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PRACTICE-ORIENTED PAPER

Seismic assessment of RC building frames using direct-displacement-based and force-based approaches

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Abstract

The conventional force-based design (FBD) method has been in practice for seismic assessment of RC building frames. In the FBD method, the main focus is on the seismic forces over the structure. In recent years, various shortcomings have been pointed out by research works, for example assumed initial stiffness of structural components, inappropriate response reduction factors, etc. To overcome these limitations of FBD, many new techniques have been developed and implemented. One such method is the direct-displacement-based design (DDBD) method. In this, the basic assumption is that strength is less critical than displacement. DDBD is a design theory in which design criteria are articulated for achieving a specified level of performance goals that are subjected to the defined level of seismic hazards. In this paper, the vulnerability of buildings situated in high seismic regions in India has been assessed. Four- and eight-storey RC building frames are taken into consideration. The non-linear time-history analysis is carried out, and the inelastic behaviour of buildings in the form of base shear, inter-storey drift ratio (ISDR) and maximum displacement is assessed. Also, fragility curves have been developed considering the effect of ISDR. It is concluded that the DDBD approach is more reliable and efficient for designing RC building frames as compared to its counterpart FBD approach.

Keywords Fragility curves · RC building frames · Time-history analysis · Direct-displacement-based design · Inter-storey drift

Introduction

Research on the DDBD method for RC building frames has been extensively carried out during the last decade. Yet, it is still an active research area for researchers across the globe. The application of the DDBD method for designing RC building frames was first carried out by Priestley and Kowalsky [1]. Consequently, with time, the DDBD method was investigated and new developments came in. Panagiotakes and Fardis (2001) compared 4-storey RC buildings designed by the DDBD procedure and the procedure prescribed in Eurocode 8 [2]. Pettinga and Priestley (2005) applied the DDBD methodology to 6-storey RC tube-frame structures and tested it using time-history analysis. They studied the change in design displacement profiles and lateral force distribution [3]. In 2007, Priestley et al. [4] gave a detailed description of the DDBD method for RC building frames. An effective comparison was carried out between conventional FBD and DDBD for RC building frames by Sil et al. (2018) and Sharma et al. (2019), and their results have been drawn out [5, 6]. Karimzada (2015) studied the DDBD approach in compliance with the Turkish Seismic Design Code. Time-history and pushover analysis were carried out to check storey drift ratio [7]. Das and Choudhury (2019) studied the influence of different stiffnesses on the performance of the RC frame building designed by the DDBD method. They also focused on evaluating the effective stiffness of column sections using the ANN method [8]. Expression was developed for the distribution of lateral load in open ground storey (OGS) buildings designed by the DDBD approach [9]. Investigation of RC asymmetric-plan structures was carried out by studying torsion effects on structures by varying eccentricity using displacement-based adaptive-pushover methodology [10].

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Similarly, DDBD procedures were developed for steel frame structures [11, 12]. Sahoo and Prakash (2019) evaluated the seismic performance of concentrically steel braced frames (CBF) designed using the DDBD procedure [13]. The design displacement profile for CBF structures was developed based on the median maximum storey displacements [14]. Yet, the investigation of both DDBD and FBD method using fragility analysis has not been explored much. Although, fragility curves were developed by using the DDBD method for other structures, mainly bridges [15]. In this paper, four-storey and eight-storey RC building frames are considered in the high seismic area (Zone-V) of Indian regions. Both RC buildings are designed by FBD and DDBD methods and their performance is assessed under seismic actions of seven ground motions using non-linear time-history analysis (NTHA). Based on the NTHA results, base shear, displacement and drifts are compared for both methods. The vulnerability of RC buildings designed by both approaches is also assessed by developing fragility curves considering ISDR as the parameter.

Description of building models

Four-storey (low-rise) and eight-storey (mid-rise) RC building frames are modelled to evaluate the seismic response and vulnerability. The RC building frames are rectangular in shape having three bays in *X*-direction and two bays in *Y*-direction. The total width in *X*- and *Y*-directions are 18.0 m and 8.0 m, respectively. The storey height of the first storey is 3.5 m, whereas a constant storey height of 3 m is considered for the rest of the floor levels. Elevation and plan are represented in Fig. 1. Other details, i.e. location, grade of concrete, grade of steel, modulus of elasticity and passion ratio, are provided in Table 1.

Both four-storey and eight-storey RC building frames are designed using FBD and DDBD approaches. For conventional FBD, RC building frames are designed using IS 1893 (2016), IS 456 (2000) and IS 13920 (1993) [16–18]; whereas, the procedure given by Priestley et al. [3] is followed for designing RC building frames using the DDBD method as shown in Fig. 2. Target drift of ($\theta = 2\%$) has been considered as performance limit as per FEMA-356 [19]. Modelling of buildings is done using SAP2000 software [20]. Plastic hinges are assigned as described in Tables 6–7 and 6–8 of FEMA-356 for concrete beams and columns.

