Civil Engineering Infrastructures Journal, 50(1): 21 – 34, June 2017
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.7508/ceij.2017.01.002

Performance-Based Plastic Design of Moment Frame-Steel Plate Shear Wall as a Dual System

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Received: 01 Mar. 2015; Revised: 15 Feb. 2016; Accepted: 08 Mar. 2016

ABSTRACT: Steel Plate Shear Wall (SPSW) is an emerging seismic load-resistant system that, compared to other systems, enjoys the advantages of stable ductile behavior, fewer detailing requirements, rapid constructability, and economy. American seismic provisions decree that a SPSW should be designed as a moment frame with a web infill plate. Specifically, in case of buildings taller than 160 ft, it decrees that a dual system must be used. This paper presents a method of Performance-Based Plastic Design (PBPD) to design steel moment frame-SPSW as a dual lateral load-resisting system. PBPD method uses pre-selected target drift and yield mechanism as its main criteria. For a specified hazard level, the design base shear is calculated based on energy work balance method, employing pre-selected target drift. Plastic design of dual frame system has been performed to meet the pre-selected yield mechanism. As presented in the paper, design procedure involves solving a system of five equations with five variables to determine the proportion of SPSW and moment frame shear, shear wall thickness, and beam/ column sections. It has been considered that a four-story structure is designed with the proposed method. Seismic performance of this dual frame system, designed with the proposed method, is evaluated by nonlinear static and dynamic analysis for both Design Basis Earthquake (DBE) and Maximum Credible Earthquake (MCE). Result analysis is in accord with the assumptions, satisfying all the performance objectives. PBPD is a direct design method in which no iteration is needed to achieve the performance objectives. Determining the proportion of SPSW and moment frame shear is an exclusive capability of this procedure.

Keywords: Dual Frame System, Moment Frame, PBPD Method, Portion of SPSW and Moment Frame Shear, Steel Plate Shear Wall (SPSW), Target Drift, Target Yield Mechanism.

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INTRODUCTION

PBPD is a new design procedure that enables the engineers to design structures with more predictable structural performance under severe earthquakes. Design factors such as member strength hierarchy, selection of desirable yield mechanism, selection of target drift for given hazard levels, and design lateral load distribution make up the basis of this method. This method has been successfully applied to steel Moment Frames (MFs), Concentrically Braced Frames (CBFs), Eccentrically Braced Frames (EBFs), Buckling Restrained Braced Frames (BRBFs), and Special Truss Moment Frames (STMFs) (Leelataviwat et al., 1999; Lee and Goel, 2001; Dasgupta et al., 2004; Chao and Goel, 2005; Chao and Goel, 2006a, 2006b; Sahoo and Chao, 2010; Liao and Goel, 2012; Banihashemi et al., 2015).

American seismic provisions decree that a SPSW should be designed as a moment frame with a web infill plate and in particular, in case of buildings taller than 160 ft, a dual system should be used. This paper presents a procedure for applying PBPD on moment frame-SPSW as a dual system. All of the dual system members can be designed simultaneously by solving a system of five equations with five variables. The proportions of SPSW and moment frame shear are determined by solving the system of equations.

The structure, considered in this study, is the four-story MCEER demonstration hospital (Yang and Whittaker, 2002; Berman and Bruneau, 2008). There are four dual frame systems in N-S direction that carry seismic load (Figure 1). The 3-bay dual frame system is designed by PBPD. The PBPD dual frame system is designed for a target drift of 3% to govern earthquake, i.e. design spectrum with 2% probability of exceedance in 50 years. The member sizes of the dual frame system are shown in Figure 8. The dual frame system was modeled and analyzed by using PERFORM-3D, a nonlinear software tool for seismic design (CSI, 2007). The results of nonlinear static and dynamic analysis for both DBE and MCE design bases are presented and discussed in this paper.

PBPD DESIGN OF THE CASE STUDY, DUAL FRAME SYSTEM

Target Drift and Target Yield Mechanism Selection

Target drift is selected for two earthquake hazard levels: a 2% maximum story drift ratio (θ_u) for an earthquake hazard with a 10% probability of exceedance in 50 years and a 3% maximum story drift ratio (θ_u) for an earthquake hazard with a 2% probability of exceedance in 50 years (Goel and Chao, 2008).

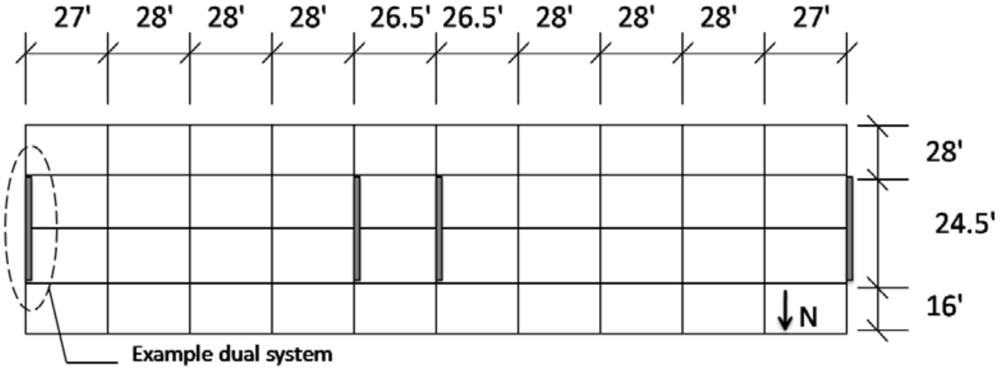


Fig. 1. Plan view of the MCEER demonstration hospital (Yang and Whittaker, 2002)

Target yield mechanism is shown in Figure 2. Design lateral forces are applied to dual frame system and are pushed to target plastic drift. Yielding of SPSWs and formation of the plastic hinge at the Reduced Beam Section (RBS) of beam ends and column bases are expected to happen in target yield mechanism. Hence, plastic hinges are not allowed to be formed at other points of beams and columns.

