

The Effects of Yield Mechanism Selection on the Performance based Plastic Design of Steel Moment Frame

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Abstract

This study concentrates on the effect of selecting a desirable yield mechanism that has a significant effect on seismic design and response of structures designed by Performance Based Plastic Design (PBPD) method. In PBPD method, the design base shear is obtained on the basis of energy-work balance equation implementing pre-selected target drift and yield mechanism. With considering the importance of selection of yield mechanism, a parametric study has been done considering the different types of yield mechanisms to design a model of steel moment frame. The results obtained by nonlinear time history analyses shown that the complete sway mechanism (strong columns-weak beams) is the most efficient in terms of required design base shear for a given target story drift. It also should be noted that it is often impossible to estimate the column moment demand during the event of sever ground motions because they undergo large moments not only from those delivered from beams but also from their own deformation. Therefore, assuming only the criteria of strong column-weak beam mechanism in PBPD method can't prevent the yielding in columns. In this paper to improvement of PBPD method, some solutions are represented to precisely obtain the required moment of columns to prevent their yielding. Because the yielding of columns leads to form undesirable mechanisms before the structure reaches the pre-selected target drift. For example, a 10 story frame has been designed based on PBPD method using strong column-weak beam mechanism. The frame has been redesigned considering all represented equations of this study (modified PBPD frame). The results obtained by nonlinear static and dynamic analyses show that the modified PBPD frame perform according to expectations in terms of yield mechanism and target drift levels whereas the PBPD frame suffer large story drifts due to flexural yielding of the columns.

Keywords: Energy-Work Balance Equation, Nonlinear Dynamic Analyses, Nonlinear Static Analyses, PBPD Method, Yield Mechanism

1. Introduction

It is well recognized that current seismic design codes are based on elastic structural behavior and account for the inelastic behavior indirectly. However, it has been noted that large inelastic deformation in a pretty unpredictable behavior will happen for structure designed by such procedures under sever ground motion. This can increase the possibility of structural member's severe buckling and yielding in an uneven manner^{1,2}. Therefore in best

conditions it can result expensive repairs or even worth, total failure in the structures. In 1999 leelviwat et al., developed a methodology that enables us to directly consider inelastic behavior of structural members for resolving the above mentioned problem³. This methodology which is called Performance Based Plastic Design method (PBPD method), removes the need for any further evaluation or iteration after initial design⁴⁻⁷. In this methodology, design criterions which directly relate to structure's degree and distribution of damage implement pre-selected target

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drift and yield mechanism. In this method target drift and yield mechanism as key performance criteria, are initially applied in order to calculate the design base shear and design of structural members. In this procedure, base shear for a deformed structure is computed by using energy balance equation through external work due to lateral forces to internal work done by the structural members. It should be noted that, a new distribution of lateral forces is applied in PBPD method which optimizes the stiffness and strength distribution in the height of a structure⁸. In order to account for the frame members, plastic design is implemented to obtain considered yield mechanism. Since selecting the yield mechanism in PBPD method is assumed one of the main parameters at the beginning of the design, selecting an optimum yield mechanism can have a significant role in seismic performance of a structure. Determination of optimum yield mechanism and design of structure on the basis of this mechanism have been drawn by many researchers. Mazollani and Piluso⁹, were of the first researchers that achieved the optimum yield mechanism and consequently a desirable design and proper performance using concepts of failure mode control. It is well recognized that determination of yield mechanism plays a key role in PBPD method. Therefore, first, this paper is going to evaluate the role of yield mechanism selection on seismic behavior of steel moment frames designed by PBPD method. For this purpose, considering the importance of selection of yield mechanism, a parametric study has been done considering the different types of yield mechanisms to design a model frame. The other point mentioned in this paper is to precisely calculate the required moment of columns. Many studies have shown that it is often impossible to estimate the column moment demand because they undergo large moments not only from those delivered from beams but also from their own deformation^{9,10}. It causes yielding in columns and also an undesirable mechanism in the structure. In PBPD method the columns must be designed as Non-Designated Yielding Members (Non-DYM) for achieving the pre-selected yield mechanism that is one of the mentioned key performance limit states^{3,4}. Therefore, in this paper some undesirable mechanisms have been recognized and also some solutions are represented to obtain the moment of columns precisely in order to prevent their yielding that leads to larger story drifts and undesirable mechanisms in the structures. Finally, the significant results achieved from time-history analysis indicate obtained from the inelastic time history analyses

indicate the validity of the represented equation in this study.

2. PBPD Method

2.1 Target Yield Mechanism

The main design factors in PBPD method are the pre-selected yield mechanism and target drift³. The optimum yield mechanism is considered at the initial steps of design. Figure 1 illustrates a type of moment frame which is pushed to the target drift under design lateral forces. All the nonlinear deformations were assumed to take place at designated yielding members (Figure 1), and the other members of the structure should remain elastic up to the point that the structure reaches the target drift.

2.2 Lateral Force Distribution for PBPD

It is recognized that regular design codes are mainly using the linear distribution of lateral forces because they assume that the structures have elastic manners and the 1st mode of vibration is dominant^{11,12}. Whereas multiple researches have proven using this distribution is not appropriate due to the fact that inelastic deformation and upper modes of vibration for high-rise buildings are not considered. Therefore building structures designed according to current codes experience lateral forces that are different from those given by the code formula when struck by earthquake ground motions. It is required to consider nonlinear behavior of structures directly in the design process for reaching the goal of performance-based seismic design, i.e., a desirable and predictable structural response¹³⁻¹⁵. Therefore, PBPD method uses a new lat-

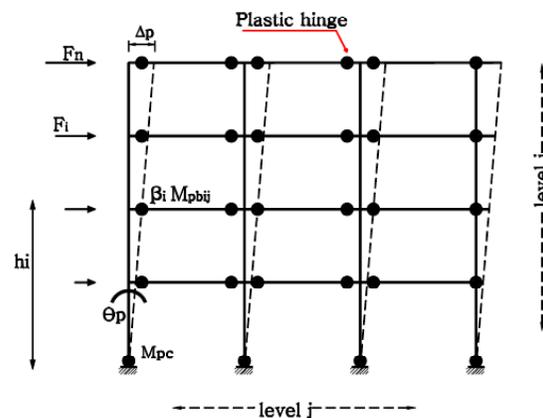


Figure 1. Pre-selected yield mechanism in PBPD method.

eral force distribution based on maximum story shears obtained by nonlinear dynamic analyses that fulfills the mentioned objective in a realistic manner⁸. It has also been suitable for all of the structural systems which are as follow:

$$F_i = C_{vi}V \tag{1}$$

$$C_{vi} = (\beta_i - \beta_{i+1}) \left(\frac{W_n h_n}{\sum_{j=1}^n W_j h_j} \right)^{0.75T^{-2}} \tag{2}$$

When $i = n$, $\beta_{n+1} = 0$

$$\beta_i = \frac{V_i}{V_n} = \left(\frac{\sum_{j=i}^n W_j h_j}{W_n h_n} \right)^{0.75T^{-2}} \tag{3}$$

In the above equations, β_i shows the shear distribution factor at level i ; V_i and V_n are respectively the story shear forces at level i , and at the top story level; W_j is the seismic weight at level j ; T is the fundamental period; F_i is the lateral force at level i ; and V is the total design base shear.