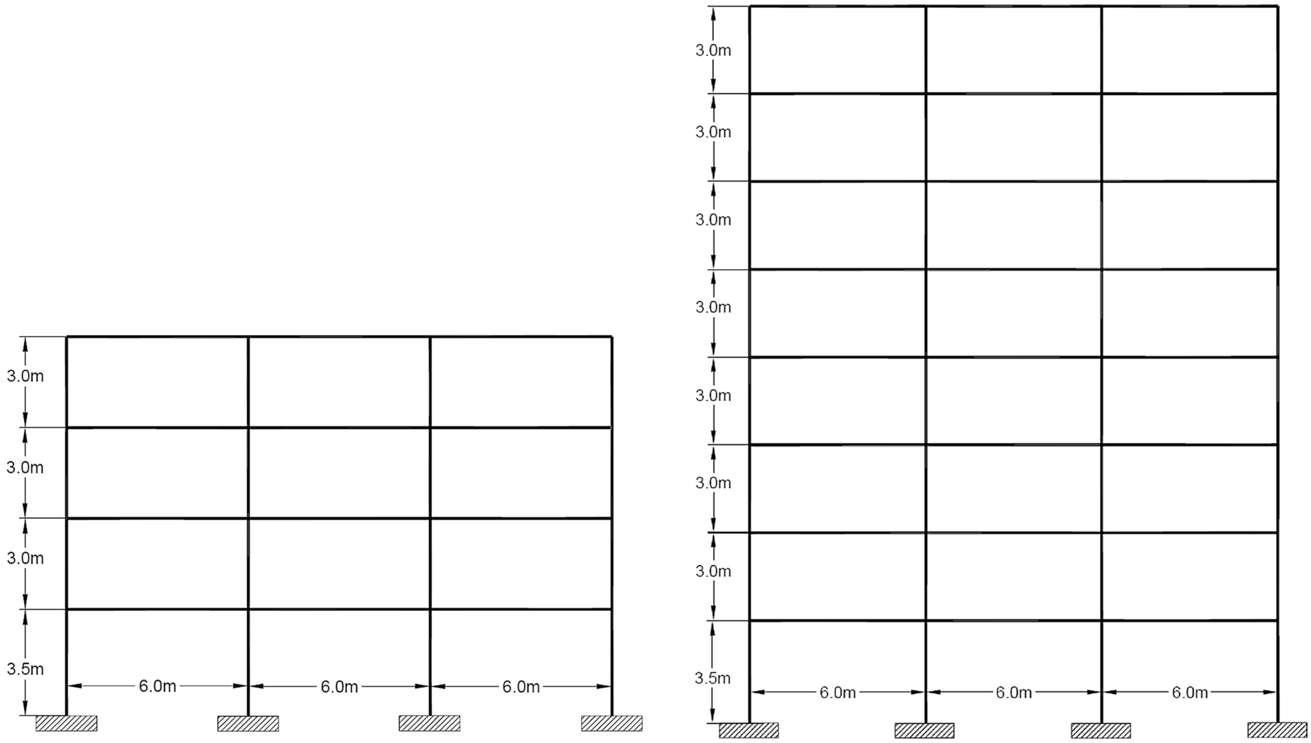
Selection of ground motions for non-linear time-history analysis (NTHA)

NTHA is one of the most accurate methods for analyzing the behaviour of RC building frames during seismic excitations. Selection of ground motions is one of the crucial parameters in the non-linear analysis of structures, as it controls the performance levels for which the RC structures are designed. As per the recommendation of FEMA-P695 [21], a minimum of seven ground motions should be considered for getting accurate results for NTHA. In this study, seven different ground motions are selected from the Centre of Engineering Strong Motion Data [22]. Details of earthquake ground motions are summarized in Table 2. As per ASCE 7-10 (2010) guidelines, the average response spectrum obtained from at least five recorded or simulated acceleration-time histories response spectra should approximately match with the design spectrum over the period range of 0.2–1.5 T, where (T) is the natural period of the considered structure [23, 24]. Figure 3a represents the comparison of selected ground motions with target response spectrum. In this study, the RC building frames considered for numerical analysis are designed for the highest seismic zone (Zone-V) as per Indian standard IS 1893 (2016) considering medium soil conditions. Thus, the ground motions are made compatible to design response spectrum corresponding to the spectrum at Zone-V using SeismoMatch software (version 2020) [25]. Each ground motion is well matched to the target spectrum, as shown in Fig. 3b, c respectively.

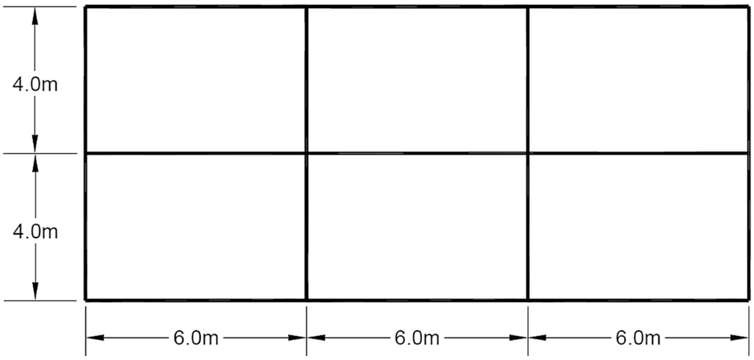
Results of NTHA for RC building frames

Inelastic seismic response of 4-storey and 8-storey RC building frames is analyzed, which are designed using FBD and DDBD methods. Target drift of 2% has been chosen as performance criteria. Frames are modelled in SAP2000 software and NTHA is conducted on frames. The beam and column dimensions of the RC building frames are summarized in Table 3. From Table 3, it can be observed that the beam and column size of the building designed using the DDBD method are comparatively smaller in sizes than the building designed using the FBD method for the same target level. Thus, for the same performance level criteria, the obtained lower sections in the DDBD method result in saving of the material as compared to the FBD method.

For selected RC building frames designed by FBD and DDBD methods, storey shear profiles observed in each storey are illustrated in Figs. 4 and 5, whereas maximum base shear (V_b) values are presented in Table 4, respectively. From the results shown in the above figures and table, it is clear that there is a percentage reduction in storey shear and base shear in the DDBD method compared to the FBD method. It is seen from Table 4, the reduction in the base shear for 4-storey buildings varies between 8% and 16%, respectively. For 8-storey buildings, the reduction in base shear response is highly considerable as it varies between 24% and 36%, respectively. This shows that, as the height increases, the DDBD method proves to be more efficient than the FBD



(a) Elevation View (4-storey frame) **(b)** Elevation View (8-storey frame)



(c) Plan View

Fig. 1 The plan and elevation of 4-storey and 8-storey RC building frames

Table 1 Parameter details used in this study

Descriptions	Details
Location of RC frames	Zone-V (0.36 g)
No. of Storeys	4 and 8
Bay length in *X*-direction	6 m
Bay length in *Y*-direction	4 m
Characteristic strength of concrete	M25
Characteristic strength of Rebar steel	HYSD 415
Elastic moduli of concrete	25000 MPa
Poisson's ratio value	0.2

method. Also, lower base shear values in DDBD results in lower stiffness and less acceleration demand [5, 6].

