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# COMPARISON OF FORCE BASED DESIGN AND DISPLACEMENT BASED DESIGN ON REGULAR BUILDINGS

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**Abstract** – *Traditional codal force based design, FBD(IS 1893:2002) methods, which design the structure for a base shear capacity characterizing a structure in terms of elastic, pre-yield, properties (initial stiffness $K_i$, elastic damping). In DDBD, the structure is designed to have a pre-defined displacement capacity, which characterizes the structure by secant stiffness $K_e$ at maximum displacement $\Delta_d$, and a level of equivalent viscous damping $\xi_{eq}$, representative of the combined elastic damping and the hysteretic energy absorbed during inelastic response. Design and Analysis were done on regular frames of four, ten, twelve, fifteen, and twenty stories based on following codes IS 456:2000, IS 1893:2002, FEMA 356 and the two design approaches were studied. Analysis and design for this study was done using Structural Analysis Program software (SAP2000). The paper presents the theory and application of this method using a reinforced concrete frame structures as an example. The results obtained using direct displacement based design method are compared to the ones obtained using equivalent lateral force* method.

***Key Words***: **Performance based design, Force based design (FBD), Direct displacement based design (DDBD), SAP2000, IS 1893:2002**

## 1. INTRODUCTION

Over the past few decades earthquake engineering has experienced a kind of revision of methods and philosophies used till now. A new approach in design called Performance Based Design is under continuous development. In addition, numerous nonlinear dynamic analyses have been made and have become a major tool in the field of earthquake engineering research.

Current regulations which based on force based design are mostly defined through probabilistic theory which considers seismic excitation without taking any damage and collapse risks directly into account. Design procedures defined in that way are well accepted and among other things, they have a long tradition. It is important to state that those procedures allow only the check of displacements and drifts of structures at the end of an analysis, without a real insight into the damage and collapse risk level. Among several different procedures developed in terms of Performance Based Design, the most significant progress was shown in a procedure called Direct Displacement Based Design. This procedure is deterministically based and shown as very rational and effective in structural analysis and design as it controls structural displacements and thus it controls damage level and collapse risk. It is important to mention that the method is primarily defined as post-elastic.

### 1.1 Force Based Design

The force-based seismic design characterizes a structure in terms of elastic, pre-yield, properties (initial stiffness Ki, elastic damping). Force based design are mostly defined through probabilistic theory which considers seismic excitation without taking any damage and collapse risks directly into account. Design procedures defined in that way are well accepted and among other things, they have a long tradition. It is important to state that those procedures allow only the check of displacements and drifts of structures at the end of an analysis, without a real insight into the damage and collapse risk level. The fundamental assumption of force based design: (i) that the initial stiffness of the structure determines its elastic response (ii) that the ductility capacity can be assigned as response reduction factors to a structural system regardless of its geometry, member strength, and foundation condition. This fundamental assumption is critically evaluated in direct displacement based design.

### 1.2 Direct Displacement Based Design

The new concept in designing structures to achieve a specified performance limit state was first introduced in New Zealand, in 1993. Over the following years, USA and Europe have put a great effort focused on research and development of the concept as a viable and logical alternative to the current force based code approaches. DDBD characterizes the structure by secant stiffness Ke at maximum displacement Δd and a level of equivalent viscous damping, representative of the combined elastic damping and the hysteretic energy absorbed during inelastic response.

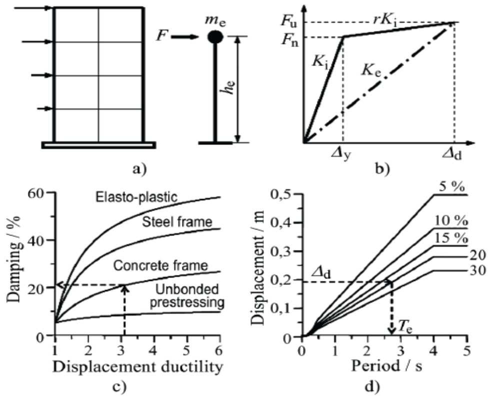


Fig.1 Fundamentals of DDBD

## 2. DDBD DESIGN PROCEDURE

Step 1: Definition of the target displacement shape and amplitude of the MDOF structure on the base of performance level considerations (material strain or drift limits) and then derive from there the design displacement Δd of the substitute SDOF structure of the MDOF.

