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PERFORMANCE-BASED DESIGN APPROACH FOR DUCTILE KNEE-BRACED MOMENT FRAMES

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ABSTRACT

This paper discusses a design approach for a structural system called knee-braced moment frame (KBMF). In the first part of the paper, the concept of KBMF is first introduced. KBMF rely on moment resisting frames together with stocky knee braces as means to resist seismic forces. For KBMF, the frames are designed with a selected yield mechanism in which the knee braces yield and buckle along with plastic hinging of beams at the ends of the beam segments outside the knee portions. The second part of the paper focuses on the design of KBMF based on an innovative design methodology called Performance-Based Plastic Design (PBPD). The design forces are derived based on the selected yield mechanism and target displacement limit using the energy balance concept. An example of KBMF frame designed by the PBPD method is then presented. The results from the dynamic analysis of the KBMF indicate that the proposed framing system designed by PBPD approach behaves in a predictable manner with a stable hysteretic characteristic. The proposed system represents a viable alternative to existing structural systems.

Introduction

A seismic design approach for a structural system that combines the salient features of moment resisting frames (MRF), concentrically braced frames (CBF), and eccentrically braced frames (EBF) is presented in this paper. The structural system considered in this paper, called knee-braced moment frame (KBMF), relies on moment resisting frames together with stocky knee braces as means to resist seismic forces. Knee braces were used in the past for wind-resistant design and have been recently explored in various forms for seismic applications (Seo and Kim 2003, Inouel et al. 2006).

In this study, the KBMF system is designed so that the knee braces will yield and buckle under seismic loads along with plastic hinging of beams at the ends of the beam segments outside the knee portions. Since the moment connections are expected to remain elastic,

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relatively simple details, or even semi-rigid connections, can be used. Consequently, demanding quality assurance procedures can be avoided. In addition, after a moderate earthquake, the knee braces can be easily repaired. This results in a much cheaper inspection and repair costs. More importantly, the knee braces provide much less obstruction as compared to the braces of conventional systems making this system attractive from an architectural point of view. They can also be utilized in seismic strengthening of existing MRF.

In this paper, the concept of KBMF is first introduced. The methodology used to design KBMF called Performance-Based Plastic Design (PBPD) is then discussed. The PBPD method is a new and innovative design procedure that explicitly integrates the yield mechanism and target displacement in selecting the design forces based on the energy balance concept (Goel and Chao 2008). An example of KBMF frame designed by the PBPD method is then presented to illustrate the performance of KBMF under selected ground motions.

Concept of KBMFs

The design concept of KBMF is based on a predetermined yield mechanism that limits inelastic activities to ductile segments of the frame. For this structural system, seismic energy is dissipated by means of the yielding and buckling of the knee braces and flexural yielding of the beams outside the knee regions with a selected yield mechanism as illustrated in Figure 1.

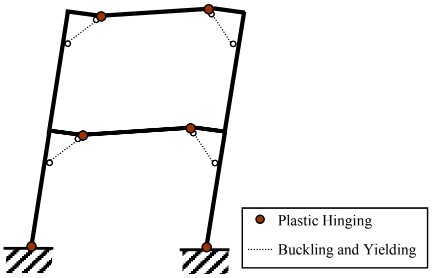


Figure 1. Yield Mechanism of KBMF.

The base shear strength of the frame (V_y) is first selected depending on the target performance of the frame. This is achieved by means of the PBPD method which will be presented later in this paper. With the required base shear strength (V_y), the strength of the beam at each level can be determined based on plastic analysis. The strength of the knee brace is then chosen based on the selected mechanism. The other members in the frame are designed to remain elastic under the largest forces generated by fully yielded and strain-hardened plastic hinges and knee braces except at the column bases where plastic hinges are required to complete the mechanism.