Displacement profiles of DDBD and FBD methods for 4-storey and 8-storey RC building frames are presented in Figs. 6 and 7. NTHA has been carried out using seven different ground motions and compared with design displacement profile. The results obtained by NTHA show that the target displacement shape from DDBD shows an excellent agreement with the NTHA results; whereas, from Fig. 7, it is observed that storey displacement obtained using the FBD method overestimates the results of NTHA for both

Fig. 2 Fundamentals of DDBD [3]

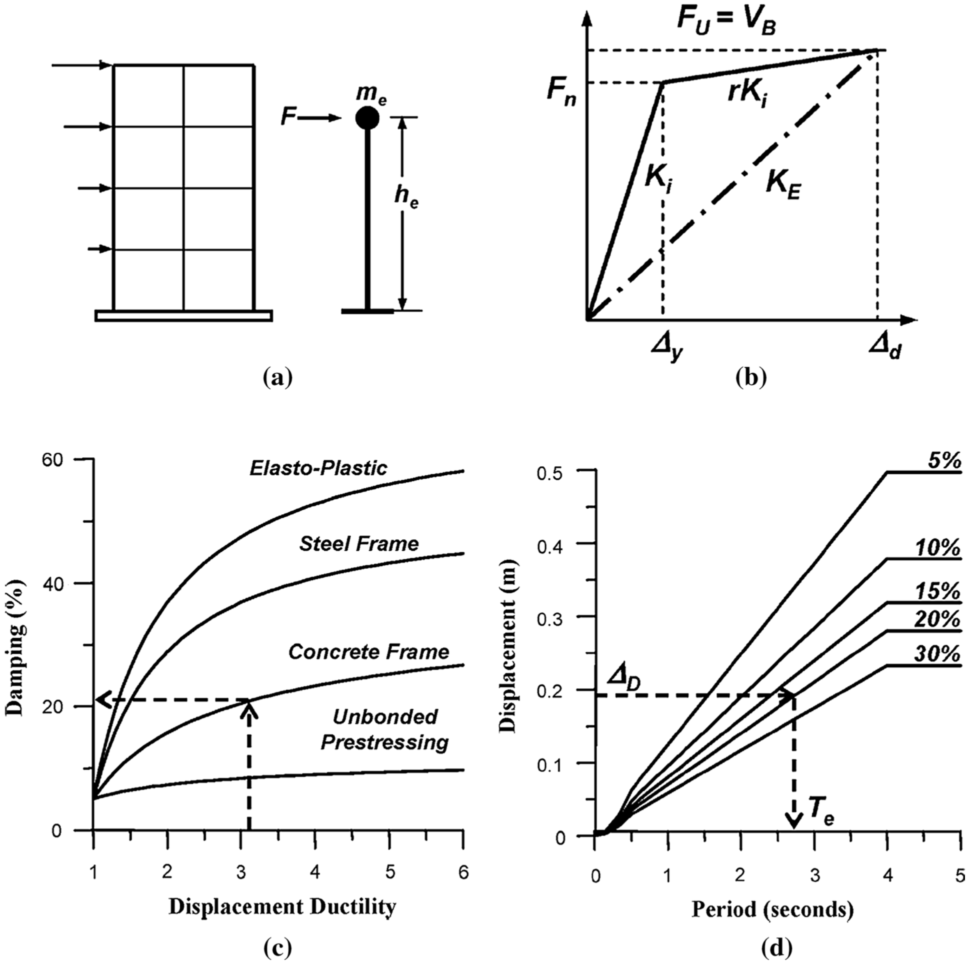
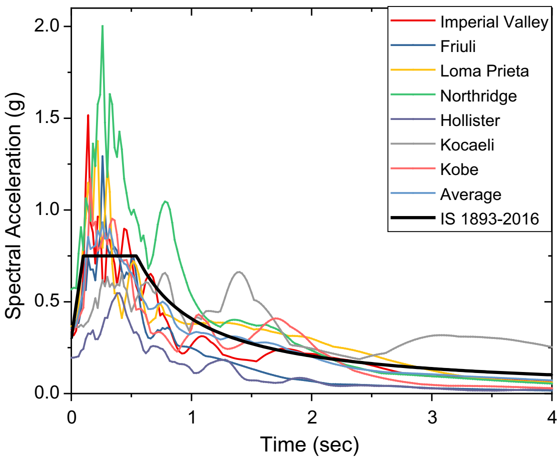


Table 2 Details of earthquake ground motions

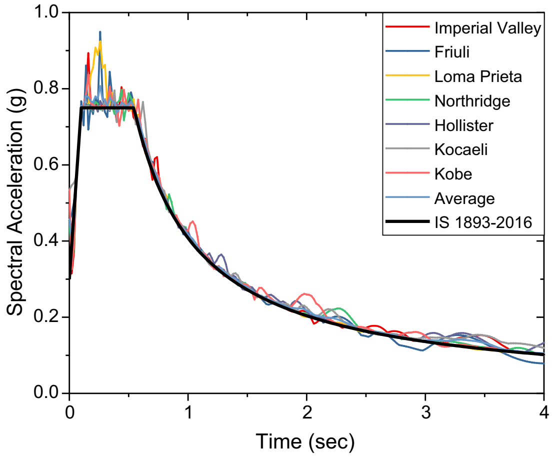
S. no.	Ground motions	Year of occurrence	Record length (s)
1	Imperial Valley	Oct 15, 1979	39.48
2	Friuli	May 06, 1976	36.32
3	Loma Prieta	Oct 18, 1989	39.90
4	Northridge	Jan 17, 1994	39.88
5	Hollister	April 09, 1961	39.93
6	Kocaeli	Aug 17, 1999	34.96
7	Kobe	Jan 16, 1995	40.90

4-storey and 8-storey buildings. Thus, the results obtained by the DDBD method show confidence in the prediction of storey displacements as compared to the FBD method. Also, similar trends can be noticed in other studies of DDBD designed for RC building frames [26, 27].