The normalised inelastic mode shape δi of the frame MDOF structure is obtained according to the number of stories, n, as:

For n ≤ 4: $\delta_i = \frac{H_i}{H_n}$ (1)

For n> 4: $\delta_i = \frac{4}{3} \times \left(\frac{H_i}{H_n}\right) \times \left(1 - \frac{H_i}{4H_n}\right)$ (2)

Knowing the displacement of the critical storey ($\Delta_c$) and the critical normalised inelastic mode shape ($\delta_c$), the design storey displacements of the individual masses are obtained from:

$\Delta_i = \omega_\theta \times \delta_i \times \left(\frac{\Delta_c}{\delta_c}\right)$ (3)

Where, $\omega_\theta$ is a drift reduction factor to take into account the higher mode effects

$\omega_\theta = 1.15 - 0.0034H_n \leq 1.0$ (4)

Step 2: Design Displacement of the equivalent SDOF structure

The equivalent design displacement can be evaluated as:

$\Delta_d = \frac{\sum_{i=1}^{n}(m_i \Delta i^2)}{\sum_{i=1}^{n}(m_i \Delta_i)}$ (5)

Step 3: Equivalent Mass of the SDOF structure

The mass of the substitute structure is given by the following equation:

$m_e = \sum_{i=1}^{n} m_i\left(\frac{\Delta_i}{\Delta_d}\right) = \frac{\sum_{i=1}^{n} m_i\Delta_i}{\Delta_d}$ (6)

Step 4: Equivalent Height of the SDOF structure

The equivalent height (Fig.2.2) of the SDOF substitute structure is given by:

$H_e = \frac{\sum_{i=1}^{n}(m_i\Delta_i H_i)}{\sum_{i=1}^{n}(m_i \Delta_i)}$ (7)

Step 5: Estimation of the level of equivalent viscous damping ξ

To obtain the equivalent viscous damping the displacement ductility μ must be known.

Displacement ductility of the SDOF structure

The SDOF design displacement ductility is given by Eq. (13) and is related to the equivalent yield displacement Δy:

$\mu = \frac{\Delta_d}{\Delta_y}$ (8)

Equivalent yield displacement

The equivalent yield displacement is given by the following equation:

$\Delta_y = \theta_y \times H_e$ (9)

Where θy is the yield drift

Equivalent viscous damping

To take into account the inelastic behaviour of the real structure, hysteretic damping ($\xi_{hyst}$) is combined with elastic damping ($\xi_0$). Usually, for reinforced concrete structures the elastic damping is taken equal to 0.05, related to critical damping. The equivalent viscous damping of the substitute structure for frames could be defined according the following equation

$\xi = \xi_0 + .565\left(\frac{\mu - 1}{\mu\pi}\right)$ (10)

Step 6: Determination of the effective period $T_e$ of the SDOF structure

The effective period of the SDOF structure at peak displacement response is found from the design displacement spectrum shown in Fig 2 for the equivalent viscous damping ξ.

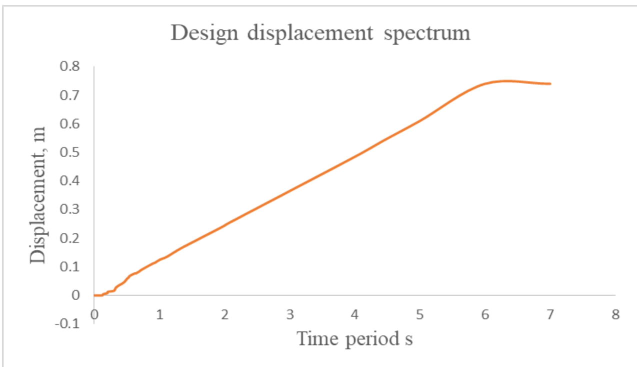


Fig.2 Displacement Response Spectrum (0.36g, Medium Soil)

Step 7: Derivation of the effective stiffness $k_e$
Effective stiffness $k_e$ of the substitute structure is derived from its effective mass and effective period according to Eq. (4).

