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Application of DDBD and FBD Methodology for 8-Story RC Frame Using IS 1893 Spectra

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Abstract

This study investigates the direct displacement based design (DDBD) and convectional force based design (FBD) approach for 8 storey RC frame building in DDBD methodology the displacement profile is calculated and the given MDOF is converted to equivalent single degree of freedom system. After calculating the effective period, secant stiffness, and viscous damping of the equivalent structure, the base shear is obtained, based on which the design and detailing process can be carried out. The designed frames as per DDBD and FBD approach are then analyzed using nonlinear pushover analysis to obtain the capacity curves and response reduction factor. Results of the analysis and comparison of 'R' factor indicate the efficiency of the DDBD approach for RC frame buildings

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1 Introduction

Current force-based design procedure adopted by most seismic design codes allows the seismic design of building structures using elastic design spectra. A fundamental problem with FBD method is when applied to a RC structure is the selection of the appropriate member stiffness assume member size before the design forces are determined. This forces are then distributed in their assumed stiffness, if member size is varying from the initial assumption then the calculated force is no longer be valid, and recalculation and recalculation, through rarely carried out, is theoretically required

(Priestley M. , 1993) had identified some of fundamental shortcomings with existing force-based seismic design methodology. A relatively new PBSD (performance-based seismic design) procedure called the direct displacement-based design (DDBD) proposed by (Priestley & Kowalsky, 2000) has currently received notable acceptance among researchers. PBSD 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 PBSD approach with more understanding of the risk of casualties, economic losses and occupancy interruption. Furthermore, structures designed through PBSD approach, would be able to show different performance levels for different earthquake ground motions. Performance objectives are the combination of performance levels and hazard levels, and Performance levels can be determined by damage states of the structural and non-structural components.

(Priestley M. , 2000) had outline the DDBD and discuss it in the context of FBD and earlier design approaches which contained some elements of PBD (performance based design) Author concluded that significant differences in seismic performance can be expected from structures designed with this approach when compared with force-based/displacement check approaches. (Priestley, Calvi, & M.J.Kowalsky, 2007) summarizes the general design approach, the background research and some of the more controversial issues related to direct displacement based design of various types of structural system. (Sullivan, Calvi, & M. J. N., 2003) presented a study that uses 8 different Displacement Based Design methods to carry out the seismic design of five different case studies. Some significant limitations with the eight methods have been identified through their application to example. The study also shows even though all of the DBD methods using the same design parameters, a large variation in design strength is acquired. (Sullivan, Priestley, & Calvi, 2005) proposed DBD methodology for structures that are comprised of both frames and then tested through examination of several case studies. (Cardone, Dolce, & Palermo, 2008) studied and explain direct displacement-based design procedure for RC framed buildings with different types of Isolation Systems. analyses Results using Nonlinear Time-History Analyses on different configurations of buildings shows the accuracy of the Direct displacement based design procedure in the attainment of the performance objective of the design. (Varughese, Menon, & Prasad, 2012) had proposed the simplified displacement based design for the stepped buildings in such a manner that the design of stepped frames and orthogonal frames can be done separately. (Malekpour & Dashti, 2013) had investigated the seismic response of different types of structural system like MR frame, dual-wall system and steel braced frame. Analyses and comparison of the nonlinear time-history analysis results indicate efficiency of the DDBD approach for different RC structural systems.

In this study, Direct Displacement-Based Design (DDBD) approach in the context of PBSD is implemented for 8 storey RC frame buildings and its performance is evaluated using nonlinear pushover analysis.

