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Direct Displacement Based Design for Fifteen Storey Reinforced Concrete Moment Resisting Frame as per IS Codes

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Abstract- *Design Methodology for Direct Displacement Based Design (DDBD) Method proposed by Priestley et al.(2007) has been presented here in IS context as an alternative to conventional Forced Based Design (FBD). The limitations of Force Based Design Method are highlighted. The paper attempts to design a 15 storey Reinforced Concrete Moment Resisting frame located in Zone-V using DDBD Method. Base shear, storey shear, beam reinforcement, percentage of column steel for frame designed by DDBD are compared to conventional FBD and concluding remarks are highlighted which shows that DDBD can be a viable design alternate.*

Keywords- *Direct Displacement Based Design, Force Based Design, base shear, economical.*

I. INTRODUCTION

The current seismic design criteria, as prescribed by codes are essentially force-based and prescribe guidelines for ductility. But it does not provide consistent damage control and protection of structures from collapse during a severe earthquake. It is widely understood now that it is not the force but displacement, which can be directly related to damage. The constancy of stiffness in force-based design is also not tenable (Priestley 1993, 2003)[1].

Through force-based method of design an engineer cannot deliberately design structure for an intended performance level. The alternative approaches are displacement-based design and performance-based design which are gradually becoming popular in recent times. In these methods the design is done for an intended displacement or, an intended performance under a perceived hazard level.

II. LIMITATION OF FORCE BASED DESIGN

The distribution of induced design forces between different structural elements are estimated based on Initial Stiffness of the members. The stiffness of a member can be determined only after the design process is completed based on the type of forces (P-M-M, P-M, M, P etc.) and the reinforcement details finalized. The basic assumption in the FBD is Member Stiffness remains constant. Thus EI = Constant = M / Φ, i.e. yield curvature is proportional to Strength of the Member. The experimental evidences show that the Curvature is essentially constant and EI is proportion to the Strength of the Member. Hence till the Member strength is determined neither its elastic stiffness nor the elastic time period can be determined. This process is iterative as well as demands incorporating nonlinear behavior.

The check for structural displacement which can be directly related to damage potential thro’ drift is carried using coarse and unreliable approach at the end of design process. As per IS 1893, the requirement is:“The storey drift in any storey due to minimum specified design lateral force, with partial load factor of 1.0, shall not exceed 0.004 times the storey height. For the purposes of displacement requirements only, it is permissible to use seismic force obtained from computed fundamental period (T) of the building without the lower bound limit on design seismic force”. Also there is no consensus amongst code on Response Reduction Factor used in Design. (Upto8 in USA, Max. 3 in Japan, Max. 5 in India). As there is uncertainty/non-uniformity in evaluation of ductility of the structure. (Varughese et.al.)

III. DIRECT DISPLACEMENT BASED DESIGN METHOD

The Direct Displacement Based Design procedure was developed with the aim of providing a greater emphasis on displacements in contrast to conventional Force Based Designby a variety of performancelimit states. A structure is designed to achieve a predefined level of displacement when subjectedto a given level of seismic intensity by selecting appropriate value of drift limit.It calculates base shear corresponding to secant stiffness at effective displacement of an equivalent SDOF system using substitute structure approach. It facilitates the use of elastic displacement spectra at equivalent damping when structure behaves inelastically under the design earthquake. The basic steps of the DDBD method for moment frame buildings are described briefly.

Design Displacement Profiles:
Displacement profiles are defined in the Model Code for regular structures by Priestley et.al. 2007, based on the results of Nonlinear Time History Analysis. For regular frame structures, the design displacement profile is

$$\Delta i = \delta_i \frac{\Delta_c}{\delta_c}$$

where, $\delta_i = \left(\frac{H_i}{H_n}\right), \quad n \leq 4$

$$\delta_i = \frac{4}{3}\left(\frac{H_i}{H_n}\right)\left[1 - \left(\frac{H_i}{4H_n}\right)\right], \quad n > 4$$

$$\Delta_c = \theta_c \, H_1$$

n is number of stories
H_n is total building height,
H_i is the heights of level i from base
θ_c is the code drift limit for the limit state considered

Design Displacement:
The design displacement of the equivalent SDOF structure is given by

$$\Delta_d = \frac{\sum_{i=1}^{n}(m_i \Delta_i{}^2)}{\sum_{i=1}^{n}(m_i \Delta_i)}$$

where, m_i *and* Δ_i are masses and displacements of the ithstorey respectively.