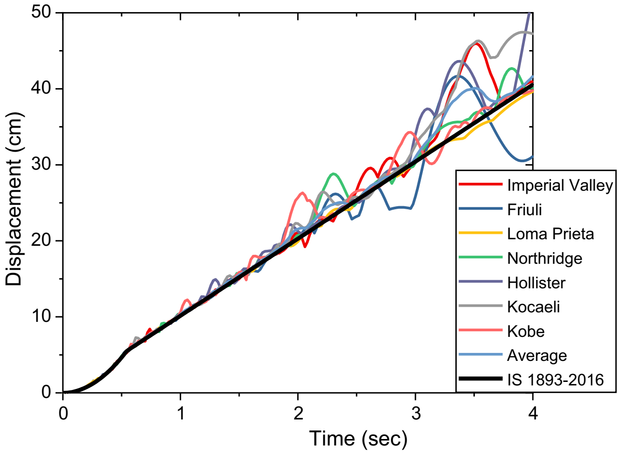
Inter-Storey Drift Ratio (ISDR) is one of the most critical parameters in analyzing the structural performance of buildings. In this study, a target drift of 2% has been chosen as a performance target limit as per FEMA-356. ISDR of low-rise (4-storey) and mid-rise (8-storey) RC buildings is presented in Figs. 8 and 9. It is found that from Figs. 8 and 9, ISDR for RC buildings designed by the FBD method is much more as compared to the DDBD method. The difference in ISDR for FBD and DDBD buildings is more for low-rise buildings. ISDR is maximum at the floors near to ground level mostly at the first storey for four-storey height buildings and at the third storey for eight-storey height buildings, respectively. Also, the time-history results of the 4-storey and 8-storey RC building frames are plotted in Figs. 10 and 11 for all ground motions. The maximum inter-storey drift ratio (M-ISDR) obtained from ground motions is compared with the target drift limit of 2%. It can be observed that both four- and eight-storey RC building frames performed



(a) Original ground motions with target response spectra



(b) Matched ground motions with target response spectra



(c) Matched ground motions with target displacement spectra

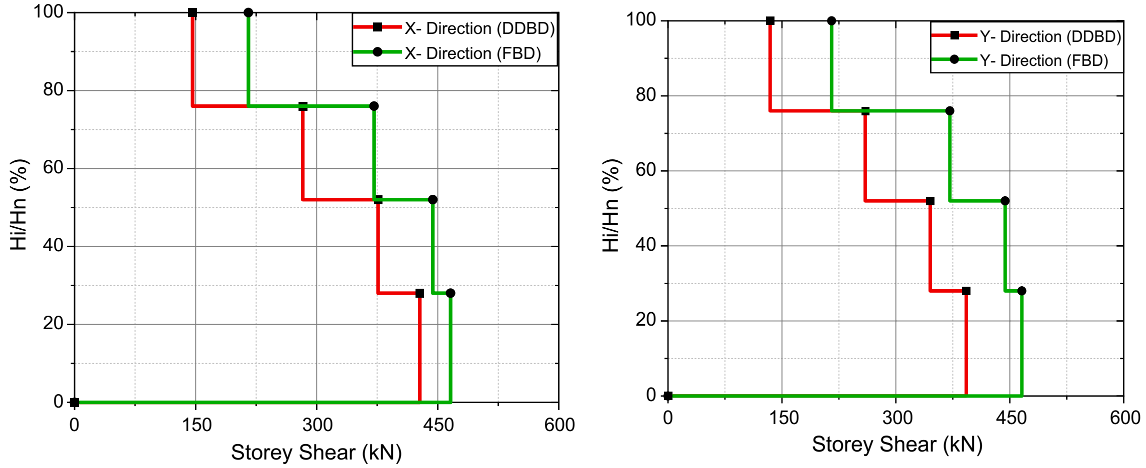
Fig. 3 Unmatched and matched ground motions with target spectra

Table 3 Beam and column dimensions of RC building frames

Method	Storey	Beam sections (m)	Column sections (m)
FBD	Four-Storey	0.35 × 0.40	0.60 × 0.60
	Eight-Storey	0.40 × 0.45	0.60 × 0.70
DDBD	Four-Storey	0.25 × 0.40	0.40 × 0.50
	Eight-Storey	0.35 × 0.40	0.50 × 0.55

