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Direct Seismic Design Methods for Buckling-Retrained Knee-Braced Frames with Single Plate Shear Connections

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Abstract: *This paper presents a comparative study on the direct seismic design methods for buckling-restrained knee-braced frames (BRKBFs) with single plate shear connections (SPSCs). Three significant methods, namely direct displacement-based design (DDBD), performance based-plastic design (PBPD), and yield point spectra (YPS) are investigated for the seismic application of the BRKBFs. The main objectives of this study are, (1) to determine the design base shear of a BRKBF system using the three direct seismic design approaches, and (2) to bring an engineering judgment for the design of the proposed framing system under severe earthquake ground motions. Thus, a comparison between the three methods is required. First, the comparison of the design base shear determined by the three direct design approaches was conducted in order to facilitate an engineering judgment of using a suitable method for the design and evaluation of the BRKBFs. Two levels of earthquake; design basis earthquake (DBE) and maximum-considered earthquake (MCE) are investigated with a target drift of 2% and 3%, respectively. The results showed that PBPD provided the most suitable and stable design base shear at both DBE and MCE hazard levels. Second, the PBPD approach was applied to an example of 3-story, 3-bay BRKBF structure with single plate shear connections. The step-by-step design process was described and the member shapes were selected based on plastic equilibrium of the BRKBF with SPSCs system. The proposed BRKBF with SPSCs system designed using the PBPD method appeared to be a viable alternative to conventional seismic load resisting structural systems, as member shapes were engineeringly acceptable. However, it is suggested that modification of energy parameters, system testing, and performance evaluation should be further studied.*

Keywords: Direct seismic design; Buckling-restrained knee braced frame; Single plate shear connections; Performance-based plastic design

1. INTRODUCTION

For the current engineering aspect, innovative structural framing systems are preferable for seismic application. One of the reasons is due to their ability to maintain the architectural and mechanical functions of the building. From that aspect, a system called "Knee-Braced Frame (KBF)" has been developed. A KBF system combines a steel frame and knee bracing elements (KBEs) at the region of beam-to-column connections, as meant to improve the seismic performance. Various types of KBF systems have been observed in seismic applications [1-5]. The KBF systems are able to improve the seismic resistance by controlling the inelastic deformation and allowing open spaces in the bays, which are beneficial to architectural, mechanical, and electrical works. In this study, the seismic design of a KBF with Buckling-Restrained Braces (BRBs) and Single Plate Shear Connections (SPSCs) is proposed with the evaluation of the required shear strength of the system. The system is called Buckling-Restrained Knee-Braced Frame (BRKBF) and is illustrated in Fig.1. The key components present their important roles in the frame performance, which contribute to the enhancement of strength, stiffness, and ductility. The co-existence of the SPSCs also provides ease for construction and reparability after a low damage earthquake.

The current seismic design has been turned into a more direct manner, in which design parameters such as deformation,

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lateral force, yield mechanism, and level of damage are considered to be the important parts of the design process. Therefore, this paper first aims to discuss the three design approaches, namely Direct Displacement-Based Design (DDBD) [6], Performance-Based Plastic Design (PBPD) [7], Yield Point Spectra (YPS) (Aschheim and Black, 2000), in order to evaluate the required shear strength of a BRKBF with SPSCs. All the approaches utilize yield mechanisms and pre-selected target drift or displacement as the main design parameters to control the structural deformation.

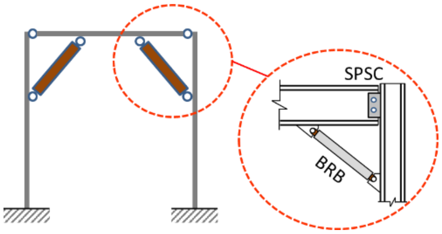


Fig. 1. Configuration of a BRKBF with SPSCs

2. DIRECT SEISMIC DESIGN METHODS

A few significant direct seismic design approaches have been developed so far and have been discussed in this paper. The approaches are used to design structures against earthquake loads based on the desirable plastic performance, in which a few design parameters, such as deformation, yield mechanism, or level of damage are preselected. In this paper, three direct seismic design methods, namely Direct Displacement-Based Design (DDBD) [6], Performance-Based Plastic Design (PBPD) [7], and Yield Point Spectra (YPS) [8], were presented and discussed. It is aimed to find a suitable design application for a 3-story BRKBF with SPSCs system. The methods described above are based on different performance aspects to directly formulate the design base shear factor ($C_y=V_y/W$). However, each method uses the design parameter with similar characteristics to ensure the desirable inelastic performance of the structures. The procedures for evaluating the design base shear are described in the following sections.

