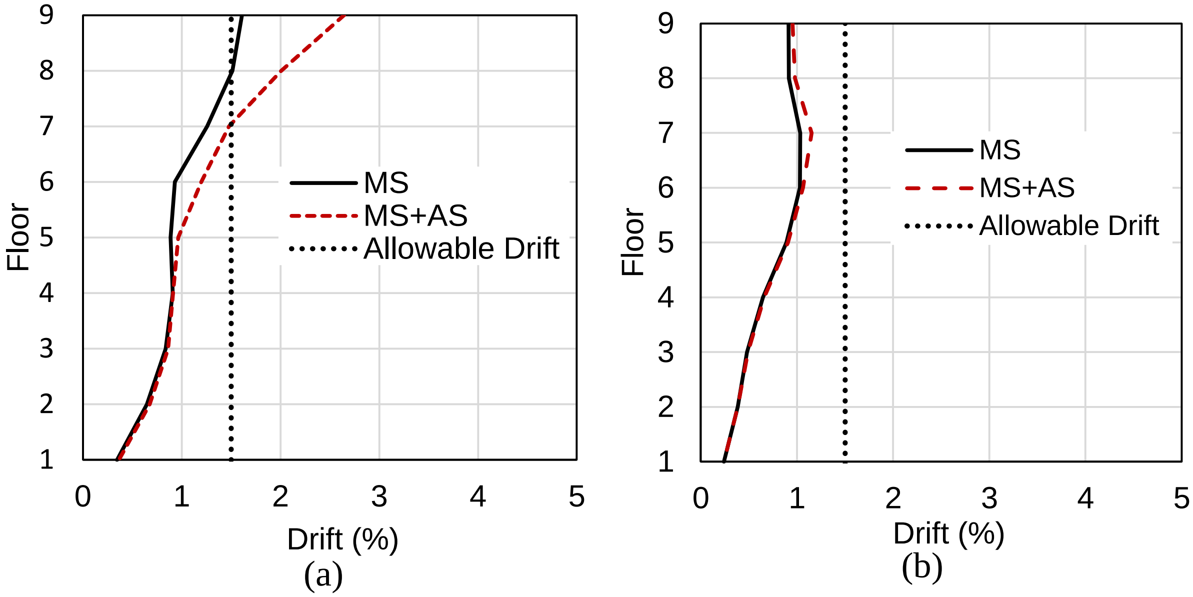

Figure 6. Mean values of maximum inter-story drifts for the 9-story frame designed based on a) conventional PBPD b) developed PBPD under 2/3MCE mainshocks and mainshock-aftershock sequences