2.3 Design Base Shear

By choosing the optimum yield mechanism, the design base shear is severely influenced in PBPD method. In this approach the design base shear will be computed based on energy balance equation. Note that no actual push-over analysis is needed for this as will be seen later. The required work is obtained by multiplying γ to elastic input energy $E = \left(\frac{1}{2} MS_v^2 \right)$ for equivalent EP-SDOF system⁴. In

PBPD method, the needed work term ($E_{\downarrow e} + E_{\downarrow p}$) is applied to compute the design base shear by setting ties among the desired yield mechanism, design drift, force displacement characteristic of the structure, and elastic input energy from the design ground motion. Determining the exact amount of the earthquake input energy demand depends on the structural specification and the selection of the earthquakes that is hard work and takes a long time to be obtained. But by using the above simple Eq. 2, determining the amount of input energy for structure is desirable. Housner¹⁶, showed that the design pseudo-velocity of the structure in most earthquakes is constant in a wide range of periods. Also, he stated that the maximum input energy of multi degree of freedom system can be equal to the amount of Eq. 2. Therefore,

the design input energy can be determined from the elastic design pseudo-acceleration spectra as given in the building codes. The energy-work balance equation is as follow:

$$(E_e + E_p) = \gamma E = \frac{1}{2} \gamma MS_v^2 = \frac{1}{2} \gamma M \left(\frac{T}{2\pi} \cdot S_a \cdot g \right)^2 \tag{4}$$

Where E_e and E_p are respectively the elastic and plastic energy of the structure, γ is the modification factor, m represents the total seismic weight of the structure and S_v is the design pseudo-velocity. Many researchers declared that γ as a modification factor is related to structural natural period that has a major effect on the ground motion input energy. (uang and bertero, 1988). The goal of this paper is to calculate the design base shear based on energy balance equation. Therefore, equation 4 is rewritten by considering Figure 2 and presented as follow:

$$\gamma \frac{1}{2} C_{eu} W \Delta_e = \left(\frac{1}{2} C_y W (2\Delta_{max} - \Delta_y) \right) \tag{5}$$

Equation 5 can be simplified as following:

$$\gamma \Delta_{\downarrow e} / \Delta_{\downarrow y} = ((\square 2\Delta_{\downarrow} \square_{\downarrow} \max - \Delta_{\downarrow} y) / \Delta_{\downarrow} e) \tag{6}$$

In which Δ_e is equal to $R_{\mu} \Delta_y$ and Δ_{max} is equal to $(\mu_s \Delta_y)$. Considering these values in equation 4, γ is as following:

$$\gamma = \left(\frac{2\mu_s - 1}{R_{\mu}^2} \right) \tag{7}$$

In Eq. 7, μ_s and R_{μ} are respectively the ductility and reduction ductility factor. Numerous studies have

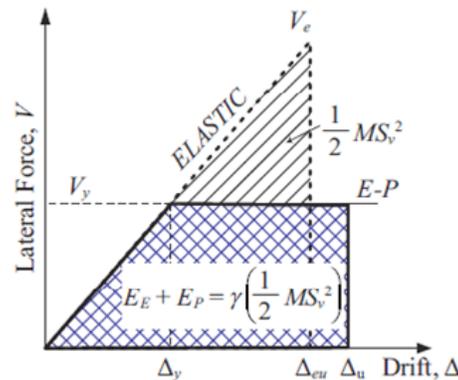


Figure 2. Structural idealized response and energy balance concept.

investigated^{17,18} the relation of these two parameters and almost all of them had similar results. Therefore in this paper, the relations presented by Newmark and Hall, 1988 which is presented in Table 1, is applied¹⁸.

According to Akyama, 1985¹⁹, if the whole structure is decreased into a system with a single degree of freedom, the elastic vibration energy can be determined. It can be written as following equation:

$$E_e = \frac{1}{2} M \left(\frac{T}{2\pi} \cdot \frac{V}{W} \cdot g \right) \quad (8)$$

In Eq. 8; $V = V_y$ is the design yield base shear. $T = (.08 * H^{.75})$ is the period of structure that is obtained by seismic design code (BHRC, 2005), and W is the total seismic weight of the structure ($W=Mg$).

Substituting Eq. 8 into Eq. 7 the total plastic energy that the structure has to dissipate during the earthquake is equal to:

$$E_p = \frac{WT^2g}{8\pi^2} \left(\gamma S_a^2 - \left(\frac{V}{W} \right) \right) \quad (9)$$

According to Figure 1 the above mentioned equation is rephrased as given in EQ 10:

$$E_p = \left((M+1)M_{pc} + 2 \sum_{j=1}^m \mu_j \sum_{i=1}^n \beta_i M_{pbr} \right) \theta_p \quad (10)$$

In Eq. 10; M_{pbr} is the reference plastic moment of beams, M_{pc} is the plastic moment of the columns at the

base, $\mu_j \beta_j M_{pbr}$ is the plastic moment capacity of beams at each level the corresponding plastic moment capacity of beams at every story, n is the number of the stories, θ_p is the plastic drift ratio, and β_i is the shear distribution factor at level i . L_r is the length of the reference bay (e.g in this paper, L_r is the maximum length of bay). L_j is the length of the bay at level j . $\mu_j = \frac{L_r}{L_j}$ is the ratio of length of bays.

Moreover, after yielding of the structure, by equating the internal work performed by plastic energy to the external work done by design lateral forces, the following equation can be produced as:

$$(M+1)M_{pc} + 2 \sum_{j=1}^m \mu_j \sum_{i=1}^n \beta_i M_{pbr} = \sum_{i=1}^n F_i h_i \quad (11)$$

In which F_i is the design lateral force applied at level i , h_i is the height of level i from the base.

