Displacement Analysis of RC Frames and its Seismic Performance Appraisal

Ahmad Farhad Farahmand, Bhartesh, Sayed Shuaib Qammer

Abstract: In India when structure engineer’s analysis and design a structure like buildings, they are checking it for displacement because of safety and control of damages; so in this paper a set of frames with different height of reinforced moment resisting frames were analyzed by two popular methods of performance-based plastic design method and direct displacement-based design method. For calculation of base shear, the IS code has been used in both methods and ETABS software used for seismic performance evaluation by nonlinear static pushover analysis. The results of analysis with different methods compared by suitable parameters and graphs, such as: (a) story lateral force, (b) beam seismic moment, (c) displacement profile and (d) capacity curve. Results show acceptable performance in 2 methods in terms of capacity and deformation.

Keywords: Performance-based plastic design, displacement profile, Seismic performance, Direct displacement-based design, beam seismic moment, capacity curve.

I. INTRODUCTION

All design methodologies those adopted by seismic codes are based on safety requirement and control of damage that may occur during an earthquake to decrease damage on any structure and increase the safety of it. In the customary and standard force based methods, the structures are designed for given loads and then checking them for displacement especially high rise buildings those considered lateral force; like seismic and wind loads on them. In other words, the purpose of structure engineers and design codes is desirable ductility and strength, it means (life safety) and control of damages as Serviceability and drift limit. Recently the structures have been designed by this method is shown that bear large inelastic deformation during occurring of major earthquake and cause unfavorable and uncertain response including total collapse or arduous and expensive repair work. Hence human society demands pushed the engineers, codes and design procedures to achieve higher performance, economy and safety, comprising life-cycle cost. So the codes are moving toward adopting performance based design framework. The performance based design idea is not new, limit state design is clear of performance requirement. For a defined performance purpose of a structure in terms of a state of damage, strain and deformation gives better index of damage rather than stress. And consequently, the target displacement applied at the first as the reaction framework of a (SDOF).

In this method performance based seismic design became notable by structure engineers and researchers since 1994 Northridge USA earthquake. Based on the requirement expand for PBSD, the structure should meet multiple performance purpose when subjected to earthquake. In order to achieve performance objective, such as Operational, Immediate occupancy, Damage control, Life safety and Collapse prevention those are (OP), (IO), (DC), (LS) and (CP) in the short sign respectively [FEMA 356] under earthquake ground motion, it is necessary to review the developed documents and approaches for RC SMF based on PBSD.

II. LITERATURE REVIEW

M.J.N.Priestley et al. has done a research with title of Direct displacement-based seismic design of structure (NZSEE Conference, 2007). The Author in this paper summarize the general design approach named Direct Displacement-Based seismic design of structures, the background of research and summarized the design procedure and he found that the study developed an approach with detailed thoughts of “real” engineering issues, like MDOF systems, irregularity of structural layout torsional response, P-Δ effects, and a wide range of different structural types including walls, frames, dual systems, bridges and seismic isolated structures.

Saleh Malekpour and Farhad Dashiti has done a research with title of application of the DDBD methodology (international journal of concrete structure). The Author in this paper investigated on the direct displacement based design (DDBD) approach for different types of reinforced concrete structural and he achieved that The PBPD method is a direct design method that uses pre-selected target drift and yield mechanisms as key performance objectives that determine the degree and distribution of expected.

Soon-Sik LEE et al. conducted an attempt with title of performance-based seismic design of steel moment frames using yield mechanism and target drift (world conference on earthquake engineering Agust,6,2004), The author has proposed a performance-based seismic design procedure for steel moment frames based on pre-selected target drift and yield mechanism using modified energy balance concept and plastic design methodology and found that the proposed method can produce structures that meet preselected performance objectives in terms of yield mechanism and target drift.

Revised Manuscript Received on August 10, 2020.