Effective Mass and Height:
Effective system mass for the substitute structure is given by

$$m_e = \frac{\sum_{i=1}^{n}(m_i \Delta_i)}{\Delta_d}$$

Effective height of SDOF system is given by

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

Yield Displacement and Ductility:
For SDOF systems, the yield displacement is required for calculating the equivalent viscous dampling and displacement ductility which depends on yield displacement. For reinforced concrete frames, yield drift can be developed from the yield curvature as below:

$$\theta_y = 0.5 \, \epsilon_y \, {}^{L_b}\!/_{h_b}$$

where, L_b *and* h_b are length and depth of beam.
Yield displacement will be $\Delta_y = \theta_y \mathrm{H_e}$ and Ductility is given by $\mu = {}^{\Delta_d}\!/_{\Delta_y}$

Equivalent Viscous Damping:
The design procedure requires relationships between displacement ductility and equivalent visous damping.
Equivalent damping for Concrete Frame building is given by

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

Time Period:
The effective period $\mathrm{T_e}$, corresponding to Δ_d and ξ_{eq} is to be obtained from the design displacement spectra.

Base Shear and Lateral Load Distribution:
The effective stiffness K_e, of the substitute SDOF structure is given by

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

The base shear can be determined from the relation

$$V_{base} = K_e \, \Delta_d$$

The base shear force is distributed to the floor levels in proportion to the product of mass and displacement, as:

$$F_i = F_t + 0.9\, V_b \frac{m_i \Delta_i}{\sum_{i=1}^{n}(m_i \Delta_i)}$$

where $F_t = 0.1\, V_b$ at roof and $F_t = 0$ at all floors.

IV. DESIGN OF 15-STOREY RC FRAME BY FBD & DDBD

Problem consists of designing a 15 storeyMoment Resisting RC frame using Force Based Design and Direct Displacement Based Design method.The frame has equal bay width of 6.0m and storey heights of 3.20m. The ground storey columns have a height of 4.20m. It is located in Zone-V. The building is assumed to be resting on medium soil condition. Member sizes and loading is taken as below:

Beam Size:
Storey 1-4: 300mm x 850mm
Storey5-9: 300mm x 700mm
Storey10-15: 300mm x 600mm

Column Size:
Storey1-4:700mm x 700mm
Storey5-9: 600mm x 600mm
Storey10-12: 500mm x 500mm
Storey13-15: 400mm x 400mm

Slab Thickness: 150mm All
Floor Finish Load: 1.00 kN/m^2
Imposed Load : 2.50 kN/ m^2
Wall Load : 15 kN/m All

For doing FBD, seismic weights at various floors are worked out and total Seismic Weight comes as 37093kN.
Base Shear is calculated as $V_{base} = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}W$
where, Z = 0.36, I = 1, R =5 (Assume SMRF)
Fundamental natural period assuming infilled frames
$T = {}^{0.09\,h}/_{\sqrt{d}} = 1.27$ sec
Sa/ g = 1.07 (from Acceleration Response Spectrum)
Thus, V_{base} = 0.038 W
= 1427 kN
The base shear is distributed vertically on all floor levels based on the relation

$$F_i = V_b \frac{W_i {h_i}^2}{\sum_{i=1}^{n}(W_i {h_i}^2)}$$

For doing DDBD, displacement profile is taken as per section III.
Assuming $\theta_c = 0.02$ as per FEMA 356 (2000) corresponding to life safety performance level.