2.1 Direct displacement-based design

Priestly et al. [6] have pioneered the DDBD method and currently, the DDBD is widely applied for various structural systems including framing systems, piers of the bridge, wall systems, and isolated base framing systems. This approach designs a structure to accomplish an inelastic performance with a required displacement. The concept requires converting a multi-degree of freedom (MDOF) system to a single degree of freedom (SDOF) system. Thus, the system mass, height, viscous damping, and period must be equivalent. The design base shear can be evaluated based on the concept of substituting a structure (SS) of an inelastic system with that of an elastic system. The substituted elastic structure maintains the effective stiffness (K_e) and peak displacement (Δ_d) which can be found in the procedure below. A substituted SDOF system and step-by-step procedures to determine the design base shear per DDBD method are summarized as in Fig.2.

2.2 Performance-based plastic design

Performance-Based Plastic Design (PBPD) is a plastic design method that uses a target drift (θ_u) and assumed yield mechanism as the vital parameters in the calculation process. Several studies insisted that the PBPD method has been used in the design of various structural systems such as knee-braced frames [2-4, 9-10] moment-resisting frames [11], eccentrically and concentrically braced frames [12,13], truss moment frames [14] , and RC frames [15]. PBPD uses the modified energy balance concept to formulate the design base shear. The selection of the yield mechanism [16] is the key step in the design procedure to ensure the inelastic performance of the structure. Fig.3 below illustrates the procedure to determine the design base shear per PBPD method. The target drift (θ_u) can be chosen in accordance with a design earthquake level, while the yield drift (θ_y) remains fixed. The plastic target drift can be written as:

$$\theta_p = \theta_u - \theta_y \qquad \text{(Eq. 1)}$$

2.3 Yield point spectra

Yield Point Spectra (YPS) given by Aschheim and Black [8], provides an alternative plastic design procedure to evaluate the required base shear. The approach uses an equivalent SDOF system to characterize the yield strength-displacement relationship. Thus, the design base shear coefficient can be determined at the equivalent yield displacement. It is worth noting that FEMA P750 [17] describes more detailed procedures to calculate the design base shear of a MDOF based on YPS method in which MDOF properties are mapped to equivalent SDOF properties. The procedures of calculating the design base shear based on YPS are summarized as in Fig.4.

3. DESIGN OF BUCKLING-RESTRAINED KNEE-BRACED FRAMES

The design of a BRKBF with SPSCs requires adequate frame strength to ensure that the deformation remains within the target value. Since SPSCs were used, the strength can be considered as provided solely by the BRBs and the column bases. The required axial strengths of BRBs can be determined by the principle of virtual work of a 3-story, 3-bay BRKBF as shown below.

$$\sum_{i=1}^{n}\left(F_i h_i \theta_p\right)=\sum_{i=1}^{n}\left(3\times 2\beta_i P_{BRB}\delta_p\right)+\left(3\times 2M_{pc}\theta_p\right) \qquad \text{(Eq. 2)}$$