Design of the Lateral Forces

The structures, designed in accordance with lateral force distribution of current codes, are expected to undergo large inelastic deformations in severe earthquakes. Utilization of structures' inelastic behavior in the design procedure results in a desirable and predictable structural response.

Lateral force distribution of PBPD is based on the maximum story shears as can be observed in nonlinear time-history analysis results (Chao et al., 2007):

$$F_i = C'_{vi} V \tag{1}$$

$$C'_{vi} = (\beta_i - \beta_{i+1}) \left(\frac{w_4 H_4}{\sum_{j=1}^{4} w_j H_j} \right)^{0.75T^{-0.2}} \tag{2}$$

$$when\ i = 4\ , \beta_5 = 0$$

$$\beta_i = \frac{V_i}{V_4} = \left(\frac{\sum_{j=1}^{4} w_j H_j}{w_4 H_4} \right)^{0.75T-0.2} \tag{3}$$

where β_i represents the shear distribution factor at level i, V_i and V are the story shear forces at level i and the total design base shear respectively, w_j is the seismic weight at level j, H_j is the height of level j from the base, T is the fundamental period of the structure and F_i is the lateral force at level i (Goel and Chao, 2008).

Design of the Base Shear

The design of the base shear can be determined thanks to an energy-work balance method (Figures 3-5) where the energy required to push an equivalent elastic-plastic Single Degree Of Freedom (SDOF) structure up to the target drift is calculated as a fraction of elastic input energy obtained from the selected elastic design spectrum.

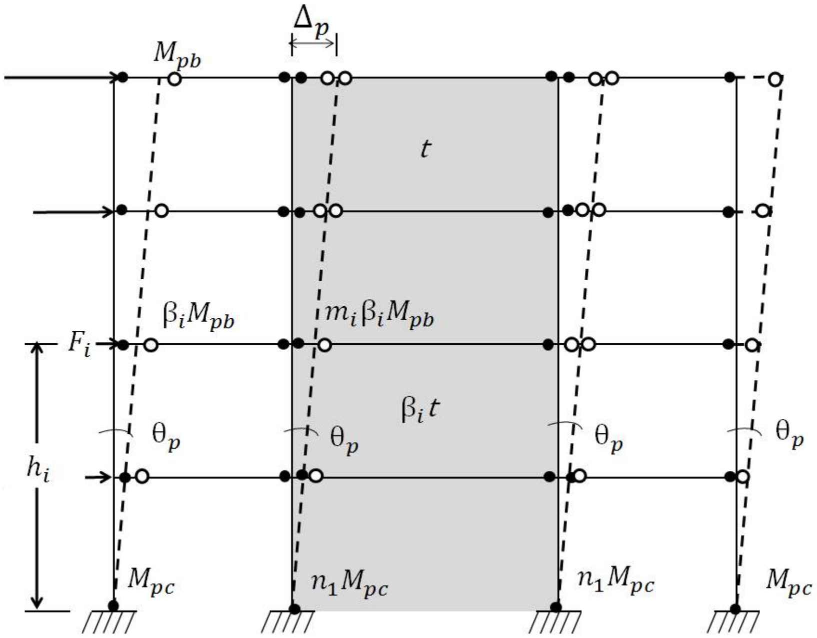


Fig. 2. Target yield mechanism of PBPD method

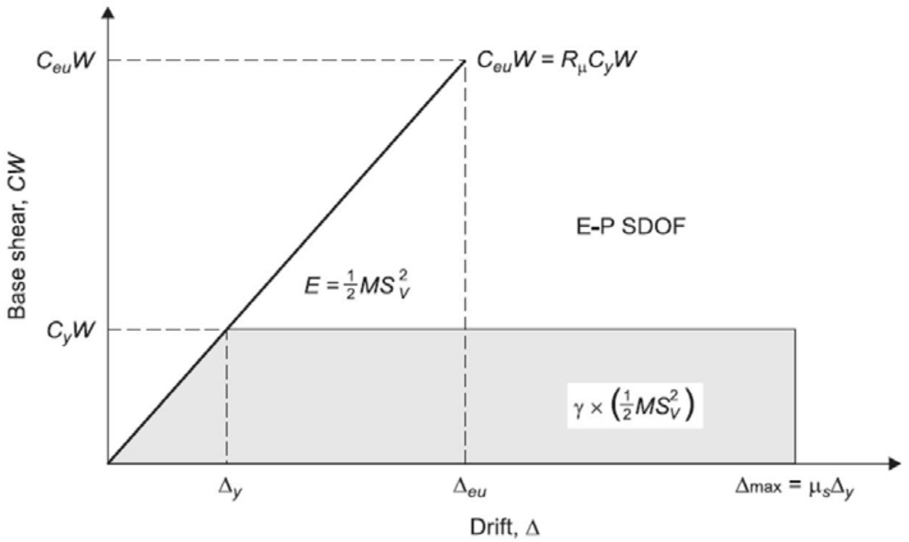


Fig. 3. Structural idealized response and energy (work) balance concept for SDOF system (Goel and Chao, 2008)

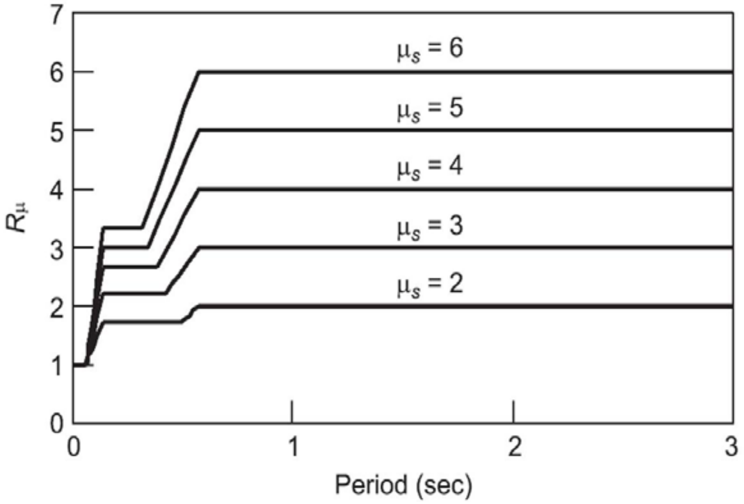


Fig. 4. Idealized inelastic spectra (Newmark and Hall, 1982)

