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Comparison of Force-Based Design Method and Performance-Based Plastic Design Method for Seismic Design of Steel Concentric Braced Frames

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Abstract - *This paper presents comparative study of seismic design considerations and design methodologies for steel concentrically braced frame by force based design and performance based plastic design method. Force based design is the design method, which is currently used in India for design of structure in elastic state of material. Performance-Based Plastic Design (PBPD) method has been recently evolved from the Performance based seismic design (PBSD) to achieve enhanced performance of earthquake resistant structures considering the participation of inelastic state of the material. The concept of design is mainly based on pre-selected target drift and yield mechanism as performance criteria. Performance Based Plastic design depends on "strong column-weak beam" theory, in which the pattern of failure is pre-determined. CBFs, when designed by conventional elastic design methods, these structures can undergo excessive story drifts after buckling of bracing members. That can lead to early fractures of the bracing members, especially in those made of popular rectangular tube sections. A brief study on recently developed energy based plastic design methodology for CBF with buckling type braces is presented in this paper which exhibit somewhat "pinched" hysteretic loops.*

***Keywords**-Pre-selected target drift, Yield mechanism, Strong column-weak beam concept, CBF, PBPD*

I. INTRODUCTION

The seismic design of structures is continuously evolving. Conventional design procedures have the objective of achieving life safety in a structure by providing sufficient strength and ductility to resist whole or partial collapse of the structure. Structures designed according to current seismic design provisions or design code should, in general, satisfy the following rules. First, to resist minor level of earthquake ground motions without damage; second, to resist moderate earthquakes without structural damage, but may experience some non-structural damage; and finally, to resist major earthquakes without collapse, but possibly with some structural and/or non-structural damage. The unexpectedly high financial losses related to functional downtime and non-structural damage from recent large earthquakes near prime locations emphasizes the limitations behind the current ductile designs using FBD method.

In today's era the aim of limiting excessive damage and to maintain functionality of the building after an earthquake is becoming more desirable. In order to predict damage to a structure in an earthquake, performance based design method is a new method which is rapidly gaining popularity. It is well known that structures designed by current codes undergo large inelastic deformations during high earthquakes. However, current seismic design approach is generally based on elastic analysis. In the current Indian design practice, it is common to calculate design base shear from code specified spectral acceleration, with the assumption that structure to behave elastic. It is also reduced by response reduction factor R. the design forces is also influenced by importance factor I, based on occupancy. By the use of these parameters lateral forces are found, member size will be selected from design results and then analysis regarding drift and deflection of the structure is done, which must be within an acceptable limit. Sometime the structures experienced high earthquake forces however, the structures designed by such procedures have been found to undergo inelastic deformations in a somewhat 'uncontrolled' manner. This may results undesirable and unpredictable behavior, sometimes total collapse, or difficult and costly repair works. So the societal requirements are pushing the practice to achieving higher levels of performance, safety and economy, including life-cycle costs.

Performance Based Plastic Design is a recent designing concept of seismic resistant structure, in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to higher level of seismic hazards. Since 1994 Northbridge earthquake and other earthquakes in the world during the end of 20th century led the structural engineer to use the concept of Performance based design.

The Indian standard code follows the force based design for structures, whereas in Performance based Plastic design method, the braces fail first due to post buckling and tension yielding. Due to this, hinges are formed in the pre-determined locations in beams. This may result into local failure only, preventing total collapse of the frame.
Concentrically Braced Frames (CBFs) are a class of structures resisting lateral loads through a vertical concentric truss system, the axes of the members aligning concentrically at the joints. This traditional form of bracing is generally

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considered less ductile seismic resistant structure than other systems due to occurrence of the brace buckling or fracture when subjected to large cyclic displacements. The special proportioning and detailing requirements are purposive to make the frames capable of resisting strong earthquake shaking without significant loss of stiffness or strength. The force based limit state design procedure for design of steel structures is used in India in accordance with IS 800: 2007 and IS 1893:2002 to assure a good earthquake resistant design which serves good in general conditions but it may fail in case of a major earthquake hazards. If a predetermined failure pattern is used at certain points of a structure based on "strong column–weak beam concept", it will ensure possible inexpensive repairs even after damage. In the Performance Based Plastic Design Method, there is always a local failure.