2 Description of DDBD and FBD procedure

2.1 Direct displacement based design (DDBD)

The fundamental philosophy of DDBD is that structures should be designed to achieve a specified performance level, defined by strain or drift limits, under a specified level of seismic intensity. 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 (Ke), equivalent height (He) and equivalent viscous damping. In DDBD method design displacement is use for design for that design displacement spectra are used. A set of equations are defining the relation of displacement ductility and damping

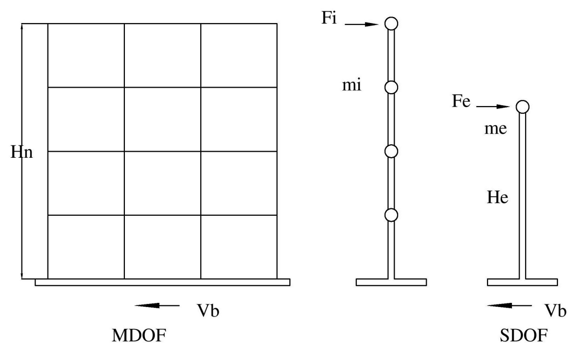

Figure 1: Simplified model of a multi-story building

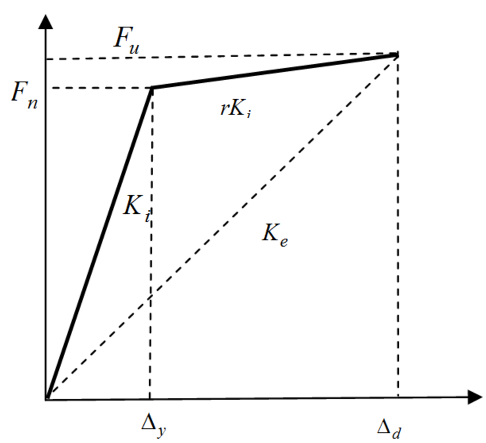

Figure 2: Effective stiffness K_e

Steps for DDBD procedure

Step 1 Find out design displacement of SDOF system

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

$$\Delta i = \omega_\theta \theta_c H_{i_i} \frac{4H_n - H_i}{4H_n - H_1} \tag{1}$$

$$\Delta_d = \frac{\sum_{i=1}^{n} m_i \Delta^2{}_i}{\sum_{i=1}^{n} m_i \Delta_i} \tag{2}$$

Where, $w_\theta = 1.15 - 0.0034\, H_n \leq 1.0$ is a reduction factor for higher mode amplification of drift, θ_c= is the code drift limit, H_n =building height, H1 and Hi are the heights of level 1 and i respectively,

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

$$m_e = \frac{\sum_{i=1}^{n} m_i \Delta_i}{\Delta_d} \tag{3}$$

$$H_e = \frac{\sum_{i=1}^{n} (m_i \Delta_i H_i)}{\sum_{i=1}^{n} m_i \Delta_i} \tag{4}$$

Step2 Estimation of equivalent viscous damping (ξ)

The equivalent viscous damping equation is given below. (Priestley, Calvi, & M.J.Kowalsky, Direct Displacement-Based Seismic Design of Structures, 2007)

For frame building

$$\xi_{eq} = 0.05 + 0.565\left(\frac{\mu - 1}{\mu\pi}\right) \tag{5}$$

For concrete wall building

$$\xi_{eq} = 0.05 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right) \tag{6}$$

Displacement ductility of the SDOF structure

$$\mu = \frac{\Delta_d}{\Delta_y} \tag{7}$$

Where μ is displacement ductility, Δd is design displacement and Δy is yield displacement

$$\Delta_y = \theta_y \times H_e \tag{8}$$

Where He is effective height, θy is yield rotation

$$\theta y = 0.5 \times \varepsilon_y \times \left(\frac{L_d}{H_b}\right) \tag{9}$$

Step 3 Determination of the effective period (T_e) of structure

The elastic displacement spectrum S_{De} for 5% damping used for DDBD is defined by EC8

$$S_{De} = S_a \left[\frac{T}{2\pi}\right]^2 \tag{10}$$

Where, Sa is elastic response spectrum, displacement spectrum other than 5% damping can be found out from the formulation in EC8

$$s_{d\xi} = s_{D5\%}\left(\frac{10}{5+\xi}\right)^{\frac{1}{2}} \tag{11}$$

Determination of the effective time period (T_e) of the SDOF structure at maximum displacement response by using the design displacement defined in equation (2) and the design displacement response spectrum corresponding to the damping level estimated in equation (5), (6)