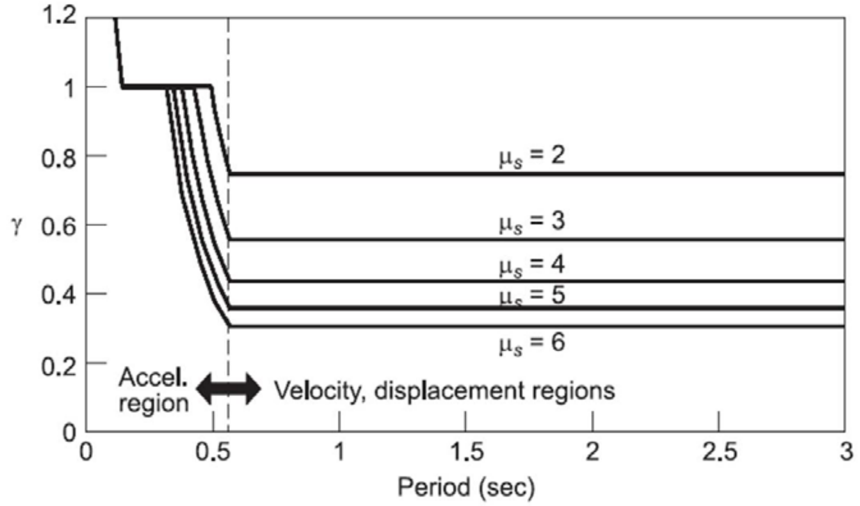


Fig. 5. Energy modification factor versus period

The design base shear can be expressed as (Goel and Chao, 2008; Miranda and Bertero, 1994; Lee and Goel, 2001; Newmark and Hall, 1982):

$$\mu_s = \frac{\Delta_{max}}{\Delta_y} \tag{4}$$

$$R_\mu = \frac{C_{eu}}{C_y} \tag{5}$$

$$\frac{V'}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma {S_a}^2}}{2} \tag{6}$$

$$\alpha = \left(\sum_{i=1}^{4}(\beta_1 - \beta_{i+1})\right) \left(\frac{w_4 H_4}{\sum_{j=1}^{4} w_j H_j}\right)^{0.75T-0.2} \left(\frac{\theta_p 8\pi^2}{T^2 g}\right) \tag{7}$$

$$\gamma = \frac{2\mu_s - 1}{{R_\mu}^2} \tag{8}$$

where M is the total mass of the system, μ_s is the structural ductility factor, R_u is the ductility reduction factor can be obtained based on Table 1, α is a dimensionless parameter, which depends on the stiffness of the structure, the modal properties and the plastic drift level, S_a is the spectral response acceleration, V' is the total design base shear, W is the total seismic weight of the structure, H_j is height of the jth story from the base, w_j is seismic weight of the jth story, θ_u is the target drift ratio, θ_y is the yield drift ratio, θ_p is the inelastic drift ratio (θ_u - θ_y), S_v is the design spectral pseudo-velocity and γ is the energy modification factor.

Table 1. Ductility reduction factor and its corresponding structural period range

Period Range	Ductility Reduction Factor
$0 \leq T \leq \frac{T_1}{10}$	$R_\mu = 1$
$\frac{T_1}{10} \leq T \leq \frac{T_1}{4}$	$R_\mu = \sqrt{2\mu_s - 1} \,.\, \left(\frac{T_1}{4T}\right)^{2.513\,.\log\left(\frac{1}{\sqrt{2\mu_s - 1}}\right)}$
$\frac{T_1}{4} \leq T \leq T_1'$	$R_\mu = \sqrt{2\mu_s - 1}$
$T_1' \leq T \leq T_1$	$R_\mu = \frac{T\,\mu_s}{T_1}$
$T_1 \leq T$	$R_\mu = \mu_s$

Note: T_1 = 0.57 sec., $T_1' = T_1 . (\sqrt{2\mu_s - 1}/\mu_s)$ sec.

In PBPD, the design of the base shear should be measured for both DBE and MCE hazard levels and the maximum rate is to be used. For the structure under study in this paper, MCE hazard level governs the behavior.

Design of the Designated Yielding Members (DYMs)

The plastic design method is used to provide adequate strength in target yield mechanism. As aforementioned, for dual frame system, SPSWs, and RBS of beam ends and column bases are expected to yield. In order to prevent yielding from being concentrated at some levels as well as distribution of the yielding events along the height, it is recommended that the distribution of structural strength should follow the distribution of design story shears at structure height. (By using coefficient) (Bayat, 2010).

$$M_{pb_i} = \beta_i M_{pb_4} \tag{9}$$

$$t_{w_i} = \beta_i t_{w_4} \tag{10}$$

t_{wi} is the thickness of SPSW in the ith story and M_{pbi} is the plastic moment of RBS section at beam ends of the ith story.