Design Displacement : $\Delta_d = 0.54$ m
Effective mass : m_e =3085 t
Effective height : H_e =32.28 m
Yield Drift : $\theta_y = 0.007$
Yield Displacement : $\Delta_y = 0.236$ m
Ductility : $\mu = 2.27$
Equivalent damping : $\xi_{eq} = 0.15$
As per Cl. 6.4.2 of IS 1893 (Part 1): 2002, $R_\xi = 0.70$
Building is located in Zone-V, so design PGA = 0.36/2 = 0.18g.
Displacement spectrum is derived from Acceleration spectrum given in code with 15% damping for medium soil condition as shown in Figure-1

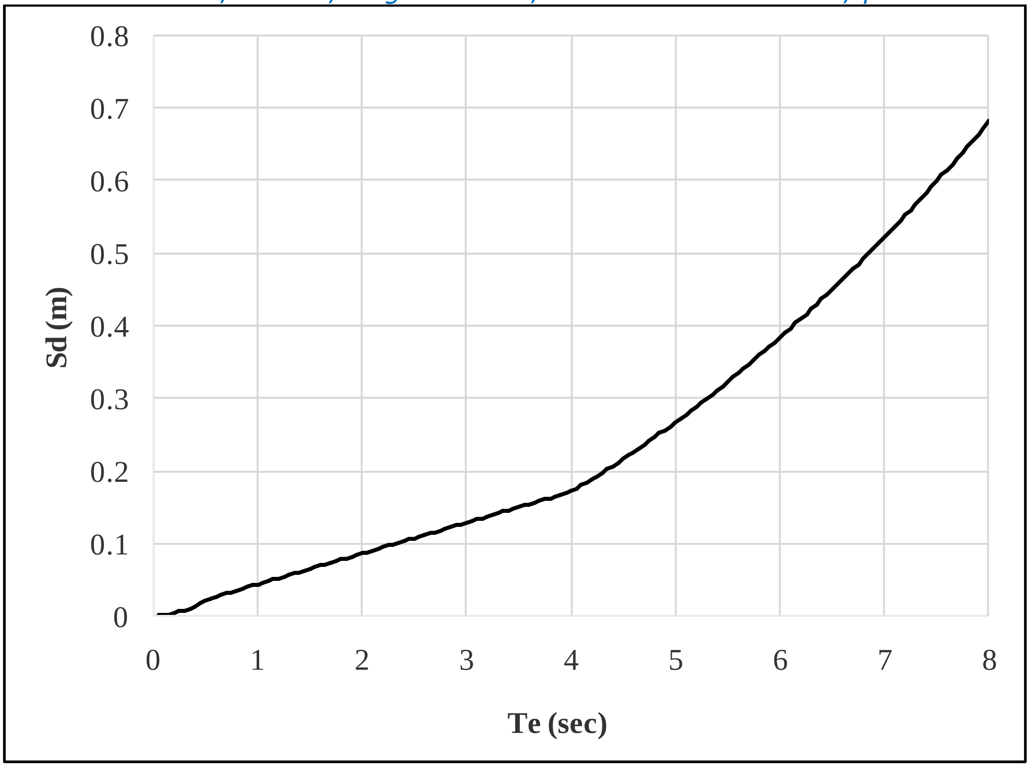

Figure 1: Displacement Spectra for 15% damping

Time Period of Equivalent SDOF system is T_e = 7.15 s.
Effective Stiffness : K_e = 2382kN/m
Base Shear : V_b = 1276 kN

The lateral force distribution obtained using FBD and DDBD is shown in Figure 2. To know the relative distribution of forces, the figure is replotted for unit base shear force as shown in Figure 3. Frames are analysed and designed using Staad Pro v8i for all load cases as per IS 1893:2002 (Part-1).