* Correspondence Author

Ahmad Farhad Farahmand, Student, Department of Civil Engineering, Alakh Prakash Goyal Shimla University, Mehli, Shimla, Himachal Pradesh, India. E-mail: farhadfarahmand290@gmail.com

Bhartesh Assistant professor, Department of Civil Engineering, Alakh Prakash Goyal Shimla University, Mehli, Shimla, Himachal Pradesh, India. E-mail: bharteshwork@gmail.com

Sayed Shuaib Qammer, Assistant professor and HOD, Department of Civil Engineering, Al Beroni University, Kohistan, Afghanistan. E-mail: shuaib.qammer@gmail.com

Published By: Blue Eyes Intelligence Engineering and Sciences Publication

DOI:10.35940/ijrte.C4250.099320

Retrieval Number: 100.1/ijrte
Displacement Analysis of RC Frames and its Seismic Performance Appraisal

Wen-Cheng Liao and Subhash C. Goel conducted an attempt with title of Performance-Based Plastic Design and Energy Based Evaluation of Seismic Resistant RC Moment Frame (journal of marine science and technology 2012). The author has presented for the first time application of the Performance-Based Plastic Design (PBPD) approach to seismic resistant reinforced concrete special moment frames (RC SMF) and developed that by modifying the determination of design base shear due to pinched hysteretic behavior and P-Delta effect, PBPD method can successfully applied to the design of RC moment frames.

III. METHODOLOGY AND CALCULATION

In India when the structure engineers’ analysis and designed structure for force and evaluate for displacement they used forced-based design method. It is clear for all that the displacement-based design method has direct relationship with structure deformations. So, to have better control on structural deformation and damage, various displacement-based design procedure has been suggested worldwide. Performance-based plastic design (PBPD) and Direct displacement-based design (DDBD) methods are the popular of all.

Set of frames those have been analyzed assumed to be made of concrete with 25Mpa for beams, 30MPa for columns compressive strength and modulus of elasticity of is 31x10^3 MPa. The steel has been used has 420Mpa yield strength and its modulus of elasticity is 2x10^5 MPa. The frames are 3 bays, the height of first story is 4.2m for all frames and 3.2m height another stories.

“Fig. 1” and “Fig. 2” Shows the two basic parameter of analysis in 2 methods.

A. Analysis of Study Frames by DDBD Method

Performance level describes the damage condition, and the damages are directly related to the deformations. Therefore, here performance levels are selected in terms of deformations (drift ratios). According to ATC-40 (Table 11-2), drift ratios for operational and life safety performance levels are 1% and 2%, respectively.

In calculation of masses, 100% of dead loads and 25% of live loads, are considered as per recommendation of IS 1389:2016 drift code.

Note that calculations are done for both drift ratios to obtain base shear forces for each frame. The base shear forces obtained for 2% drift ratio were significantly larger than the base shear forces obtained for 1% drift ratio, therefore, here calculations for only 2% drift ratio are shown in the Table 2 and initial parameters given in Table 1 only for 8 story frame.

| Table 1. Initial parameter for 8 story frame | value |
|---------------------------------------------|------|
| H1 (m)                                      | 4.200 |
| Hn (m)                                      | 26.60 |
| Drift limits                                 | 2%   |
| First story Displacement Δ₁ (m)              | 0.084 |
| Critical story displacement Δ₀ (m)           | 0.084 |
| Critical normalized inelastic mode shape     | 0.202 |
| Drift reduction factor ω₂                  | 1    |

Where, H1 and Hn are height of first story and roof respectively, and another parameter have defined bellow in procedure.

The design floor displacements of the frame are related to a normalized mode shape and critical story displacement; it is given in Eq. 1. That is 0.42 for roof.

\[ \Delta_0 = \omega_2 \cdot \delta_1 \cdot \left( \frac{H_1}{H_n} \right) \] (1)

Where \( \omega_2 \), is the drift reduction factor, that found from Eq. 2.

\[ \omega_2 = 1.15 - 0.0034H_n \leq 1.0 \] (2)

For calculation of design displacement for 8 story frame, from Eq. 3 and Table 2 it is equal to \( \Delta_d = \frac{40.95}{200.03} = 0.304 \text{m} \)

\[ \Delta_d = \sum_{i=1}^{n} \left( m_i \Delta_i \right) \sum_{i=1}^{n} \left( m_i \Delta_i \right) \] (3)