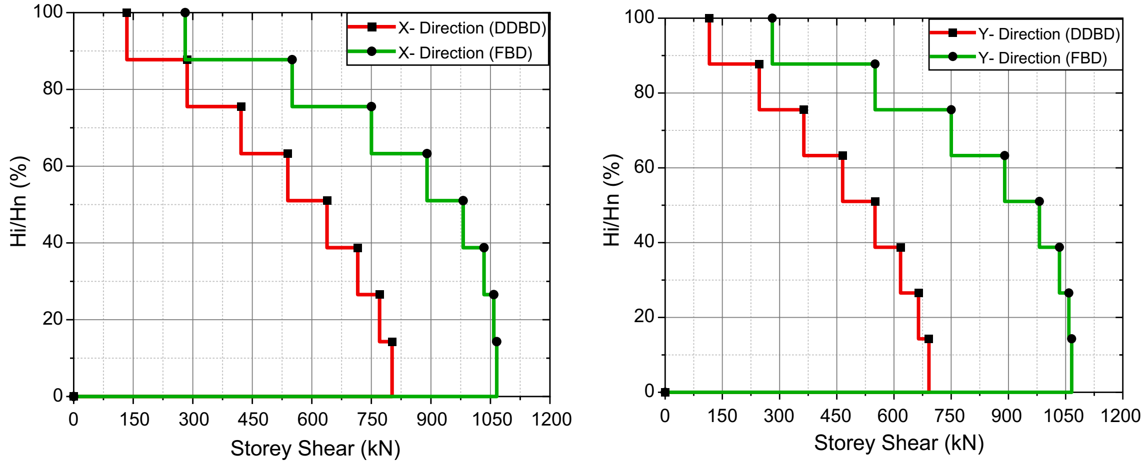
exceptionally well under Imperial Valley and Kocaeli earthquakes. The M-ISDR for Imperial Valley and Kocaeli earthquakes is computed as 70% and 52% less than the target drift value for four-storey frames. Whereas, for eight-storey, it reduces up to 38% and 32%, respectively. It can be noticed that the more the value of drift variation, the better the RC frames designed by the DDBD approach performed. This means that the M-ISDR is well under control when compared to the selected target drift. Whereas, in RC frames designed by the FBD approach, less variation in drifts as compared to target chosen drift better the RC frames performed. As expected, even RC frames designed by the FBD approach performed quiet well under Imperial Valley and Kocaeli earthquakes. For all other selected ground motions, the performance of RC frames is nearly the same. Also, it is observed that for all ground motions, the maximum target drift of 2% has not exceeded for DDBD buildings. Whereas, FBD buildings failed to anticipate the target limitation of 2%. Thus, RC building frames designed by the DDBD procedure significantly reduce the drift response.

Fragility curves have been obtained considering the effect of ISDR. Fragility curves can be defined as the statistical measure when it shows the probability of exceedance (POE) of a selected engineering demand parameter for a selected damage level for a specific ground motion intensity measure (IM). IM could be Peak Ground Acceleration (PGA), Permanent Ground Deformation (PGD), Pseudo-Spectral Acceleration (PSA), Spectral Acceleration (SA) and in some cases spectral velocity also [28–30]. But, among all IMs, PGA has been the most common IM and widely popular among researchers [31–34]. However, few researchers recommend PSA as IM in fragility analysis [35–37]. But, using PSA as IM in fragility analysis has its limitations. Klugel (2007) discussed the limitations of PSA by energy-conversation principles, noticing that seismic events with very different energy content may have similar PSA [38]. Similarly, various concerns regarding the performance of PSA have been addressed by Schotanus et al. (2004), Kohrangi et al. (2016) and Radu and Grigoriu (2018) [39–41]. Also, Pragalath (2015) has given a comparison of using IM as PGA and SA



(a) Storey shear profiles in X- Direction **(b)** Storey shear profiles in Y- Direction

Fig. 4 Storey shear profile for four-storey RC building frames



(a) Storey shear profiles in X- Direction **(b)** Storey shear profiles in Y- Direction

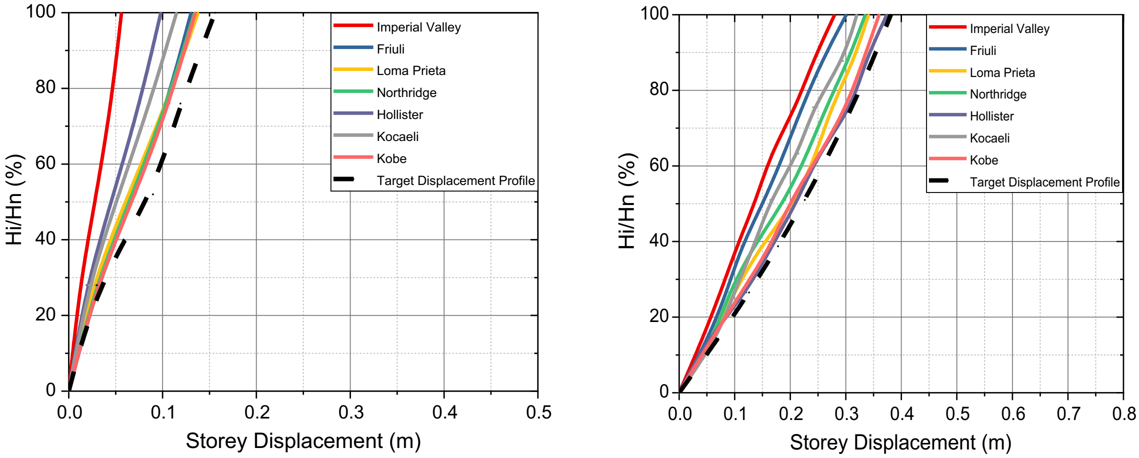
Fig. 5 Storey shear profile for eight-storey RC building frames

Table 4 Percentage reduction in base shear of RC building frames

Directions	No. of storeys	Methods	Maximum base shear (kN)	% reduction in base shear
X-Direction	4-Storey	FBD	465.93	8.15%
		DDBD	427.73	
Y-Direction		FBD	465.93	15.83%
		DDBD	392.93	
X-Direction	8-Storey	FBD	1065.96	24.73%
		DDBD	802.26	
Y-Direction		FBD	1065.96	35.12%
		DDBD	691.58	

