Review on Displacement based design methods for RC Structures in India

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Received: January 30, 2019 Accepted: March 13, 2019

ABSTRACT: *Presented in this paper is an updated literature review of the Displacement-Baseddesign (DBD) methods in India. Force Based Design procedure is commonly adopted by code IS 1893-2016 for seismic analysis of the structures. To get more anticipated structural behavior prone to intense earth shaking, understanding of eventual structural performance as non-linear relation among force and deflection are essential to know. An alternative design method based on displacements have been developed and implemented for the structures under strong earthquake ground motions. Displacement Based Design method is one of the methods and is widely adopted with Force Based Design Method (FBD) all over the world. This paper represents different Displacement Based Design methods which are Direct Displacement based design (DDBD) method, DDBD method using inelastic spectrum, Capacity spectrum method, Yield point spectrum method, Deformation controlled design, Performance based plastic design method.*

Key Words: : *Displacement Based Design methods, Performance-based plastic design, Force Based Design.*

I. Introduction

Structural engineer designs the structure which ensure to sustain different types of load imposed by various activity. Nowadays in India Design of structures is carried out using current seismic code IS 1893:2016 and standard procedure to satisfy some performance level and life safety parameter (earthquake design). The current design of the structure only ensures that the structure will not collapse and have the adequate strength but the cost factor is of less attention. In addition to that, life safety performance level is obtained for different structures, the concept of uniform risk is not satisfied.

In the modern time the main earthquakes, it has been observed that the seismic risk in metropolitan city is become higher and the structural convenience is far-away from socio-economically admissible levels. It is necessary to change current state and it is well recognised that most patronise way of executing this with Displacement Based Earthquake Engineering (DBEE) in which the design of structure is depends on the anticipated performance of the structural members prone to strong earth motions.

Over the last decade, as the importance of displacement, rather than forces, has become better appreciated, and because of that Displacement based seismic design (DBSD) procedure is continuously under development and a new approach for the design of new structures and evaluation and retrofitting of existing structures, which attracts many professionals and researchers, recently. Structures can be designed with DBSD approach with more understanding of the risk of damage, money losses and occupancy interruption. Furthermore, structures designed through DBSD approach, would be able to show different performance levels for different earthquake ground motion.

ADVANTAGES OF DBSD METHOD

In Comparison of standard design methods, displacement-based design gives an efficient way for inspection of the performance scope of a structure. It could also provide authentic performance at a economical cost, to check the equal performance of alternatives, or affirm better performance required for ultimate convenience. It facilitates a foundation to determining at what cost, level of serviceability and safety and level of asset protection are permissible to stakeholder's adjunct to the definite requirements of a design.

DBSD is both productive and efficient to avert future losses due to earthquake. The methodology used for implementation ofdisplacement-based seismic design is transferrable, and could be adjusted for use in other excessive risk including wind, snow, flood, fire.

The benefits of DBSD over the procedures followed in the present seismic design code are outlined as follow:

1. Multilevel seismic risks are considered with an attention on the understanding of performance targets.
2. The design is based on performance objectives which are defined by technical parameters as performance criteria.
3. Performance of building components guaranteed due to limited beyond elastic deformation in augmentation to ductility and strength.
4. The structure will satisfy the recommended performance objectives satisfactorily with accepted credibility.
5. An analytical method through which the performance of the structure, particularly the nonlinear behaviour of structure is conceivably obtained.

DESIGN PROCEDURE OF THE DBSD METHODS

In this paper six methods were selected, a brief description of which is given in table 1.

Table 1: important features of DDBD methods under review

Sr No.	Method	Important features
1	Direct Displacement based design (DDBD)	• Substitute structure approach • Based on secant stiffness • Uses elastic displacement spectrum with equivalent damping
2	DDBD using inelastic spectrum	• Procedure same as method 1. • Initial stiffness approach • Uses inelastic displacement spectrum
3	Capacity spectrum method	• Capacity and demand curves in acceleration-displacement format (ADRS) • Needs a pushover analysis • Secant stiffness approach
4	Yield point spectrum method	• Design to a number of performance criteria in a single step • Based on initial stiffness • Utilizes inelastic yield point spectra • Ductility is controlled
5	Deformation controlled design	• Integrates DBD approach within the entire structural design process • Considers full multi storeyed building • Based on initial stiffness
6	Performance based plastic design	• Considers full multi-storeyed building • Uses energy concepts to calculate base shear • Uses a new distribution of lateral force consistent with inelastic dynamic response • Yielding members are designed by plastic design and non-yielding members by capacity design principles.