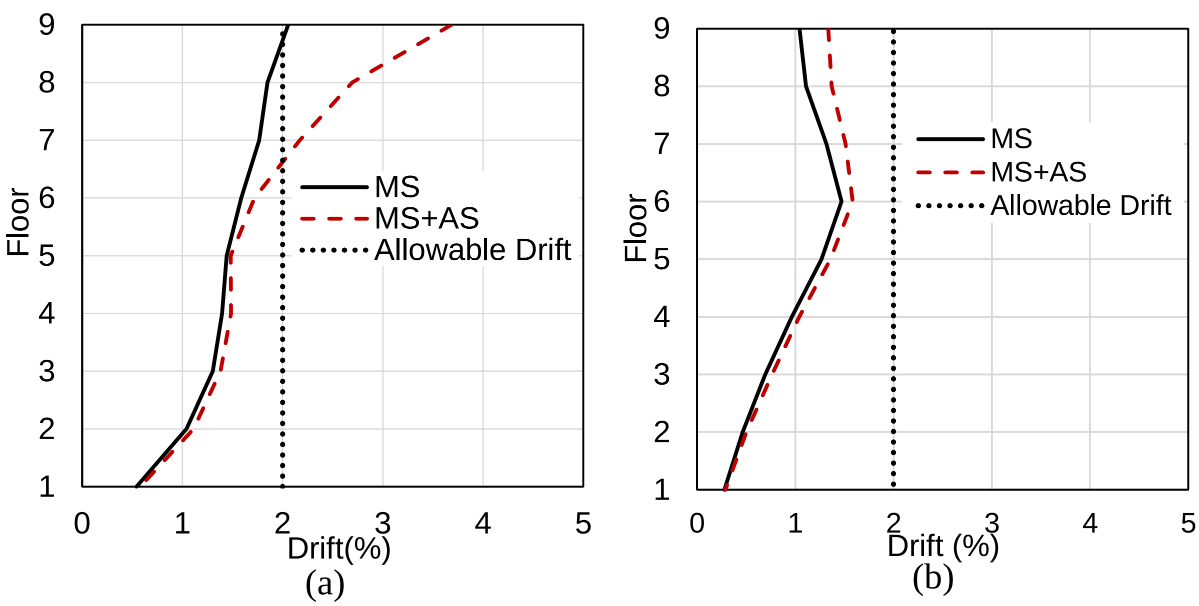

Figure 7. Mean values of maximum inter-story drifts for the 9-story frame designed based on a) conventional PBPD b) developed PBPD under MCE mainshocks and mainshock-aftershock sequences

Plastic hinges distribution

As previously mentioned, according to the PBPD method, it is expected that plastic hinges occur at braces and the base of the first story columns. Figure 8 presents the distribution of plastic hinges in conventional PBPD and developed PBPD frames under MS and MS-AS sequences. According to Figure 8a, when the conventional PBPD frame is under MS, the frame shows a desirable performance as plastic hinges form at braces and 1st story columns. However, when exposed to the aftershock, the plastic hinges form at the 2nd floor columns, resulting in undesirable performance. Figure 8b illustrates that the developed PBPD frame shows desirable performance after being exposed to the aftershocks, as plastic hinges occurred at braces and the basis of the 1st story columns. Similarly, Figure 9 shows that the 9-story developed PBPD perform well under the MS-AS sequence.

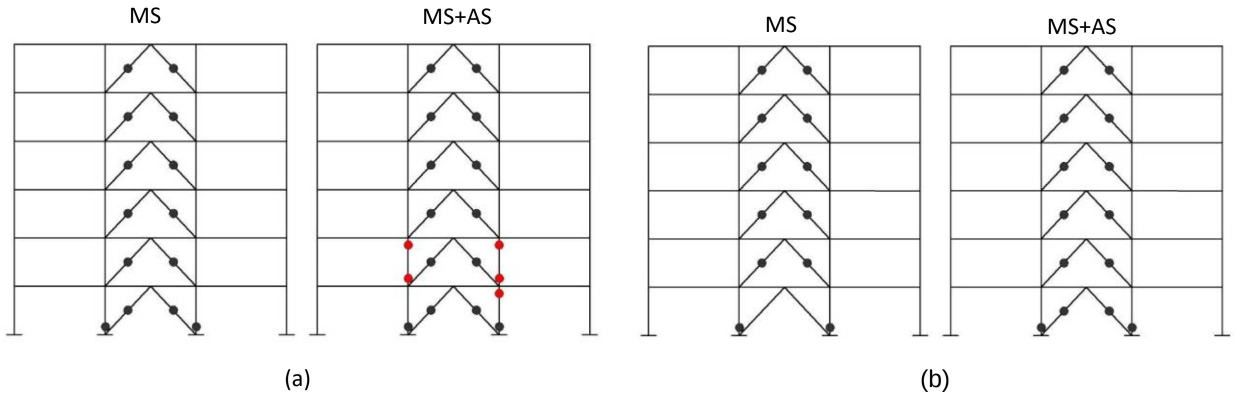

Figure 8. The distribution of the plastic hinges on the 6-story building under Chy101 mainshock and mainshock-aftershock sequence a) conventional PBPD b) developed PBPD