II. EVALUATION OF PBPD METHOD

To achieve higher performance of the structure under seismic actions, following documents were established in first generation procedure of performance based design: SEAOC Vision 2000, ATC 40 (1996), FEMA 273 and 274 (1996).

Structural Engineer Association of California (SEAOC) in 1995 proposed PBSD of building known SEAOC Vision 2000. The goal of this document is to develop the framework for procedures that lead to design of structures of predictable seismic performance and is able to accommodate multiple performance objectives. Possible design approaches covers various elastic and inelastic analysis procedures such as:

1) Conventional force and strength methods
2) Displacement-based design
3) Energy approaches
4) Prescriptive design approaches

Applied Technology Council (ATC) proposed ATC 40 document, performance-based design concept refers to the methodology in which structural criteria are expressed in terms of achieving a performance objective. The document was limited to concrete buildings and emphasizes the use of the capacity spectrum method.

The Federal Emergency Management Agency (FEMA), report FEMA 273/356 document which gives a variety of performance objectives with associated probable ground motions, Analysis and design approaches for the multi-level performance range from linear static to inelastic time history analysis. The document defines performance levels for non-structural elements and systems and assumed drift limits for various lateral load resisting structural systems at different performance levels.

The development and study of performance based plastic design method was carried out by the authors and they developed concept for analysis of the structure for performance based design incorporating the concept of plastic analysis and energy equilibrium. They studied amount of energy releases in the structure at the time of seismic actions in terms of elastic energy and plastic energy using energy balance equation. They developed the method based on pre-determined failure pattern of the structure at time of earthquake to ensure inexpensive repairs even after strong earthquake shaking of ground.

III. ANALYSIS AND DESIGN PROCEDURES FOR CBFs BY FBD METHOD AND PBPD METHOD

The Performance-Based Plastic Design Method has been retrieved from the suggestions by Goel and Chao, 2009. In FBD Method as per Indian Code of practice, the structure is designed for force (strength) and checked for displacement (serviceability). FBD Method has served very well, except in case of very severe earthquake, in which total collapse of structure is observed.

Whereas in PBPD Method the structure is designed for pre-determined target drift and yield mechanism. This prevents total collapse of the structure. As there are no guidelines available for PBPD Method in Indian code, it is suggested that the design base shear and distribution of lateral force can be done based on suggestions given by Chao, 2007. The calculation of forces and moments is also done based on suggestions given by Chao, 2006.

Fundamental Natural Time Period (T) for Moment Resisting Frame without infill panels can be calculated as per IS-1893: 2016 clause 7.6.2(a).

1) For RC MRF buildings: $T = 0.075h^{0.75}$
2) For RC-Steel composite MRF buildings: $T = 0.080h^{0.75}$
3) For Steel MRF buildings: $T = 0.085h^{0.75}$

Where,

h = height of building in metre.

3.1. Lateral force calculation and distribution in FBD method

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The lateral seismic loads to be applied on the structure are calculated based on the Elastic Design Spectra prescribed in IS 1893:2002 which gives the design spectral acceleration, *"S_a"* of the structure having time period *"T_n"* due to elastic response (μ = 1). The ductility factor "μ" is defined as the ratio between the maximum displacement and the yield displacement (u_{max}/u_y) or maximum drift and the yield drift (θ_{max}/θ_y) at the top of the structure. Which means, when μ=1, it will be an elastic response and when $\mu > 1$, it will be an inelastic response.

In the current method seismic parameters like response reduction factors *"R"*, zone factors *"Z"*, S_a/g value for ductility 1 *and* importance factors *"I"* are considered for calculation of the total base shear *"V_B"*. The seismic zone factor *(Z)* used to evaluate the value of design forces has been proposed after seismic zonation of our country and is based on the previous earthquake data available. The importance factor *(I)*, depends on the functional use of the structure. From the above information it is clearly understood that the design forces derived from the current code are quite assumptive as the factors governing the design of forces are mainly based on engineering judgments. Because of these reasons, the structures may undergo large inelastic deformations during major earthquakes.