Consideration of Overall Mechanism Formation

The unknown variables of DYMs, can be calculated by equating external work to internal work which is caused by a small overall mechanism rotation (θ) (Figure 2) (Berman and Bruneau, 2008):

$$\begin{aligned}\sum_{i=1}^{4} F_i h_i \theta &= \sum (M_{pc\,ext\,column_1} + M_{pc\,VBE_1})\theta \\ &+ \sum_{i=1}^{4} M_{pb\,ext\,beam_i} \eta_{b\,ext\,beam} \theta \\ &+ \sum_{i=1}^{4} M_{pb\,HBE_i} \eta_{b\,HBE} \theta \\ &+ \sum_{i=1}^{4} (\Delta\omega_{xb_i} l_{b\,HBE}) h_i \theta\end{aligned} \quad (11)$$

$$\eta_b = \frac{l_b}{l'_b}$$
$$\omega_{xb_i} = .5 F_{yw} t_{w_i} \sin 2\alpha$$
$$\omega_{yb_i} = F_{yw} t_{w_i} (\cos\alpha)^2$$
$$\omega_{xc_i} = F_{yw} t_{w_i} (\sin\alpha)^2$$
$$\omega_{yc_i} = .5 F_{yw} t_{w_i} \sin 2\alpha$$

in which θ is the small overall mechanism rotation, $M_{pc\,ext\,column_i}$ is the plastic moment of external column in the ith story, $M_{pc\,VBE_i}$ is the plastic moment of VBE in the ith story, $M_{pb\,ext\,beam_i}$ is the plastic moment of external beam at RBS section in the ith story, $M_{pb\,HBE_i}$ is the plastic moment of HBE at RBS section in the ith story, η_b is the coefficient of converting frame rotation to beam rotation, l_b is the distance between column axes along the beam, l'_b is the distance between RBS sections of the beam, ω_{xb_i} is the horizontal distributed load, applied to the HBE of the ith story, ω_{yb_i} is the vertical distributed load, applied to the HBE of the ith story, ω_{xc_i} is the horizontal distributed load, applied to the VBE of the ith story, ω_{yc_i} is the vertical distributed load, applied to the VBE of the ith story, F_{yw} is the yield stress of SPSW(36 ksi), R_y is equal to 1.3 (AISC, 2005a) and α is the angle of tension stress in web plate with vertical line.

By assuming that α is the proportion of moment frame shear force and β, the proportion of SPSW shear force, the aforementioned work-energy equation is divided into two equations wherein α and β specify the proportion factor of lateral load distribution, applied to moment frame and SPSW respectively. Hence, two equations can be written as follows.

$$\begin{aligned}\alpha \sum_{i=1}^{4} F_i h_i \theta &= \sum (M_{pc\,ext\,column_1} + M_{pc\,VBE_1})\theta \\ &+ \sum_{i=1}^{4} M_{pb\,ext\,beam_i} \eta_{b\,ext\,beam} \theta \\ &+ \sum_{i=1}^{4} M_{pb\,HBE_i} \eta_{b\,HBE} \theta\end{aligned} \quad (12)$$

$$\beta \sum_{i=1}^{4} F_i h_i \theta = \sum_{i=1}^{4} (\Delta\omega_{xb_i} l_{b\,HBE}) h_i \theta \quad (13)$$

Consideration of Local Mechanism Prevention

Another way for calculating the unknown variables of DYMs is to prevent dual frame system from forming soft story mechanism, which means no soft story mechanism would happen in the first story when 1.1 folds of the design lateral forces are applied on the dual system (Leelataviwat et al., 1999). Eq. (14) is formed by equating the external work to the internal one, which is caused by a small local mechanism rotation (θ) (Figure 6):

$$\begin{aligned}1.1V\, H_1 \theta = 2 \sum (&M_{pc\,ext\,column_1} \\ &+ M_{pc\,VBE_1})\theta \\ &+ \omega_{xb_1} l_{b\,HBE} H_1 \theta\end{aligned} \quad (14)$$

where V is the contribution of one dual frame system from total design base shear.

Calculation of α, β

In order to determine the portion of moment frame shear force and the portion of SPSWs shear force, simplified force-displacement diagram of the dual system should be taken into consideration (Sabouri, 2001). As shown in Figure 7, simplified behavior diagram of equivalent SPSW and equivalent moment frame are drawn separately with the dual system's behavior, obtained from their results. Slope of equivalent SPSW diagram is equal to equivalent lateral stiffness of 4 shear wall plates of dual frame system assumed to be sequential. Similarly, the slope of the corresponding moment frame diagram is equal to the equivalent lateral stiffness of 4 stories of dual frame system, assumed to be sequential. As expected, the lateral stiffness of SPSW is greater than moment frame. In the first case, SPSW sustains a greater portion of shear force and yields. After SPSW yielding, the portion of moment frame shear force increases and the formation of plastic hinges causes a yield mechanism. Yield point displacement of equivalent moment frame is calculated by applying α times lateral load distribution to moment frame and determining the roof displacement. Similarly, calculation is done for equivalent SPSW by applying β coefficient (Tahuni, 1996).

$$k_{f_i} = \frac{24\,E}{{h_i}^2(\frac{2}{\sum k_{c_i}} + \frac{1}{\sum k_{bb_i}} + \frac{1}{\sum k_{bt_i}})} \tag{15}$$

$$k_{f_1} = \frac{24\,E}{{h_1}^2(\frac{2}{\sum k_{c_1}} + \frac{1}{\sum k_{bt_1} + \frac{\sum k_{c_1}}{12}})} \tag{16}$$