Direct Displacement based design (DDBD)

The primary ideology of DDBD is that structure should be designed to attain a predetermined performance objective, determined by drift limits, prone to a predetermined intensity of seismic severity. In Direct displacement-based design methodology, the original structure (MDOF) is converted into the SDOF system. This system is represented by equivalent mass (me), equivalent stiffness (K_e), equivalent height (H_e) and equivalent viscous damping. In DDBD method design displacement is use for design for that design displacement spectra are used. Set of equations
are defining the relation of displacement ductility and damping.

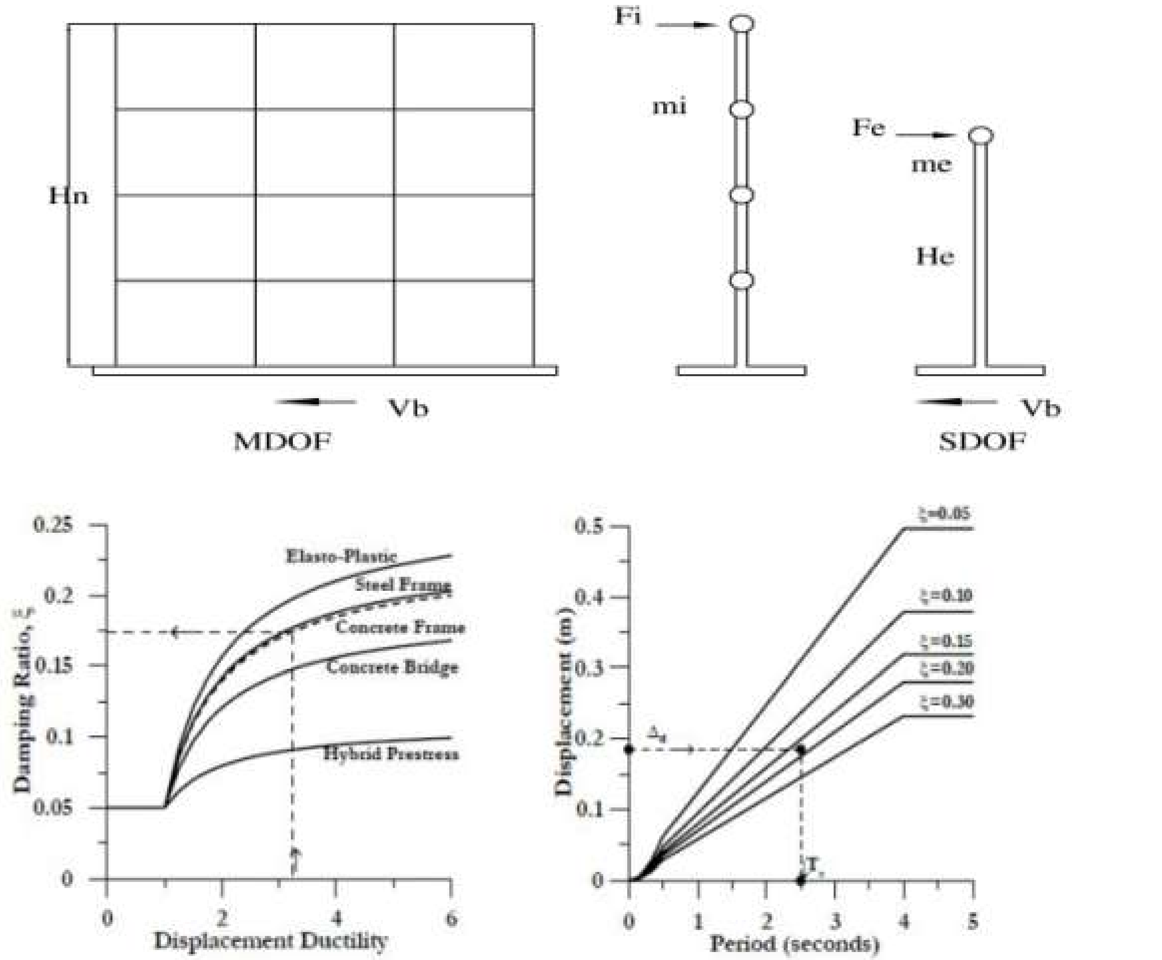

Figure 1: Fundamental of DDBD procedure

Steps of DDBD procedure

Step 1: Compute the seismic weight of the building (*W*).