Substituting equations 1 and 9 into Eq. 11 and solving for $\frac{V}{W}$ gives:

$$\frac{V}{W} = \frac{-\alpha + \sqrt{(\alpha^2 + 4\gamma S_a^2)}}{2} \quad (12)$$

In which v is the design base shear and α is a dimensionless parameter that is related to the modal properties, stiffness of the structure, plastic drift ratio; that is as follow:

$$\alpha = \left(\sum_{i=1}^n (\beta_i - \beta_{i+1}) h_i \right) \cdot \left(\frac{W_n h_n}{\sum_{j=1}^n W_j h_j} \right)^{.75 T^{-2}} \cdot \left(\frac{\theta_p 8\pi^2}{T^2 g} \right) \beta_{n+1} = 0, \text{ when } i = n \quad (13)$$

In Eq. 12, v depends on the lateral force distribution (modal properties), the design plastic drift ratio, θ_p , and the pre-selected yield mechanism. The design target drift is built into Eq. 12. Therefore, the drift control is taken care at the beginning of the design process. It should be mentioned that the value of plastic drift ratio is the deference between the pre-selected target drift ratio (θ_u) and yield drift ratio (θ_y). For steel moment frame, θ_u is considered 2% in according to seismic design code²⁰. The yield drift ratio for some structures was considered to be

Table 1. Ductility reduction factor and period

PERIOD RANGE	DUCTILITY REDUCTION FACTOR
$0 \leq T < \frac{T_1}{10}$	$R_\mu = 1$
$\frac{T_1}{10} \leq T < \frac{T_1}{4}$	$R_\mu = \sqrt{2\mu_s - 1} \cdot \left(\frac{T_1}{4T} \right)^{2.513 \cdot \log\left(\frac{1}{\sqrt{2\mu_s - 1}}\right)}$
$\frac{T_1}{4} \leq T < T_1'$	$R_\mu = \sqrt{2\mu_s - 1}$
$T_1' \leq T < T_1$	$R_\mu = \frac{T\mu_s}{T_1}$
$T_1 < T$	$R_\mu = \mu_s$

constant⁵. The yield drift ratio for steel moment frame was equal to $\theta_y = 1\%$.

2.4 Design of Structural Members

2.4.1 Design of Designated Yielding Members

Design of structural members in PBPD method depends on the type of intended yield mechanism^{3,4}. A basic comprehension of plastic design method is adequate for designing yielding members in the structures designed by PBPD method. Plastic design method is applied to provide the desirable strength, ductility and yield mechanism. The strength distribution along the height of the structure should be according to the lateral force distribution obtained from nonlinear dynamic analysis⁸. This guarantees that the input energy will dissipate and will prevent the concentration damage in a story. Therefore, the required strength for Designated Yielding Members (DYM) at each level can be determined by equating the external work to the internal work due to a small mechanism deformation, θ , as follow (Figure 1).

$$(M + 1)M_{pc}\theta_p + 2\sum_{j=1}^m \mu_j \sum_{i=1}^n \beta_i M_{pbr} \theta_p = \sum_{i=1}^n F_i h_i \theta_p \quad (14)$$

Since the beams deformation in PBPD method is unsymmetrical, the uniformly distributed gravity loading does not accomplish any external work therefore it is not considered in the energy-work balance equation as represented in eq.14.

By determining the values of $B_p, M_{pc}, F_p, h_p, \mu_p, \theta_p, W_p$, the only unknown parameter M_{pbr} in Eq. 14, can be calculated, and consequently the nominal strength required for beam at each level, M_{pbij} is determined as follow:

$$\phi M_{pbij} \geq \mu_j \beta_i M_{pbr} \quad (15)$$

In Eq. (15); ϕ is the resistance factor according to the AISC, 2005²¹.

2.4.2 Design of Non-DYM

Non designated yielding members are expected to stay elastic under combined forces of gravity loads and maximum strength of the yielding members. In order to design these members, capacity design approach is applied in accordance with AISC, 2005²¹.

3. Role of Selecting Yield Mechanism in PBPD

It should be noted that selecting the yield mechanism in PBPD method has an effective role to determine the design base shear and designing the structural members. Thus, selecting a desirable yield mechanism at the beginning of the design process leads to have a structure with suitable seismic performance during the sever ground motion³⁻⁵. In this study, in order to show the importance of this parameter, a model frame with different yield mechanisms has been considered. The amount of design base shear in each frame will be determined separately. Then, the intended frames will be designed and evaluated. In continue, by analyzing the obtained results, some techniques will be represented to achieve the desirable yield mechanism for all frames.

3.1 Study Frame

In this study a moment frame with 4 stories is illustrated in Figure 3. In order to design and analysis purposes; one-bay model was used as a representative Other required data that was applied to design the frame members, are given in Tables 2 and 3. In order to show the role of yield mechanism for designing the frames, the other parameters extracted from codes, are considered constant.

3.2 Design Yield Mechanisms

Four different yield mechanisms and the same set of lateral forces were considered to design the frame by plastic method, as seen in Figure 4. It should be mentioned that a lot of mechanisms can be predicted in the structure. In usual design approaches according to current codes, it's hard or somewhat impossible to obtain the optimum yield mechanism in the structure when subjected to major earthquakes. Thus, some optimization methods and sophisticated nonlinear analyses are

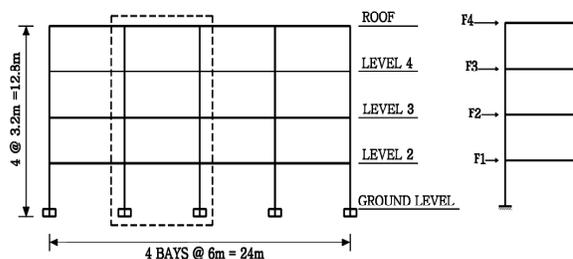


Figure 3. 4-STORY MOMENT FRAME.