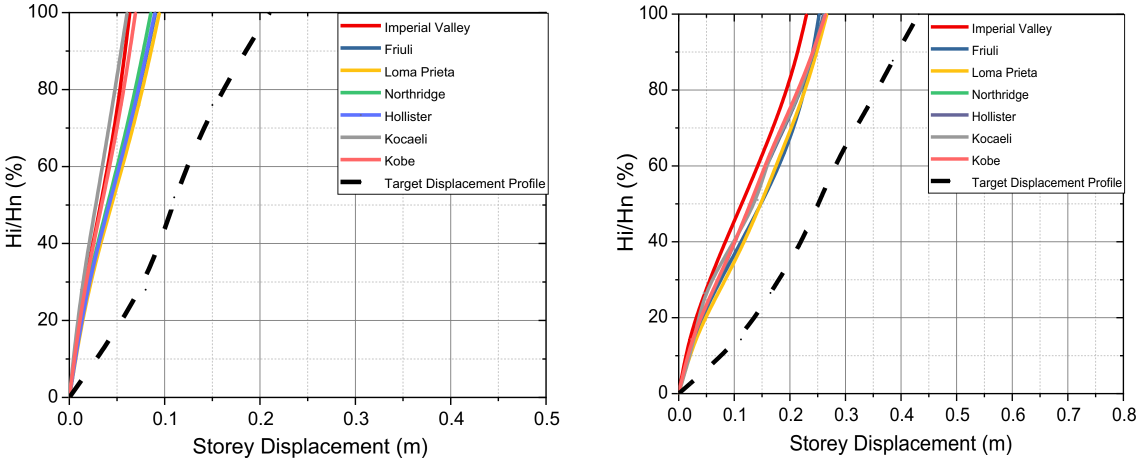
for RC building frames, where the researcher concluded that using PGA as IM is a better option as the standard seismic hazard curves in Indian regions are available in terms of PGA [42]. This makes PGA a suitable IM. In this study, PGA is used as IM. The probability of exceeding or being in a particular damage state ds, for a given seismic parameter (PGA), is given by lognormal standard cumulative normal distribution function as expressed in Eq. 1

$$P\left[d_s/S_{\mathrm{PGA}}\right] = \varphi\left[\frac{1}{\beta_{\mathrm{ds}}}\ln\left(\frac{S_{\mathrm{PGA}}}{S_{\mathrm{PGA,ds}}}\right)\right] \quad (1)$$



(a) Four-Storey RC buildings **(b)** Eight-Storey RC buildings

Fig. 6 Displacement profile shape for RC buildings designed by (DDBD) method

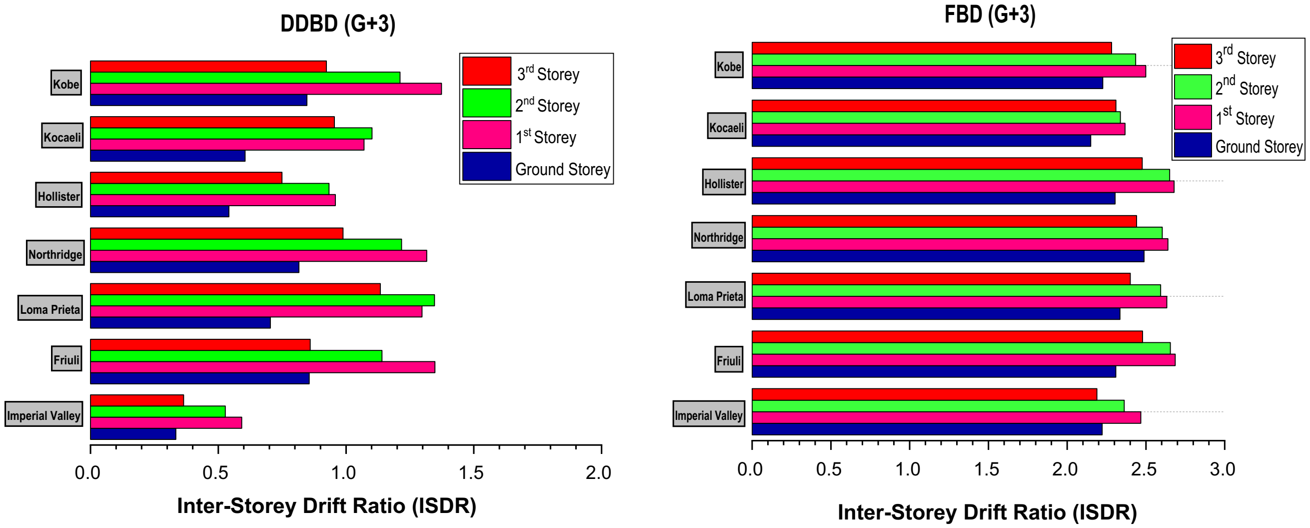


(a) Four-Storey RC buildings **(b)** Eight-Storey RC buildings

Fig. 7 Displacement profile shape for RC buildings designed by (FBD) method

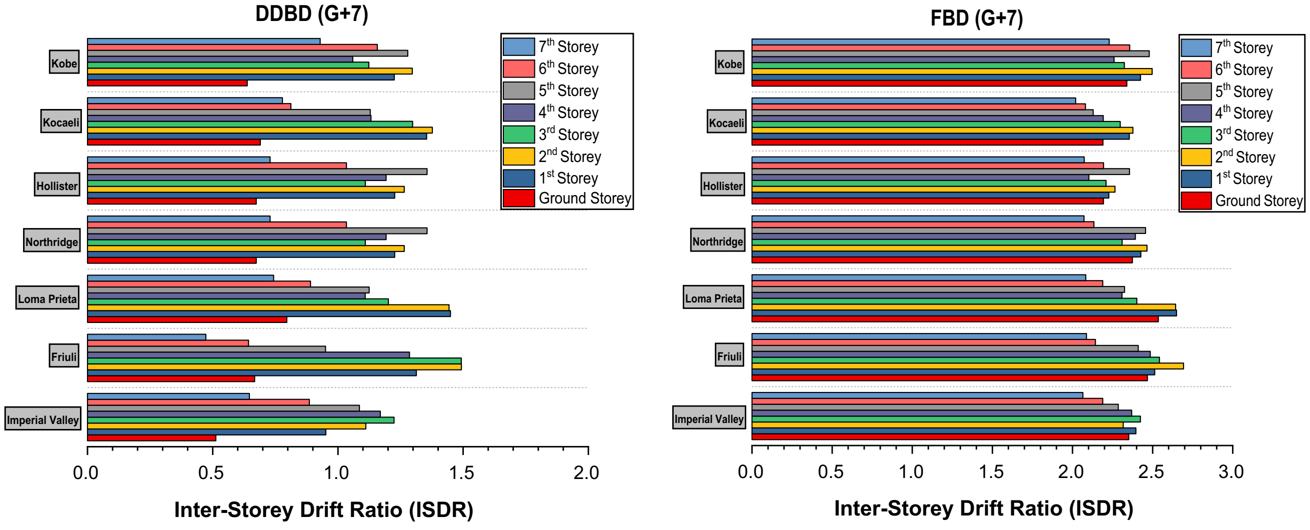
where φ = standard normal cumulative distribution function, $S_{\mathrm{PGA,ds}}$ = median value of PGA at which the building reaches the threshold of damage state, β_{ds} = lognormal standard deviation of PGAs for a given damage state.