The total Base Shear in this method is calculated by [IS 1893: 2016/clause 7.6.1]

$$VB = Ah \bullet W$$

In Which W is the total seismic weight of the structure and Ah is the horizontal seismic co-efficient. [IS 1893: 2016 /clause 6.4.2]

$$Ah = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

This Base Shear is distributed among the floors, which is known as lateral force distribution at each floor level, "Qi" as per [IS 1893: 2016/clause 7.6.3]

$$Qi = VB \bullet \beta i$$

Where,

Q_i = Design lateral force at floor i.

W_i = Seismic weight at floor i.

h_i = Height of floor i.

Note: One can define βi as shear distribution factor = $\dfrac{Wi\ hi^2}{\sum_{j=1}^{n} Wj\ h_j^2}$

In general, the frame is applied the above seismic lateral loads along with gravity loads and then static analysis is carried out. This seismic lateral force is applied at all the joints of all the bays at each floor. It means that the frame is supposed to remain connected as a continuous system. Based on the obtained values of axial force, shear force and bending moment, all the structural members of the frame are designed using the limit state design approach satisfying IS 800:2007 criteria.

3.2. Lateral force calculation and distribution in PBPD Method

PBPD Method is mainly based on displacement based method. The structure is designed to fail at the location which is pre-determined at the time of designing. So the failure mechanism in PBPD method is pre-determined. The design base shear for selected hazard level is assessed by equating the work needed to push the structure monotonically up to the target drift to the corresponding energy demand of an equivalent SDOF oscillator.

The Performance Based Plastic Design Method for Concentrically Braced Frames can be used for the Indian codal provisions by following the analysis procedure as proposed by Chao and Goel, because it is based on equilibrium equations available at the time of failure of the structure. Once the analysis is completed and forces and moments are calculated, the design of the members is done satisfying the IS 800:2007.

The total Base Shear in this method is calculated based on work energy equation which is expressed as

$$V_B = \left(\frac{-A_h + \sqrt{A_h^2 + 4(\gamma/\eta) S_{a\ inelastic}^2}}{2}\right) W$$

$$A_h = \left(\sum_{i=1}^{n} (\beta_i - \beta_{i+1}) \cdot h_i\right) \left(\frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j}\right)^{0.75T^{-0.2}} \left(\frac{\theta p\ 8\ \pi^2}{T^2\ g}\right)$$

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The Ductility factor is related to energy modification factor *"γ"* in the following way by applying the Energy balance concept as proposed by Lee and Goel.

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

Where,

μ_s = Structural ductility Factor
R_μ = Strength Reduction factor
h_i (and h_n)= Height of level i (and roof) measured from base
w_i (and w_n)=Seismic weight of level i (and roof)
θ_p= the selected global inelastic drift ratio of the structure (θ_{max}-θ_y) i.e. pre-determined target drift

This *"γ"* is divided by a factor *"η"* (η=A1/A2 ,figure 1) for those systems who do not possess ideal Elasto-Plastic force deformation behavior and full hysteretic loops such as steel braced frame and buckling type frames. For moment resisting frames(MRFs) it is taken as unity. The pin connected rigid beams and columns showed that the dissipated energy of a Concentrically Braced Frame is 35% of the energy dissipated by corresponding frame with full elastic plastic hysteretic loop, with both frames having same strengths.
In PBPD method, first the lateral force at roof level (Q_n) is calculated as

$$Q_n = \frac{V_B}{\sum(\beta_i - \beta_{i+1})}$$

Then the lateral force at each floor (Qi) is distributed with reference to the force of roof.