$$\sum k_b = \sum ({}^{I}\!/_{l})_b \tag{17}$$

$$\sum k_c = \sum ({}^{I}\!/_{h})_c \tag{18}$$

$$k_{f\,eq} = \frac{1}{\sum_{i=1}^{4} \frac{1}{k_{f_i}}} \tag{19}$$

$$k_{w_i} = \frac{l_{b\,HBE} t_{w_i}}{4h_i} E \tag{20}$$

$$k_{w\,eq} = \frac{1}{\sum_{i=1}^{4} \frac{1}{k_{w_i}}} \tag{21}$$

$$\Delta_{yf} = \alpha \sum \frac{V_i}{k_{f_i}} \tag{22}$$

$$\Delta_{yw} = \beta \sum \frac{V_i}{k_{w_i}} \tag{23}$$

where k_{f_i} is the lateral stiffness of middle stories, k_{f_1} is the lateral stiffness of first story by assuming that column bases are restraint, $\sum k_{c_i}$ is the summation of ${}^{I}\!/_{h}$ of the ith story columns, $\sum k_{bb_i}$ is the summation of ${}^{I}\!/_{l}$ of the ith story bottom beams, $\sum k_{bt_i}$ is the summation of ${}^{I}\!/_{l}$ of the ith story top beams, h_i is the ith story height, $k_{f\,eq}$ is the equivalent lateral stiffness of moment frame, k_{w_i} is the lateral stiffness of the ith story SPSW, $k_{w\,eq}$ is the equivalent lateral stiffness of SPSWs, E is the modulus of elasticity of steel, Δ_{yf} is the yield point displacement of equivalent moment frame, Δ_{yw} is the yield point displacement of equivalent SPSW, V_i the ith story shear and α is equal to the proportion of moment frame maximum shear strength to dual frame system maximum shear strength. Similarly, β is calculated as follows.

$$\alpha = \frac{k_f \Delta_{yf}}{k_f \Delta_{yf} + k_w \Delta_{yw}} \tag{24}$$

$$\beta = \frac{k_w \Delta_{yw}}{k_f \Delta_{yf} + k_w \Delta_{yw}} \tag{25}$$

As can be seen, story lateral stiffness, used in Eqs. (24) and (25), depends on second moment of area of the frame elements (I_{b_i} and I_{c_i}), whereas variables of Eqs. (12-14) include M_{pb} and M_{pc}. Hence, I_{b_i} and I_{c_i} should be determined based on M_{pb} and M_{pc} respectively:

$$\begin{aligned} M_{pb_i} &= Z_{b\,RBS_i} F_{yf} \\ &= \frac{\mu I_{b\,RBS_i}}{c_{b_i}} F_{yf} \\ \rightarrow \quad I_{b\,RBS_i} &= \frac{c_{b_i} M_{pb_i}}{\mu F_{yf}} \end{aligned} \tag{26}$$

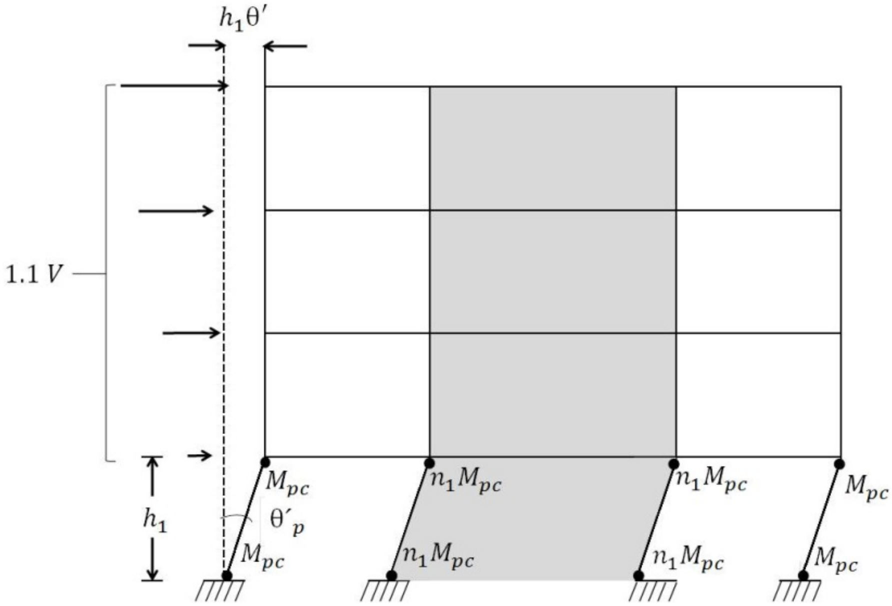


Fig. 6. Dual frame system with soft-story mechanism

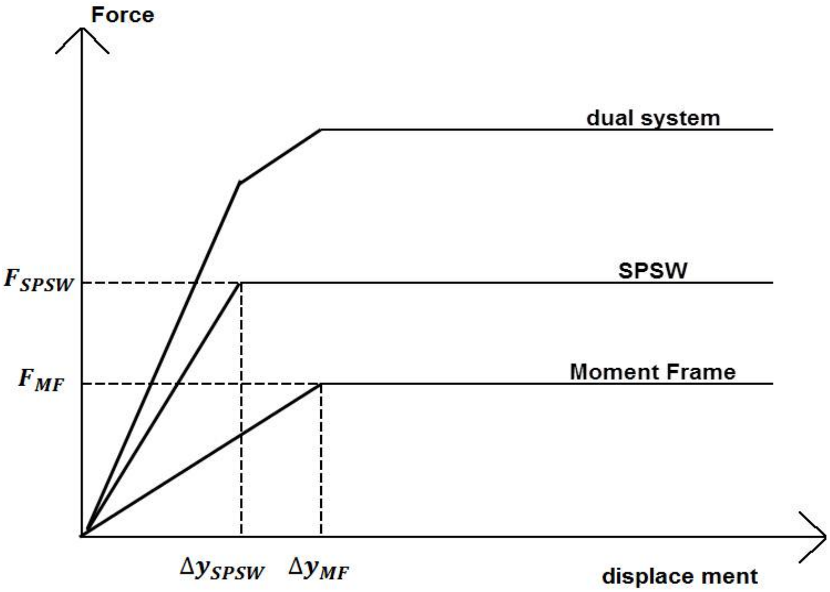


Fig. 7. Simplified Force-Displacement diagram of dual frame system

$$M_{pc_i} = Z_{c_i}F'_{yf} = \frac{\mu I_{c_i}}{c_{c_i}}F'_{yf} \rightarrow \quad I_{c_i} = \frac{c_{c_i}M_{pc_i}}{\mu F'_{yf}} \tag{27}$$