Thus, using Eq. 1, fragility curves are developed. The same procedures were adopted by Danish and Rawal (2016) and Samanta and Swain (2019) in their study [43, 44]. The methodology for developing fragility curves is shown in Fig. 12, whereas developed fragility curves are represented in Fig. 13. It is observed that, for the same PGA values, the ISDR values are higher in FBD as compared to DDBD buildings due to more lateral displacement. Thus, fragility curves for FBD show more probability of damage as compared to DDBD buildings, having higher median and lognormal standard deviation of PGA corresponding to higher ISDR values for both 4-storey and 8-storey RC building frames. From overall results, it can be found that risk is greater in FBD buildings and is more vulnerable as compared to DDBD buildings. Also, it is noted that the DDBD method does not lead to an



(a) (DDBD) Method **(b)** (FBD) Method

Fig. 8 Inter-storey drift ratio (ISDR) for four-storey RC buildings



(a) (DDBD) Method **(b)** (FBD) Method

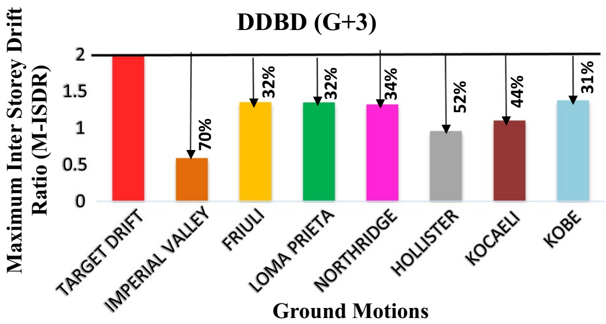
Fig. 9 Inter-storey drift ratio (ISDR) for eight-storey RC buildings

over-estimation design and can be considered as an efficacious design approach for the RC building frames.

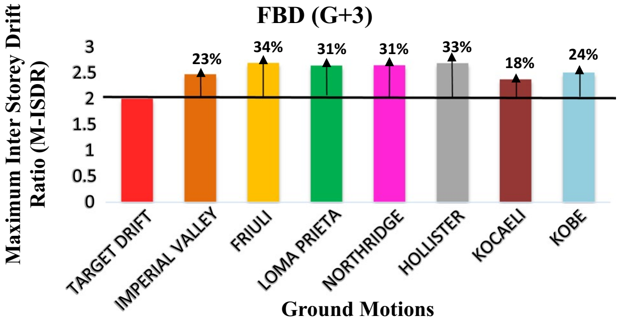
Conclusions

A comparative study of the two alternative methods, namely FBD and DDBD, is conducted using low-rise (4-storey) and mid-rise (8-storey) RC building frames, respectively. Using different ground motions, the NTHA analysis is conducted and the results are drawn out for various seismic parameters. The major conclusions from this study are as follows:-

(a) The designed RC sections using DDBD are economical for both 4-storey and 8-storey buildings. Resulting in more savings of materials in the DDBD method than the FBD method.

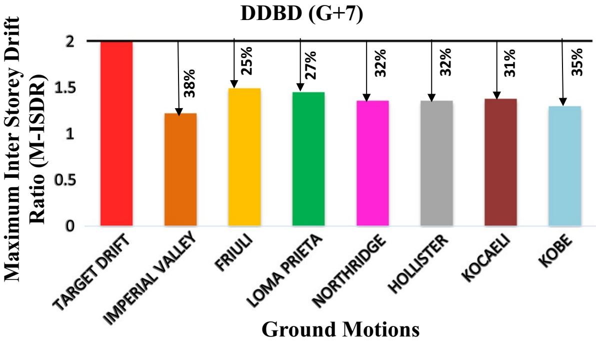


(a) Drift Variation in 4 storey (DDBD Method)

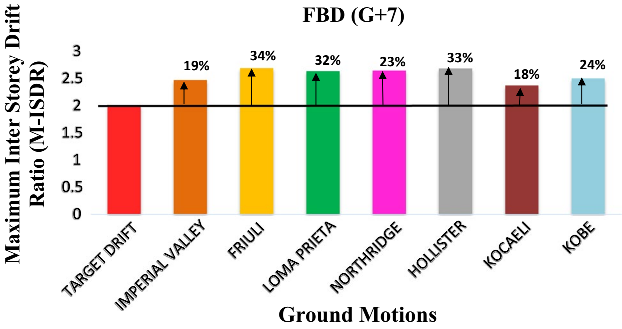


(b) Drift Variation in 4 storey (FBD Method)

Fig. 10 Drift variations in ground motions for four-storey RC building frames



(a) Drift Variation in 8 storey (DDBD Method)



(b) Drift Variation in 8 storey(FBD Method)

Fig. 11 Drift variations in ground motions for eight-storey RC building frames

(b) Lower base shear values are found for DDBD buildings as compared to FBD buildings, leading to lower stiffness and lesser acceleration demands in DDBD RC building frames.