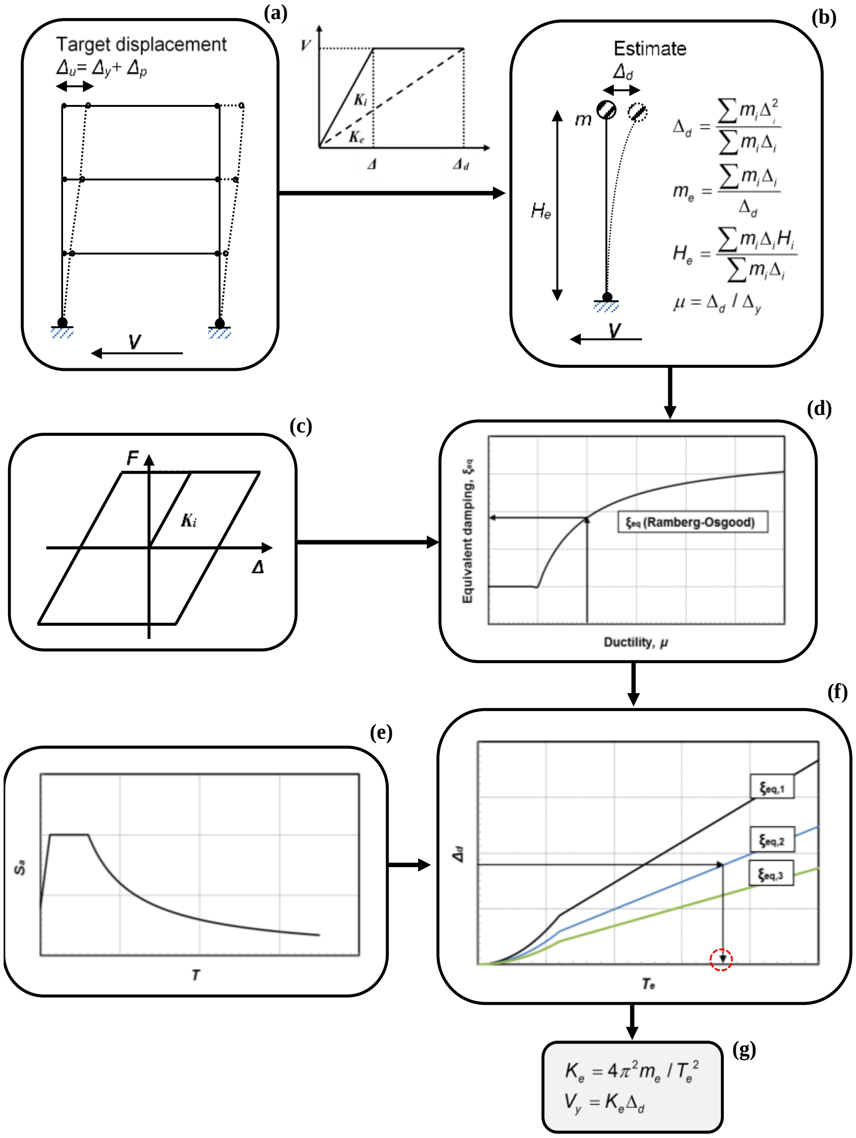


Fig.2. A substituted SDOF system and step-by-step procedures per DDBD

where F_i is the lateral force at floor level i for three bays, θ_p is the plastic target drift, P_{BRB} is the required axial strength of the BRB at roof level, δ_p is the plastic axial deformation of the BRB, β_i is shear proportioning factor accounts for the strength of the BRB at floor level i to that of the roof level, and M_{pc} is the required plastic moment capacity of the first story column. The yield mechanism of a 3-story, 3-bay BRKBF is depicted in Fig. 5.

3.1 Design of BRBs

Using the required strength of the BRB, the core sizes can be chosen based on AISC specification [18] . The steel core area of the BRB in a given story can be calculated by

$$\phi P_{ysc} = 0.9F_{ysc}A_{sc} = \beta_i P_{BRB} \qquad \text{(Eq. 3)}$$

where F_{ysc} is the nominal yield stress of the steel core and A_{sc} is the cross-sectional area of the steel core. A factor of 0.9 is the strength reduction factor for LRFD.

The plastic axial deformation of the BRB (δ_p) is a function of the frame drift. Based on the kinematics of the frame, δ_p can be expressed as:

$$\delta_p = \frac{l_k \theta_p \sin 2\varphi}{2} \qquad \text{(Eq. 4)}$$

where l_k is the length of the BRB, and φ is the angle between BRB and a horizontal line. The relevant deformed configuration of the BRB is shown in Fig. 6 below.

