

# Parametric Study of Performance-Based Seismic Design of Plan Irregular RC Frames—Indian Scenario



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## 1 Introduction

Earthquake-resistant design based on traditional approaches aims to attain the prescribed limits on strength and serviceability criteria as per code provisions. Even after practising those design practices, earthquakes incurred catastrophic damages to structures and led to huge loss of life and economy. Joshi et al. found that 52.86% of hospitals, 64.58% of schools and nearly 60% of other important surveyed buildings would collapse immediately after an earthquake in Uttarakhand [1]. Gautam et al. highlighted the urgent need to revise the Indian code by comparing the performance of structural forms during Bhuj, Chile, Kashmir, Haiti, L'Aquila and Turkey earthquakes from the past two decades worldwide [2]. Moreover, nonlinear analysis methods are not included in Indian building codes and no changes are expected in the near future [3]. Shukla and Dalal found that though the response reduction factor ( $R = 5$ ) as per IS code is valid, but hinges are formed in columns and so the strong-column–weak-beam concept does not hold true [4]. The column/beam moment-capacity ratio (M.R.) in IS 13920:2016 is found uneconomical for regular frames [5].

In reality, many existing reinforced concrete (RC) buildings have irregular configurations especially in the plan [6]. Many researchers tried to study the effect of irregularity on the seismic performance of the structure. Chen et al. provided a framework for three-dimensional models to account for the torsional behaviour of asymmetric buildings [7]. It is found that the CSM-FEMA440 method better matched the

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nonlinear dynamic analysis in plan irregular frame buildings [8]. The pushover analysis provides displacements within the range of ASCE but greater than the conventional code-based approach and must be considered when analysing irregular buildings [9]. An attempt has been made to know the difference in seismic response of two buildings having diaphragm discontinuity and without diaphragm discontinuity [10].

In engineering practice, standard and convenient member sizes are generally considered [11]. This results in a lower ductility capacity of the structure. The commitment of PBSB in earthquake engineering is to build structures of which the seismic performance is attained as desired. The potential loss of occupancy, repair costs and life safety impacts come under the desired seismic performance. The performance level is defined as the maximum acceptable damage state or condition caused by physical damage within a building, the threat to building occupant's life safety due to damage and serviceability of the structure post-earthquake. In this type of design, the decision-maker chooses the structural performance required as per his interest. The engineer uses his skills and provides a design that is capable of satisfying the decision-maker requirements. The combined effort of professionals and designers is required to make this commitment into reality. Mohd. Zameeruddin et al. reviewed recent developments in performance-based seismic design by defining the performance objectives (levels), evaluation techniques and assessment procedures [12]. Because of the advancements that took place recently in assessing seismic hazards, facilities for performing experiments and computer applications, many design engineers and developers in earthquake-prone regions attracted to performance-based seismic design. Hopefully, we can say that within a very short period of time PBSB becomes a conventional design method.

## 2 Description of Selected Frames

Six G + 4 RC frames which are having regular (R), torsional irregular (Ir-1), re-entrant corners (Ir-2), excessive cut-outs (Ir-3), out-of-plane offsets in vertical elements (Ir-4) and non-parallel lateral force system (Ir-5) confirming to clause 7.1 of IS 1893 (Part1):2016 [13] are modelled in Zone IV and Zone V. The software used for analyses is ETABS 2018. Dimensions of columns and beams are varied to find critical sections required in life safety and collapse prevention state. Figure 1 shows the geometry of all selected frames. The nomenclature of frames is done such that the Zone is followed by the regularity/irregularity conditions and then the type of irregularity. Hence, frame IV-Ir-1 represents an irregular frame of Type 1 (torsional irregularity) in Zone IV and V-R represents a regular frame in Zone V.