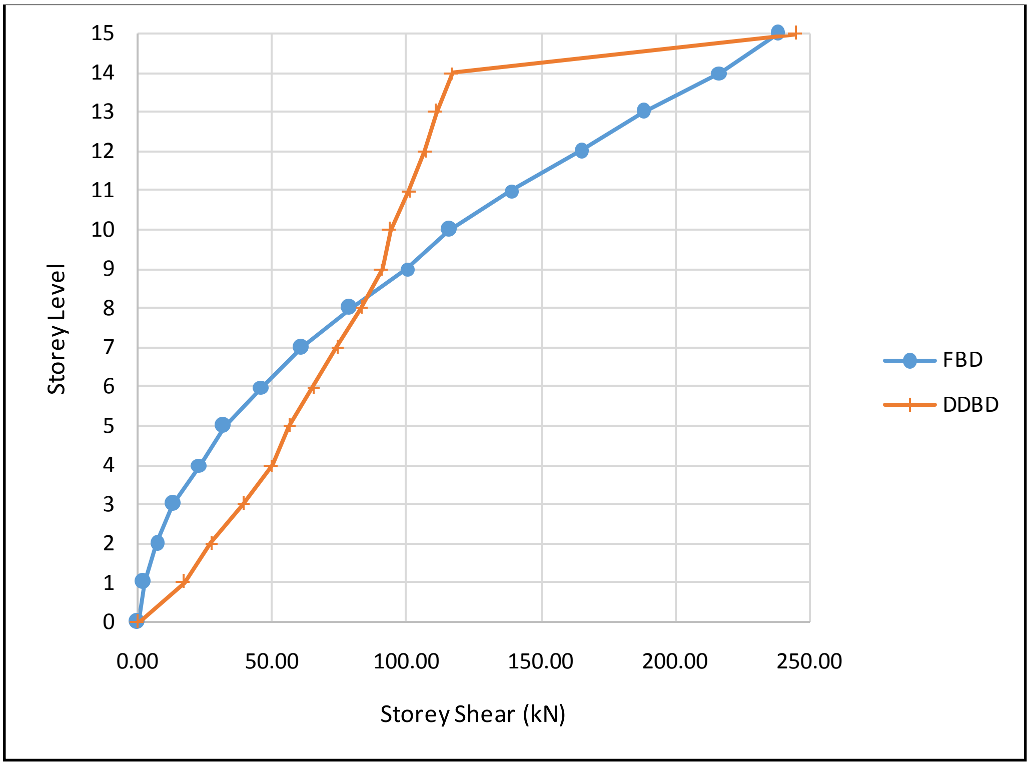

Figure 2: Lateral Load Distribution

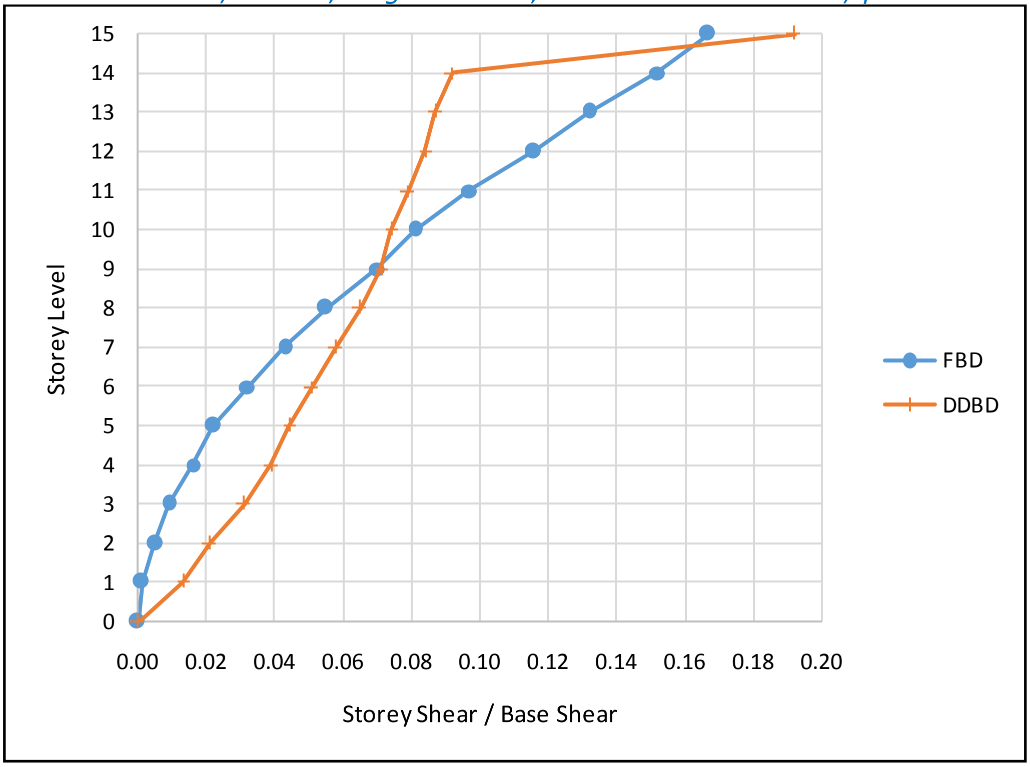

Figure 3: Unit Distribution

Beam cross-section and reinforcement provided for FBD and DDBD frame are given in Table 1. Column cross-section and reinforcements provided for outer and inner columns for both the methods are given in Table 2.

Table 1: Reinforcement Percentage (%)for Beams

Storey	Size	FBD				DDBD			
		End I - pt(%)		End J - pt(%)		End I - pt(%)		End J - pt(%)	
		Top	Bot	Top	Bot	Top	Bot	Top	Bot
1	300 x 850	1.05	0.56	0.95	0.50	1.17	0.64	1.12	0.69
2	300 x 850	1.14	0.61	0.93	0.60	1.21	0.66	1.05	0.73
3	300 x 850	1.19	0.64	0.90	0.66	1.23	0.66	0.99	0.76
4	300 x 850	1.25	0.67	0.90	0.71	1.21	0.66	0.94	0.76
5	300 x 700	1.62	0.85	1.23	0.83	1.74	0.91	1.42	1.08
6	300 x 700	1.70	0.89	1.23	0.92	1.71	0.89	1.32	1.04
7	300 x 700	1.69	0.88	1.17	0.91	1.66	0.87	1.22	0.99
8	300 x 700	1.67	0.87	1.10	0.91	1.61	0.85	1.11	0.92
9	300 x 700	1.63	0.85	1.04	0.86	1.50	0.79	1.02	0.83
10	300 x 600	1.87	0.97	1.31	0.80	1.86	0.96	1.40	0.91
11	300 x 600	1.80	0.93	1.20	0.74	1.74	0.91	1.23	0.77
12	300 x 600	1.60	0.84	1.08	0.56	1.54	0.81	1.13	0.60
13	300 x 600	1.29	0.69	0.84	0.43	1.29	0.69	0.96	0.50
14	300 x 600	1.07	0.57	0.59	0.30	1.17	0.63	0.76	0.39
15	300 x 600	0.61	0.31	0.46	0.23	0.79	0.41	0.67	0.35