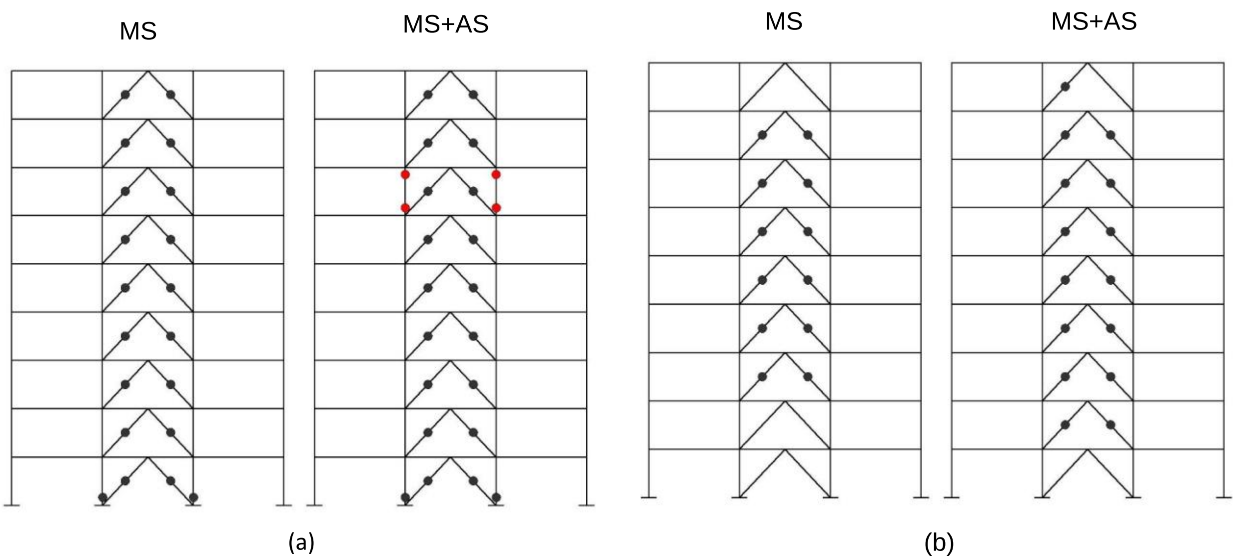

Figure 9. The distribution of the plastic hinges on the 6-story building under Chy101 mainshock and mainshock-aftershock sequence a) conventional PBPD b) developed PBPD

Development of fragility curves

To evaluate the seismic vulnerability of frames designed using PBPD and the developed PBPD methods, fragility curves for the 6-story frames subjected to MS-AS have been developed. The fragility curve depicts the likelihood of structural damage under seismic loads. In this investigation, fragility curves were developed using peak ground acceleration (PGA) as the intensity measure and inter-story drift as the demand parameter. The cumulative likelihood of damage equal to or greater than the damage level is denoted by Eq. (1).

$$\boldsymbol{P}(\leq \boldsymbol{D}) = \boldsymbol{\varphi}\left(\frac{\ln \boldsymbol{x} - \boldsymbol{\lambda}}{\boldsymbol{\xi}}\right) \tag{1}$$

Where φ is the standard normal distribution, x is defined as the lognormal distributed earthquake index (PGA), λ is defined as the mean of $\ln x$ and ξ is the mean standard deviation of $\ln x$.

The fragility curve was developed using incremental dynamic analyses of thirty ground motions obtained from PEER ground motion database from different earthquake events. Figure 10 shows the comparison of fragility curves for the conventional PBPD and developed PBPD CBSFs under MS-AS sequences for different damage states. In this study, fragility curves were generated based on three limit states. Damage levels for immediate occupancy (IO), life safety (LS), and collapse prevention (CP) are defined as inter-story drifts of 0.5%, 1.5%, and 2%, respectively [12]. Figure 10a-c show the fragility curve for the CBSFs for all three damage levels. As can be seen, the probability of the frame designed based on the developed PBPD method has lower probability of exceeding a certain damage level at all levels of PGA considered. For example, the probability of the conventional PBPD frame experiencing LS damage state under sequential MS-AS with the PGA of 0.2g, 0.3g, and 0.4g is about 40%, 75%, and 95%, respectively while the probability for the proposed PBPD is approximately 10%, 40%, and 70%. Also, for the CP damage state, the median collapse PGA (50% probability of exceedance) for the PBPD frame is 0.27g while it is 0.47g for the PBPD frame designed using the proposed method. Thus, it can be concluded that the proposed PBPD method decreases the vulnerability of the frames significantly under mainshock-aftershock sequences.