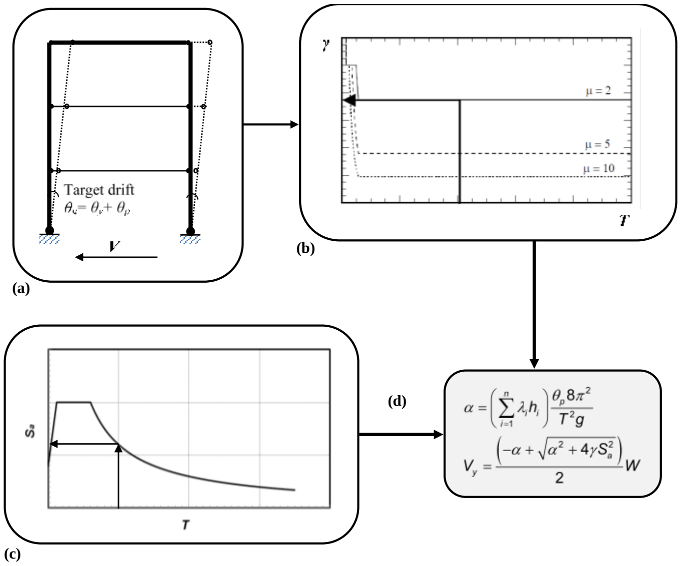


Fig. 3. Performance-Based Plastic Design Procedures

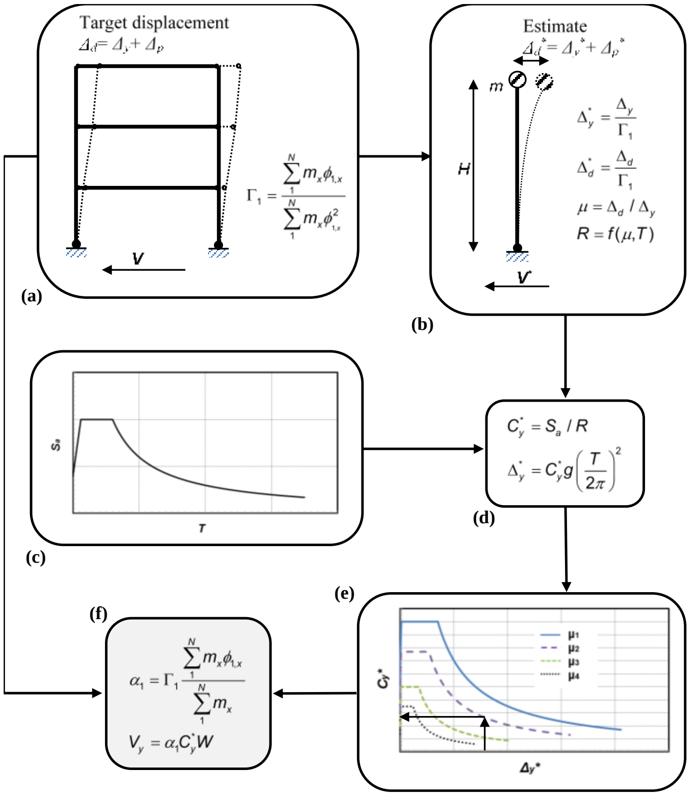


Fig. 4. Yield Point Spectra Procedures

Once the target drift is selected, Eq. 2 can be solved to find the required strength of the BRB. In addition, the target drift should ensure that the strain in the BRB is kept less than the fracture strain. The strain in the core of the BRB at the design target drift level can be estimated using δ_p and by assuming that the yielding length (core length) of the BRB is approximately 70 % of the total length.

$$\varepsilon_p = \frac{\delta_p}{0.7 l_k} = \frac{\theta_p \sin 2\varphi}{1.4} \qquad \text{(Eq. 5)}$$