Table 2. Design forces for one-bay model

$F_i = C_{vi} V$ (ton)	Story shear $V_i=(\text{ton})$	C_{vi}	$\beta_i=(V_i/V_n)$	Weight W_i (ton)	Height h_i (m)	Floor
43	43	0.46	1	120	12.8	roof
26	69	0.278	1.6	120	9.6	4 th
16.5	85.5	0.176	2	120	6.4	3 rd
8	93.5	0.085	2.175	120	3.2	2 nd

Table 3. Design parameters for study frames

γ	R_μ	μ_s	$\theta_p = \theta - \theta_y$	θ_y	θ	(T)	(S _a)
0.75	2	2	1%	1%	2%	0.54	0.8

required to achieve the optimum yield mechanism^{22,23}. This shortcoming was eliminated by using the PBPD method. In this method the optimum pre-selected yield mechanism is assumed in the beginning of design, so that it is not necessary to use the complex mathematical methods and sophisticated nonlinear analyses and time consuming work to model the members in nonlinear range of deformation. It has to be noted that the four mentioned mechanisms of this paper were formed in the structures during past earthquakes such as 1985 Mexico City, and 1994 Kobe²³. They are also possible to be formed in the structures subjected to the sever ground motion in

the future. Therefore the main reason here is to evaluate the structures that are designed by PBPD method using these mechanisms and finding some proper techniques to improve the PBPD method for obtaining the optimum yield mechanism. In this paper, different mechanisms are mentioned as MECH1, MECH2, MECH3 and MECH4 and illustrated in Figure 4. Regarding to Figure 4 the formation of plastic hinges didn't cause any opposing interference and fully separated the mechanisms. In addition the plastic moment capacities of structural members are calculated for each mechanism using the energy balance equation. As a result for a specific target drift and yield mechanism of a structure, the plastic energy capacity E_p in equation 10 is presented by E_{pc} , and that in Eq. 9 as the plastic energy demand, E_{pd} (internal work). In this study the values of two energy terms are calculated as follow: (Units: ton-m)

$$E_{pd} = 8.33 - 17.48 \left(\frac{V}{W} \right)^2 \tag{16}$$

$$MECH1 \ E_{pc1} = ((C_{v1} + C_{v2} + C_{v3} + C_{v4})h_1).W. \left(\frac{V}{W} \right). \theta_p = 15.36 \left(\frac{V}{W} \right) \tag{17}$$

$$MECH2 \ E_{pc2} = ((C_{\downarrow v1}h_{\downarrow 1} + C_{\downarrow v2}h_{\downarrow 2} + C_{\downarrow v3}h_{\downarrow 3} + C_{\downarrow v4}h_{\downarrow 4}).W.(V/W). \theta_{\downarrow p} = 47.78(V/W) \tag{18}$$

$$MECH3 \ E_{pc3} = ((C_{\downarrow v2} + C_{\downarrow v3} + C_{\downarrow v4})(h_{\downarrow 2} - h_{\downarrow 1})).W.(V/W). \theta_{\downarrow p} = 14.054(V/W) \tag{19}$$

$$MECH4 \ E_{pc4} = ((C_{\downarrow v1}h_{\downarrow 1} + C_{\downarrow v2} + C_{\downarrow v3} + C_{\downarrow v4})h_2).W.(V/W). \theta_{\downarrow p} = 29.415(V/W) \tag{20}$$

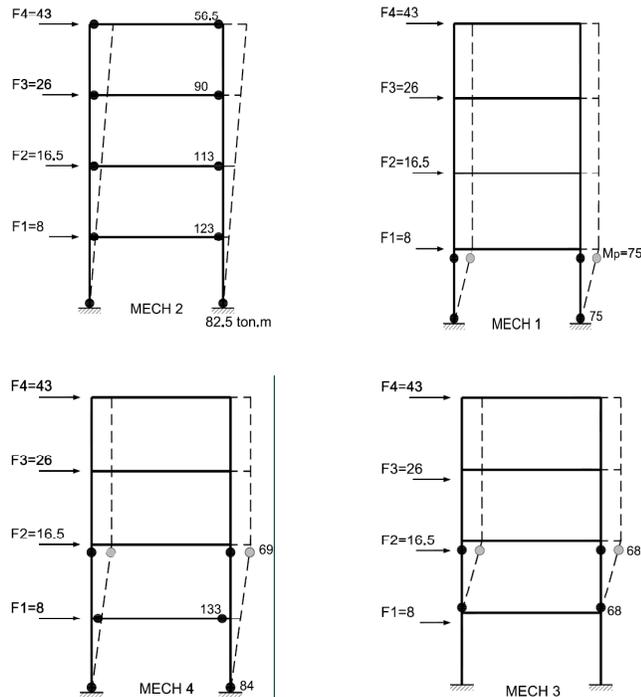


Figure 4. Types of MECHANISMS (UNITS: ton-cm).

The values of E_{pc} and design base shear corresponding to the four mechanisms are shown in Table 4. For all mechanisms, the required plastic values of yielding members were illustrated in Figure 4. It is presumed that the moment capacity of the plastic hinges is less than the required moment capacity of the other structural members which ensures the occurrence of each mechanism. In addition it is noteworthy that the section's dimensions of structural members without plastic hinge formation were relatively conservative.

The above mentioned equation and Table 4 demonstrate a relationship between $\frac{V}{W}$ and E_{pc} . The rate of work performed by lateral forces in MECH 2 is

indicated by a multiplier called “Work Index”. MECH 2 has proven to have the largest multiplier of $\frac{V}{W}$

which the base she has the smallest value. MECH 1 and MECH 3 present soft story mechanisms in the 1st and 2nd stories create the smallest index and as a result the largest base shears. It is demonstrated in Table 4. This study indicates that MECH 2 is more efficient than other mentioned mechanism applied for designing structures.

As a result it is inferred that the target yield mechanism that needs the largest amount of external work is the most desirable one. In other word mech 2 which needs the maximum external work to reach its state was considered as the most efficient one. The analysis of the results obtained from work energy equation demonstrates the values of V and presented in Table 4. Another way to determine the values of V is implementing graphical method. The target design base shear is obtained by sketching equation 9 and 10 where the intersection point is representative of the values of V for respective mechanisms. According to Figure 5, various plots of different mechanisms were drawn based on a function of V it's axiomatic that mech 2 is the most desirable one since the highest level of steep on the slope and the least value of V is determined in this state.

3.3 Verification by Nonlinear Dynamic Analyses

The four mentioned frames were subjected to some records and illustrated in Figure 6 and given in Table 5. Figure 7 shows the maximum story drifts of the frames. This figure represents that the maximum story drifts for the frame with MECH 2 are spread in a relatively uniform way over the height of structure, but in other mechanism types, they are larger in magnitude and more concentrated in “soft” stories. Finally, the results obtained from nonlinear dynamic analyses and the graphic and analytic

Table 4. Plastic energy capacity (E_{pc})-base shear-story drift

Average maximum story drift ratio	V (Target drift ratio = 2%)	E_{pc} (V/W)	MECH
3.42%	193.5	15.36	1
2.04%	86	47.78	2
3.6%	202	14.085	3
2.9%	130	29.415	4

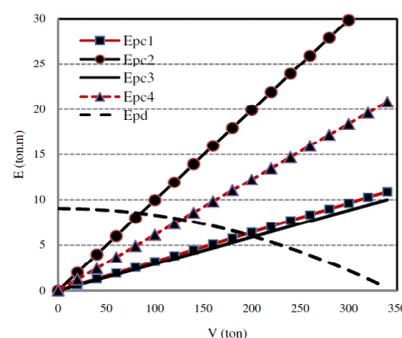


Figure 5. Graphical solution of work-energy equation.

studies, represented in this paper, show that assuming a pre-selected yield mechanism for steel moment frames can lead to desirable results when it is tried to prevent the formation of yielding in columns; except for the base of columns that will lead to the formation of a complete yield mechanism.