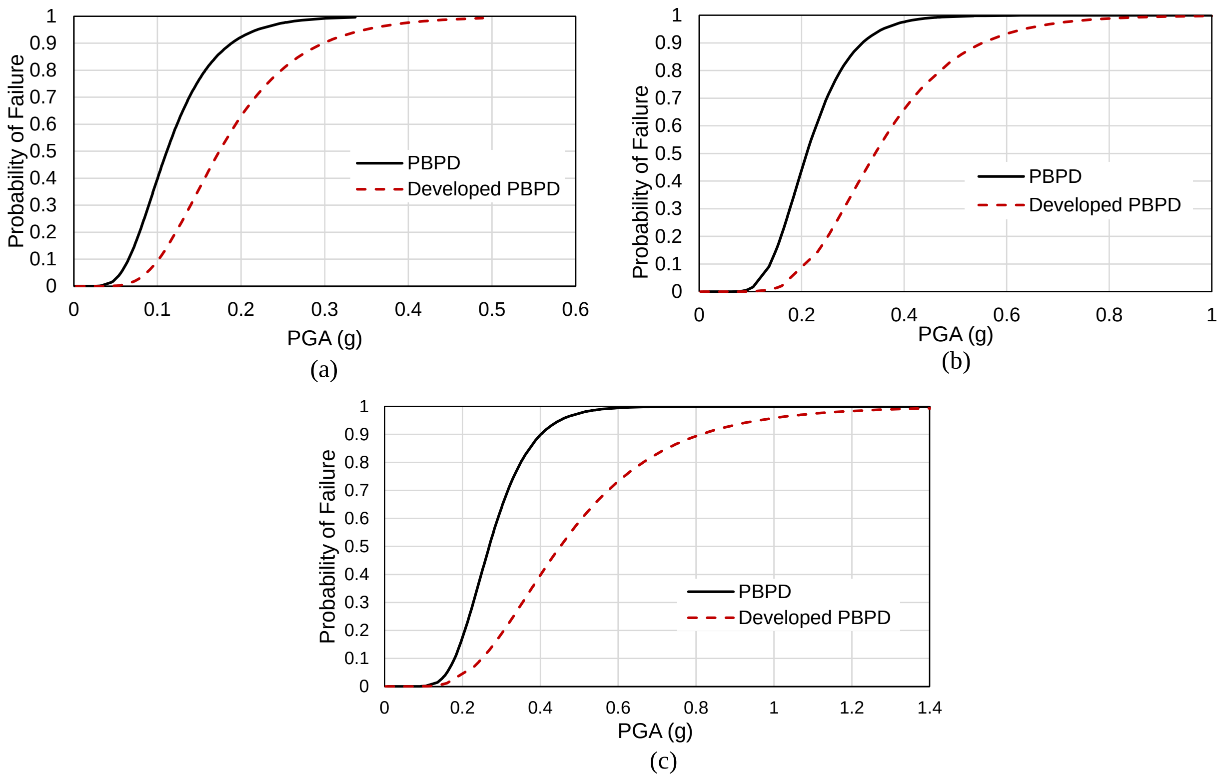

Figure 10. Comparison of fragility curves for the frames designed based on conventional PBPD and developed PBPD methods under MS-AS sequences for the damage levels of a) IO b) LS c) CP

CONCLUSION

This study aims to evaluate and compare the seismic performance of the CBSFs designed based on conventional PBPD and developed PBPD methods under MS-AS sequences. The parameters that were evaluated were inter-story drifts and the distribution of plastic hinges. Fragility curves were also developed to compare the vulnerability of the frames under MS-AS sequences. The results are summarized as follows:

- The inter-story drift of PBPD frames during 2/3 MCE and MCE mainshocks do not exceed the drift limits (1.5% and 2%, respectively). But, following the aftershock, the inter-story drift increased and surpassed the limits. The rise in inter-story drifts is a result of the decreased stiffness of mainshock-damaged structures and the frequency content of aftershock records.
- The CBSFs designed using the developed PBPD approach demonstrated a desired performance both in terms of inter-story drifts and plastic hinge distribution under mainshock-aftershock sequences.

- Comparing the inter-story drifts of the developed PBPD frames with those of conventional PBPD frames reveals that the damage level of structures under mainshocks influences the value of inter-story drift for frames during aftershocks. While developed PBPD frames suffered less damage from mainshocks than conventional PBPD frames, the aftershock-induced rise in inter-story drifts for these frames was lower.
- To compare the seismic vulnerability of six-story frames designed based on PBPD and developed PBPD under mainshock-aftershock sequences, fragility curves was developed. The result demonstrates that the likelihood of the PBPD structure achieving the damage levels of IO, LS, and CP at a particular PGA is greater than that of the frame designed using the produced PBPD. Thus, the suggested PBPD approach considerably reduces the frame's fragility under mainshock-aftershock sequences, making it safer than standard PBPD frames.

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