Performance-Based Seismic Design of RC Frame Buildings in Moderate Seismic Zones According to Indian Seismic Code

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ABSTRACT

In earthquakes, reinforced concrete structures can suffer damage due to poor design choices such as using weaker concrete, insufficient reinforcement, or mismatched beam and column strength. This study examines a low-rise office building with a reinforced concrete moment frame structure in seismic zone IV with soil category II. The building's lateral design forces are based on IS 1893:2016, and its design follows IS 456:2000. The use of a strong column-weak beam approach is also imposed by IS 13920:2016. The study aims to assess the seismic resistance of the low-rise office building to ensure its safety during earthquakes. To assess how a structure responds to seismic activity, selected five low-intensity, short-range ground motion data sets and scaled them to match the desired design spectrum. Then measured the structure's seismic response at both Design Basis Earthquake and Maximum Credible Earthquake levels. Through seismic analysis, evaluated the structure's ultimate capacity and distribution of inelastic deformations. We evaluated a structure's desired performance level (IO, LS, and CP) based on ASCE/SEI-41 standards. By examining the ultimate conditions of the structure using both local and global criteria, analysis found that the middle story experienced soft story failure, and the beam's plastic rotations were greater than those of the column. However, the structure met the basic safety objectives of the ASCE/SEI-41 criteria through various performance levels observed at the global and member levels. The design and detailing were effective in preventing the strong beam-weak column failure mechanism, ensuring overall structural safety.

Keyword: Column strength, low-intensity, short-range earthquake, Damage criteria, Plastic rotations

Introduction

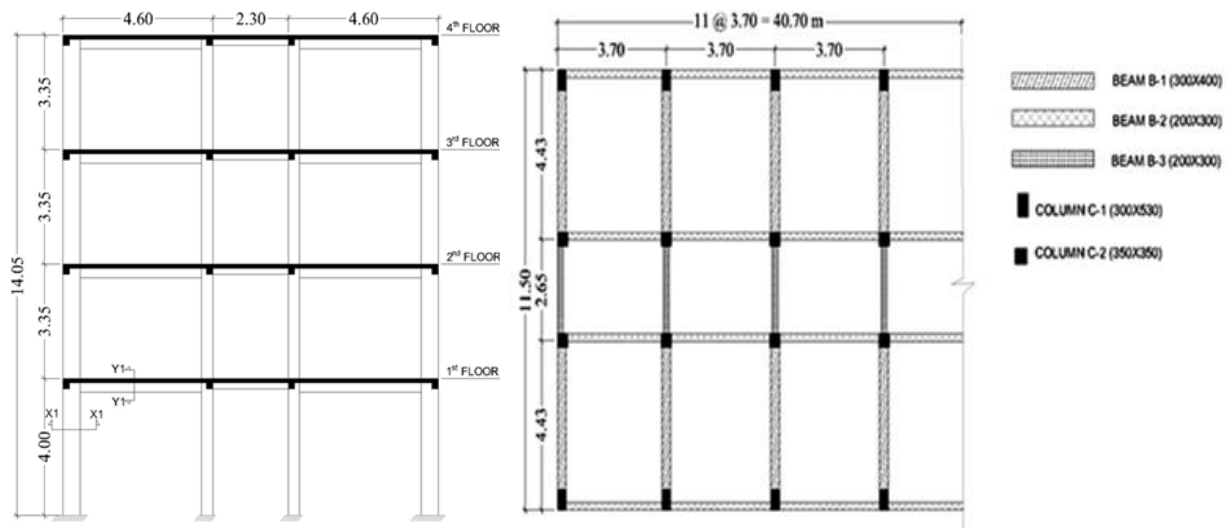
Earthquake is solitary of the greatest distressing disaster causing loss of life, loss of economy, destruction and damage to infrastructures. It is the violent shaking of the ground resulting from sudden release of energies which creates seismic waves and the building vibrates around one particular frequency called natural frequency. The actual threat comes from man-made structures and due to the shaking these structures receive during earthquake events causing building collapsing. Since earthquake forces are random in nature and prediction of future earthquake may not be possible but ensuring earthquake resistant design criteria's while constructing buildings will reduce number of casualties and economic loss. The building damages due to various reasons which are responsible for numerous damages. It is difficult to relate it in computable manner because of dynamic nature of seismic action and inelastic response of structure. Natural period, damping, ductility, stiffness, drift and building configurations are various different characteristics that affects building performance during earthquake**.** Poor construction practices, low-grade materials, and non-ductile design caused collapses in reinforced concrete buildings during past earthquakes **(Isler 2008).** Response of reinforced concrete single degree of freedom (SDOF) systems to multiple earthquakes (**Manafpour and Moghaddam 2018** , **Solberg et al. 2008**) used for quantify the effects of the earthquakes on the structures. The response based damage indices and its applicability in seismic damage evaluation (**Ghobarah et al. 1999)** prevent catastrophic damages **(Chandersekaram et al. 2008).** Observations reveal that there is a close relationship between the overall damage in the actual frame and SDOF damage established from pushover analysis, and the two correlate in a consistent manner **(Wei and Lu 2009).** The nonlinear behavior of reinforced concrete buildings under single and repeated earthquake excitations significantly affect the interstory drift and ductility demand, and that the R factor and occurrence of earthquakes influence the seismic response (**Adiyanto et al. 2011)**. Therefore it is important to consider repeated earthquakes in structural analysis. Comparison between past and current code of practices revealed the need for enhancement in lateral load resisting system **(Rama raju et. al. 2012).**