Effective height formula given:

\[ H_e = \frac{\sum_{i=1}^{n} \left( m_i \Delta_i h_i \right)}{\sum_{i=1}^{n} m_i \Delta_i} \] (4)

Hence from Table 2 it is equal to \( H_e = \frac{2623}{100.03} = 18.11 \text{m} \) and effective mass calculated by Eq. 5 and Table. 2

\[ m_e = \frac{200.03}{0.504} = 658 \text{ton} \] (5)

Equivalent viscous damping for the equivalent SDOF system is equal to: \( \xi_{eq} = 0.05 + 0.565 \left( \frac{1.039}{1.085} \right) = 12\% \), it has been procured using of \( S_d \) values that is in “Fig. 2”

Effective period \( T_e \) has been found 5.11 according location of frame that supposed it is located in zone- V and \( \Delta_d = 304 \text{ mm} \), so effective stiffness \( (k_e) \) has been found from Eq. 6.

\[ k_e = \frac{4 \pi^2 \cdot 658}{5.11^2} = 995 \text{ kN/m} \]
\[ K_s = \frac{4\pi^2 \ m_e}{T^2} \]  
(6)

Design base shear \( V_b \) is found from product of effective stiffness and design displacement which is given in Eq. 7
\[ V_b = 995 + 0.304 = 302 \text{ kN} \]
(7)

Where \( K_s \) is effective stiffness and \( \Delta_d \) design displacement

To find out the condition of P-Delta effect on frame we have to calculate overturning moment which is calculated and axial force to estimate stability index \( \theta_3 \). From Eq. (8)
\[ \theta_3 = \frac{P \Delta_{\text{max}}}{M_B} = 0.41 \]
(8)

Where \( P \), is the axial force due to gravity load, \( \Delta_{\text{max}} = \Delta_{d} \), \( M_B \) = OTM (overturning moment).

**B. Analysis of Study Frames by PBPD Method**

The important parameters for 8 story RC SMF is shown in Table 2. The time period is calculated based on Eq. 9 and spectral acceleration. \( (S_a) \) is calculated based on design basis earthquake as recommended by IS 1893 (2016) draft code.

| \( T \) (sec) | \( \theta_y \) | \( T_a \) | \( S_a \) | \( Y_r \) | \( Y_m \) | \( W_{\text{entary}} \) (kN-m) |
|-------------|------------|---------|----------|---------|---------|-----------------|
| 0.5985      | 0.50%      | 0.988   | 0.50     | 0.41    | 5.4     | 3.4             |

\( \Delta_{d} = \frac{1}{2} \Delta_{s} \)  
(9)

For calculate later force by PBPD Eq. (10) to (16) were used. It showed be noted the design base shear was calculated for 2\% maximum story ratio.

\[ E_s + E_p = \gamma \left( \frac{1}{2} M \cdot S_a^2 \right) = \frac{1}{2} \gamma \cdot M \cdot (\frac{1}{2\pi \cdot T_a} S_a \cdot g)^2 \]
(10)

where \( E_s \) and \( E_p \) are the elastic and plastic parts of the energy (work) required to push the structure up to the target drift respectively; \( S_y \) is the design pseudo-spectral velocity and \( S_a \) is the pseudo spectral acceleration, which can be get it from the seismic design response spectrum from IS 1893-1(2016) \( T \) is the natural period; and \( M \) is the total mass of the system.