3.3.1 Earthquake Selection and Scaling

Ten ground motions are considered to be far 25 to 50 km, for a set of fault rupture with strike-slip and reverse mechanism at magnitude range 6.2 to 7.4. The soil at the site corresponds to NEHRP site class D for V_s (Shear-wave velocity) 180-360 m/s equal to soil type III according to code 2800. The specifications of the used records are given in Table 4.

To scale the records to the 2/3 MCE level according to seismic design code, BHRC 2005, each ground motions are normalized to their peak ground acceleration, PGA. Then, response spectrum of each record is calculated (Figure 6). Then, the average of these 10 spectra are compared with the standard spectrum within a, Matching Period Interval, MPI and scaled so that not fall below such target in the employed MPI. The obtained scale factors

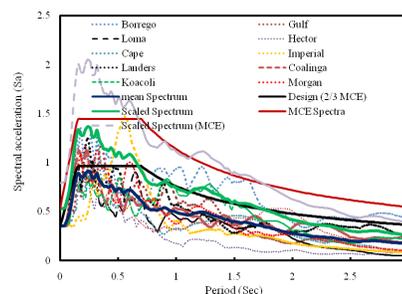


Figure 6. Scaling the earthquake records according to seismic design code, BHRC 2005, to 2/3 MCE and MCE hazard levels.

Table 5. Earthquake records data

No.	Earthquake	Date	Magnitude	Station	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Morgan	1984/4/24	6.2	CDMG 56012	43.16	0.051	8.25	1.87
2	Borrego	1968/4/8	6.6	USGS 117	45.13	0.087	17.57	9.63
3	Cape	1992/4/25	7	CDMG 89530	28.78	0.19	6.22	2.92
4	Landers	1992/26/28	7.3	CDMG 23559	34.86	0.135	25.84	18.2
5	Hector	1999/10/16	7.1	USGS	36	0.095	13.64	10.66
6	Loma	1989/10/17	6.9	USGS 1002	43.06	0.274	53.64	12.53
7	Imperial	1979/10/15	6.5	UNAMUCSD 6610	31.92	0.122	6.43	1.83
8	Kocaeli	1999/8/17	7.4	Goynuk	31.74	0.119	8.77	3.04
9	Coalinga	1983/5/2	6.4	CDMG 36453	27.1	0.098	11.85	2.32
10	Gulf	1995/11/22	7.2	Eilat	44.1	0.097	13.96	4.56

are used to amplify the records before being employed as time history analysis input. The process of scaling shows that the resulted scale depends on the applied MPI, given $[0.2T_{Str}, 1.5T_{Str}]$ in terms of Iran seismic design standard 2800. The basic period T_{Str} indicates the natural period of the structure and is obtained based on considering empirical design code relations. Finally, it worth to mention that in order to achieve the ground motion records with 2% probability of exceedance in 50 years, with the return period of 2500 years, they should be scaled with 1.5 times design spectrum of code no. 2800.

4. Techniques to Prevent Undesirable Mechanism

One another main goal of this paper is to represent some techniques in order to prevent the formation of undesirable yield mechanism in steel moment frames. The main reason of forming an undesirable yield mechanism in the structures is that the required moment to design the columns was underestimated. Many studies have shown that it is often impossible to estimate the column moment demand because they undergo large moments not only from those delivered from beams but also from their own deformation^{9,10}. It causes yielding in columns and also an undesirable mechanism in the structure. Therefore, in this paper some undesirable mechanisms have been recognized and also some solutions are represented to obtain the moment of columns precisely in order to prevent undesirable mechanisms in the structures. The formation of undesirable mechanisms and the solutions in order to prevent them are as follow:

4.1 Soft Story Mechanism in a First Story

In order to prevent the soft story mechanism in the first story, previously in PBPD method a factor of 1.1 times the lateral forces is applied on the frame to obtain the moment of columns at the base, $M_{pc}^{3,4}$. By presuming that the formation of plastic hinges occurs on the two ends of 1st story columns (Figure 8), the respective work equation for a little deformation θ is as follow

$$M_{pc} = \frac{1.1(V_1 h_1)}{4} \quad (21)$$

In the above mentioned equation v_1 presents the design base shear which is resulted from dividing V by number of bays. h_1 is the height of the first story; and the factor 1.1 was considered as margin factor to consider the states in which the load is more than tolerable level as because of hesitation and strain hardening in material strength in order to prevent formation of soft story mechanism^{3,4}. However, some other factors can also potentially cause the base shear in the designed frame to be greater than the design base shear. In order to have better confidence that the soft story mechanism is prevented under the ultimate lateral forces; those factors should also be accounted for in the calculation of M_{pc} . The influencing factors include: (1) design resistance factor for beams ($\phi = 0.9$)²¹, strain hardening of beams (1.1)²¹, and also an average oversize factor when selecting design sections for beams 1.05²⁴. Taking these factors into account, and also considering a 5% margin of safety, a resultant factor of $(1.09) \times (1.1) \times (1.05) \times (1.05) = 1.32$ would be needed. Therefore, a value of 1.3 is used in the modified equation, Figure 8

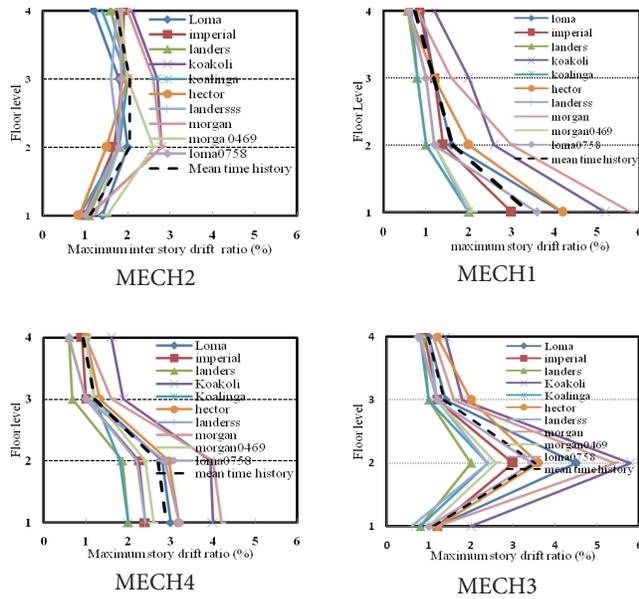


Figure 7. Maximum story drift for different yield mechanism.