Step 8: Calculation of the design base shear $V_{base}$

$$V_{base} = k_e \times \Delta_d \quad (11)$$

Step 9: Distribute the base shear force at different levels of the building using the following equation

$$F_i = V_{base} \frac{m_i H_i}{\sum m_i H_i} \quad (12)$$

## 3.MODELLING

### 3.1 Building Geometry

Regular frames with storey height 3.1m and bay width 5m in X dirction and 4m in Y direction are considered. Frames with four, ten, twelve, fifteen, and twenty stories are studied. The design of all the frames was according to the Indian standards IS 456(2000), seismic code IS 1893(2002) and ductile detailing code IS 13920:1993. The two dimensional 4, 10, 12, 15 & 20 storey frames were modelled by assigning the beam and column dimensions. A series of iteration was carried out for the structure to get apt section.

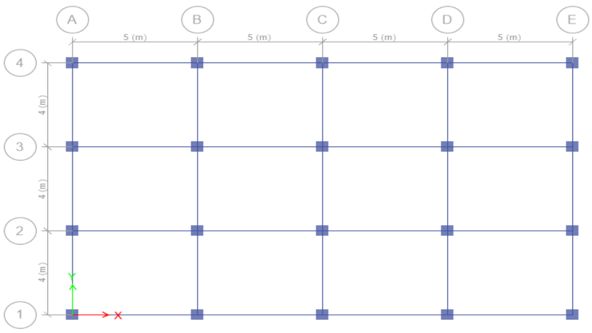


Fig. 3 Typical Plan View of Building

### 3.2 Material Properties and Loading Details

Grade of Concrete: M 25
Grade of Reinforcing Steel: Fe-415
All the load values as shown in table 1 are taken from IS 875-1 & 2, IS 1893-2002(Part-1) codes.

Table-1: Load Values for Frames

| Types of Loads | Values |
|---|---|
| Dead load | Self weight |
| Weight of partition wall | 4.6kN/m$^2$ |
| Parapet load | 1 kN/m$^2$ |
| Live load on typical floor | 3.5 kN/m$^2$ |
| Live load on roof | 1.5 kN/m$^2$ |
| Earthquake load<br>Zone<br>Soil type | <br>V<br>Medium soil |

Force based design uses characteristic material strength in the design stage. Here, it uses variable beam sections according to the demand and range of percentage reinforcement; load combination: (1) 1.5(DL+IL), (2) 1.2(DL+IL±EL), (3) 1.5(DL±EL), (4) 0.9DL±1.5EL, where DL stands for dead load, IL for imposed load and EL for seismic load along the frame. In displacement based design, design is done with expected material strengths. The load combinations are as below:

DL +I L (13)
DL+IL±EL$_X$ (14)
DL+IL±EL$_Y$ (15)

ELx and ELy stand for seismic load in two mutually perpendicular directions of the building for the floor concerned.

## 4.ANALYTICAL RESULTS

Analysis and design results of all building models for both methods (FBD and DDBD) are discussed and to compare both methods in such type of parameters like, Base shear, Storey displacement, lateral force distribution.

### 4.1 Comparison between Base Shear Calculated By FBD And DDBD Method:

The base shear calculated for all FBD building models by FBD method according to IS 1893:2002 is compared with base shear calculated using DDBD method as described in section 2 for all DDBD building models.

Table-2 Base Shear Calculated

| Building | FBD(kN) | DDBD (kN) |
|---|---|---|
| 4- Storey | 996 | 894 |
| 10-Storey | 2581 | 1840 |
| 12-Storey | 2690 | 2050 |
| 15-Storey | 2720 | 2744 |
| 20-Storey | 2838 | 4644 |

Table-2 shows the total base shear for FBD and DDBD building models. It is observed that total base shear calculated by DDBD method is less for 4, 10, and 12–storey compared to FBD building models.