It is assumed that member sections are selected from American wide flange sections, column sections have the same depth and similarly, and beam sections have the same depth. So, last equations become:

$$I_{b_i} = \frac{c_b M_{pb_i}}{\mu F_{yf}} \tag{28}$$

$$I_{c_i} = \frac{c_c M_{pc_i}}{\mu F'_{yf}} \tag{29}$$

in which $Z_{b\,RBS_i}$ is the plastic modulus of RBS section of the ith story's beam, assumed to be $0.75Z_{b_i}$, Z_{b_i} is the plastic modulus of section of the ith story's beam, Z_{c_i} is the plastic modulus of section of the ith story's column, F_{yf} is the yield stress of frame members (50 ksi), F'_{yf} is the reduced flexural yield stress of column due to attendance of its compressive force (FEMA 356, 2000a), R_y is equal to 1.1 (AISC, 2005a), μ is the shape factor, I_{b_i} is the second moment of area of the ith story's beam, $I_{b\,RBS_i}$ is the RBS second moment of area of the ith story's beam, I_{c_i} is the second moment of area of the ith story's column and c_{b_i}, c_{c_i} are the frame member section depth divided by two.

It should be noted that the presence of compressive force in columns reduces their flexural capacity. By reducing column flexural yield stress to the amount of $0.66F_{yf}$, the effect of axial load-moment interaction can be inputted in the system of five equations with five variables.

It is noted, that RBS is the first point of beam that becomes inelastic. So the RBS second moment of area ($I_{b\,RBS}$) should be used to calculate the story lateral stiffness.

Amplification Factor of Hbes and Vbes

As discussed in the previous section, there is a moment frame, subjected to α folds of the lateral load distribution as well as a shear wall, subjected to β folds of the lateral load distribution. Furthermore, interaction between SPSW and moment frame should be considered.

In order to analyze the Moment Frame, the portal method has been employed. According to this method, portion of column lateral load is equal to portion of column vertical load. Beam and column moments are calculated parametrically by portal analysis. Furthermore, HBEs and VBEs are affected by SPSW interactions that produce moment in them. So in each story, boundary elements (beams or columns) will be amplified by the design moment rather than adjacent elements. For simplicity, the moment which is produced by SPSW in the ends of boundary elements approximated by $\omega\frac{l^2}{12}$. The amplification factor can be calculated as:

$$m_i = \frac{\left(M_{VBE\,portal_{i+1}} + M_{VBE\,portal_i}\right) - \left(M_{ext\,column\,portal_{i+1}} + M_{ext\,column\,portal_i}\right)}{\left(M_{ext\,column\,portal_{i+1}} + M_{ext\,column\,portal_i}\right) + \Delta\omega_{yb_i}\frac{{l_{b\,HBE}}^2}{12}} \qquad (30)$$

$$n_i = \frac{M_{VBE\,portal_i} + \omega_{xc_i}\frac{{h_i}^2}{12}}{M_{ext\,column\,portal_i}} \qquad (31)$$

where m_i, n_i, $M_{HBE\,portali}$, $M_{ext\,beam\,portali}$, $M_{VBE\,portali}$, $M_{ext\,column\,portali}$ and V_i are the amplication factor of HBE and VBE, the portal analysis moment of HBE at column axes, the portal analysis moment of external beam at column axes, the portal analysis moment of external VBE at beam axes, the portal analysis moment of external column at beam axes and the shear force in the ith story, respectively.

In total, there are five unknown variables, dealt with in the five aforementioned Equations 12-14 and 24-25. Three variables are directly related to DYMs: 1) SPSW thickness at top story, 2) RBS plastic moment of external beam at top story, and 3) plastic moment of external column base. Two last unknown variables are the portion of SPSW shear force and portion of moment frame shear force (α and β). By selecting the beam and column typical depth, c_b, c_c can be determined. System of five equations with five variables is solved by a Mathematical program and t_4 , $M_{pb\,ext\,beam_4}$, $M_{pc\,ext\,column_1}$, α and β are calculated. So, dual system members are determined as:

$$t_i = \beta_i t_4 \tag{32}$$

$$M_{pb\ ext\ beam_i} = \beta_i M_{pb\ ext\ beam_4} \tag{33}$$

$$M_{pb\ HBE_i} = m_i M_{pb\ ext\ beam_i} = m_i \beta_i M_{pb\ ext\ beam_4} \tag{34}$$

$$M_{pc\ ext\ column_i} = \frac{V_i}{V_1} M_{pc\ ext\ column_1} \tag{35}$$

$$M_{pc\ VBE_i} = n_i M_{pc\ ext\ column_i} = n_i \frac{V_i}{V_1} M_{pc\ ext\ column_1} \tag{36}$$

Beam section is designed based on plastic moment which calculated by Eqs. (33-36).

$$M_{pb_i} = Z_{b\ RBS_i} F_{yf} \rightarrow Z_{b\ RBS_i} = \frac{M_{pb_i}}{F_{yf}} \rightarrow Z_{b_i} = \frac{Z_{b\ RBS_i}}{0.75} \tag{37}$$

Design of Non-Designated Yielding Members (Non -Dyms)

Column section is designed based on plastic moment which is calculated by Eq. (37).

$$M_{pc_i} = Z_{c_i} F'_{yf} \rightarrow Z_{c_i} = \frac{M_{pc_i}}{F'_{yf}} = \frac{M_{pc_i}}{0.66 F_{yf}} \tag{38}$$

Columns (except their bases) are intended to remain elastic; therefore, they should be designed based on capacity design approach. Axial force of the column is the consequence of the interaction between SPSW, connected beams shear force, and factored gravity loads. Moment of column is calculated by the above-mentioned equations. Finally, for capacity design approach, the interaction between flexure and compression in column should be checked by equations H1-1a and H1-1b of AISC 360-05 (AISC, 2005b).