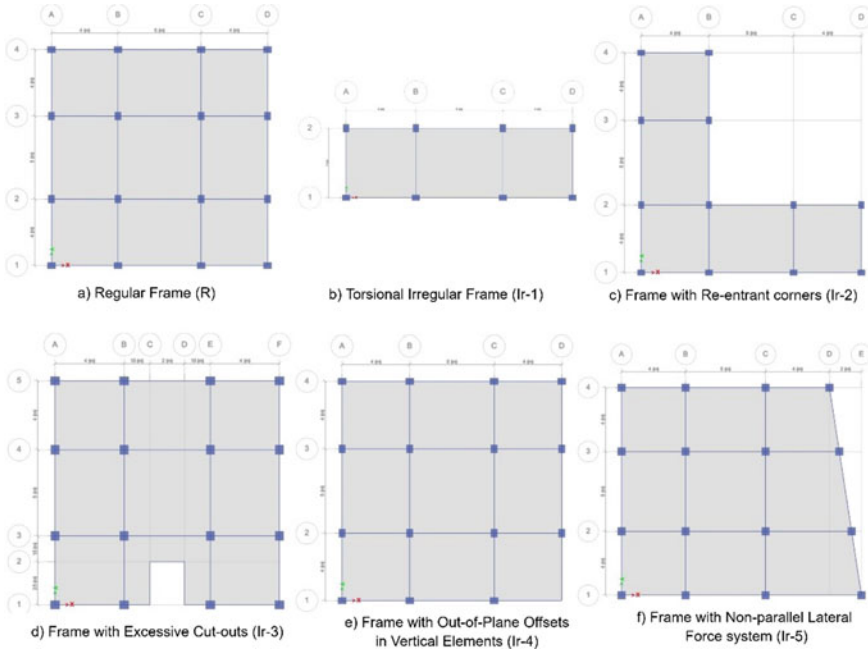


Fig. 1 Various configurations of irregularities as per IS 1893(Part-I):2016

### 3 Modelling of RC Frames

Three-dimensional modelling of frames is done in ETABS 2018. A concrete hysteresis model is used. M25 concrete and Fe500 rebar is used [14]. A floor height of 3 m is considered in all selected frames. The loads are assigned to structural elements as per IS 875 [15, 16] and earthquake loads as per IS 1893:2016. Wall load is applied on beams as uniformly distributed load taking a 30% reduction for openings. Moment of inertia for beams and columns are taken in accordance with IS 13920:2016 [17]. Since the frames are in Zone IV and Zone V, the frames are considered as special moment-resisting frames. All frames have been given an importance factor of 1.5 for lifeline buildings.

### 4 Methodology

In this study, six G + 4 RC bare frames are modelled having a floor height of 3 m. The desired performance objectives of collapse prevention and life safety are selected. Preliminary design is done to the building for linear analysis where the dead load, imposed load and seismic loads are acting. The oscillation type in fundamental mode is verified by modal analysis. Then, it is verified whether all the structural elements

are sufficient enough to carry the elastic loads. Next, nonlinear static analysis is performed. For this, the gravity load case is modified to a nonlinear load case. Now displacement-controlled pushover analysis is performed in both x and y directions which starts at the end of nonlinear gravity analysis. The capacity (pushover) curve obtained is converted to acceleration–displacement response spectra (ADRS) format and superimposed on the demand spectrum and the performance point is obtained. The corresponding coordinates of the performance point on the x- and y-axis give the spectral acceleration and spectral displacement. Using the performance point displacement of the roof and the base shear at that point is obtained. The global response of the building is verified by drift limits given in Table 11.2 [18] of ATC-40. The local response of the elements is also verified by plastic hinge rotation limits in Table 11.3 [18] for beams and Table 11.4 [18] for columns of ATC-40 whether they are within the acceptable limit or not. After verifying the limits, it is confirmed whether the structure possesses the required performance objective or not. If not, the structure is redesigned or the performance of the frames are enhanced.

## 5 Results and Discussions

### 5.1 Cross-sections of Beams and Columns

The primary aim of this study is to find the critical dimensions of beams and columns for life safety and collapse prevention state. Each type of plan irregular frame is compared with the regular frame. First, the preliminary design of members is done to check the minimum dimensions of beams and columns. The minimum dimensions of beams and columns are considered in Trial-1 as per IS 13920: 2016 since the frames are considered in Zone IV and Zone V. In Trial-1 Zone IV, Ir-1 and Ir-2 passed with lesser beams and columns dimension. Frame Ir-3 required the highest dimension among all considered frames to pass the preliminary design. This suggests that among all plan irregularities, buildings with excessive cut-outs would require more dimensions of beams and columns to pass the preliminary design as per codal provisions.

### 5.2 Capacity Curve

The capacity curves for all plan irregular frames are compared with that of the regular frame. It is found that the building with excessive cut-outs has maximum base shear among all plan irregular and regular frames.

**Table 1** Cross-sectional dimensions of beam and column for various cases

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Beam (Trial-1)	350×450	300×350	300×350	500×500	350×400	420×450
Beam (Trial-2)	450×450	450×450	450×450	500×500	450×450	450×450
Column (Trial-1)	400×500	350×450	350×450	500×550	400×500	500×500
Column (Trial-2)	450×600	450×600	450×600	450×600	450×600	450×600

**Table 2** Trial-2 roof displacement and base shear for the frame using response spectrum method in Zone IV

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	194.4	206.6	221.92	120.4	114.13	157
Base shear (kN)	5011.5	1556.92	2400.1	7501.94	4152.7	6258.3

**Zone IV**

*Trial-1.*

An initial analysis is performed using the response spectrum method for all the irregularities as shown in Table 1. The maximum roof displacement and maximum base shear values for all the frames are shown in Table 2. The maximum roof displacement value for the Ir-2 frame is higher than Ir-1 for the same cross-sections and reinforcement of beams, columns and slabs as there is a higher force at the base generated due to seismic activity for a frame with a re-entrant corner (Table 3).