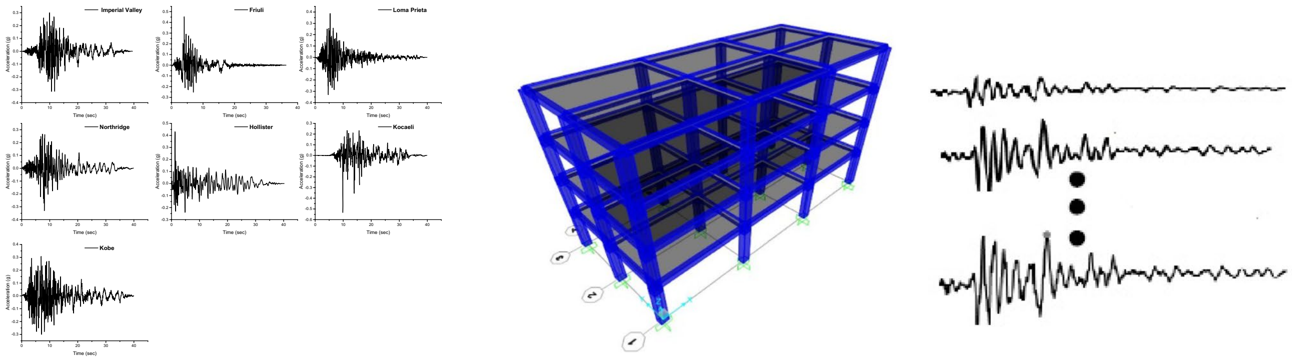
(c) For a given RC building frame, the design displacement profiles are developed and compared. The displacement profile of DDBD shows good agreement with the NTHA results. Thus, it can be inferred that the DDBD approach is more suitable for designing low and mid-rise RC building frames.

(d) The maximum allowable drift of 2% has been chosen as the design limit state as per FEMA-356. Inter-Storey Drift Ratio (ISDR) has been calculated and found that, for DDBD buildings, ISDR is well under the control of the maximum allowable limit; whereas, the same cannot be said for FBD buildings as for both 4-storey and 8-storey buildings the maximum permissible limit of 2% is not satisfied.

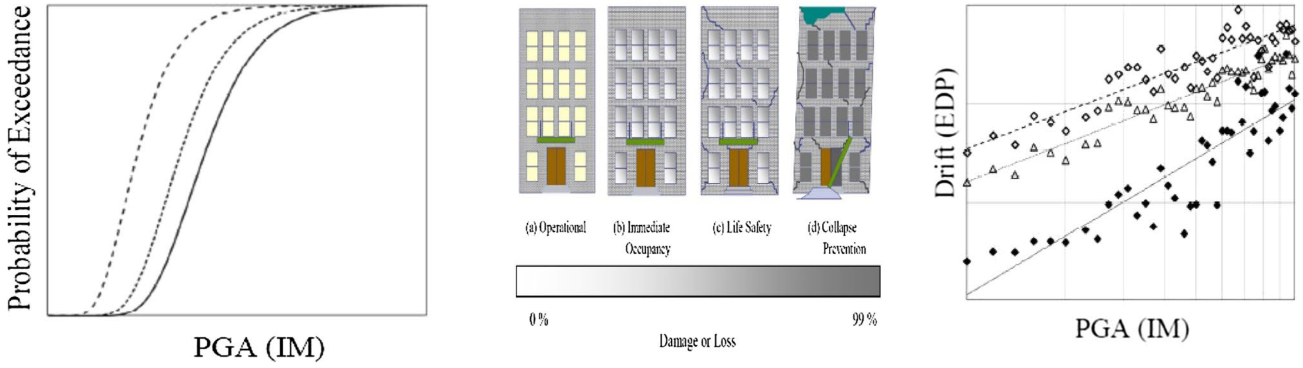
(e) It can also be concluded that the weak-beam strong-column mechanism is well satisfied in the DDBD method as compared to the FBD method.

(f) Fragility curves are plotted, which visually show the POE of life safety limit damage state. Fragility curves for the FBD method show more POE than the DDBD method. Thus, buildings designed using the DDBD method are less vulnerable as compared to the FBD method.

(g) A further study can be carried out for tall buildings accounting higher mode effects.

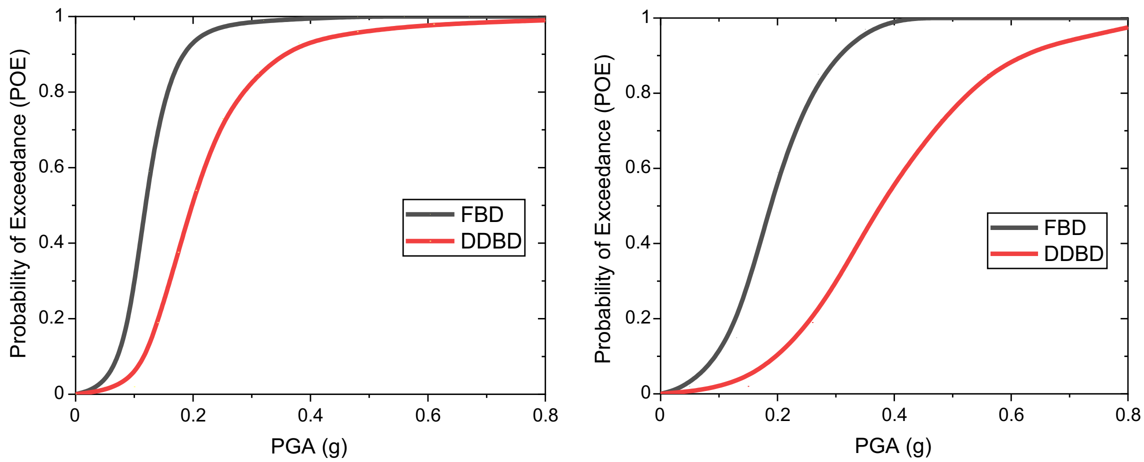


(a) Ground Motions Selection **(b)** Develop Building Models **(c)** Estimate Buildings Response



(f) Develop Fragility Curves [42] **(e)** Define Limit State [19] **(d)** Develop PSDM Model [42]

Fig. 12 Methodology for developing fragility curves



(a) Fragility Curve for 4-Storey building **(b)** Fragility Curves for 8-Storey building

Fig. 13 Development of fragility curves

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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