MODELING AND VERIFYING BY THE ANALYSIS

As aforementioned, the PBPD design method is applied to design the four-story MCEER demonstration hospital (Yang and Whittaker, 2002) with Moment Frame-SPSW as lateral load-resisting system. The plan and elevation views of the designed dual systems are shown in Figures 1 and 8. After modeling dual frame system with a nonlinear computer program, perform-3D, its seismic performance is evaluated by nonlinear static and dynamic analysis (pushover and time-history analysis).

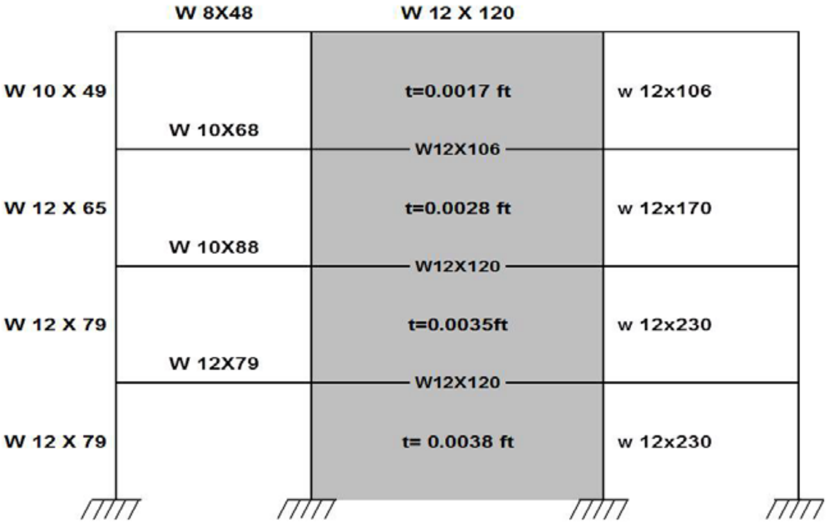


Fig. 8. PBPD method for dual system

As can be seen in Figures 1 and 8, the PBPD dual frame system reaches its intended performance objectives such as yield mechanism and target drift under both levels of seismic hazards.

Pushover Analysis Results

The dual frame system is analyzed with pushover method. Design base shear force and pushover curve are shown in Figure 9. As can be seen, the ultimate strength of the frame is greater than design base shear force in the target drift. In this analysis, the global P-Δ effects due to the gravity load are also included.

The PBPD dual frame system reached its intended yield mechanism at intended target drift (Figure 10) and performance level of dual frame system is obtained: Collapse Prevention (CP), which is in accordance with provisions for MCE hazard level (FEMA 356, 2000a).

Time-History Analysis Results

For the nonlinear dynamic analysis, two sets of SAC ground motions for LA site (Somerville et al., 1997) with an exceedance probability of 10% in 50 years (DBE hazard level) and with exceedance probability of 2% in 50 years (MCE hazard level), are used. Figure 11 illustrates the maximum inter-story drift responses as well as their mean values for dual frame systems. Accordingly, in both figures the mean values are within the design target drift (2% for DBE and 3% for MCE).