### 4.2 Comparison between Lateral Load Distribution of FBD and DDBD Method:

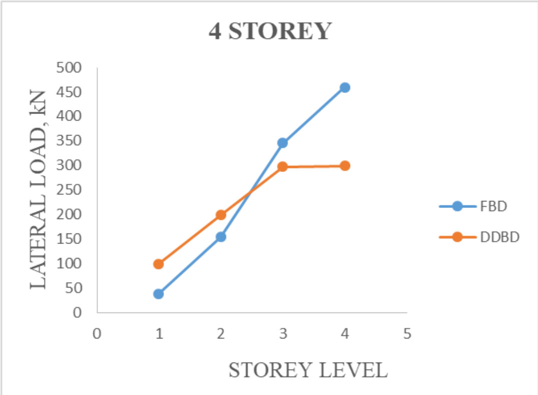


**Chart-1** Lateral load distribution 4-storey

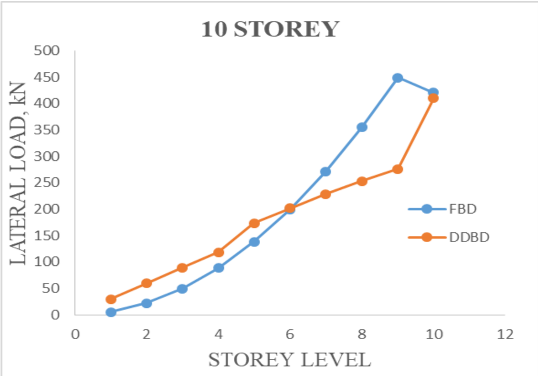


**Chart-2** Lateral load distribution 10-storey

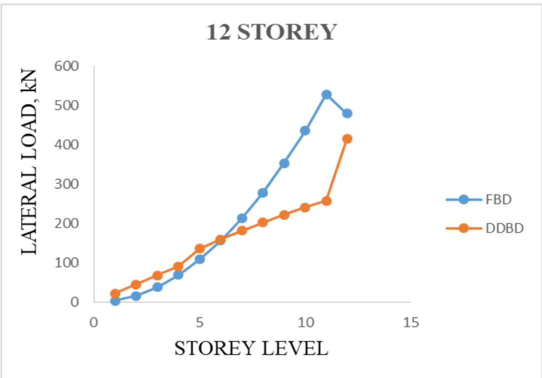


**Chart-3** Lateral load distribution 12-storey

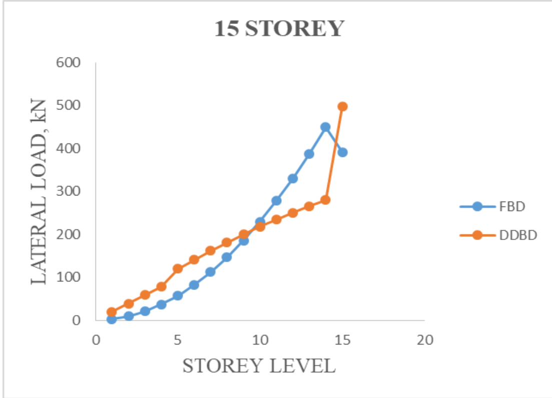


**Chart-4** Lateral load distribution 15-storey

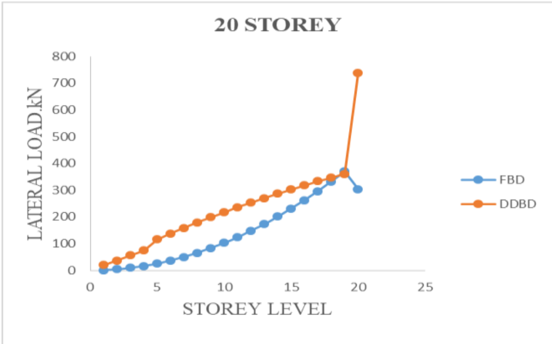


**Chart-5** Lateral load distribution 20-storey

The DDBD and FBD differ in the distribution of design base shear up the height of the building. For 4-storey and 10-storey, 12-storey, 15-storey the FBD estimates lower lateral load than DDBD at lower storeys whereas at upper storeys, the FBD estimates lateral load higher than DDBD. But this trend is not visible is the case of 20-storey frame where the DDBD gives higher values of lateral load than FBD throughout the height of the building. In case of 10, 12, 15, 20 storey frame DDBD estimates sudden increase lateral load on roof.