With the assumed yield drift \( \theta_y \) for different type of structure \( (\theta_y = 0.5 \text{ for RC SMRF}) \), the energy modification factor, \( \gamma \) depends on the structural ductility factor \( (\mu_s) \) and the ductility reduction factor \( (R_p) \), and can be obtained by the following relationship:

\[ \gamma = \frac{2\mu_s - 1}{R_p} \]
(11)

By substituting the elastic and plastic component of the energy (work) needed to push the structure up to target drift in the equation \( (\omega_B = 1.15 - 0.0034H \leq 1.0) \) and by simplifying the equation the required design base shear becomes:

\[ \frac{V}{w} = -\frac{\alpha + \frac{\alpha^2 + 4\gamma^2 S_y^2}{2}}{2} \]
(12)

Where \( V \) is the design base shear and \( \alpha \) is a dimensionless parameter, which depends on the stiffness of the structure, the modal properties, and the design plastic level is given by:

\[ \alpha = (\sum_{i=1}^{n} (\beta_i - \beta_{i+1})h_i) \cdot \left( \frac{W_{h_i}}{W_{h_{n+1}}} \right)^{0.75} T^{-0.2} \]
(13)

The term \( \beta_p \) represent the plastic component of the target drift ratio, which is \( \beta_p = \beta_u - \theta_3 \), the proposed New lateral force distribution equation for PBPD method is given:

\[ F_i = C_{ri} V \]
(14)

Where,

\[ C_{ri} = (\beta_i - \beta_{i+1}) \cdot \left( \frac{W_{h_i}}{W_{h_{n+1}}} \right)^{0.75} T^{-0.2} \text{ when } i = n, \beta_{n+1} = 0 \]

\[ \beta_i = \frac{\gamma_i}{\gamma_m} = \left( \frac{\sum_{j=1}^{n} W_j h_j}{W_{h_{n+1}}} \right)^{0.75} T^{-0.2} \]
(16)

In the above equation \( \beta_i \) represent the shear distribution element at level i, \( V_i \) and \( V_n \), are the story shear forces at level i and at top (nth) level respectively, \( W_j \) is the seismic weight at level j, \( h_j \) is the height of level j from base, \( W_{h_{i+1}} \) is the weight at the top level, \( h_{i+1} \) is the height of roof level from base. \( T \) is the fundamental period, \( F_i \) is the lateral force at level i , \( h_i \) and \( V_i \) is the total base shear.

For analysis of all frames the procedure were applied and based on that spread sheet for each story was made to analyze frame for DDBD and PBPD. The obtained result for each story is shown here inform of graphs “Fig. 3” and “Fig. 4”.

“Figure. 3” shows Distribution of lateral force of all frames for both methods and “Figure. 4” shows seismic moments of all frames for both methods.
“Figure 3” Distribution of lateral force of all frames for both methods: “a” 4 story frames, “b” 8 story frames, “c” 12 story frames, “d” 15 story frames.
C. Seismic Evaluation of Study Frames

Seismic assessment and design of structure is required because of earthquake. Earthquake may lead to significant damage and/or collapse of building, infrastructure systems etc. To quantify the damage of both structural element and entire structure, design methodology and/or assessment procedure developed based on nonlinear static and dynamic analysis.

In this study for performance evaluation of RC frame, designed by PBPD and DDBD approaches, nonlinear static (pushover) analysis were performed. Nonlinear static (pushover) were carry out by using ETABS 15 program (CSI 2016). The results shown by proper graphs.

The nonlinear pushover analysis procedure naturally called Pushover Analysis or POA. POA is a technique in which a computer model of a structure is subjected to a predetermined lateral load pattern, which approximately represents the relative inertia forces generated at positions of fundamental mass.

The intensity of the load is increased, i.e. the structure is ‘pushed’, and the succession of cracks, plastic hinge formations, yielding, and the load at which failure of the various structural components occurs is recorded as function of the increasing lateral load.

This incremental process continues until a predetermined displacement limit.

The main outcome of pushover analysis is capacity curve (Base shear force vs top displacement), from target displacement. The capacity curve shows nonlinear behavior of the structure under increasing base shear force. Furthermore, at each step of pushover analysis structural elements will start yielding continuously one after other which will cause different damage states to develop in these elements (i.e. plastic hinges will occur in elements), and after the structure reaches to its yield capacity, the structure as a whole will start losing its lateral stiffness. The slope of the capacity curve will be change, which shows a nonlinear behavior of the structure.
"Fig. 5". Capacity Curve “a” 4 story DDBD “b” 4 story PBPD “c” 8 story DDBD “d” 8 story PBPD.