Step 4 Effective stiffness K_e of the substitute SDOF structure

$$K_e = 4\pi m_e^2 / T^2_e \tag{12}$$

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

The design base shear

$$V_{base} = K_e.\Delta_d \tag{13}$$

Distribution of base shear carried out using following formula

$$F_i = V_{base}\frac{(m_i\Delta_i)}{\sum_{i=1}^{n}(m_i\Delta_i)} \tag{14}$$

$$F_i = F_t + 0.9V_{base}\frac{(m_i\Delta_i)}{\sum_{i=1}^{n}(m_i\Delta_i)} \tag{15}$$

For n <10 use equation (14) and for n>10 use equation (15)

2.2 Force-Based Design (FBD)

In force-based design procedure, seismic base shear force is calculated by multiplying the seismic weight of the structures with design horizontal spectral acceleration at fundamental natural period of the structure derived from the design spectrum at design basic earthquake. Then calculated lateral seismic shear is distributed along the height of the structures based on the lumped mass at story level. Typically, in FBD approach, it is assuming that the fundamental mode of the vibration is the most dominant and mass and stiffness are evenly distributed. This assumption may be right for regular low rise structures but in irregular and tall structures, the contribution of the higher modes may be important. The steps to evaluate the seismic shear using FBD procedure is summarized as follows.

Steps for FBD procedure

Seismic co-efficient method using IS 1893:2002

First calculating lump mass at the story level and calculate total seismic weight (Wh)

$$V_{base} = \frac{Z \times I \times S_a}{2 \times R \times g} W_h \tag{16}$$

Where, Z=zone factor, R=response reduction factor, Sa/g=spectral acceleration coefficient, I=importance factor, W_h=total seismic weight of structure

Distribution of design force

$$Q_i = V_b \times \frac{W_i H_i^2}{\sum_{j=1}^{n} W_i H_i^2} \tag{17}$$

Where, Q_i= design lateral force at floor i, H_i= height of floor i, W_i= seismic weight of floor i, n= number of story

3 Application of the design procedure to example

The structural systems considered for this study are RC frame structures having 8 story which is located in seismic zone IV. The considered RC building has four numbers of bays of 5 m each in both directions as shown in Figure 3 Typical story height is 3.75m. The thickness of the interior and exterior wall is assumed as 115 mm and 230 mm respectively. The slab thickness is assumed as 150 mm. The live load of 4 kN/m2 and floor finish 1 kN/m2 is assumed on slabs. The study buildings are assumed on medium soil and to be located in zone IV. The grade of concrete and steel assumed were M25 and Fe415 respectively. A typical plan and elevation for the 8-storied frame building is shown in figure 3

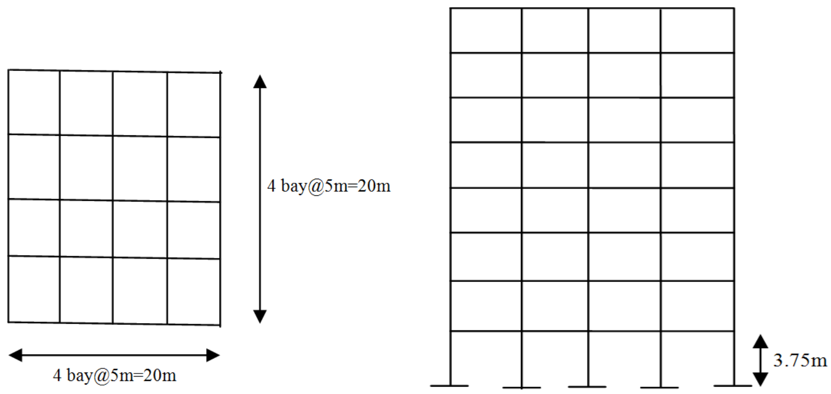

Figure 3: Structural arrangement of Building in Plan and Elevation

3.1 Evaluation of seismic design base shear DDBD approach (PGA=0.12g)

The DDBD parameters calculation for the considered RC frame buildings are shown below. The design displacement spectra for PGA= 0.12g (i.e. zone factor = 0.24) are shown on Figure 4