To date, cyclic tests to investigate the seismic behavior of KBMF have been carried out (Suksen 2007). In order to illustrate the merits of the proposed system, the result of one such test is provided below. An overview of the test set-up and the observed deformation of the test frame at 4% story drift are shown in Figure 2. The test frame consists of a 4 meters long W250x125-29.6 kg/m beam, 2 meters high W250x250-72.4 kg/m columns, and ∅76.2x3.9 knee braces (all dimensions in mm). Based on the results of cyclic tests of KBMF, it has been found that the system behaves in a ductile manner with a stable hysteretic characteristic with all inelastic behavior confined to only the designated elements in the frame. Due to limited space, the detailed of the test specimen and test results will be presented elsewhere.

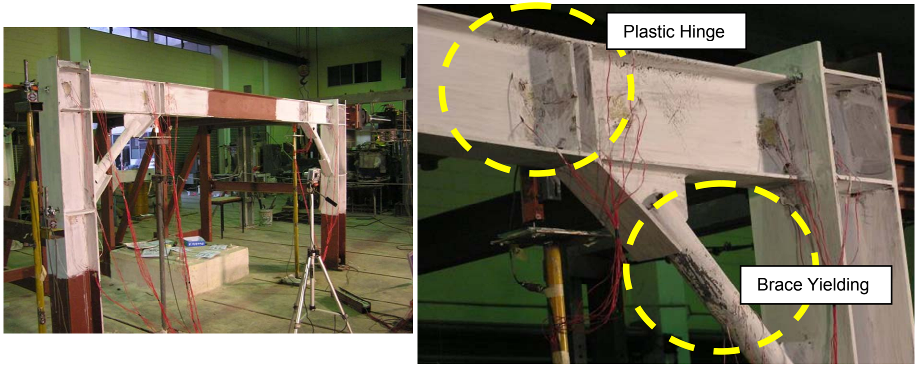


Figure 2. Overview of a KBMF test frame and its deformation at 4% story drift.

Performance-Based Plastic Design of KBMFs

Design Base Shear

Since the KBMF are expected to undergo significant inelastic deformation during a severe ground motion, it is important to design the structure to ensure the formation of the preselected yield mechanism with adequate strength and ductility. Recently, an innovative performance-based design procedure which directly accounts for inelastic behavior has been developed (Goel and Chao 2008). The design base shear for a selected hazard level is calculated by equating the work needed to push the structure monotonically up to the target drift to that required by an equivalent elastic-plastic single degree of freedom system to achieve the same state (Leelataviwat et al. 1999; Lee and Goel 2001). The method has been called Performance-Based Plastic Design (PBPD).

At the heart of PBPD methodology is the energy balance concept. Lee and Goel (2001) presents a modified energy balance concept that is based on the assumption that the energy computed from the monotonic load-deformation response of the inelastic system and the one computed from the corresponding elastic system are related (Figure 3).

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

where E_e and E_p are, respectively, the elastic and plastic components of the energy needed to push the structure up to the target drift, S_v is the design pseudo-spectral velocity, M is the total mass of the system, and γ is the energy factor (Lee and Goel 2001). The energy factor is defined as the ratio of the energy absorbed by the inelastic system to that of the equivalent elastic system and is given by:

$$\gamma = \frac{2\mu - 1}{R_y^2} \tag{2}$$

where μ is the ductility ratio and R_y is the yield force reduction factor (V_e / V_y). The energy factor can be computed for a given ductility level using any R_y-μ-T equation such as the one developed by Newmark and Hall (1982). For seismic design purposes, a target ductility level can be selected and the energy factor can be computed.

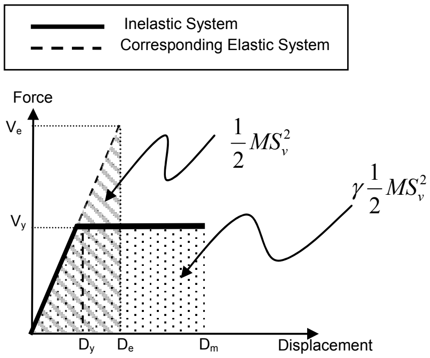


Figure 3. Energy balance concept (Lee and Goel, 2001).