### 4.3 Comparison between Displacement Profile for FBD and DDBD Method

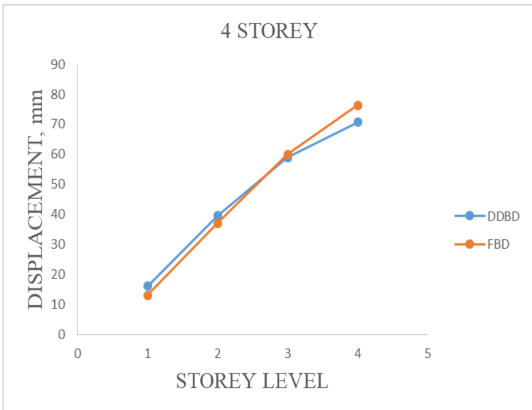

**Chart-6** Displacement profile for 4 storeyed frame

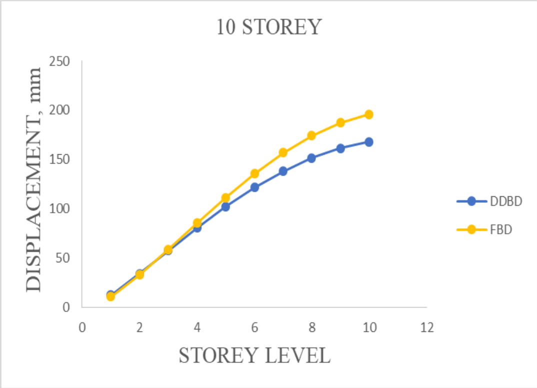


**Chart-7** Displacement profile for 10 storeyed frame

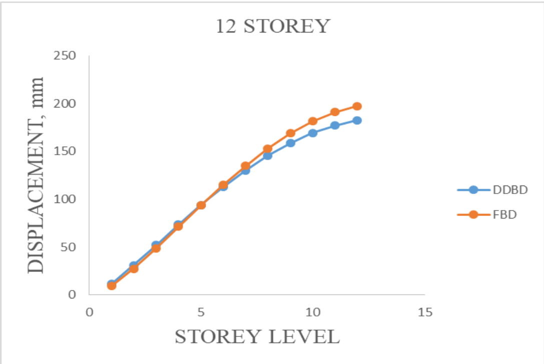


**Chart-8** Displacement profile for 12 storeyed frame

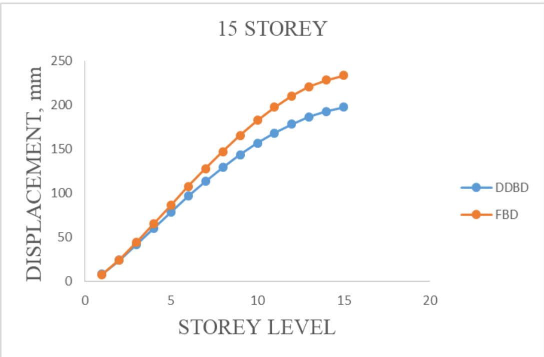


**Chart-9** Displacement profile for 15 storeyed frame

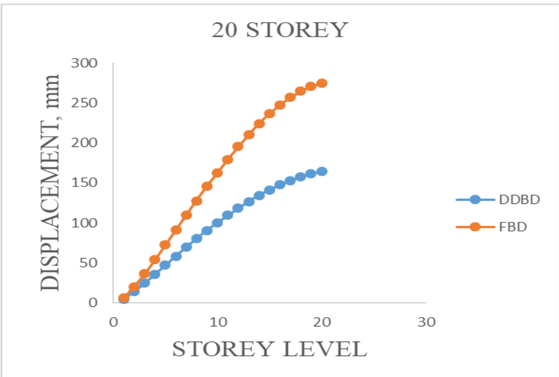


**Chart-10** Displacement profile for 20 storeyed frame

Displacement at each storey level is shown in chart 6-10. Displacement profile for all frame shows similar trend. At lower stories, FBD has smaller displacements than DDBD.

## 5.CONCLUSIONS

The main conclusions of this study includes

At lower storeyed frames, including 4, 10, 12– storeys base shear for FBD more than DDBD. Lower natural periods lead to greater seismic forces which again lead to oversized structural elements and/or, as in the case of reinforced concrete members, to a greater amount of reinforcing steel. In force based design procedures this approach is mostly considered safe-sided. However, such underestimation of the period of vibration has just the opposite effect since the displacements, calculated on the basis of unrealistically small periods, are also unrealistically small. If we consider that the displacement capacity, in comparison to strength, is a key and most important characteristic in defining inelastic behaviour, it is obvious that we are not on the safe side with lower periods of vibration. 15 storeyed frame shows similar base shear for force based design and direct displacement based design.

Frames having more than 10 storeys use more lateral load at roof in DDBD. This is because DDBD allocates 10 % of base shear at the roof level and the remaining 90 % of base shear was distributed based on storey shear at various levels.

For 20 storey frame, difference in roof displacement for FBD (274.55 mm) and DDBD (164.432 mm) is very higher.

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