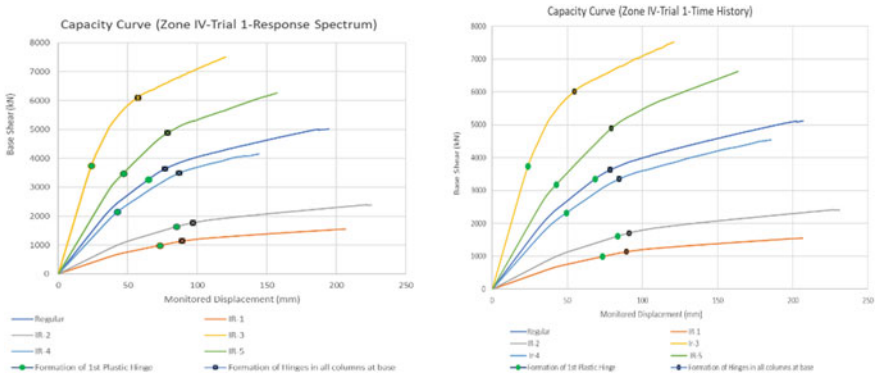
The maximum roof displacement for a regular and torsional irregular frame is nearly the same for different cross-sections of beams and columns. However, in the case of the response spectrum, the Ir-1 value was 6.3% higher than the frame R-value. It is interesting to know that in the case of a frame with out-of-plane offsets in vertical elements (Ir-4), the value of maximum roof displacement is 62.6% (highest) higher in the case of the time history method than the response spectrum method. While in all other frames, there is no significant deviation in values of maximum roof displacement for the time history and response spectrum method (Fig. 2).

*Trial-2*

From Tables 4 and 5, it is observed that the maximum roof displacement values of regular and frame with a non-parallel lateral force-resisting system (Ir-5) are the

**Table 3** Trial-1 roof displacement and base shear for the frame using time history analysis in Zone IV

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	206.78	206.58	227.13	120.96	185.6	163.42
Base shear (kN)	5120.5	1556.92	2413.1	7519.1	4248.5	6636.5



**Fig. 2** Trial-1 capacity curves for various irregularities in Zone IV

**Table 4** Trial-2 roof displacement and base shear for the frame using response spectrum analysis in Zone IV

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	184.94	213.05	258.2	132.15	189.73	169.86
Base shear (kN)	7484.5	3298.9	5363.5	7232.8	6743.7	7616.1

**Table 5** Trial-2 roof displacement and base shear for the frame using time history analysis in Zone IV

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	184.2	172.13	171.45	156.9	161.6	169.89
Base shear (kN)	7468.6	3413.9	5058.9	7574.53	6869.1	7616.1

same in response spectrum and time history method as the cross-sections of beams and columns of all frames are kept the same in Trial-2. However, the maximum roof displacement values are higher by 23.8, 50.6 and 17.4% for frames Ir-1, Ir-2 and Ir-4 in the case of response spectrum than the time history method. For a frame with excessive cut-outs (Ir-4), the maximum roof displacement was 18.73% lower in the case of response spectrum than the time history method (Figs. 3 and 4).

**Zone V**

*Trial-1*

For Zone V similar trends are observed as that of Zone IV for trials 1 and 2, as shown in Tables 6, 7.

*Trial-2*

See Tables 8, 9 and Fig 5.

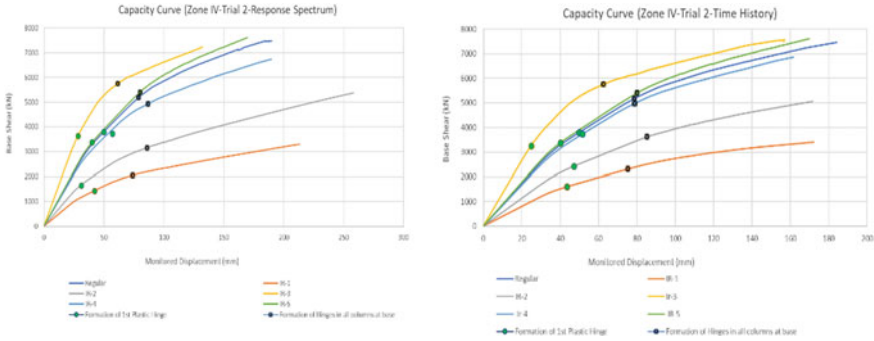


Fig. 3 Trial-2 capacity curves for various irregularities in Zone IV

Table 6 Trial-1 roof displacement and base shear for the frame using response spectrum analysis in Zone V