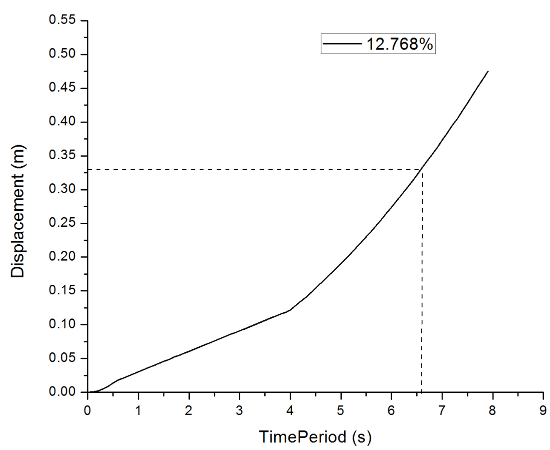

Figure 4: Design Displacement Spectra for PGA=0.12g

Total seismic weight of the building is 47800.27 kN

Story	Hi(m)	wt. in (ton)	Δi(m)	miΔi	miΔi2	miΔihi	Vb(kN)
8	30	435.13	0.465	202.12	93.89	6063.86	183.003
7	26.25	617.78	0.423	261.56	110.74	6865.93	236.811
6	22.5	617.78	0.377	233.16	88.00	5246.13	211.100
5	18.75	617.78	0.327	201.77	65.90	3783.27	182.683
4	15	646.03	0.271	175.05	47.43	2625.81	158.491
3	11.25	646.03	0.210	135.98	28.62	1529.77	123.113
2	7.5	646.03	0.145	93.77	13.61	703.34	84.906
1	3.75	646.03	0.075	48.45	3.63	181.69	43.868
			∑	1351.8	451.83	26999.8	1223.98

Table 1: DISTRIBUTION OF DESIGN SEISMIC SHEAR (DDBD)

The design story displacement (Δ_i)

$$\Delta_i = 1\times 0.02\times 30\times\left(\frac{4\times 30-30}{4\times 30-3.75}\right) = 0.465m$$

Design displacement, effective height and effective mass

$$\Delta_d = \frac{\sum_{i=1}^{n} m_i \Delta^2{}_i}{\sum_{i=1}^{n} m_i \Delta_i} = \frac{451.84}{1351.89} = 0.334m$$

$$H_e = \frac{\sum_{i=1}^{n}(m_i \Delta_i H_i)}{\sum_{i=1}^{n} m_i \Delta_i} = \frac{26999.83}{1351.889} = 19.972m$$

$$m_e = \frac{\sum_{i=1}^{n} m_i \Delta_i}{\Delta_d} = \frac{1351.889}{0.334} = 4044.830t$$

Estimation of the level of equivalent viscous damping (ξ)

$$\theta_y = 0.05\times \varepsilon_y \times\left(\frac{L_d}{H_b}\right) = 0.010$$

$$\Delta_y = \theta_y \times H_e = 0.010\times 19.972 = 0.190m$$

$$\mu = \frac{\Delta_d}{\Delta_y} = \frac{0.334}{0.190} = 1.76$$

$$\xi_{eq} = 0.05 + 0.565\left(\frac{1.76-1}{1.76\times 3.14}\right) = 12.768\%$$

Time period estimation

Design displacement is 0.334m and equivalent viscous damping is 12.768% so according to design displacement spectra time period is 6.6 second from Figure 4

Effective stiffness and base shear calculation

$$K_e = \frac{4\pi^2 m_e}{T_e^{\,2}} = \frac{4\times\pi^2\times 4044.830}{6.6^2} = 3662.112KN/m$$

$$V_{base} = K_e.\Delta_d = 3662.112 \times 0.334 = 1223.975kN$$

The calculation of seismic base shear and corresponding lateral forces on the buildings are summarized in Table 1