$$Q_i = Q_n\ (\beta_i - \beta_{i+1})$$

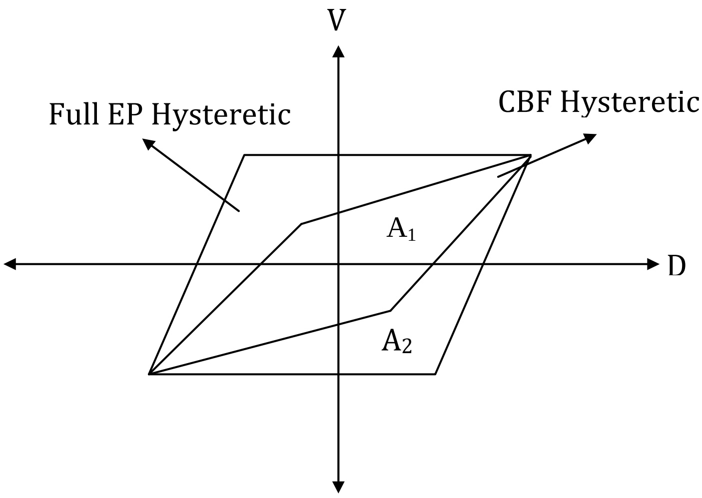

Figure 1. Full Elasto-Plastic Hysteretic Loop and CBF hysteretic Loop

A predetermined failure pattern (figure 2) and target drift *(θu)* is selected. The seismic weight of the floors as well as the total design seismic load *"W"* and the natural time period is calculated as per the general procedure. The lateral seismic loads are calculated as explained above for the desired ductility factor based on the Inelastic Design Spectral acceleration *("Sainelastic/g")*. Once the lateral seismic loads are calculated, it is first distributed in bracings of each floor. While designing the bracing of a particular floor, the sum of design lateral seismic forces at all levels above the storey under consideration (known as storey shear *"Vi"*) is used.

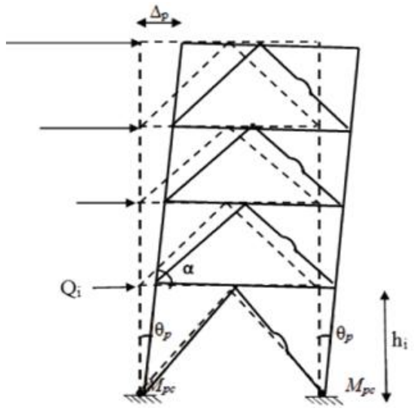

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Figure 2. Pre-determined Failure Pattern & Yield Mechanism

3.3. Analysis and design of bracings as per PBPD and FBD method

Bracing section in PBPD method should satisfy following criteria:

$$V_i \leq \frac{(P_y + 0.5\, P_{cr})\cos\alpha_i}{\gamma_{mo}}$$

Where,

P_y = Tension yielding state load and $P_y = f_y A_g$
P_{cr} = Post buckling state load and $P_{cr} = f_{cr} A_g$
f_y = yield stress
A_g= Gross area of the section
α = Angle of bracing member with horizontal
γ_{mo}= Partial safety factor for material strength

In which,

$$f_{cr} = 0.877\, f_{cc}\ ,\ \text{When } f_{cc} < 0.44\, f_y$$

$$f_{cr} = (0.658^{\frac{fy}{f_{cc}}})\, fy\ ,\ \text{When } f_{cc} \geq .44\, f_y$$

and

$$f_{cc} = \frac{\pi^2 E}{(\frac{KL}{r})^2}$$

E = Modulus of Elasticity
KL / r = Effective Slenderness ratio

In FBD method, proper design axial force for bracing members is found out first and then the bracings are to be designed as per clause 6.1 and clause 7.1 of IS-800:2007.

3.4. Analysis and design of beams as per PBPD and FBD method

In PBPD Method beams intersected by the braces should be designed assuming that no gravity loads are resisted by braces. The beams should also be designed to support vertical and horizontal unbalanced loads resulting from the force difference in the tension and compression braces as shown in figure 3.