The seismic weight of the building is the weight obtained from the sum of all floors seismic weight, the floor includes dead weight and imposed load.

Step 2: Find out design displacement of SDOF system

The design story displacements (Δ_i) of the specific masses are obtained from:

$$\Delta_i = \omega_\theta \theta_c H_i \frac{4H_n - H_i}{4H_n - H_1}$$

$$\Delta_d = \frac{\sum m_i \Delta_i^2}{\sum m_i \Delta_i}$$

Where,

ω_θ=reduction factor for higher mode amplification of drift =1.15 - 0.0034Hn≤ 1.0

H_n= height of the building, H_i and H_1 are the heights of level i and 1 respectively

θ_c= The code drift limit for considered limit state.

Equivalent Mass of the SDOF structure & Equivalent Height of the SDOF structure

$$m_e = \frac{\sum m_i \Delta_i}{\Delta_d}$$

$$H_e = \frac{\sum m_i \Delta_i H_i}{\sum m_i \Delta_i}$$

Step3: Estimation of the level of equivalent viscous damping (ξ)

The equivalent viscous damping equation is given below

For frame building

$$\xi_{eq} = \xi_0 + 0.565\,\frac{\mu-1}{\mu\pi}$$

For concrete wall building

$$\xi_{eq} = \xi_0 + 0.444\,\frac{\mu-1}{\mu\pi}$$

Displacement ductility of SDOF structure

$$\mu = \frac{\Delta_d}{\Delta_y}$$

Where μ is displacement ductility.

Where Δ_d is design displacement, Δ_y is yield displacement

$$\Delta_y = \theta_y \times H_e$$

Where H_e is effective height, θ_y is yield rotation

$$\theta_y = 0.5\,\varepsilon_y\,\frac{L_b}{H_b}$$

Step 4 Determination of the effective period (T_e) of structure

The elastic displacement spectrum S_{de} for 5%damping used for DDBD is defined by Eurocode 8

$$S_{de} = S_a(T)\left(\frac{T}{2\pi}\right)^2$$

Where, Sa is elastic response spectrum, displacement spectrum other than 5% damping can be found out from the formulation in Eurocode 8

$$S_{d\xi} = S_{D5\%}\left(\frac{10}{5+\xi}\right)^{\frac{1}{2}}$$

Determination of the effective time period (T_e) of the SDOF structure at maximum displacement response by using the design displacement defined in equation 3.7 and the design displacement response spectrum corresponding to the damping level estimated in equation.

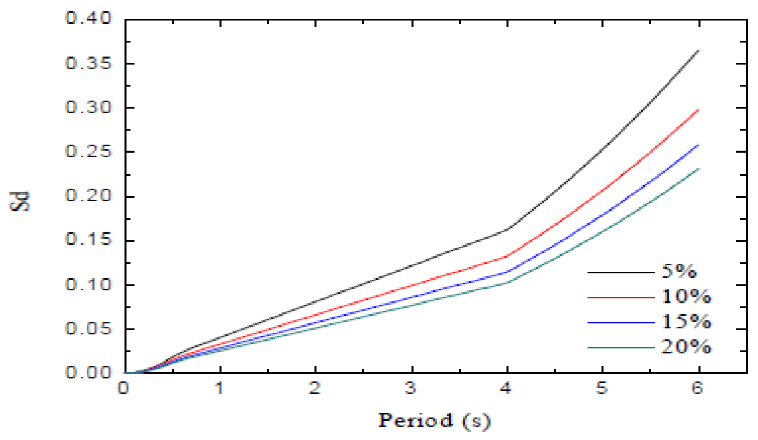

Figure 2 Design response spectra for medium soil PGA=0.12g

Step 5 The effective stiffness Ke of the substitute SDOF structure

$$K_e = \frac{4\pi^2 m_e}{{T_e}^2}$$

Where, m_e is effective mass, Te is time period that calculated from the response spectra