By assuming an appropriate lateral force distribution along the height of the frame and using the selected mechanism, the E_e and E_p components in Equation 1 can be evaluated. Equation 1 can then be solved to obtain the required base shear strength (V_y) of the system (Lee and Goel 2001).

$$\frac{V_y}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma C_e^2}}{2} \tag{3}$$

where W is the weight of the structure, C_e is normalized design pseudo acceleration (S_a / g) and α is a parameter given by:

$$\alpha = \left(\sum_{j=1}^{n} \lambda_i h_i \right) \frac{\theta_p 8\pi^2}{T^2 g} \tag{4}$$

In which θ_p is the target plastic story drift, T is the period, and h_i is the height from the ground to floor level i, and λ_i is the lateral force distribution factor. The lateral force at level i is assumed to be of the form:

$$F_i = \lambda_i V_y \tag{5}$$

In general, the lateral force distribution should closely represent an actual pattern that occurs under earthquake ground motions. Because of the lack of available data for KBMF, a distribution based on the inelastic response of steel MRF systems (Choa and Goel 2007) is used in this study and is given by:

$$\lambda_i = (\beta_i - \beta_{i+1})\left(\frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j}\right)^{0.75T^{-0.2}} \tag{6}$$

where w_n is the weight of the structure at the top level n, h_n are the height from ground to the top level, and β_i is ratio of the story shear at level i to that of the top story (level n).

$$\beta_i = \frac{V_i}{V_y} = \left(\frac{\sum_{j=i}^{n} w_j h_j}{w_n h_n}\right)^{0.75T^{-0.2}} \tag{7}$$

Plastic Design of KBMFs

For the plastic design of KBMF, the relative strength of the beam at each level is first assigned based on the ratio of the story shear given by β_i. The virtual work equation is then applied to the frame. Using a three-story, multi-bay, KBMF as shown in Figure 4 as an example, by neglecting the work done in the knee braces, the virtual work equation can be written as follows:

$$\sum_{i=1}^{n}\left(N_b \times 2\beta_i M_{pb} \times (1 + 2L_k / L_c)\right) + (N_b - 1)M_{pcIn} + 2M_{pcEx} = \sum_{i=1}^{n}\lambda_i F_i h_i \tag{8}$$

where N_b is the number of bays, M_{pb} is the reference plastic moment of beam, M_{pcIn} and M_{pcEx} are the plastic moment of interior and exterior columns at the bases, L_k is the length of knee portion, and L_c is the clear span length.

By assigning the values for the plastic moment of columns in the first story (M_{pcIn} and M_{pcEx}), the required plastic moment of beam at each level ($\beta_i M_{pb}$) can be calculated. To avoid soft-story mechanism in the first story, an appropriate value of M_{pcIn} and M_{pcEx} must be chosen. If the bay width of the multi-bay frame is constant or nearly constant, the design moments in interior columns can be taken as twice of those in exterior columns. The plastic moment of the first-story columns to prevent soft-story mechanism can be calculated as:

$$M_{pcEx} = M_{pcIn} / 2 = \frac{1.1 V_y h_1}{4N_b} \tag{9}$$

where h_1 is the clear height from the ground to the knee-to-column joint. The factor 1.1 is used to account for the possible strain-hardening in the plastic hinges.

After the beam sizes have been determined, the knee braces were selected to ensure that no plastic hinges would form within the knee portion. By considering the local equilibrium of the knee portion where the beam is fully yielded and strain-hardened and the brace is in its post-buckling state, the following relationship can be obtained.

$$M_c = \phi_c(\beta_i M_{pb}) = \xi(\beta_i M_{pb}) + (2\frac{\xi\beta_i M_{pb}}{L_c})L_k - \alpha_c P_{cr}\sin(\theta)L_k \tag{10}$$

where M_c is the bending moment at the beam-to-column connection, P_{cr} is the buckling strength of the knee brace, α_c is the post-buckling strength reduction factor (Remenikov and Walpole 1998), θ is the angle the knee brace makes with the beam, ϕ_c is a numerical factor with a value less than 1, and ξ is the overstrength factor to account for strain-hardening. The factor ϕ_c can be chosen depending on the allowable moment at the beam-to-column connection to ensure that no plastic hinges would form within the knee portion. The required strength of the knee brace at each level can be solved using Equation 10.