"Fig. 6". Capacity Curve “a” 12 story DDBD “b” 12 story PBPD “c” 15 story DDBD “d” 15 story PBPD.

"Fig. 7". Capacity Curve “a” 18 story DDBD “b” 18 story PBPD “c” 20 story DDBD “d” 20 story PBPD.
IV. CONCLUSION

1. DDBD used effective time period $T_e$, corresponding to design displacement $\Delta_d$, and equivalent damping $\xi_{eq}$, which can be obtained from displacement spectra.

Displacement spectra can be blotted by using acceleration response spectrum as defined for 5% damping for 1.0 PGA by IS 1893 (part I):2016 draft code and can be formulated for design basis earthquake as $(S_a = \frac{2}{2} \cdot S_g)$. Hence $T_e$ become long and caused lesser design base shear and lateral force distribution.

2. PBPD use elastic response acceleration, corresponding to design basis earthquake. IS 1893 (part I):2016 draft code gives $S_a = \frac{2}{2} \cdot S_g$ and cause lesser design base shear.

3. Same ductility factor was used for DDBD and PBPD to evaluate the result of both methodologies.

4. For 4 and 8 story frame lateral force base shear and distribution obtained from DDBD is lesser than PBPD.

5. For 12 and 15 story frame based shear and lateral force distribution seems to have nearby values.

6. Due to lesser amount of base shear and lateral force distribution, the design of member caused to lighter sections.

7. The base shear obtained through nonlinear static pushover analysis as shown in fig 5(a,c,), fig 6(a,c) which is larger than the base shear obtained from DDBD procedure. Accordingly the base shear obtained through nonlinear static pushover analysis as shown in fig 5(b,d,) and fig 6(b,d) for DDBD frames which is larger than the base shear obtained from PBPD procedure. The frames designed by both methods are much stiffer than expected.

8. The design base shear is less in PBPD method compared DDBD method, this is more significant in tall building.

9. The lateral load distributed evenly in both methods of PBPD and DDBD.

10. Performance point exist for all frame of both methods.

11. The 4 and 15 storied frames of DDBD method is lied below LS level, 8 and 12 storied frames of PBPD method lied beyond level but below capacity level in terms of capacity.

12. All frames located beyond LS level in DDBD method.

V. FUTURE SCOPE AND RECOMMENDATION

The seismic codes those exist in India for analysis and design of structures, they proposed the methods of (Response Spectra, Equivalent Static and Dynamic analysis) for estimation of seismic force. As explained earlier displacement-based design is the popular method that use for analysis and seismic design in many countries.

According this study, it is possible to combine these two methods with new version of IS code, but it is suitable and efficient when the specification of current code explained and combined with these methods properly and We should do seismic performance evaluation of structure by pushover and time history analysis to ensure the structure has enough strength and ductile because these methods are still in progress stages. There is not any code in India to analysis of structure against earthquake by nonlinear method but we are able to do it by the help of some another codes like FEMA and ASCE.
REFERENCES