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	211.3	230.2	249.4	120.3	140.6	161.5
Base shear (kN)	5153.5	1615.9	2482.2	7502.6	4095.6	6305.9

Table 7 Trial-1 roof displacement and base shear for the frame using time history analysis in Zone V

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	195	201.4	222	120.4	114.1	157
Base shear (kN)	5007.8	1548.5	2400.1	7502	4152.7	6258.3

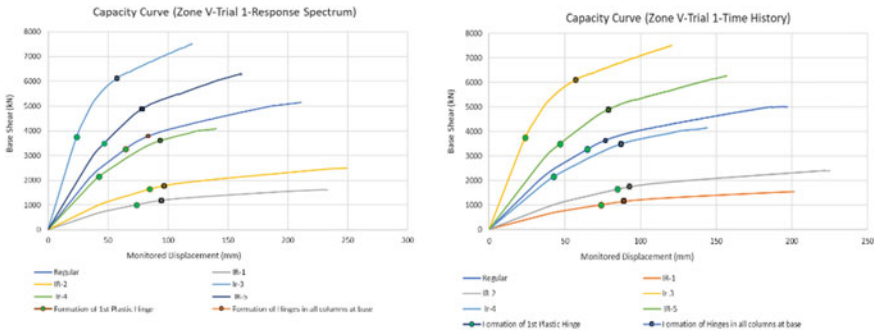


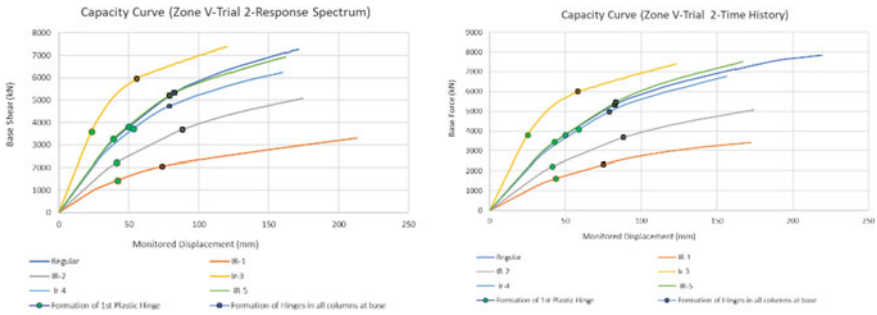
Fig. 4 Trial-1 capacity curves for various irregularities in Zone V

Table 8 Trial-2 roof displacement and base shear for the frame using response spectrum analysis in Zone V

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	171.3	213.1	174.5	120.2	160	162.1
Base shear (kN)	7277.1	3298.9	5072.1	7388.4	6238.6	6930.8

**Table 9** Trial-2 roof displacement and base shear for the frame using time history analysis in Zone V

	R	Ir-1	Ir-2	Ir-3	Ir-4	Ir-5
Roof displacement (mm)	219.3	172.1	174.5	123.3	156.3	167
Base shear (kN)	7829.8	3413.9	5072.1	7395.2	6773.4	7503.3



**Fig. 5** Trial-2 capacity curves for various irregularities in Zone V

### 5.3 Formation of Plastic Hinges and Hinge Response

From the initial analysis with constant cross-section dimensions of 300 mm × 450 mm, it is observed that all the categories of frames have reached a performance level of collapse prevention (CP) in Zone V. The corresponding performance points and spectral coordinates are shown in Table 10. In order to reduce the vulnerability of the chosen irregular frames, the cross-sectional dimensions have been modified as given in Table 1. From the analysis it is observed that the frame with torsional irregularity, non-parallel lateral force system and out of plane offsets have reached life safety level which proved to be safe for earthquake ground motion (Fig. 5; Tables 11 and 12).