$$M_{pc} = \frac{1.3(V_1 h_1)}{4} \tag{22}$$

Another issue with using Eq. 21, is that the moment at the top of first story columns generally comes out greater than the moment at the base (M_{pc}), making the design moment larger moment than M_{pc} . This issue can also be resolved by using the modified equation for M_{pc} , because by considering all possible sources of over strength in the calculation of M_{pc} and corresponding lateral forces the moment at the top of first story columns will be smaller or equal to M_{pc} . In other words, by using Eq. 22 for M_{pc}

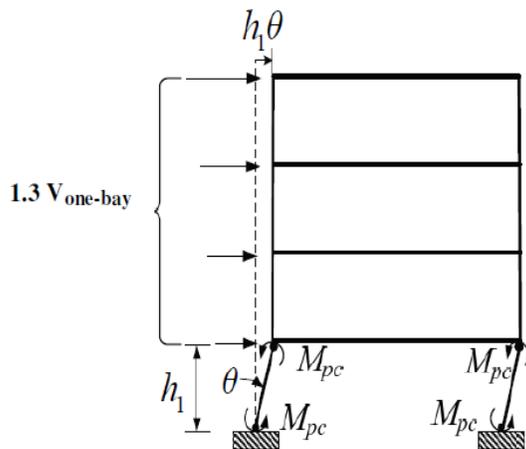


Figure 8. One bay frame with soft story mechanism.

calculation, the maximum moment in the first story columns will occur at the base.

4.2 Formation of Plastic Hinge in Columns before Beams

In order to overcome this shortcoming, the formation of strong column-weak beam mechanism has been suggested to design the columns with the maximum applied forces. For this purpose, a proper resistant factor (ξ) is multiplied by nominal plastic moment (M_{pb}) which determines the moment required for designing the beams. Assuming the suitable quantity ξ equal to 1.05²⁵, the design moment of beams are obtained at each level. When all of the beams reach the strain hardening, the values of lateral forces should be recalculated. At this stage with the assumption that the distribution of lateral forces maintains the same as Eq. 1, their magnitude is obtained using the equilibrium of free body diagram as shown in Figure 9. For example the sum of required balancing lateral forces, F_p applied on the free-body of an interior column tree can be obtained as follow:

$$F_L = \frac{\left(\sum_{i=1}^n \left(\xi M_{pbij} + \xi M_{pbi(j-1)} \right) + 2M_{pc} - \sum_{i=1}^n \left[W_i \left(\frac{L_j + L_{j+1}}{2} \right) + \frac{2\xi M_{pbi(j-1)}}{L_{j-1}} - \frac{2\xi M_{pbij}}{L_j} \right] \theta_u h_i \right)}{\sum_{i=1}^n a_i h_i} \tag{23}$$

$$a_i = \frac{(\beta_i - \beta_{i+1})}{\sum_{i=1}^n (\beta_i - \beta_{i+1})} \tag{24}$$

In accordance with Figure 10, and Eq. 23, P_{ci} is the axial load on the column due to gravity loads, M_{pbij} and $M_{pbi(j-1)}$ are respectively the plastic moment of beams at level i and bay j and $j-1$.

Having the value of $\alpha_i F_i$ from Eq. 23, the moment distribution in columns at each level is as follow:

$$M_c(h) = \sum_{i=1}^n \delta_i \left(\xi M_{pbij} + \xi M_{pbi(j-1)} \right) - \sum_{i=1}^n \delta_i \alpha_i F_i (h_1 - h) - \sum_{i=1}^n \left[\omega_i \left(\frac{[L]_{j-1} + L_j}{2} \right) + \frac{2\xi M_{pbi(j-1)}}{L_{j-1}} - \frac{2\xi M_{pbij}}{L_j} \right] \theta_u (h_1 - h) \tag{25}$$

$$\delta_i = 1 \text{ if } h \leq h_1 \tag{26}$$

$$\delta_i = 0 \text{ if } h > h_1 \tag{27}$$

Where $M_c(h)$ is the moment of columns with the distance from the base level.

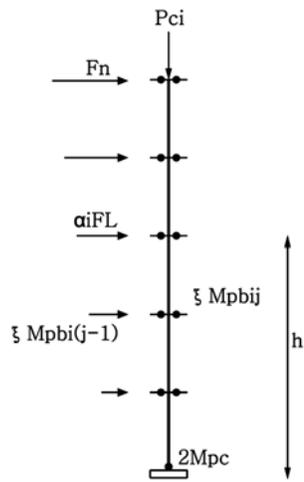


Figure 9. Strong column-weak beam.

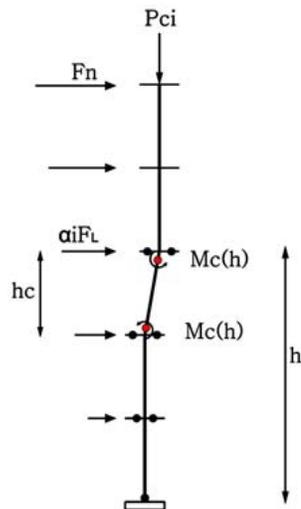


Figure 10. Soft story mechanism.

4.3 Soft Story Mechanism in Columns of a Story before the Formation of Plastic Hinge in Beams of Upper Stories

As it is known another type of shortcomings, therefore in order to overcome, Figure 10, presents a column tree diagram in which the soft story has been formed. At this stage the moment of columns is determined by the following equation as:

$$M_c(h) = \frac{1.1 * \left(\sum_{i=1}^n \delta_i \alpha_i F_i (h_c) + \sum_{i=1}^n \delta_i \omega_i \left(\frac{L_j + L_{(j-1)}}{2} \right) \theta_p h_c \right)}{2} \quad (28)$$

In which h_c is the expected story height and ω is the distributed gravity loads on beams.

The maximum moment of columns obtained by equations 25 and 28 at each level should be taken as required plastic moment of columns ($M_{j(P req)}$) in order to design the columns.