The design base shear $V_{base} = K_e \Delta_d$

Distribution of base shear carried out using following formula

For n <10 use equation

$$F_i = V_b \frac{m_i \Delta_i}{\sum m_i \Delta_i}$$

For n>10 use equation

$$F_i = F_t + 0.9\, V_b \frac{m_i \Delta_i}{\sum m_i \Delta_i}$$

DDBD using inelastic spectrum

Inelastic spectra for various ductility levels were developed using Newmark-Hall method. Here the allowable plastic rotation (θ_p) for life safety performance is taken as 0.01 radians (ATC 40). Design displacement is given by the equation $\Delta_d=\Delta_y+ H_e\theta_p$, where Δ_y is yield displacement and H_e is effective height of frame. From the inelastic spectrum, fundamental period is obtained and the corresponding initial elastic stiffness is calculated. Initial estimation of base shear is given by $V_b = K_i\Delta_y$. This base shear is distributed as lateral load and the frame is designed for all load combinations given in IS1893:2016. Pushover analysis, for this lateral force distribution is done to find out yield displacement and the corresponding yield force. The frame is redesigned, considering this yield force as the base shear and the above procedure is repeated till yield force determined by pushover analysis and design yield force matches.

Capacity spectrum method

Capacity spectrum method is reliable tool to anticipate seismic capacity and demands of the structures expose to designated earthquake ground motions. In CSM capacity of the structure is compared to earthquake ground motion demands of using the graphical method. "The Force vs Displacement curve, also known as a nonlinear pushover curve is used to represent capacity of the structure. The recent arrival of performance-based design may allow the nonlinear static push-over analysis to evaluate the structural capacity. The roof displacements and base shear are transformed to corresponding spectral accelerations and spectral displacements, respectively, through the coefficients which represents effective modal masse and modal participation factor. The capacity spectrum is determined by these spectral values. The response spectra represent earthquake ground motion demands." A graphical interpretation that accommodate both demand and capacity spectra, an junction of the curves shows the performance of the structure due to seismic action.

Yield point spectrum method

Yield point spectra for different ductility levels are developed. Target displacement is decided to assure the drift limits for desired damage states. For this objective displacement, the drift control branch is dawn satisfying $\mu\, \Delta_y = \Delta_T$ and the permissible design region is recognized equivalent to allowable ductility. An appropriate $\Delta_y$for the structure is elected and from that calculation of essential yield strength coefficient (C_y) being processed. Base shear can be calculated using the equation

$V_b = m_{eff}C_yg$.

Deformation controlled design

The much appropriate method for accomplishment of the aims of performance-based seismic design for displacement-based performance purpose seems to be the deformation-controlled design method. It is expected that deformation-controlled method can be added in next codes, either by developing force-based design by conformation of deformation objectives or by the improvement of direct deformation-based design methodologies. Many software is required to anticipate the inelastic dynamic response of complex structures. Extended attempts are supposed to be require to expand versatile and robust, yet efficient, numerical standard software to replicate seismic response of 3-D structure by considering different non-linearities. It is essential that these procedures be design-oriented instead of research-oriented. The popular design procedures may have to go further the procedures that considers a SDOF representation of the structure. Because of this appropriation, there is critical limitation on the accuracy of the predicted performance. At the stake of sacrificing simplicity, it is essential to get a proper prediction of the local displacements inside the structure, consider higher-mode effects, and account for the sequence of element damage. Nonlinear static pushover analysis combined with latest methodology (other than Single degree of freedom-based spectra) to get demand, or nonlinear inelastic dynamic analysis, may give a much appropriate approximation of the performance.

Performance based plastic design

Performance-Based Plastic Design (PBPD) method has been recently developed to obtain enhanced performance of earthquake resistant structures. The main performance limit states utilized in the PBPD method are the pre-assumed yield mechanism and target drift, which are directly related to level of structural damage and distribution, respectively. During the severe earthquake, in order to avoid the structural collapse, to dissipate seismic energy at most, and to endow the structure with sufficient strength and ductility, a reasonable yielding mechanism should be chosen at the beginning of the design.