1. Subhash C. Goel and Shih-Ho Chao, (2008), Performance based plastic design: Earthquake Resistant Steel Structure, ICC publication, USA.
2. Shibata A, sozen m. (1976), “Substitute structure method for seismic design in reinforced concrete “. J struct Div, ASCE, Vol.102, No.1, PP 1-18.
3. Moechle JP. (1996), “displacement-based seismic design criteria”, In: proceedings of 11th world conference on Earthquake Engineering, Acapulco, Mexico. Paper no. 2125. Oxford: pergamon.
4. SEAONC. (Vision 200), “performance based seismic design of buildings”, vol. I and II. conceptual framework Sacramento (CA): Structure Engineering Association of California.
5. ATC 40(1996), “Seismic evaluation and retrofit of existing concrete buildings”, Redwood city (CA): Applied Technology Council.
6. FEMA 273 (1996),” NEHRP guidelines for the seismic rehabilitation building” FEMA 274 commentary. Washington (DC): Federal Emergency management Agency.
7. R> O> Hamburger, C. Rojahn and J. A. Heintz , and m. G. Mahoney. (2012) “ FEMA p58: Next-Generation Building Seismic performance Assessment Methodology”, WCEE.
8. GULKAN, P. and Sozen, M.A. (1974). Inelastic response of reinforced concrete structures to earthquake motions. ACI journal. 71(12): p. 604-610
9. Shibata, A. and Sozen, M.A. (1976). Substitute-structure method for seismic design in RC journal structure division. 102(1): P. 1-18
10. Moehli, J.P. (1992). Displacement-based design of building structures subjected to earthquakes. Earthquake spectra. 8(3): P
11. Kowalsky, M.J, Priestly, M.J.N, and MacRae, G.A, (1995). Displacement-Based Design of RC Bridge columns in seismic Reoions. Earthquake Engineering and Structural Dynamics. 24(12): P. 1623-1643.
12. Calvi, G.M. and kingsly, G.R, (1995). Displacement-based seismic Design of Multi-Degree-of-freedom, Bridge Structura. Earthquake Engineering and Structure Dynamics. 24(9): p. 1247-1266.
13. Chopra, A.K. and Goel, R.K. (2001). Direct Displacement-based Design: Use of Inelastic Design Spectra Versus Elastic Design Spectra. Earthquake Spectra, EERI 17(1): p. 47-64.
14. Priestley M.J.N., Calvi, M.C., and Kowalsky, M.J. 2007., Direct Displacement-Based Seismic Design of concrete building. Bulletin of the New Zealand Society for Earthquake Engineering. 33(4), 421-444.
15. Sullivan, T.J., Priestley, M.J.N., and Calvi, G.M., (2006). Direct Displacement-Based design of Frame-Wall Structures. Journal of Earthquake Engineering. 10(sup001): p. 91-124.
16. Priestley, M.J.N., and Calvi, M.C., and Kowalsky, (2007). Direct Displacement-Based design of Structures, NZSEE Conference.
17. Sullivan, T.J. and Lago, A., (2012). Towards a simplified Direct DBD Procedure for the seismic design of moment resisting frames with viscous dampers. Engineering Structures, 35: P. 140-148.
18. Malekpour, S., GHaffarzadeh, H., and Dashi, F., (2013). Direct displacement-based design of steel-braced reinforced concrete frames. Structural Design Tall and Special Buildings. 22(18): P. 1422-1438.
19. Chao, C.-H, Goel, S. C., and Lee, S.-S. (2007). “A seismic design of lateral force distribution based on inelastic state of structures,” Earthquake Spectra, Earthquake Engineering Research Institute, Vol. 23, NO. 3, pp. 547-569.
20. Leelataviwat, S. 1999 “Drift and Yield Mechanism based Seismic Design and Upgrading of Steel Moment Frames.” Ph.D. Thesis, Department of Civ. & Env. Engrg., University Michigan, Ann Arbor, MI, USA.
21. Lee, Soon-Sik and Goel, S. C. 2001, “Performance-Based Design of Steel Moment Frames Using Target Drift and Yield Mechanism” Report No. UMCEE 01-17, Department of Civ, & Env. Engrg., University of Michigan, Ann Arbor, MI, USA.
22. Goel, S. C. and Chao, S.-H. (2009). Performance-Based Plastic Design: Earthquake-resistant Steel Structures, ICC, USA.
23. Wen-Cheng Liaol and Subbash C. Goel, (2012). “Performance-Based Plastic Design and Evaluation of Seismic Resistant RC Moment Frame”, Journal of Marine Science and Technology.
24. Priestley, M.J.N., and Calvi, G.M., and Kowalsky, M.J., “Displacement-Based design of Structures”, IJSS Press, Press, pavia, Italy, 2007.
25. Alok Madan, Arshad K. Hashmi., “Performance based design of masonry infilled reinforced concrete frames for near-field earthquakes Using energy methods” International Journal of Civil, Environmental,