Performance-Based Plastic Design (PBPD) Method For Earthquake-Resistant Structures

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Current Seismic Design Practice in the U.S.

**Elastic Design Approach**

- Design Base Shear
  
  \[ V = C_e W \left( \frac{I}{R} \right) \]

- **Elastic Analysis/Design**

- **Drift Check**
  
  \[ C_d \Delta < \Delta_{\text{limit}} \quad (\Delta \text{ is elastic drift}) \]

- Prescribed Ductility Detailing

- Pushover Assessment *(Iterations needed to reach the final design)*

(Works most of the time – But not always!)
Performance-Based Plastic Design (PBPD) Method

1. Design Base Shear

Pre-selected Yield Mechanism and Target Drifts

Base Shear Coefficient, $C$

\[ C_e = R_p C_y \]

Work-Energy Equation:

\[ (E_e + E_p) = \gamma \left( \frac{1}{2} MS_y^2 \right) = \frac{1}{2} \gamma M \left( \frac{T}{2\pi} C_e g \right)^2 \]

$\gamma$: Energy modification factor

Valid for MDOF either (paper no. 05-01-0037 by Leelataview et al.)
For the given system,

\[ E_e = \frac{1}{2} M \left( \frac{T}{2\pi} \frac{V}{W} g \right)^2 \]

Akiyama (1985)

\[ E_p = \sum F_i h_i \theta_p = \sum (\lambda_i V) h_i \theta_p \]

Using Newmark-Hall Inelastic Spectra \((R_\mu-\mu_s-T)\) for E-P SDOF,

\[ \gamma = \frac{2\mu_s - 1}{R^2_\mu} \]

\(\mu_s\) ductility factor

\(R_\mu\) ductility reduction factor
Inelastic response spectra proposed by Newmark and Hall [1973]

\[ \gamma = \frac{2\mu_s - 1}{R_{\mu}^2} \]

Energy modification factor versus period

\( \mu_s \) ductility factor

\( R_{\mu} \) ductility reduction factor
Solution of Work-Energy Equation $\rightarrow$ Design Base Shear

$$\frac{V}{W} = \frac{-\alpha + \sqrt{\alpha^2 + 4\gamma C^2}}{2}$$

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

Note: drift control has been included in the beginning of the design
Typical relation between the PBPD design base shear, design target drift ratio, and period

\[ \theta_p = \theta_u - \theta_y \]

Note: Linear elastic first mode lateral force distribution along the building is used by the current codes.

\[ F_i = C_{vl} V \]  

(1)

\[ C'_{vl} = (\beta_i - \beta_{i+1}) \left( \frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j} \right)^{0.75T^{-0.2}} \]  

when \( i = n, \beta_{n+1} = 0 \)  

(2)

\[ \beta_i = \frac{V_i}{V_n} = \left( \frac{\sum_{i} w_i h_i}{w_n h_n} \right)^{0.75T^{-0.2}} \]  

(3)

Shear Distribution Factor \( \beta_i \) represents the shear distribution factor at level \( i \).
3. Plastic Design Method (for proportioning designated yielding members, DYM, such as beams in moment frames):

Pre-Selected Yield Mechanism
(assuming PH is away from column face)
Pre-selected yield mechanism of some typical framing systems

(a) Moment Frame
(b) Eccentrically Braced Frame
(c) Special Truss Moment Frame
(d) Concentrically Braced Frame
(e) Coupled wall system
4. Design of Members outside the designated yielding members (Column-Tree Approach):

\[ \alpha_n F_L \rightarrow (P_c)_i \]

\[ \alpha_i F_L \rightarrow (V'_{RBS})_i (V_{RBS})_i (M_{pr})_i \]

\[ \alpha_i F_L \rightarrow (P_c)_i \]

\[ h_i \]

\[ 2M_{pc} \]

\[ h \frac{d_c}{2} \]

\[ h \frac{d_c}{2} \]

Interior “Column Tree” of a moment frame
Advantage of PBPD

1. The main advantage of the PBPD method is that it is a direct design method without the need for iteration and assessment (such as pushover analysis) to achieve the desired targeted performance in terms of drift and yield mechanism control.

2. This translates into enhanced performance and safety, especially under severe ground motions, as well as ease and economy of repair costs when needed.
Verification of PBPD Method through Nonlinear Dynamic Analyses
Example 1. Steel Moment Frames (LA38 ground motion, 2%/50yrs)

Current practice (elastic design)

PBPD

No Plastic Hinge in Columns except at the Base

Column Plastic Hinge

Gravity column

[Paper No. 05-01-0412 by Bayat et al.]
Story Drift Responses under LA35 (2% in 50 yrs)

[Paper No. 05-01-0412 by Bayat et al.]

Current practice (elastic design)

PBPD Frame

Collapse due to story mechanism

No column plastic hinging
Example 2. Concentrically Braced Frames

For a braced frame having strength/stiffness degradation due to brace buckling, the design base shear is calculated by a modified energy balance concept.

\[ \gamma E = \eta (E_e + E_p) \]
\[ \eta = \frac{\text{Energy under degraded hysteresis loop}}{\text{Energy under full hysteresis loop}} \]
\[ \frac{V}{W} = -\alpha + \sqrt{\alpha^2 + 4 \left(\frac{\gamma}{\eta}\right) c_e^2} \]
\[ \frac{V}{W} = \frac{2}{2} \]
Comparison between CBFs designed by current practice and PBPD

(a) 3V-NEHRP (current practice)

(b) 3V-PBPD (target drift = 1.25% under 2/3MCE)
Confidence level (collapse prevention) assessment for 3-story CBFs (2% in 50 yrs ground motions) [Paper No. 05-01-0033 by Chao et al.]

<table>
<thead>
<tr>
<th>Frame</th>
<th>Median Drift Capacity (from IDA) $C$</th>
<th>Capacity factor $\phi$</th>
<th>Median Drift Demand $D$</th>
<th>Demand factors $\gamma$</th>
<th>Demand factors $\gamma_a$</th>
<th>Confidence Parameter $\lambda = \frac{\gamma \cdot \gamma_a \cdot D}{\phi \cdot C}$</th>
<th>Confidence Level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3V-NEHRP</td>
<td>0.064</td>
<td>0.628</td>
<td>0.068</td>
<td>3.37</td>
<td>1.06</td>
<td>6.04</td>
<td>&lt;&lt; 1%</td>
</tr>
<tr>
<td>3V-PBPD</td>
<td>0.078</td>
<td>0.766</td>
<td>0.015</td>
<td>1.56</td>
<td>1.06</td>
<td>0.41</td>
<td>&gt; 99.9%</td>
</tr>
</tbody>
</table>
In Summary…

1. The new seismic design procedure (PBPD) using energy and plastic design concepts, and pre-selected yield mechanism and target drift as performance criteria, has been successfully applied to MF, BRBF, EBF, STMF, and CBF to achieve the desired performance objectives, such as target drifts, intended yield mechanism, etc.

2. $R$ (force modification factor), $I$ (importance factor), and $C_d$ (deflection amplification factor), are not needed for design by PBPD method since inelastic behavior is directly accounted for. No iterative evaluation or refinement, such as by nonlinear static (pushover) or dynamic analysis after initial design, is needed either.