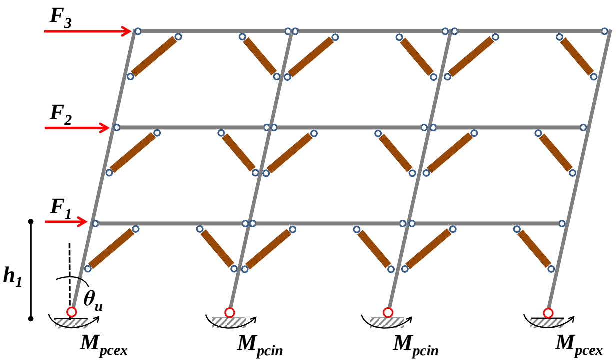


Fig. 5 . Yield mechanism of a 3-story, 3-bay BRKBF

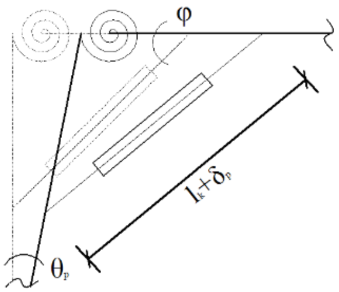


Fig. 6. Deformed and Undeformed of the BRB Configuration at the Knee Region

3.2 Design of beam and columns

The design concept for the beam is based on the free-body diagram associated with the beam. The beam is designed to remain elastic under gravity loads and the forces from the complete plasticity of BRB, as shown in Fig.7. The adjusted nominal strength of BRB both in tension and compression are given respectively as:

In tension,

$$P_{ut} = \omega R_y P_{ysc} \qquad \text{(Eq. 6)}$$

In compression,

$$P_{uc} = \omega \beta_0 R_y P_{ysc} \qquad \text{(Eq. 7)}$$

where ω is an adjustment factor to account for strain hardening, β_0 is an adjustment factor for overstrength in compression, and R_y is the material overstrength factor. The values of ω, and β_0 can be obtained based on the BRB test results. In this study, the approximate values of ω and β_0 are considered as 1.4 and 1.1, respectively. These approximate values can be found in Merritt et al. [19]. R_y can be taken as 1.0 if the actual yield strength is used.

The columns are designed to form plastic hinges at their bases. The free-body diagram of the column, known as "column tree) allows calculating the required strength used for the design (Fig.8). In order to ensure equilibrium, the lateral forces must be compatible with fully-yielded and strain-hardened conditions. Since SPSCs are assumed as pins for the design, the moment produced by the connections is neglected. The lateral force acting on a column under the above condition can be computed as follows.

For exterior column (leftmost):

$$F_{uex(left)} = \frac{M_{pcex(left)} - \sum_{i=1}^{n} N_{B,i} h_i - \sum_{i=1}^{n} P_{ut,i} h_i^{'} \cos\varphi}{\sum_{i=1}^{n} \alpha_i h_i} \qquad \text{(Eq. 8)}$$

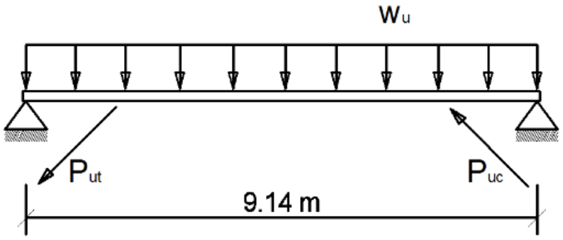


Fig. 7. Free-Body Diagram of the Beam

For exterior column (rightmost), the update force in the rightmost column is combined with the normal force in the beam and can be expressed as:

$$F_{uex(right)} = \frac{M_{pcex(right)} - \sum_{i=1}^{n} P_{uc,i} h_i^{'} \cos\varphi}{\sum_{i=1}^{n} \alpha_i h_i} \qquad \text{(Eq. 9)}$$

For interior column:

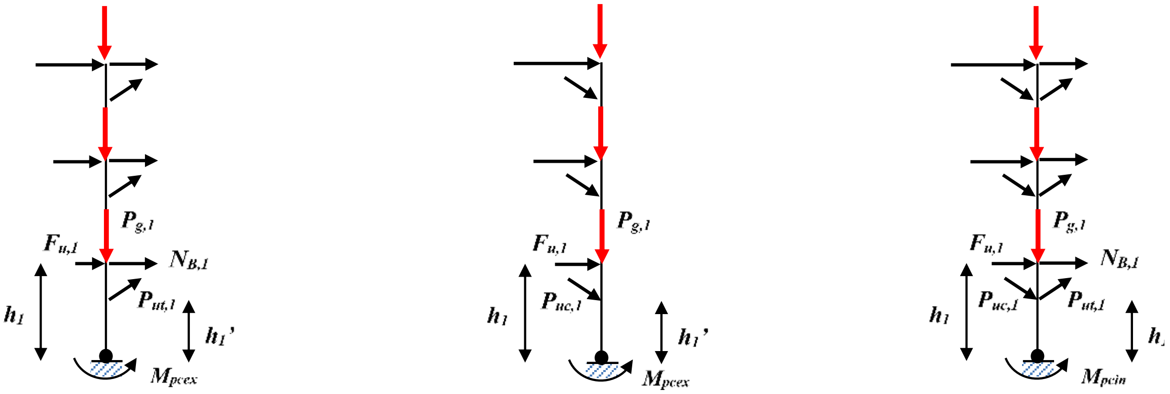
$$F_{uin} = \frac{M_{pcin} - \sum_{i=1}^{n} h_i N_{B,i} - \sum_{i=1}^{n} h_i^{'} (P_{ut,i} + P_{uc,i}) \cos\varphi}{\sum_{i=1}^{n} \alpha_i h_i} \qquad \text{(Eq. 10)}$$

where h'_i is the height of the lowest end of the BRBs at floor level i to the ground, $N_{B,i}$ is tension or compression axial forces produced by beams at floor level i, $P_{ut,i}$ and $P_{uc,i}$ are respectively the adjusted nominal strengths of the BRBs in tension and compression at floor level i, and α_i is the distribution factor at floor level i, defined as:

$$\alpha_i = \frac{(\beta_i - \beta_{i+1})}{\sum_{i=1}^{n} (\beta_i - \beta_{i+1})} \qquad \text{(Eq. 11)}$$

where β_i is given in Eq. 15. Once the total lateral force is determined, the distributed lateral force acting on a column at floor level *i* can be given by

$$F_{u,i} = \alpha_i F_u \qquad \text{(Eq. 12)}$$



(a) Leftmost column (b) Rightmost column (c) Interior column

Fig. 8. Column tree analysis

3.3 Lateral force distributions

Lateral force to each floor level is normalized by lateral force distribution factor (λ_i) and can be given as:

$$F_i = \lambda_i V \qquad \text{(Eq. 13)}$$

The factor λ_i can be determined by

$$\lambda_i = \left(\beta_i - \beta_{i+1}\right)\left(\frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j}\right)^{0.75T^{-0.2}} \qquad \text{(Eq. 14)}$$

where w_n is the seismic weight at floor level *n* (top level), h_n is the height from top floor level *n* to the ground floor level *0*, β_i and β_{i+1} are respectively, the shear proportioning factors at floor level *i* and *i+1* and $\beta_{i+1}=0$ when $i = n$. *T* represents the fundamental period of the structural system. The shear proportioning factor can be found by

$$\beta_i = \left(\frac{\sum_{j=i}^{n} w_j h_j}{w_n h_n}\right)^{0.75T^{-0.2}} \qquad \text{(Eq. 15)}$$

4. DESIGN OF AN EXAMPLE FRAME

A case study of an example 3-story building was selected for the investigation. The building was designed for office use. Each story has an equal height of 3.96 m. The building has 3 bays in the North-South (N-S) direction and 4 bays in the East-West (E-W) direction. Each bay spans 9.14 m.

In this case study, the perimeter frames in the N-S are assumed to be BRKBF with SPSCs. For the E-W direction, the earthquake was assumed to be resisted by conventional braced frames which were not included in this study. The study frame is shown in Fig.9. A36 steel grade was utilized for all structural members of the building. The length of BRBs was set to be l_k = 2.15 m with an angle φ = 45°. The parametric studies on the BRBs with different lengths, angles, and maximum drifts has been demonstrated in Leelataviwat et al. [2], and Junda et al. [3].