$$P_{cr} \geq \left[\frac{(\xi - \phi_c)}{L_k} + \frac{2\xi}{L_c}\right]\frac{\beta_i M_{pb}}{\alpha_c \sin(\theta)} \tag{11}$$

After all the beam and knee brace sizes have been determined, the columns can be designed for the forces generated by the beam and the knee braces. Capacity design approach that considers the equilibrium of the entire column (Chao and Goel 2008) subjected to forces generated by the beams and the knee braces can be used. Alternatively, a pushover analysis can be carried out assuming elastic columns and the forces obtained from the analysis can then be used to design the columns.

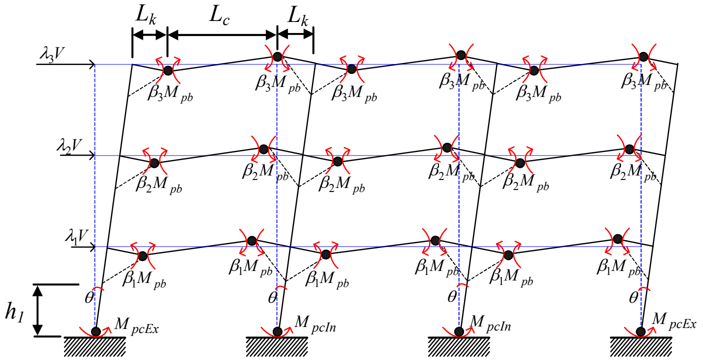


Figure 4. Example of 3-story 3-bay KBMF yield mechanism.

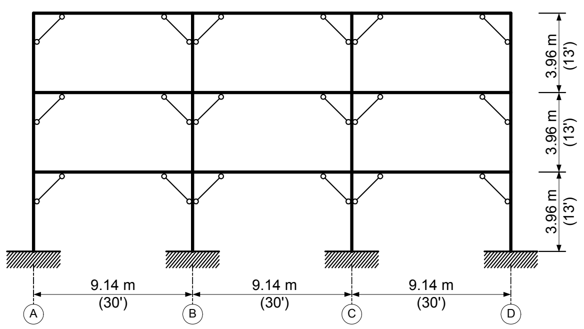
Example Application

Example KBMF

An example KBMF was selected to study the seismic response of the proposed system. The elevation view of the study frame is shown in Figure 5 along with the floor masses and the member sizes. The frame was designed using the previously described PBPD method using a design spectrum following the IBC-2000 provisions. The important constants used to calculate the design spectrum were S_1 = 0.8g and S_S = 1.2g, Seismic Use Group I, Soil type B, and estimated period of 0.75 sec. The length of the knee portion was chosen to be at 20% of the span length. The overstrength factors (ξ) were taken as 1.4 for the 2nd floor beams and 1.3 for the 3rd and roof floor beams. For the knee braces, the post buckling strength reduction factor, α_c, was taken as 0.80. The design was carried out using an expected yield strength of 340MPa (49 ksi).

For this example KBMF, the maximum target drift was selected as 2.0% at the design basis earthquake level with an assumed yield drift at 1.0% resulting in a target plastic drift, θ_p, of 1%. The design base shear coefficient (V_y/W) calculated by Equation 3 was 0.314. The design lateral force at each floor level and the distribution factors, β_i and λ_i, are shown in Table 1.

Although, in this example, the frame was designed using one level of seismic hazard, in practice, multiple levels of ground motion intensity can be considered, each with different performance target drift. The governing design base shear value can then be selected to ensure that the performance will be satisfactory in all hazard levels.



Floor	Mass (kg)
Roof	266500
3	281000
2	281000

Story	Exterior col.	Interior col.	Beam	Knee Brace
1	W14 × 132	W14 × 176	W27 × 84	TS6 × 6 × 1/2
2	W14 × 132	W14 × 176	W24 × 84	TS5 × 5 × 1/2
3	W14 × 132	W14 × 176	W24 × 55	TS4 × 4 × 3/8

Notes: Member sizes indicated in inches and lbs/ft

Figure 5. Example KBMF.