4.4 The Formation of Plastic Hinge in Columns of Structure from Up To Down

In order to overcome this shortcoming, it is required to form the plastic hinges of columns at each story earlier than the upper story. Therefore, it is suggested to make relationship between the maximum required plastic moment of columns, $M_{p req}$, and the designed plastic moment of columns, $M_{p design}$, that is as follow:

$$\left(\frac{M_{p design}}{M_{p req}} \right)_i \leq 1.01 \left(\frac{M_{p design}}{M_{p req}} \right)_{i+1} \quad (29)$$

By obtaining the moment of columns from the above mentioned equations and determining the value of axial force from the following equation, each column is designed based on capacity approach by using the AISC-LRFD code²¹. The axial force of columns is determined as follow:

$$P_{\downarrow e}(h) = \sum_{\downarrow} (i=1)^{\uparrow n} \delta_{\downarrow} i ((2 \zeta M_{\downarrow} p b i j) / L_{\downarrow} j - (2 \zeta M_{\downarrow} (p b i (j-1))) / L_{\downarrow} ((j-1)) + \omega_{\downarrow} i ((L_{\downarrow} j + L_{\downarrow} ((j-1)))) / 2 \quad (30)$$

In Eq. 30; ω_i is the gravity load applied on the beams.

It should be noticed that the equations represented in this paper determine the moment of columns with good precision. It prevents the yielding in columns that finally leads to more desirable results, so that the structure can better achieve the desired performance. The results obtained by extensive nonlinear analyses show the validity of the mentioned techniques as given in continues.

5. The Validity of the Suggested Techniques to Prevent Undesirable Mechanism

5.1 Design Frame

In order to ensure the validity of represented equations to prevent the formation of undesirable mechanisms,

a 10 story frame with 3 bays has been designed based on PBPD method using MECH2. It is well mentioned that according to previous studies^{3,4}, this mechanism is considered as pre-selected yield mechanism to design the moment frames. The main aim of using this mechanism is to prevent the yield mechanism in columns of steel moment frames. But many researchers have shown that assuming only the criteria of strong column-weak beam can't prevent the yielding in columns during the event of sever ground motions^{9,10}. Thus, in order to overcome this shortcoming, the above mentioned frame has been re-designed considering all represented equations of this study (modified PBPD frame). The story height and bay length of the model is respectively 3.2m and 6m. The live and dead loads distributed on beams are taken respectively 1000 kg/m and 2500 kg/m. In this paper, according to seismic design code, BHRC 2005²⁰, the pre-selected target drift ratio is considered to be 2% for the earthquake hazard level with 10% probability of exceedence in 50 years. Assuming the yield drift ratio as 1% for steel moment frame³, all of the parameters related to PBPD method can be calculated. The results are of design of frames represented in Table 6. The European standard profiles (IPB and IPE) are respectively used for the columns and beam sections. Also, the weight comparison between PBPD and ED frames are shown in Table 7. Although the weight of PBPD frames and ED frames are almost equal, the merit of PBPD method is justified by its performance as shown by nonlinear analysis.

5.2 Nonlinear Analysis Results

Structures generally deform far beyond the elastic range when struck by strong ground motions. In order to give a proper description of nonlinear behavior of structures, a more sophisticated analysis is required. Nonlinear analyses can offer greater perception of the structure's attitude and determine if the structures satisfy performance requirements. Two types of nonlinear analyses, static and dynamic analyses are performed for the mentioned frames by applying PERFORM-3D program²⁶. This program is a highly focused nonlinear software tool for earthquake resistant design. For modeling of the members in this software, all frame members, beams and columns are considered as rigid-ended. Also the nonlinear behavior of members is suggested by FEMA-356²⁷. The p-delta effect was taken into account by adding a lumped p-delta column to the structure.

Table 6. Design parameters for PBPD method

Number of story	Period (T)	S _a	Yield drift (θ _y)	Plastic drift (θ _p)	γ	A	V/W
10	1.076(sec)	0.53	0.01	0.01	0.75	1.68	0.112

Table 7. Material weight for steel moment resistant frames

10 story steel moment resistant frame			
Weight calculation	PBPD (Kg)	Modified PBPD (Kg)	Modified PBPD/PBPD
Beam	13070	12680	0.97
Column	17400	17860	1.027
Total	30410	30540	1.004

The results of pushover analyses for the 10 story PBPD frame and modified PBPD frame is shown in Figure 11. The pushover curves demonstrate the yield drift ratio; θ_y is equal to 1% as it was assumed at the beginning of design procedure. Also, pushover curve shows that although the design base shear for PBPD and Modified PBPD frame is equal, the ultimate strength of modified PBPD frames have proven be superior to that of PBPD frames. The main reason of increasing the overstrength in modified PBPD frame is the change in the size of columns. This change is because of applying the proposed equations to prevent the yielding in columns. Figure 12, shows the distribution of plastic hinges for the two mentioned frames, in 3.5% of roof drift. Also, the rotation angle of each plastic hinge, formed on frames, has been shown graphically. The formation of plastic hinge in columns of PBPD frames in lower stories is significantly noted, whereas in modified PBPD frame, no plastic hinge has been formed in the columns, therefore more favorable yielding and deformation has occurred. This result can be an important reason to prove the represented equations of this paper in order to prevent the yielding in columns of steel moment frames.

Nonlinear dynamic analyses implementing ten earthquake records as seen in Table 5 are performed for both frames. It should be noted that these earthquakes are match well with the design spectrum in accordance with Iranian Standard Code No. 2800²⁰. The design spectrum in code No. 2800, is for the earthquakes with the probability of 10% exceedence in 50 years (2/3 MCE). In order to evaluate the structure in higher hazard level, the earthquakes have been scaled with 1.5 times design spectrum

of code no. 2800 which represents ground motions with the probability of a 2% exceedance in 50 years (MCE). It should be noted that to scale the records to the 2/3 MCE and MCE levels, all of acceleration records are normalized to their peak value. It means that maximum value of each acceleration record is equal to (g). All normalized records were multiplied by the same scale factor. The scaling factor was obtained by the ratios of 2/3 MCE and MCE pseudo acceleration elastic spectrum to the mean pseudo acceleration spectrum of all 10 normalized ground motion set. The detailed calculation is shown in Iranian Standard Code No. 2800²⁰. For simplicity only the mean value of maximum inter story drift, as shown in Figure 13, are considered in order to compare the results. It is concluded that the mean peak inter story drifts of the modified PBPD frames meets the required domain of the target drift value, i.e., 2% for 2/3 MCE and 3% for MCE while the PBPD frame indicate that the mean peak inter

story drifts are higher than the target drift value. Also, the formation of plastic hinges in columns and story mechanism in the lower part of the PBPD frame under some ground motion can be clearly noticed in Figure 14. On the contrary, by using some equations that are represented to prevent the formation of the plastic hinges in the columns, no plastic hinge has been formed in columns.

