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Seismic Vulnerability Assessment of RC Frame Building using Direct Displacement-based Approach

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***Abstract*—To overcome the limitations of the force-based seismic design approach for addressing inelastic behaviour in structures, a direct displacement-based seismic design was developed. In the present study, Seismic design issues are investigated by carrying out a seismic performance assessment of 4-story RC frames with a different design approach, i.e., forced-based and direct displacement-based, followed by fragility analyses. Non-linear static pushover analysis is applied to observe the response of the configured RC frames. Using the capacity-spectrum method, the probability of damage states was determined by converting the pushover curve into the capacity spectra (ATC-40) and obtaining the performance-point values of spectral acceleration (S_a) and spectral displacement (S_d) for seismic demand zone-V. Fragility curves and a mean damage matrix were created to compare the performance of FBD and DDBD design approaches. It is observed from vulnerability analyses that there is a practically decreased 20 percent probability of complete damage by adopting the DDBD approach.**

***Index Terms*— RC frame, Vulnerability assessment, Pushover analysis, Direct-displacement based method.**

I. INTRODUCTION

The last decade shows the development of performance-based design in the research community and structural design practices due to its more accurate and efficient design technics. It allows a designer to design structures based on the building owner's requirement and their site specification. It is allowed a higher safety margin during lateral load compared to other traditional design approaches [15,19].

A direct displacement-based seismic design technique is being developed to allow concrete buildings to be constructed to reach a specified amount of tolerable damage under the design earthquake. Qammer et al. (2019) studied seismic assessment of the RC frame building with various story height design with the Forced-based method (FBD) and Direct Displacement-based design (DDBD) approach. Due to its compatibility and low repetition requirements, the DDBD approach for RC frame structures has received much attention in recent years [12,13,14]. The seismic vulnerability assessment method appropriately describes the most likely damage that occurs during the specific seismic demand [2]. An optimum value of the uncertainty (β) was derived for the current study [10]. Finally, for the current study, the process for estimating the seismic vulnerability of RC buildings is detailed below.

- Design the sample structural members of RC frame buildings with a forced-based approach as per IS 1893:2016 (Part-1) and Direct Displacement-based method for performance limit criteria IO (1%) drift.

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- Non-linear Static Pushover Analysis (NSPA) was conducted to derive the pushover curve, and analyses for the FBD and DDBD approaches.
- Seismic Vulnerability analysis of study RC frame buildings is done to determine the most likelihood of damage using the capacity-spectrum method (CSM) and fragility analysis.

II. DETAILS OF THE STUDY RC FRAME BUILDING

The study building is assumed to construct on medium-strength soil in Surat, zone-V (PGA= 0.36-g), which is the most seismically demanding zone in India, encompassing a large portion of northern and western India. 1 kN/m^2 for the floor finish and 3 kN/m^2 as live load are allotted on the slab, respectively. Diaphragm action is used to simulate the effect of a 150 mm thick slab. The fundamental time-period of these frames is designed for a 5% damped response spectrum for a medium-stiff soil and seismic zone-V. The design material properties of RC frames are based on M25 concrete, and Fe500 rebars as per IS 456 (2000).

A. Direct displacement-based design approach

Two sets of mid-rise RC frames are analyzed and designed utilizing Indian seismic provision force-based design (FBD) and direct-displacement based design (DDBD), 4-storey with 3.5 m floor height each. The base shear in moment resisting frame is found using the DDBD technique for immediate occupancy (IO) performance state with 1% design drift as mentioned in ATC-40 (1996). Subsequently, the India standard 1893 (2016) was utilized to generate the response spectra, and the equation below was employed to convert such acceleration Vs time-period spectra into displacement Vs time-period spectra.