Table 1. PBPD lateral forces and distribution factors.

Floor Level	h_i (m)	β_i	λ_i	F_i (kN)
Roof	11.88	1.00	0.56	1442.0
3	7.92	1.53	0.29	758.7
2	3.96	1.77	0.14	353.8

Performance Evaluation

Analytical studies were carried out to evaluate the behavior of the example KBMF designed by the PBPD method. Inelastic static as well as inelastic dynamic analyses were used to obtain the overall inelastic behavior and the response of key members. A nonlinear finite element code SNAP-2DX (Rai et al. 1996) developed at the University of Michigan was used to perform the analyses.

For the nonlinear static analyses, the frame was analyzed under the gravity and increasing lateral loads. The gravity loads included the dead loads and 25 percents of live loads. The purpose of the pushover analysis was to determine the lateral load capacity, the failure mechanism, the sequence of inelastic activity leading to collapse, and the progressive change in the internal force distribution.

The plot of the base shear coefficient versus roof drift is shown in Figure 6 along with the sequence of inelastic activities. The response of the KBMF was elastic up to a drift level of about 0.8% when the first set of plastic hinges formed. The inelastic activities then quickly spread out into the knee braces resulting in a significant reduction in lateral stiffness.

Figures 7 shows the inelastic activities of the KBMF frame when one of the inter-story drifts reached 2.0% level, the target drift used in PBPD. At this target drift, the full mechanism had not formed. This was due to the allowance for strain-hardening and post-buckling strength (in terms of factors ξ and α_c) used in the design process. The full mechanism formed at the roof drift level about 2.6%. Although the design was slightly on the conservative side, it did not affect the overall performance of the frame. It can be seen that the locations of plastic hinges occurred at the ends of beam segments outside knee regions. In the columns, plastic hinges occurred at the bases only. This was consistent with what envisioned in the design concept of the KBMF system.

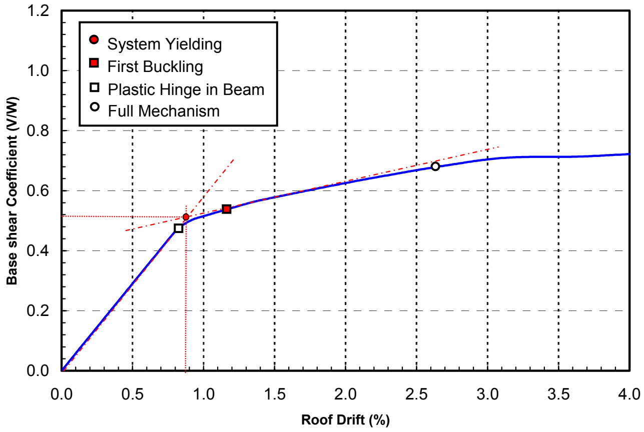


Figure 6. Base shear versus Roof drifts from Nonlinear Static Analysis.

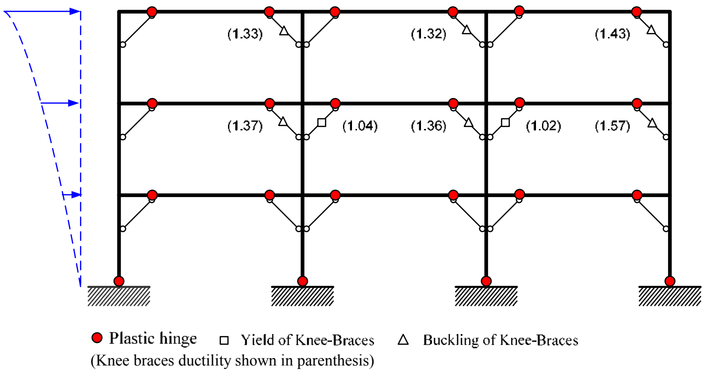


Figure 7. Inelastic activities in the example KBMF at 2% story drift.

In the nonlinear dynamic analyses, the study frames were subjected to seven selected earthquake records from another study (Somerville et al. 1997). The ground motions were scaled to represent the IBC (2003) spectrum. The selected ground motions were scaled such that their average S_a values between the periods of 0.2T to 1.5T are not less than those obtained form the

IBC design spectrum.