The design base shear of this study frame was calculated using the three methods mentioned previously. The structural system was assumed to be type D with earthquake level $S_1 = 0.6g$ and $S_s = 1.5g$ [20]. The design base shear of the study frame was evaluated at two hazard levels, DBE and MCE. The spectral accelerations and target drift at MCE level were derived from the concept where such properties at DBE level were scaled up by 1.5 times. This concept was expected to bring stable design base shear for the two hazard levels. The yield drift of the system was assumed to be 0.7%. The design base shear for a BRKBF with SPSCs by DDBD PBPD, and YPS methods is summarized in Table 1 below.

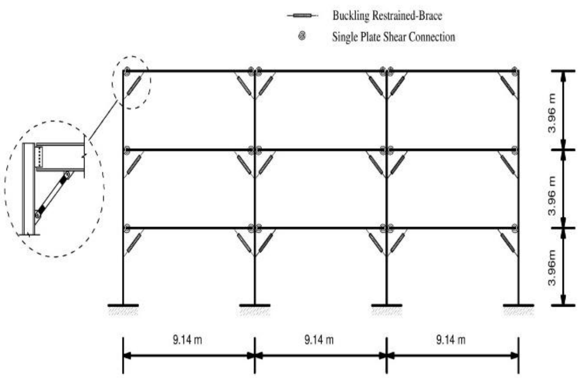


Fig. 9. Selected frame for study (BRKBF)

Table 1 shows that all the approaches provided slightly different design base shears for the system. At DBE hazard level, DDBD and PBPD methods delivered almost identical base shears. However, it is observed that YPS method provided low design base shear compared with that given by DDBD and PBPD. That was convincing that DDBE and PBPD were in favor at DBE level as the results became close. For MCE hazard level, both PBPD and YPS methods contributed almost stable design base shear. However, the design base shear by DDBD method much increased due to the increase of hazard level and target drift. For both DBE and MCE, the DDBD method did not bring a stable design base shear. This status showed that PBPD gave a central result and should be the most rational design method as it provided a very direct design procedure using a design spectral acceleration (S_a) at its initial period (T) to evaluate the design base shear. Using the procedure described in the preceding sections, the lateral force distributions corresponding to PBPD base shear are given in Table 2. The member sizes are summarized in Table 3.

Table 1 Comparison of Base Shear

Method		DBE	MCE
DDBD	$\frac{V_y}{W} = \frac{K_e \Delta_d}{W}$	0.189	0.25
PBPD	$\frac{V_y}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma C_e^2}}{2}$	*0.188*	*0.179*
YPS	$C_y^* = \frac{S_a}{R}$ *and* $\frac{V_y}{W} = \alpha_1 C_y^*$	0.154	0.154

Table 2 Lateral Force Distribution

Floor	h_i *(m)*	w_i *(kN)*	β_i	λ_i	F_i *(kN)*
Roof	11.88	2642	1.0000	0.5508	894
3	7.92	2993.5	1.5574	0.3070	498
2	3.96	2993.5	1.8157	0.1422	231

Table 3 Summary of BRB Sizes

Floor	BRB	Beam	Column		
	Capacity (kN)	All bay	Story	Exterior	Interior
Roof	423	W24x76	3	W14x176	W14x211
3	658	W27x94	2	W14x176	W14x211
2	767	W27x102	1	W14x176	W14x211

5. CONCLUSIONS

This study described three direct seismic design methods, namely Direct Displacement-Based Design (DDBD), Performance-Based Plastic Design (PBPD), and Yield Point Spectra (YPS). The plastic mechanism and step-by-step procedure were discussed, and the design base shears were compared in order to capture the overview of the three methods. The key findings of this study can be summarized as follows.

(1) BRKBF with SPSCs can be proposed into a direct seismic design method with the target drift and the designated yield mechanism.
(2) PBPD method appeared to be suitable as a direct seismic design procedure for BRKBF with SPSCs.

However, extensive studies are required to widen the viable use of the method for BRKBF with SPSCs systems. Those studies should include the modification of energy parameters, system testing, and performance evaluation.

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