## 6 Conclusions

Five-storied regular and plan irregular frames are analysed using nonlinear dynamic time history analyses and linear dynamic response spectrum methods in Zones IV and V for two trial cross-sections of primary structural members. The conclusions are as follows:

- It is found that out of all plan irregularities, Ir-2 and Ir-3 are safe in both Zones IV and V, and other configurations are vulnerable to seismic actions. Frame



**Table 10** Performance level and points for Zone V with preliminary c/s dimensions

Type	Performance level	Performance point	Spectral coordinates
Regular	IO	(94.5 mm, 10,250.9 kN)	(74.8 mm, 1.08 g)
	LS	(102.9 mm, 8794.8 kN)	(83.7 mm, 0.92 g)
	CP	(120.8 mm, 4302.1 kN)	(99.60 mm, 0.52 g)
IR-1	IO	(85.1 mm, 3724.0 kN)	(68.2 mm, 1.03 g)
	LS	(106.0 mm, 2822.8 kN)	(86.41 mm, 0.87 g)
	CP	(130.6 mm, 1340.8 kN)	(109.1 mm, 0.48 g)
IR-2	IO	(102.4 mm, 5910.0 kN)	(80.31 mm, 1.00 g)
	LS	(118.8 mm, 4285.0 kN)	(91.41 mm, 0.81 g)
	CP	(142.2 mm, 2044.5 kN)	(116.23 mm, 0.44 g)
IR-3	IO	(48.6 mm, 7899.3 kN)	(42.6 mm, 0.81 g)
	LS	(78.3 mm, 6452.9 kN)	(68.1 mm, 0.693 g)
	CP	(76.4 mm, 6575 kN)	(66.42 mm, 0.71 g)
IR-4	IO	(101.3 mm, 8468.3 kN)	(86.7 mm, 0.96 g)
	LS	(108.9 mm, 5818.0 kN)	(92.9 mm, 0.72 g)
	CP	(117.2 mm, 3901.9 kN)	(102.0 mm, 0.52 g)
IR-5	IO	(106.1 mm, 9054.7 kN)	(88.97 mm, 0.88 g)
	LS	(120.4 mm, 6561.2 kN)	(99.94 mm, 0.70 g)
	CP	(110.2 mm, 5991.1 kN)	(91.04 mm, 0.645 g)

with excessive cut-outs is also vulnerable in both the zones using the preliminary and modified cross-sections based on maximum base shear, maximum roof displacement which is higher than the other regular and plan irregular frames.

**Table 11** Performance level and points Zone IV with modified c/s dimensions

Type	Performance level	Performance point	Spectral coordinates
Regular	LS	(116.3 mm, 6264.4 kN)	(93.7 mm, 0.72 g)
	CP	(123.52 mm, 4290.4 kN)	(102.2 mm, 0.52 g)
IR-1	LS	(132.8 mm, 1333.9 kN)	(111.7 mm, 0.47 g)
	CP	NA	NA
IR-2	LS	(117.6 mm, 4265.9 kN)	(90.33 mm, 0.81 g)
	CP	(144.1 mm, 2047 kN)	(118 mm, 0.44 g)
IR-3	LS	(83.08 mm, 6259.0 kN)	(70.7 mm, 0.705 g)
	CP	(76.82 mm, 6578 kN)	(66.81 mm, 0.71 g)
IR-4	LS	(119 mm, 3837.7 kN)	(104.3 mm, 0.50 g)
	CP	NA	NA
IR-5	LS	(118.2 mm, 5850.8 kN)	(100.4 mm, 0.63 g)
	CP	NA	NA

A more detailed study on all vertical irregularities can provide a complete understanding of critical dimensions for each performance objective. Further, strengthening techniques for each type of irregularity can be suggested so as to improve the performance at each level.

**Table 12** Performance level and points Zone V with modified c/s dimensions

Type	Performance level	Performance point	Spectral coordinates
Regular	LS	(115.7 mm, 6242.2 kN)	(93.2 mm, 0.72 g)
	CP	(120.8 mm, 4302.1 kN)	(99.60 mm, 0.52 g)
IR-1	LS	(106.0 mm, 2822.8 kN)	(86.41 mm, 0.87 g)
	CP	NA	NA
IR-2	LS	(118.8 mm, 4285.0 kN)	(91.41 mm, 0.81 g)
	CP	(142.2 mm, 2044.5 kN)	(116.23 mm, 0.44 g)
IR-3	LS	(78.3 mm, 6452.9 kN)	(68.1 mm, 0.693 g)
	CP	(76.4 mm, 6575 kN)	(66.42 mm, 0.71 g)
IR-4	LS	(108.9 mm, 5818.0 kN)	(92.9 mm, 0.72 g)
	CP	NA	NA
IR-5	LS	(120.4 mm, 6561.2 kN)	(99.94 mm, 0.70 g)
	CP	(110.2 mm, 5991.1 kN)	(91.04 mm, 0.645 g)

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