This paper analyzes a low-rise office building designed according to Indian codes IS 456:2000 and IS 13920:2016. The study aims to assess seismic performance for design basis earthquake (DBE) and maximum credible earthquake (MCE), evaluating global and member-level responses. It proposes eliminating the strong beam-weak column criterion and presents results in terms of capacity curve, inter-story drift ratio, plastic rotation, and moment curvature.

Case study of the building

A G+3 RCC office building with dimensions 40.70m x 11.05m is used for analysis and design. It consists of 11 bays in the X direction and 3 bays in the Y direction. The building is 14.05m tall, with the first story at 4m and upper stories at 3.35m. See Fig.1 for the building's plan and elevation.

The Gurugram-based building is designed according to Indian codes IS 456:2000 and IS 13920:2016 for seismic zone IV. It considers a design peak ground acceleration of 0.12g for soil Class II. Earthquake loading is combined with gravity load (DL + 0.5 LL), including self-weight of members, exterior brick wall (16.75 kN/m), interior partition walls (10.05 kN/m), floor finishing (0.5 kN/m² floor, 1.5 kN/m² roof), and live loads (3.5 kN/m² floor, 1.5 kN/m² roof).



(a) (b)

Fig.1. Building configuration (a) Elevation of the model (b) Typical plan of the building

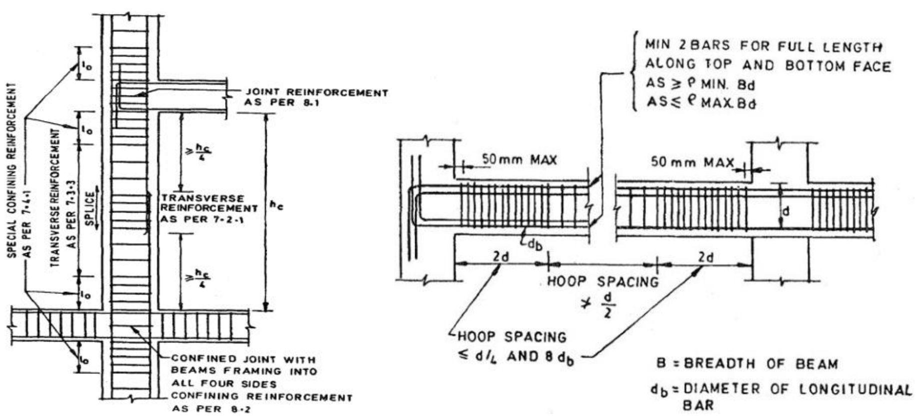
The analysis and design of a G+3 storey RC building frame are illustrated in three different cases based on the aspect ratio. The base model is considered as the G+3 storey RC building with an aspect ratio of 1.22 (case1) and two additional cases based on aspect ratios of 1.5 (case 2) and 2 (case 3) with different building height. The brief specification of the building as per the design shown in Table 1.

Table 1: Specification of the building cases as per aspect ratio and different building height

Component	Case 1	Case 2	Case3
Plan dimension	40.70m X 11.5m	40.70m X 13.8m	40.70m X 15.4m
No. of stories	G+3	G+5	G+8
Aspect Ratio	1.22	1.5	2
Size of exterior column	300mm X 530mm	400mm X 550mm	500mm X 600mm
Size of interior column	350mm X 350mm	400mm X 400 mm	500mm X 500mm
Size of longitudinal beam	200mm X 300mm	250mm X 400mm	250mm X 400mm
Size of exterior transverse beam	300mm X 400mm	300mm X 480mm	300mm X 480mm
Size of interior transverse beam	200mm X 300mm	250mm X 480mm	250mm X 480mm

Modeling parameters

Structural concrete members are designed following the Indian National Standard for Plain and Reinforced Concrete. Fig.2 provides member dimensions and reinforcement details for selected elements in the transverse direction, including a 150 mm thick slab.



a) b)

Fig.2. Typical reinforcement details at joint as per IS:13920:2016.