$$S_d = S_a \frac{T^2}{4\pi^2} \tag{1}$$

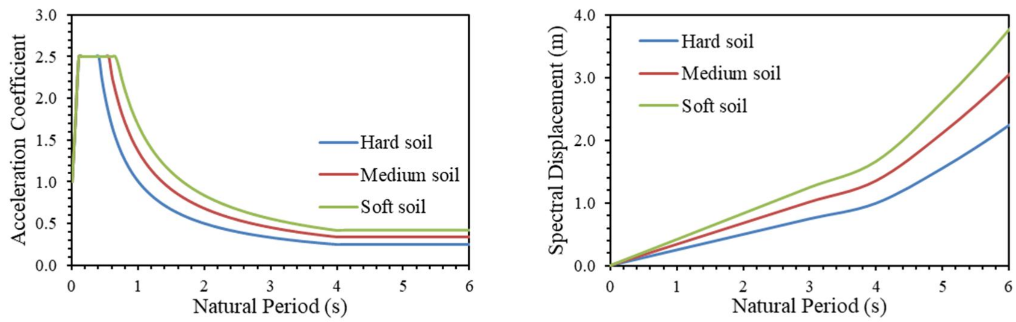


Figure 1. Design acceleration and design displacement spectrum as per IS 1893:2016

Direct displacement-based design steps to calculate base shear at every floor for RC frame building [17] elaborate as follows:

1. Establishment of design displacement (Δ_d), effective mass (m_e), and effective height (H_e) of structure

The design displacement of each story is determined considering mode shapes (Δ_i) given in equation (3), which is multiplied by critical displacement (Δ_c) at the first mode shape at the design drift limit.

$$\Delta_i = \delta_i\left(\frac{\Delta c}{\delta c}\right) \tag{2}$$

$$\delta_i = \frac{H_i}{H_n} \text{ for } n \leq 4;\ \delta_i = \frac{4}{3}\left(\frac{H_i}{H_n}\right)\left(1-\frac{H_i}{H_n}\right) \text{ for } n > 4 \tag{3}$$

Where n = number of stories, H_i = height of the ith story, H_n = total height of a building

For buildings having several stories more than ten, equation (2) is multiplied with ω_θ given below (4),

$$\omega_\theta = 1.15 - 0.0034\ H_n \qquad \leq 1.0 \tag{4}$$

Now, the design displacement (Δ_d), the effective mass (m_e), and the effective height (h_e) of substitute structure are calculated from:

$$\Delta_d = \sum_{i=1}^{n}(m_i\Delta_i^{\,2}) / \sum_{i=1}^{n}(m_i\Delta_i) \tag{5}$$

$$m_e = \sum_{i=1}^{n}(m_i\Delta_i) / \Delta_i \tag{6}$$

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

Where m_i is the mass of story i.

2. Determination of equivalent viscous damping (ξ_{eq})

The displacement ductility must be determined to obtain the corresponding viscous damping. The ratio between the design displacement and the yield displacement is called displacement ductility.

$$\mu = \frac{\Delta_d}{\Delta_y} \tag{8}$$

The equivalent yield displacement is calculated using approximation equations proposed by (Priestley et al.,2007).

$$\Delta_y = \theta_y * H_e \tag{9}$$

Where, $\theta_y = 0.5\varepsilon_y L_{b,x} / H_{b,x}$ .Here, ε_y is the yield strain of steel, $L_{b,x}$ is the beam length of span x and $H_{b,x}$ is the beam section depth of beam x. Then equivalent damping is found out by (11)

$$\xi_{eq} = 5 + 120\left(\frac{1-\mu^{-0.5}}{\pi}\right)\ \% \tag{11}$$

The damping correction factor, which should be multiplied by equivalent damping to obtain an effective period, is given by (12):

$$\eta = \left(\frac{10}{5+\xi_{eq}}\right)^{1/2} \tag{12}$$

3. Determination of effective time-period (T_e) of the SDOF structure

The effective period of the SDOF structure at peak displacement response is determined by entering the design displacement of the substitute SDOF structure Δ_d and obtaining the effective period T_e (see Figure-2).