Table 2: Reinforcement Percentage (%)for Columns

Storey	Size	Exterior Column Pt(%)		Interior Column Pt(%)	
		FBD	DDBD	FBD	DDBD
1	700 x 700	2.80	2.45	3.21	3.21
2	700 x 700	2.00	2.04	2.80	2.80
3	700 x 700	1.43	1.59	2.00	2.00
4	700 x 700	1.17	1.28	1.60	1.60
5	600 x 600	2.64	2.64	3.27	3.41
6	600 x 600	1.75	2.09	2.73	2.87
7	600 x 600	1.47	1.47	2.18	2.32
8	600 x 600	1.05	1.05	1.64	1.77
9	600 x 600	1.05	1.05	1.24	1.23
10	500 x 500	2.29	2.01	3.14	3.14
11	500 x 500	1.29	1.11	2.36	2.36
12	500 x 500	1.01	1.01	1.57	1.57
13	400 x 400	2.80	2.36	2.80	3.44
14	400 x 400	2.36	2.36	2.01	2.36
15	400 x 400	2.36	2.36	1.57	1.79

V. CONCLUSION

Fifteenstorey moment resisting regular RC frame was designed as per FBD and DDBD method.It is observed that base shear for frame designed by DDBD is less than that of frame design by FBD. The parameters like lateral force distribution, beam and column design reinforcement are compared for both methods. The results shows that reinforcement requirement in both methods are similar and DDBD can be a viable alternate design method. Detailed behavior of frames under seismic excitation can be verified using nonlinear time history analysis and evaluating interstorey drift ratio to assess whether the target drift demand is achieved.

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