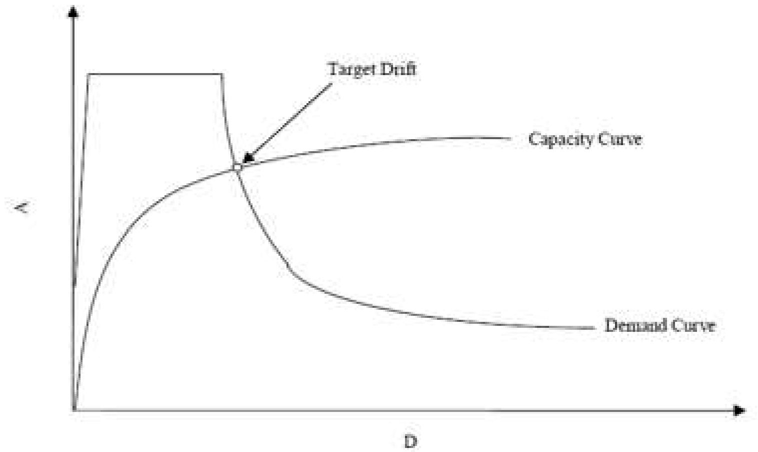

Figure 3: Procurement of the Target Drift

A modern lateral force distribution is applied which is based upon dependent storey shear distribution compatible with results of dynamic inelastic response. Design is executed as plastic deign to the members and connections of the frame in order to attain the intentional yield mechanism and behaviour. By intersection of the capcity diagram and demand diagram of the structure the intended drift is achieved. A plastic hinge pattern in beam members and at the base column is chosen for yield mechanism as shown in figure 2.

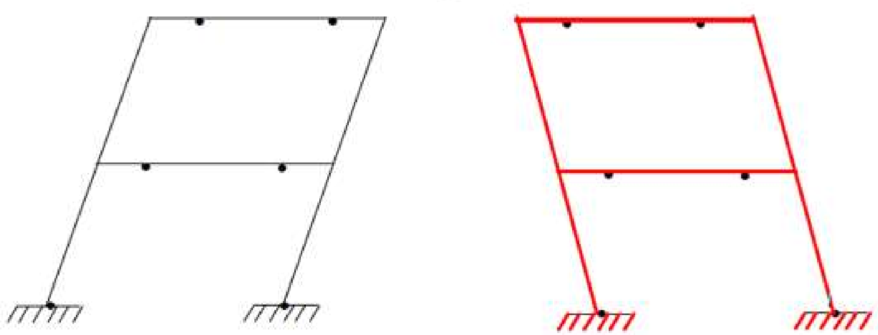

Figure 4: The Formation of Plastic Hinges for the yield mechanism

Steps of PBPD methodology-

Step 1: **Fundamental Natural Time Period (T)**

Fundamental Natural Time Period (T) for the frame can be calculated as per IS-1893-2016 clause 7.6.2(a).

$T = 0.075\ h^{0.75}$

Where,

h = height of structure (in meter)

Step 2: Design Base Shear

In PBPD procedure main step is calculation of the design base shear for a predetermined damage level and is estimated through comparing the work required to push the structure uniformly till the intended displacement to that needed by an equivalent elastic-plastic SDOF system to attain the equal condition. Assuming an idealized E-P force-deformation behaviour of the system (refer below Figure),