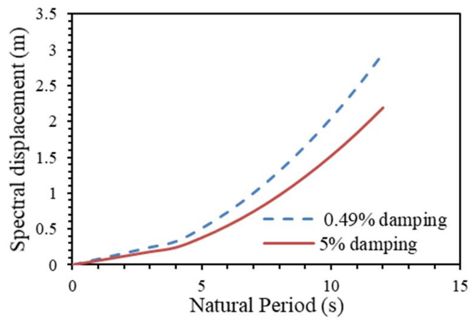


Figure 2. Design displacement spectrum for performance level IO (Priestley et al., 2007)

4. Determination of effective stiffness (K_e) of the SDOF structure

From the effective time-period and effective mass, the effective stiffness is obtained by (13),

$$K_e = \frac{4\pi^2 m_e}{T_e^{\,2}} \tag{13}$$

5. Determination of lateral load distribution (Q_i) at each story

The lateral load distribution at a different story for our frames is given by (14),

$$Q_i = V_b\,(m_i\Delta_i / \textstyle\sum_{i=1}^{n}(m_i\Delta_i)) \quad \text{for stories} \le 10; \; V_b = K_e * \Delta_d \tag{14}$$

From Table [1], It should be noted that the minimum design base shear to be considered as per IS 1893 (2016) is around 260 kN in the seismic zone-V. A sample calculation of the base shear of the four-story DDBD frame is presented in Table [2]. Table [3] shows the design consideration of the 4-story RC frame building using the FBD and DDBD approach.

B. Seismic performance assessment

The non-linear static pushover analysis is carried out according to the FEMA 356 (2000) design. ASCE 41 (2012) performance criteria and default hinges are used for structural components such as beams and columns. The capacity curve recommended by the ATC-40 (1996) and HAZUS (2003) is then converted from the derived Pushover curve. The fragility curves for various damage states are derived using this translated spectral displacement. A fragility curve describes the likelihood of reaching or exceeding a specific damage state as a

TABLE I. THE DETAILS OF STUDY FOR FBD AND DDBD FOR FOUR-STORY FRAMES

Parameter	FBD	DDBD
Height of the roof from base, h_n (m)	14	14
Total seismic weight, W (kN)	2884.2	2884.2
Critical normalized mode shape, δ_c	-	0.25
Drift reduction factor, ω_θ	-	1
Design displacement, Δ_d (m)	-	0.1
Yield displacement, Δ_y (m)	-	0.125
Displacement ductility, μ	-	0.8
Effective mass, m_{eff} (t)	-	244.27
Effective stiffness, k_{eff}, (kN/m)	-	6327.57
Effective time-period, T_{eff} (s)	-	1.23
Base shear, V_b (kN)	259.58	634.36

TABLE II. THE SAMPLE CALCULATION FOR FOUR STOREY DDBD FRAME

Level	h_i	M_i	δ_i	Δ_i	$m_i\Delta_i$	$m_i\Delta_i^2$	$m_i\Delta_i h_i$	Q_i
4	14.0	55.74	1.00	1.00	7.80	1.09	109.25	202.14
3	10.5	79.46	0.75	0.11	8.34	0.88	87.60	216.11
2	7.0	79.46	0.50	0.07	5.56	0.39	38.93	144.08
1	3.5	79.46	0.25	0.04	2.78	0.10	9.73	72.04
Σ					24.49	2.46	245.51	634.37

TABLE III. REINFORCEMENT DETAILING OF THE 4-STORY RC FRAME BUILDING DESIGN USING FBD AND DDBD LIMIT STATES

Performance limit criteria	Floor	Beam Design			Column Design	
		Size (mm)	p_t %		Size (mm)	p_t %
			Bottom	Top		
FBD	3-4	230 x 400	1.10	0.60	475 x 475	1.01
	1-2	230 x 400	1.10	0.60	500 x 500	1.11
DDBD	3-4	230 x 400	1.70	0.85	475 x 475	1.30
	1-2	230 x 400	1.70	0.85	500 x 500	1.74

function of a parameter characterizing the seismic activity to which the building is subjected to a particular damage state. As shown in (15), the lognormal probability density function is widely used to depict fragility curves appropriately.