6. Conclusion

The selection of the desirable yield mechanism is one of the main criteria in PBPD method. With considering the importance of the selection of yield mechanism, a parametric study has been done considering the different types of yield mechanisms to design a model of moment frame. The conclusions obtained by nonlinear time history analyses show that the complete sway mechanism (strong columns-weak beams) is the best mechanism in terms of required design base shear for a given target story drift. It also should be noted that it is often impossible to estimate the column moment demand during the event of sever ground motions (especially for earthquakes with 2% probability of exceedance in 50 years) because they undergo large moments not only from those delivered

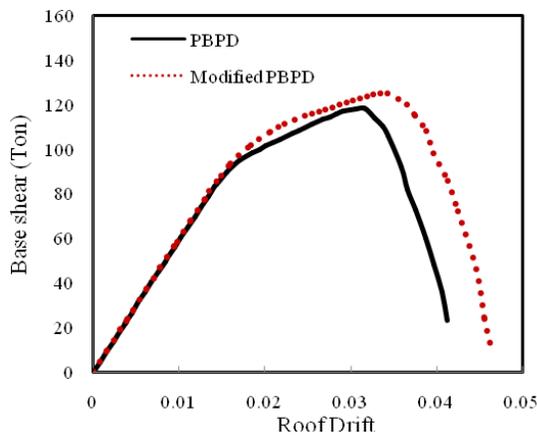


Figure 11. Comparison pushover curve for 10 stories PBPD and Modified PBPD frame.

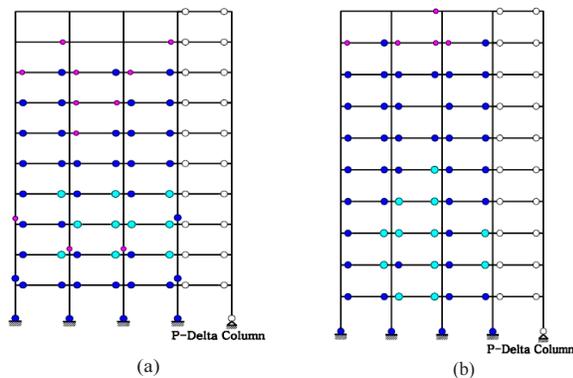


Figure 12. Plastic hinge distributions at 3.5% roof drift (a) PBPD frame (b) Modified PBPD frames; Push over analysis.

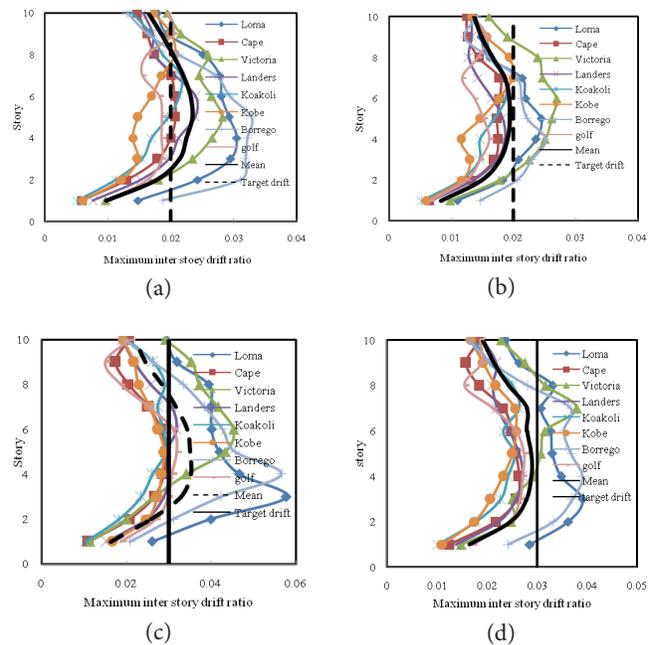


Figure 13. Comparison of maximum inter storey drifts by dynamic analysis (a) PBPD frame for 2/3 MCE; (b) Modified PBPD frame for 2/3 MCE; (c) PBPD frame for MCE; and (d) Modified PBPD frame for MCE hazard levels.

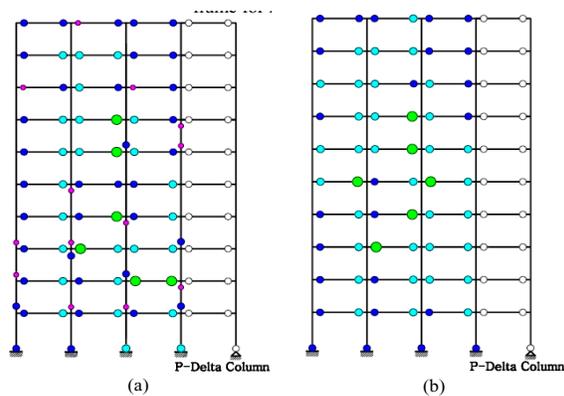


Figure 14. Plastic Hinge Locations for (a) PBPD Frame (b) Modified PBPD frame under Loma record scaled to MCE.

from beams but also from their own deformation. It causes yielding in columns and also an undesirable mechanism in the structure. Therefore, in this paper by reviewing different yield mechanisms, some techniques are represented to precisely obtain the required moment of columns to prevent their yielding. In order to validate the proposed techniques, a 10 story frame is designed by PBPD method using strong column-weak beam mechanism and then the same frame is redesigned considering all represented techniques of this study (modified PBPD frame). The frames are subjected to extensive nonlinear static and dynamic analyses. Following main conclusions are drawn from this study.

- ❖ Since the nonlinear behavior of the structure is taken into account from the beginning of design in PBPD method, there is no need for any further evaluation.
- ❖ In PBPD method, the only condition of strong column-weak beam can not merely guarantee the prevention of yielding in columns that leads to larger story drift and undesirable mechanism in the structure. In comparison, by using some solutions represented in this paper to precisely obtain the moment of columns, the frame designed by modified PBPD method gave excellent results as expected *i.e.*, the formation of plastic hinges in columns and undesirable mechanisms were not observed.
- ❖ As it was expected, modified PBPD frame performed far better than those of corresponding PBPD frame when analyzed with both nonlinear static pushover and dynamic analysis.
- ❖ It is concluded that the mean peak inter story drifts of the modified PBPD frames meets the required domain of the target drift value, *i.e.*, 2% for 2/3 MCE and 3% for

MCE while the PBPD frame indicate that the mean peak inter story drifts are higher than the target drift value.

- ❖ The modified PBPD frame results in more desirable deformed shapes and yield mechanism in all of the ground motions. On the contrary, in the PBPD frame, Plastic hinges in columns and story mechanism in the lower part of the frame can be observed under some ground motions representing the MCE hazard level.

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