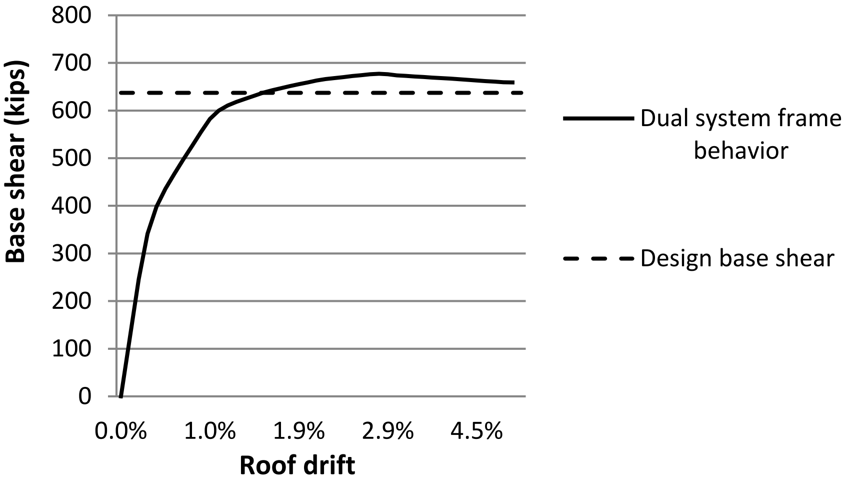


Fig. 9. Pushover curve of PBPD dual frame system

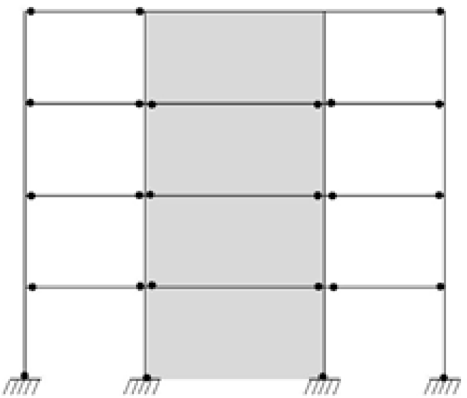
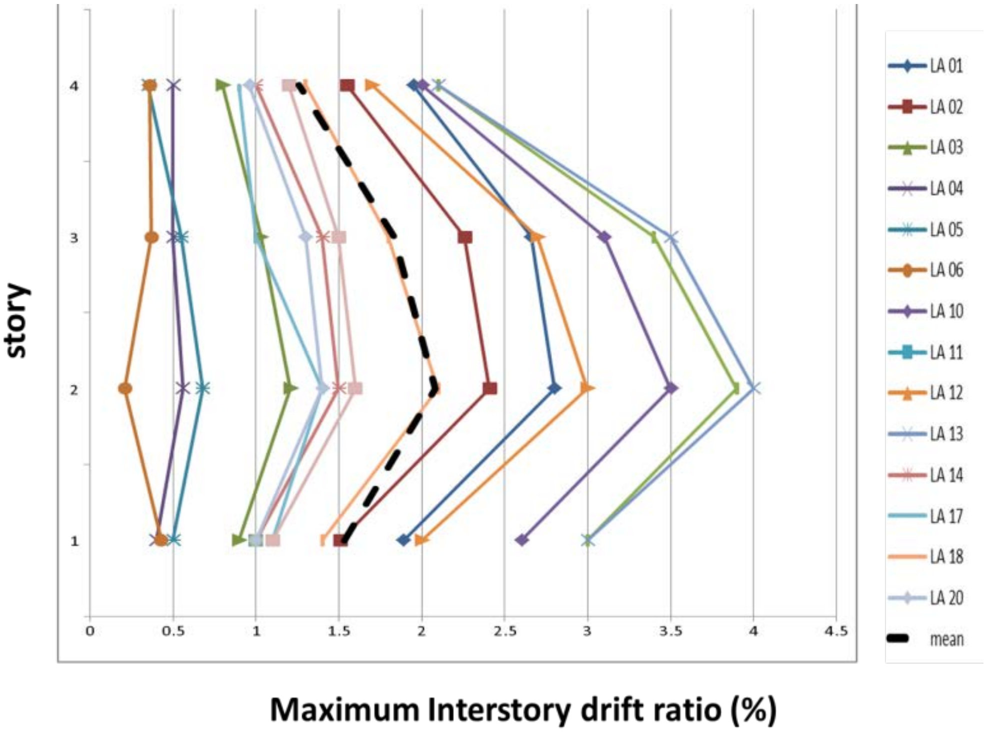
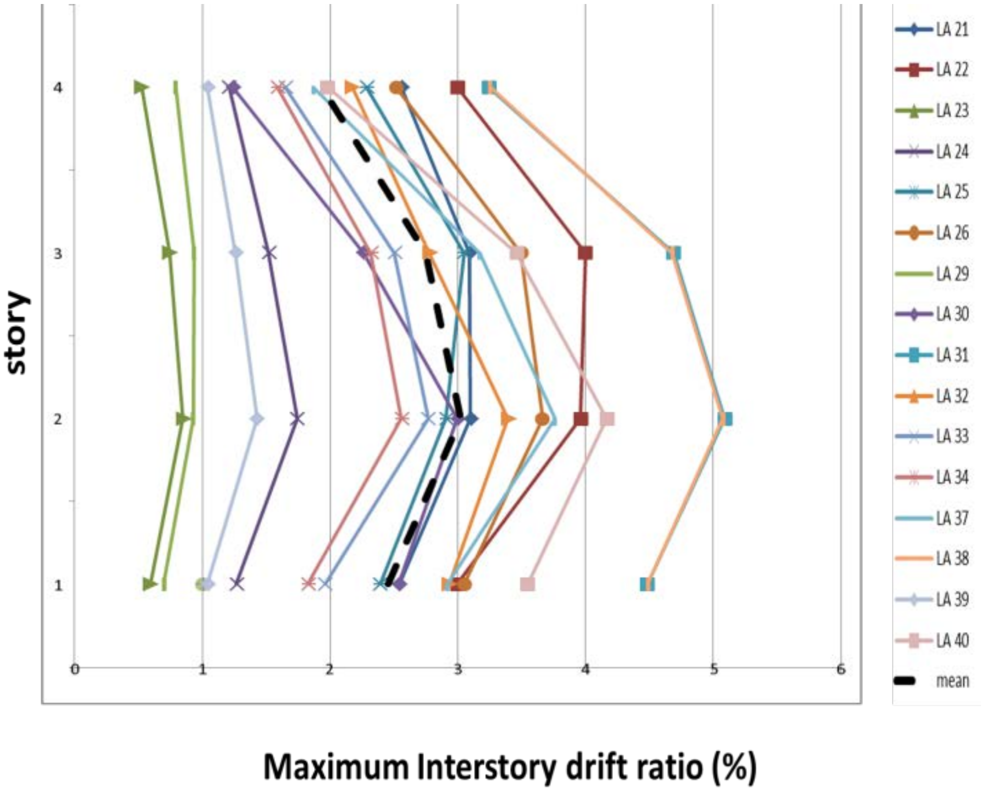


Fig. 10. Yield mechanism of PBPD frame system



(a)



(b)

Fig. 11. Maximum inter-story drift ratios of dual frame system for different hazard levels, a) DBE, b) MCE

CONCLUSIONS

As mentioned before, American seismic provisions decree that a SPSW should be designed as a moment frame with a web infill plate and, particularly in case of buildings taller than 160 ft, it decrees that a dual system should be made use of (Sabelli and Bruneau, 2007; ASCE, 2005).

This paper presented a procedure to apply the PBPD method to moment frame-SPSW as a dual system. All of the dual system members can be designed simultaneously by solving a system of five equations with five variables. The portion of SPSW and moment frame shear can be determined by solving the system of equations.

To verify this method, a four-story frame has been designed and analyzed. For this model, nonlinear static analysis results show that in the target drift, the target yield mechanism is formed and the ultimate strength of the dual frame system has been greater than design base shear force. Also, nonlinear dynamic analysis results show that the mean value of maximum inter-story drift responses in both sets of DBE and MCE hazard levels are within the design target drift (2% for DBE and 3% for MCE).

According to nonlinear analysis results, the proposed PBPD method has been successfully applied to design moment frame-SPSW as a dual system, being a direct design method, needless of any iteration to achieve the performance objectives.

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