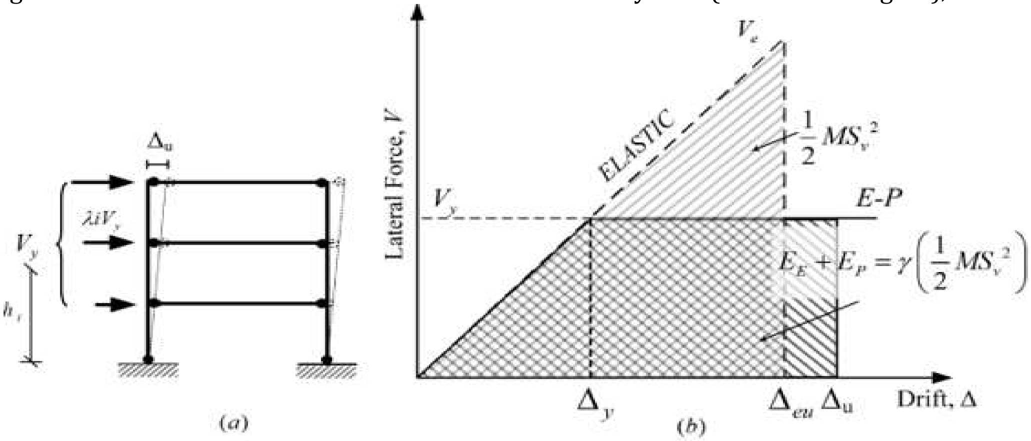

Figure 5: PBPD concept

The equation of work-energy is given by:

$(Ee \; + \; E\,p\,) \; = \gamma * (\frac{1}{2}\,M*S_v^2) = \frac{1}{2}\,\gamma * M * (\frac{T}{2\pi}S_a * g)^2$

Here E_e and E_p = The elastic and plastic components of the energy (work) needed to push the structure up to the target drift, respectively.

The admissible solution of Equation (3-5) gives the required design base shear coefficient, V_y/ W :

$$\frac{Vy}{W} = \frac{(-A_h + \sqrt{A_h{}^2 + 4\gamma Sa^2})}{2}$$

Where A_h is a dimensionless parameter given by,

$$A_h = h^* \frac{\Theta_p \; 8\pi^2}{T^2 \; g}$$

θ_p = plastic part of the target drift ratio; which is,
$\theta_p = \theta_u - \theta_y$ and $h^* = \sum (\lambda_i h_i)$

Step 3: Lateral Force calculation and distribution

choose a desired Target Yield Mechanism for design earthquake hazard.

Figure shows the design yield mechanism of moment resisting frame subjected to lateral force and pushed through the design target plastic drift, "Δp"

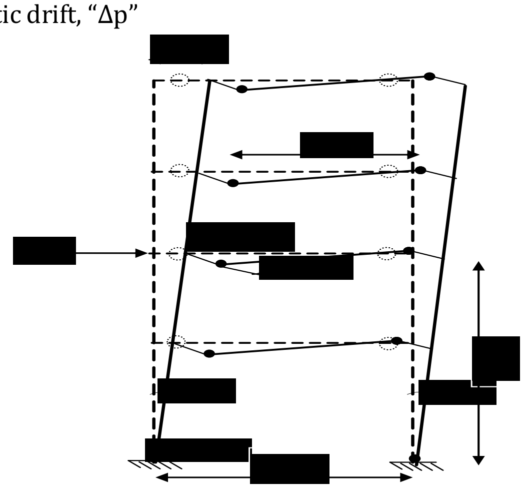

Figure 6: Pre-Selected Yield Mechanism of Moment Frame with Beam Plastic Hinges away from Column Faces

Calculate the shear distribution factor "β_i" of each floor. (Chao & Goel, 2007)

$$\beta i = \frac{V_i}{V_n} = \left(\frac{\sum_{j=1}^{n} w_j h_j}{w_n h_n}\right)^{0.75T^{-0.2}}$$

Calculate A_h (Dimensionless parameter). (Housner, 1960) It is estimated through comparing the work required to push the structure uniformly up till the intended drift to that required by an identical EP-SDOF system to attain the equal condition. The formula for A_h can be given as by,

$$A_h = \left(\sum_{i=1}^{n}(\beta_1 - \beta_{i-1})h_i\right).\left(\frac{w_n h_n}{\sum_{j=1}^{n} w_j h_j}\right)^{0.75T^{-0.2}}.\left(\frac{\theta_p 8\pi^2}{T^2 g}\right)$$

Calculate Story shear "V_b" (Chao & Goel, 2007)

$$V_b = \left(\frac{-A_h + \sqrt{A_h^2 + 4YSa^2}}{2}\right) * W$$

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

$$S_{a,\text{ inelastic}} = \frac{S_{a,\text{ elastic}}}{R_\mu}$$

Find the Design Lateral force "Q_n" at top Floor.

$$Q_n = \frac{V}{\Sigma(\beta_i - \beta_{i+1})}$$

Find the Design Lateral force "Q_i" of each level.