3.2 Evaluation of seismic design base shear FBD approach

The design base shear as per the seismic coefficient method suggested by IS 1893:2002 is given by

$$V_{base} = \frac{Z \times I \times S_a}{2 \times R \times g} W_h = \frac{0.24 \times 1}{2 \times 5} \times 2.5 \times 47800.27 = 2584.23kN$$

The calculation of seismic base shear and corresponding lateral forces on the buildings are summarized in

Table 2

story	Wi (kN)	Hi (m)	WiHi2	Qi (kN)
8	4268.70	30.00	3841.83	624.80
7	6060.40	26.25	4176.00	679.15
6	6060.40	22.50	3068.08	498.96
5	6060.40	18.75	2130.61	346.50
4	6337.58	15.00	1425.95	231.90
3	6337.58	11.25	802.10	130.45
2	6337.58	7.50	356.48	57.98
1	6337.58	3.75	89.12	14.49
		∑	15890.198	2584.23

Table 2: DISTRIBUTION OF DESIGN SEISMIC SHEAR (FBD)

3.3 Comparisons of seismic base shear

Table 3 shows the design seismic base shear of considered 8 storey building evaluated using DDBD and FBD approach. Figure 5 shows the distribution of seismic lateral forces at different story level.

Base shear	Medium soil (PGA=0.12g, zone =IV)
DDBD	1223.975 kN
FBD	2584.23 kN

Table 3: COMPARISON OF BASE SHEAR FOR DDBD AND FBD

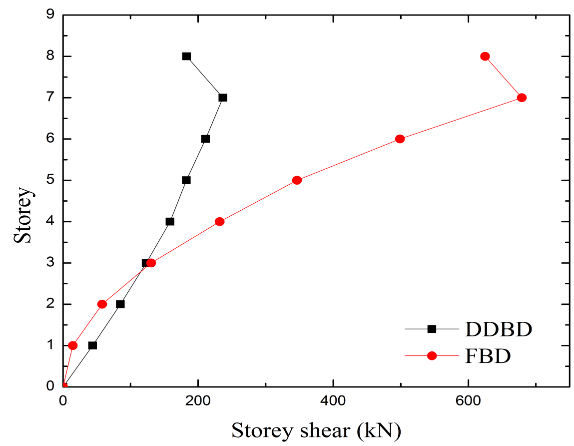

Figure 5: Comparison of storey shear for DDBD and FBD

3.4 Design of 8 story RC frame building

A typical eight-story asymmetric RC frame building shown in Figure 3 was analyze and designed considering the all possible load combination according to Indian code of practice IS 456-2000, IS 1893-2002 and IS 13920-1993. Table 4 and Table 5 shows the design details of beam and columns of considered RC frame buildings using DDBD and FBD approach.

Member	floor	Width (mm)	Depth (mm)	Reinforcement details
Beam	1-4	300	600	5#20(top)+4#16(bottom)
Column	1-4	600	600	12#25 (uniformly distributed)
Beam	5-8	300	550	5#20(top)+4#16(bottom)
Column	5-8	500	500	12#25 (uniformly distributed)

Table 4: RC SECTION DETAILS (DDBD APPROACH)

Member	floor	Width mm)	Depth (mm)	Reinforcement details
Beam	1-4	300	600	8#20(top)+4#20(bottom)
Column	1-4	600	600	12#25+4#16(uniformly distributed)
Beam	5-8	300	550	8#20(top)+4#20(bottom)
Column	5-8	500	500	12#25(uniformly distributed)

Table 5: RC SECTION DETAILS (FBD APPROACH)

3.5 Nonlinear static pushover analysis of considered RC frames

Considering the symmetry of the buildings, the interior RC frame is analyzed using the nonlinear static pushover analyses (NSPA) to obtain the capacity/pushover curve. Plasticity was assumed to be lumped at probable locations in RC members. The program defined plastic hinge properties of ETABS 2015 Program were used to take into account the material nonlinearity in various members of considered RC buildings. A coupled axial force and biaxial bending moment hinge (P-M2-M3 hinge) and M3 hinge was assigned at the both ends of the columns and beam respectively. The lateral force distribution obtained from DDBD and FBD approach is used as loading pattern to obtain the pushover curve. Figure 6 ,7 shows the pushover curve of the interior RC frame designed using DDBD and FBD approach respectively. The capacity curve obtained from the nonlinear pushover analysis is approximated by an idealized bilinear relationship using equal energy method. The method assumes that the area enclosed by the curve above the bilinear approximation is equal to the area enclosed by the curve below the bilinear approximation.