$$P_k(S_d) = P\,[DS \geq DS_k \mid S_d] = \Phi\,[\frac{1}{\beta_k}\ \ln(\frac{S_d}{S_{d,ds}})] \qquad (15)$$

S_d is the spectral displacement, $S_{d,\,ds}$ is the mean spectral displacement where a building ranges the damage grade threshold; β_k is the standard deviation of a natural logarithm of spectral displacement for damage grades, and Φ is the standard normal cumulative distribution function. They established a damage grade threshold based on the building structure's yielding and ultimate spectral changes, as illustrated in Table [4].

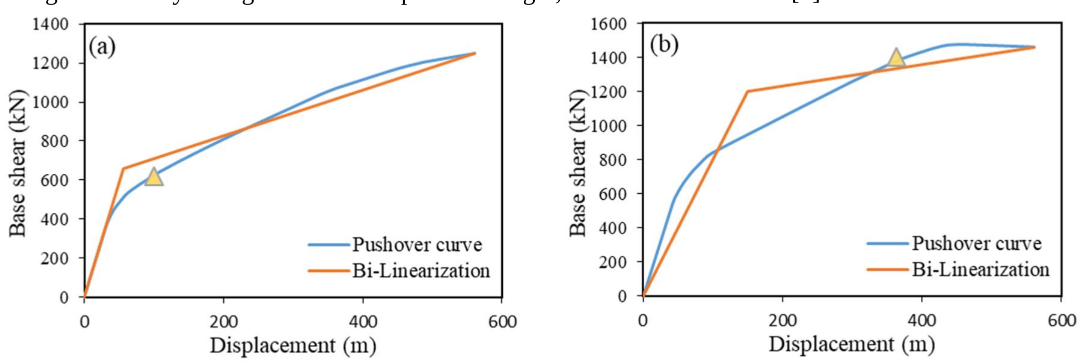


Figure 3. Pushover curve derived using (a) Force-based designed method and (b) DDBD method of 4-story RC frame building

Damage likelihood matrices (DPM) are defined as the weighted average damage index (DS_m) for the maximum likelihood of the RC frame building damage state, which can be derived from the following (16):

$$DS_m = \sum_{i=1}^{4} k\, p_k[N, d] \tag{16}$$

For the damage grades considered in the study, the value of k is taken from 1 to 4, and p_k [N, d] demonstrates the equivalent likelihood of occurrence. The most likely damage status, which is the mean damage index for individual RC frame buildings, is shown by damage states. According to Alex Barbat, the range of DS_m values for these damage levels is tabulated (See Table [5]). The DS_m value, for example, is 2.10 according to the preceding equation. It is more likely that the most expected degree of damage to a related building is less than moderate.

TABLE IV. MORE LIKELY DAMAGE STATES, DAMAGE STATE THRESHOLD, AND CORRESPONDING MEAN DAMAGE INDEX INTERVALS

More likely damage state	Damage state threshold	Mean damage index intervals
No-damage (Sd_0)	-	0.0-0.5
Slight (Sd_1)	0.7*(Sd_y)	0.5-1.5
Moderate (Sd_2)	Sd_y	1.5-2.5
Severe (Sd_3)	Sd_y + 0.25 * (Sd_u - Sd_y)	2.5-3.5
Complete (Sd_4)	Sd_u	3.5-4.0