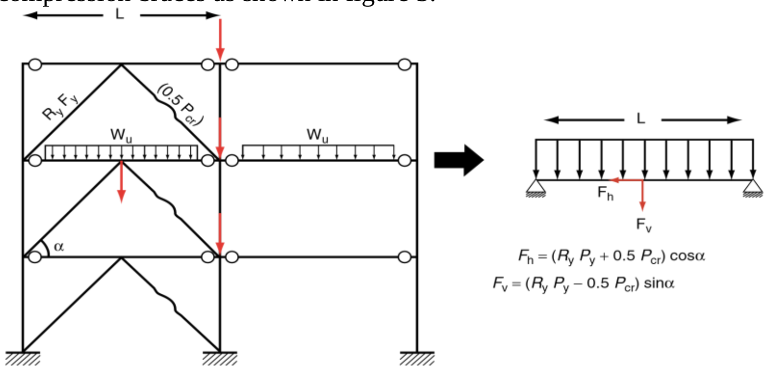

Figure 3. Beam Design Forces for a Chevron Type CBF

Axial Force:

$$F_h = (\gamma_{mo} P_y + 0.5\, P_{cr})\ cos\ \alpha$$

Shear Force:

$$Fv = (\gamma_{mo} P_y - 0.5\, P_{cr})\ cos\ \alpha$$

Moment:

$$M = \frac{wl^2}{8} + \frac{F_v\, l}{2}$$

After getting the proper design bending moments, shear force and axial force for beam members by using both the methods as discussed above ,beams are to be designed as per IS-800:2007 clause 8.2 for flexure and clause 8.4 for shear and checked for deflection as per clause 5.6.1.

3.5. Analysis and design of columns as per PBPD and FBD method

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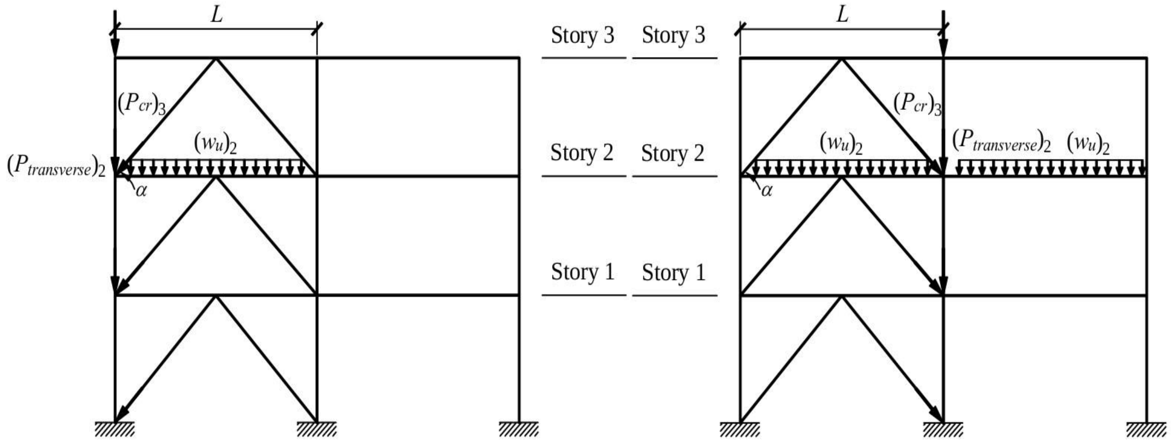
Only axial loads are considered for column design, including the fixed base first story columns. Axial forces result primarily from the gravity loads and vertical component of the braces.
Two limit states are considered for the design of columns.

a) Pre-Buckling limit state:

Prior to brace buckling, no unbalanced force occurs in the beam, and the design axial force for in a typical exterior and interior column is given by:

Typical exterior column: $P=(P_{transverse})_i+ (P_{beam})_i+(P_{cr}\sin\alpha)_{i+1}$
Typical Interior column: $P=(P_{transverse})_i+ \Sigma(P_{beam})_i+(P_{cr}\sin\alpha)_{i+1}$