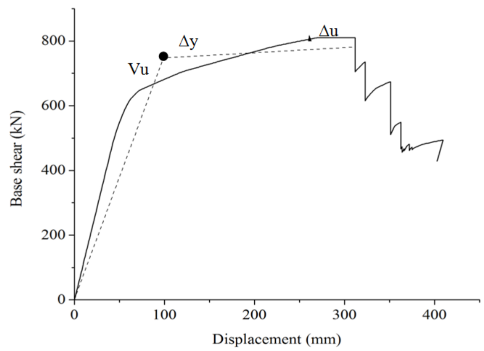

Figure 6: Pushover curve of DDBD method

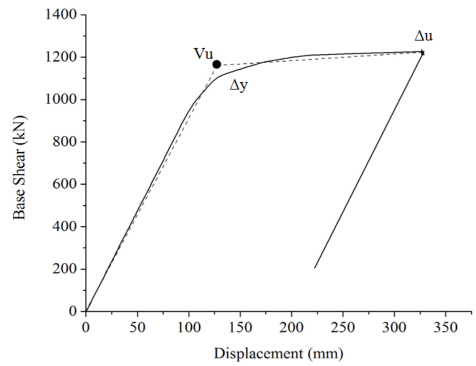

Figure 7: Pushover curve of FBD method

3.6 Computation of R for the 8-story RC frame

The response reduction factor is a function of ductility factor, strength factor, damping factor and redundancy factor.

$$R = R_S R_\mu R_\xi R_R \tag{18}$$

where R_S=strength factor, R_μ =ductility factor, R_ξ=damping factor, R_R =redundancy factor and strength factor which is obtained by;

$$R_s = \frac{V_u}{V_d} \tag{19}$$

Where V_u= ultimate base shear and V_d= design base shear.

As per (Miranda & Bertero, 1994) the ductility factor(R_μ) is obtained by

$$R_\mu = \frac{\mu - 1}{\phi} + 1 \tag{20}$$

For medium soil

$$\phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T} e^{2(\ln(T) - 0.2)^2} \tag{21}$$

The redundancy factor (R_R) is taken as one assuming the structure having a sufficient redundancy.

Table 6 shows the Pushover parameter and component of 'R' factor of considered building frame

Frame	V_d (kN)	V_u (kN)	Δ_y (mm)	Δ_u (mm)	R_S	R_μ	R_R	R
DDBD	244.8	750	100	260	3.06	2.40	1	7.4
FBD	516.8	1168.1	127	328	2.26	2.41	1	5.4

Table 6: PUSHOVER PARAMETER AND COMPONENT OF 'R' FACTOR

The evaluated values of response reduction factor of 7.4 and 5.4 for considered RC frame designed using DDBD and FBD approach, are higher than the IS 1893 specified value(R=5.0). That shows the satisfactory structural performance of considered RC frame design using DDBD and FBD approach.

4 Concluding remarks

1. In this study, direct displacement based design method are studied in details and their results are compared with the force based design for 8-story RC frame building. Based on the results obtained, it is seen that DDBD method appear to be promising.
2. The Base shear obtained from the DDBD method is 47% lesser than the obtained from FBD method.
3. The design obtains from the result of DDBD method is comparatively economical as compared to the design obtained from FBD method for the considered RC frame building.
4. The satisfactory performance of the direct displacement based design has also been validated by the computation of '*R*' factor. However, there is need and scope for further research to validate performance and suggest improvements, for taller buildings.

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