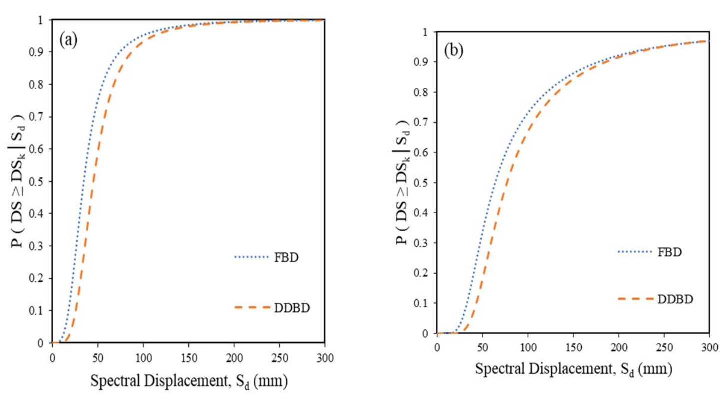
Sd_y = yield spectral displacement, Sd_u = ultimate spectral displacement

III. RESULTS AND DISCUSSIONS

Figure (4) shows a 4-story RC moment resistant frame used to assess the probability of damage using Force-based design (FBD) and Direct displacement-based design (DDBD) for the maximum considered earthquake (MCE) in zone-V. To accomplish the performance point is evaluated using an iterative equal displacement approximation approach provided in ATC-40. The intersection of the capacity and demand spectrums is the performance-point, according to the capacity spectrum approach. Table [5] reveals that the DDBD approach produces better results than the FBD method in terms of spectral displacement calculated using fragility curves, which are 198 mm for the FBD method and 160 mm for the DDBD method. While designing with the FBD approach, it observed a 99 per cent predicted chance of exceedance in slight damage, 92 per cent moderate damage, 65 per cent severe damage, and 24 per cent full damage. Using the DDBD approach, 98 per cent of the damage is minor, 85 per cent is moderate, 53 per cent is severe, and 16 per cent in total. As a result, it is clear that, in the case of MCE, a structure designed using DDBD will deliver the best output for the required performance compared to FBD.

TABLE V. DAMAGE INDEX AND MORE PROBABLE DAMAGE STATE FOR RC FRAME BUILDING DESIGN WITH FBD AND DDBD.

Design	Damage state probability of occurrence					Damage index	More probable damage state
	Sd_0	Sd_1	Sd_2	Sd_3	Sd_4		
FBD	1%	8%	27%	41%	24%	2.74	Severe damage
DDBD	2%	13%	33%	37%	16%	2.49	Moderate damage



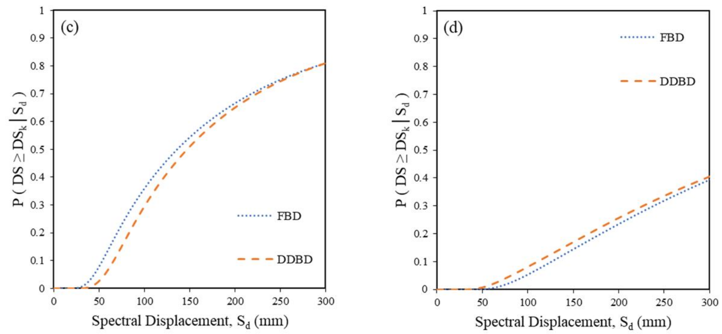


Figure 4. Comparison of the FBD and DDBD method for the 4-story RC frame building of damage state (a) slight, (b) moderate, (c) severe, and (d) complete

IV. Conclusions

In this work, the seismic performance and damages of a lateral load planned mid-rise 4-story RC frame building were analyzed at the MCE level using the FBD and DDBD methods for seismic zone-V (soil type-II). Fragility curves that represent the expected structural damage in a probabilistic manner were created using fragility analysis. To determine the state of the building's damage and damage probability matrices are used. Compared to DDBD, the fragility curves showed that the traditional provisional approved FBD technique had a greater damage likelihood. Using the damage index and mean damage state has been observed that FBD-based constructed RC frame buildings are more likely to experience severe damage, but DDBD-based structures are more likely to moderate damage at the MCE level.

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