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

Step 4: Determination of Probable moment in beams:

$$M_{pc} = \frac{\psi V' h_1}{4}$$

$$\beta_i\, M_{pb\text{-positive}} = \frac{\beta_i(\sum_{i=1}^{n} Q_i\, hi - 2\, Mpc)}{(1+X)\sum_{i=1}^{n}(\beta i\, .\, L/L')}$$

Step 5: Design of columns:

$$V_i = \frac{|Mu_{\text{- positive}}|_i + |Mu_{\text{- negative}}|_i}{2} + \frac{W_{i\text{-tributary}} \cdot L'}{L'}$$

$$V_i' = \frac{|Mu_{\text{- positive}}|_i + |Mu_{\text{- negative}}|_i}{2} - \frac{W_{i\text{-tributary}} \cdot L'}{L'}$$

Column Forces:

$$F_{L\text{-int}} = \frac{\sum_{i=1}^{n}(|M_{u\text{-negative}}|_i + |M_{u\text{-positive}}|_i) + \sum_{i=1}^{n}\{V_i + V_i'\}\cdot(L-L'/2)_i + 2Mpc}{\sum_{i=1}^{n}\alpha_i h_i}$$

$$F_{L\text{-ext}} = \frac{\sum_{i=1}^{n}(M_{u\text{-negative}})_i + \sum_{i=1}^{n} V_i\cdot(L-L'/2)_i + Mpc}{\sum_{i=1}^{n}\alpha_i h_i}$$

$$\alpha_i = \frac{(\beta i - \beta i_{+1})}{\sum_{i=1}^{n}(\beta_i - \beta i_{+1})}$$

Step 6: After getting the proper design bending moments, shear force and axial force for columns by Free-body diagram, the columns are designed for bending moment as per IS 456:2000.

RESULTS AND DISCUSSION

In DDBD method the base shear is given by the equation $V_b = K_e\Delta_d$ where K_e and Δ_d denote the stiffness and design displacement respectively. As the number of storeys increases, both K_e and Δ_d increase, and thus base shear increases. In the second method which is DDBD by using inelastic spectrum uses inelastic spectra for different ductility levels. Once the initial stiffness is obtained, base shear is calculated as $V_b = K_i\Delta_y$, where K_i and Δ_y denote the initial elastic stiffness and yield displacement respectively. Base shear obtained by this method is higher than the first method for low rise frames, for high rised frames the base shear becomes almost same. While the other methods capacity spectrum method, Yield point spectrum method, Deformation controlled method, gives the higher values of base shear compared to both the methods. Also, lateral load distribution in all the methods mentioned above is same but the PBPD method follows the different methods for lateral load distribution. In PBPD method the procedure for calculating the design moments is based on plastic design corresponding to plastic yield mechanism. It has been noticed that using the PBPD method, it gives the most economical design for beams and also for columns the size is increasing from top to bottom, the lowermost columns becomes very heavy compared to the uppermost columns. DDBD method gives the lower estimates of design moments compared to other methods. The most economical design in terms of performance levels is given by DDBD and PBPD methods. Also, it has been observed that taller the frames give maximum values of displacements because the frames are more flexible and lateral load distributed is also less.

CONCLUSION

Displacement based design methods have emerged recently as a more rational and economical alternative to the conventional forced based method: however, they are yet to be adopted by national codes. In this paper six displacement-based design methods are studied in details.

Based on the study, it is seen that the original DDBD proposed by Priestley and Kowalsky appears to be the most promising. It calculates the base shear corresponding to secant stiffness at effective displacement of equivalent SDOF system and utilizes the displacement spectra at equivalent damping. It gives a entire design process and provides economical design for low to medium rise frames; but in lower seismic zone for tall structures, this results in conservative designs, as the design displacement capacity is much more than the seismic design. The relative conservative structural design obtained using DDBD, especially for taller frames, shows the need for some modification and iteration in design steps.

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