The envelopes of maximum inter-story drifts are shown in Figures 8. Under the selected ground motions, the maximum inter-story drift was approximately 1.9%, very closed to the target drift of 2.0% while the mean-plus-one-standard deviation values are less than the 2.0% target. The envelopes of the story shear forces normalized by the base shear are compared to the story shear distribution used in PBPD in Figure 9. It can be seen that the story shear distribution used for MRF can closely represent the story shears in the example KBMF resulting in a uniform energy dissipation along the height of the frame as indicated by the story drift envelopes.

Figure 10 shows the inelastic activities under the selected ground motions. The plastic hinges occurred at the ends of beam segments outside knee regions and at the column bases only. Under the selected ground motions, the yielding and buckling were detected in all the knee braces.

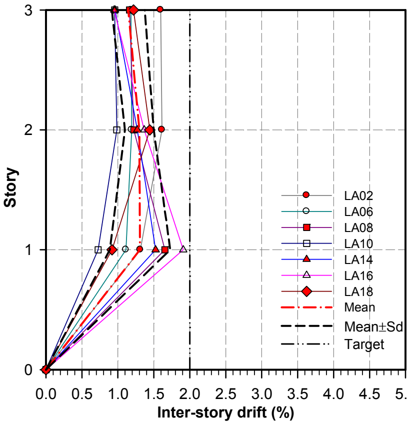


Figure 8. Maximum inter-story drifts under selected ground motions.

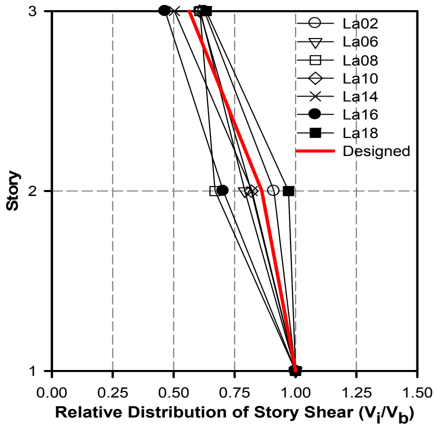


Figure 9. Normalized Story shear distributions under the selected ground motions.

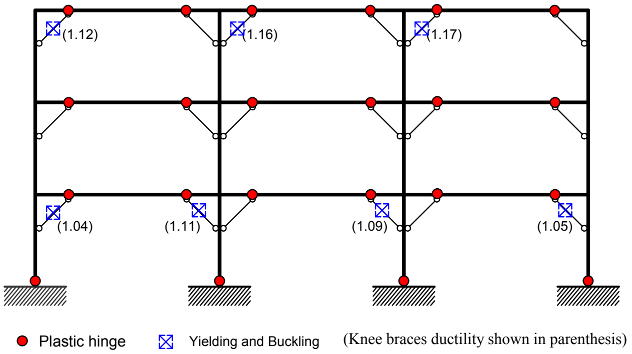


Figure 10. Inelastic activities under the selected ground motions.

Summary and Conclusions

This paper discusses a design approach for KBMF structural system. The KBMF rely on moment resisting frames together with stocky knee braces as means to resist seismic forces. The design of KBMF is based on an innovative design methodology called Performance-Based

Plastic Design (PBPD). The main findings for this study are as follows.

1) Overall, it can be seen that the concept of KBMF is viable and that the PBPD design procedure using a pre-selected mechanism and target drift is an attractive method for the design KBMF system. From the nonlinear analyses, the locations of plastic hinges occurred only at the ends of beam segments outside knee regions. In the columns, plastic hinges occurred at the bases only. This is consistent with the design concept. The yielding activities in the example KBMF occurred in a rather uniform manner in all three stories with the story drifts all within the target value. The lateral force distribution used in this study corresponds very well with the nonlinear force distribution in the example KBMF under actual ground motions.

2) The design factors suggested in the example were found to be slightly on the conservative side, however, they did not affect the overall performance of the frame and hence could be used for future design of KBMF.

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