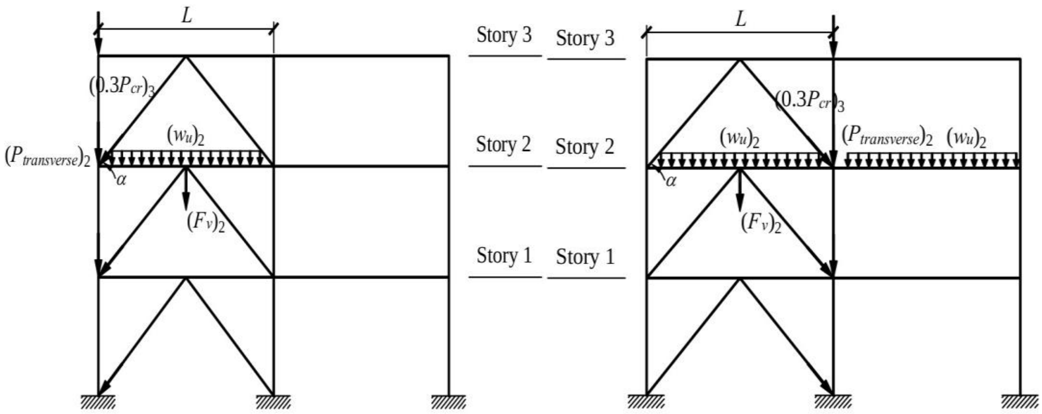
(a) Exterior Column (b) Interior Column

Figure 4. Axial force components for brace pre-buckling limit state

b) Post-Buckling limit state:

When a chevron type CBF reaches its ultimate state, an unbalanced force is created in the beam and the axial force demand in the exterior and interior column can be determined as given below.

Typical exterior column: $P=(P_{transverse})_i+ (P_{beam})_i+(P_{cr}\sin\alpha)_{i+1}+0.5Fv$
Typical interior column: $P=(P_{transverse})i+ \Sigma(P_{beam})_i+(P_{cr}\sin\alpha)_{i+1}+0.5Fv$



(a) Exterior Column (b) Interior Column

Figure 5. Axial force components for brace post-buckling limit state

Where,

P_u = Design axial force
$(P_{transverse})_i$ = Tributary factored gravity load (1.2 DL+0.5LL) on columns from transverse direction at level i
$(P_{Beam})_i$ = Tributary factored gravity load from the beam at level i ($0.5(W_u)_iL$)
$(P_{cr})_{i+1}$ = Buckling force of brace at i+1 level
F_v = Vertical force from brace

After getting the proper design bending moments, shear force and axial force for columns by using FBD methods, the columns are to be designed as per clause 9.3 of IS 800:2007 for combines axial force and bending moment.

It should be noted that in PBPD method columns are designed for axial load only as per clause 7.1 of IS 800:2007

IV. SUMMARY AND DISCUSSION

Proper design methodology for CBFs using PBPD method proposed by researchers have been briefly reviewed in this paper and it is observed that more research work is needed especially for development of proper design methodology in PBPD method for various other different types of structures such as eccentrically braced frames and special truss moment frames. It is important to note that in the PBPD method, drift control and yielding is taken into account in the beginning itself, eliminating the need for lengthy iterative process to arrive at the final design results. Other advantages include the fact that development of innovative structural schemes can be done by selecting suitable yielding members and/or devices and placing them at strategic locations, while the designated non-yielding members can be detailed for no or minimum ductility capacity. All of these would lead to enhanced performance, safety and economy in life-cycle costs. In FBD method S_a/g value is considered for ductility factor μ=1using Elastic design spectra, where as in PBPD method $S_{a\ inelastic}/g$ value can be determined for desired ductility factor by applying reduction factors proposed by Newmark & Hall, Vidic etc. In FBD method, analysis is done for the frame as statically indeterminate and moments & forces are calculated using M.D. Method, kani's method or other standard method (matrix method if software is used), whereas in PBPD method, analysis is simply carried out with the help of basic equations of equilibrium as three hinges in bracings, two hinges are formed in beam and one at base of each column, making it a determinate structure as per Chao and Goel 2006.

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