The beams of 4.6 m span are 300 X 400 mm, while the other remaining beams are 200 X 300 mm. All exterior columns are 300 X 530 mm and all interior columns are 350 X 350 m min cross-section. The design loads and load combinations for beams and columns as per software analysis results are shown in Table 2 and Table 4. The beam straight, extra at support-mid span and hoop reinforcement are shown in Table 3. The column main reinforcement and hoop reinforcement are shown in Table 5. The concrete in the frame has a compressive strength of 20 MPa, while the design steel yield strength is 500 MPa.

Table 2: Design loads and load combinations for beams as per software analysis results.

Member	Critical Load Combination	Design BM (kN-m)	Design Shear (V)
B-1 (300X400)	1.50(DL+EQ_Y)	191.82	150.29
B-2 (200X300)	1.50(DL+LL), 1.50(DL+EQ_Y)	49.43	97.76
B-3 (200X300)	1.50(DL+EQ_Y)	64.49	88.31

Table 3: Beams reinforcement schedule as per design for critical load combination

Beam Member	Straight Bar @Top	Extra Bar @Top	Straight Bar @ Bottom	Vertical Stirrups
B-1 (300X400)	2-20#	4-20#	3-20#	8# @ 80/150 mm C/C
B-2 (200X300)	2-20#	1-20#	2-20#	8# @ 80/150 mm C/C
B-3 (200X300)	2-20#	1-20#	3-20#	8# @ 80/150 mm C/C

Table 4: Design loads and load combinations for columns as per software analysis results.

Member	Critical Load Combination	Design Axial Load P (kN)	Design Moment	
			M_y (kN-m)	M_z(kN-m)
Column C1 (300X530)				
Up to 1st Floor Level	1.50(DL-EQ_Y)	930.195	246.581	57.7819
1st to 2nd Floor Level	1.50(DL-EQ_Y)	516.625	138.203	74.6368
2nd to 3rd Floor Level	1.50(DL-EQ_Y)	516.625	138.203	74.6368
3rd to 4th Floor Level	1.50(DL-EQ_Y)	516.625	138.203	74.6368
Column C2 (350X350)				
Up to 1st Floor Level	1.50(DL+EQ_Y)	782.962	42.4138	124.177
1st to 2nd Floor Level	1.50(DL+EQ_Y)	461.201	60.7602	123.118
2nd to 3rd Floor Level	1.50(DL+EQ_Y)	461.201	60.7602	123.118
3rd to 4th Floor Level	1.50(DL+EQ_Y)	461.201	60.7602	123.118

Table 5: Column reinforcement schedule as per design for critical load combination

Story	C1 (300x530)		C2 (350x350)	
	Main R/F	Lateral Ties	Main R/F	Lateral Ties
Up to 1st Floor Level	12-20#	8# @ 70/150	10-20#	8# @ 70/150
1st to 2nd Floor Level	8-20#	8# @ 70/150	6-20#	8# @ 70/150
2nd to 3rd Floor Level	8-20#	8# @ 70/150	6-20#	8# @ 70/150
3rd to 4th Floor Level	8-20#	8# @ 70/150	6-20#	8# @ 70/150

Beam and column joint strength

Columns sized as per IS: 13920:2016 for capacity design at joints to ensure joint strength in beam-column connections.

$$\sum Mc \geq 1.4 \sum Mb$$

Where ∑Mc represents column resistance moments at the joint, while ∑Mb represents beam flexural strength moments at the joint shown in Fig.3. Such that the sum of nominal design strength of columns shall be at least 1.4 times the sum of design flexural strength of beams meeting at a beam-column joint which suggest SCWB design to prevent story mechanism

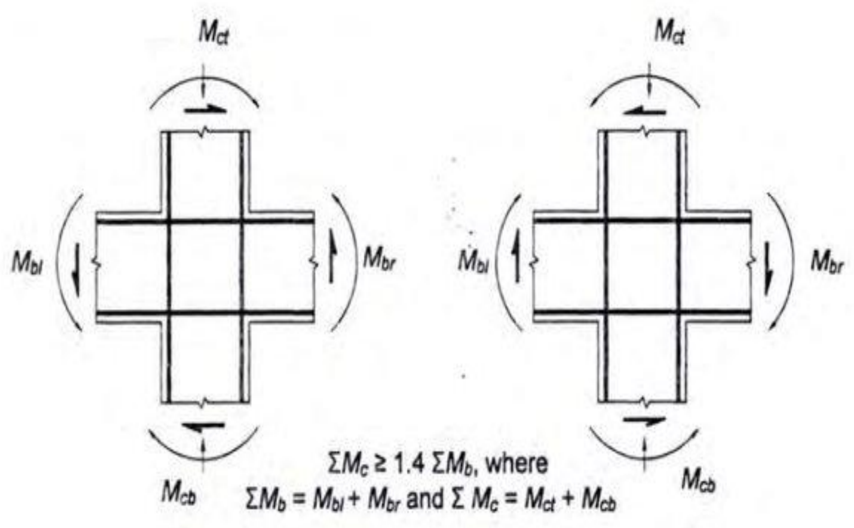
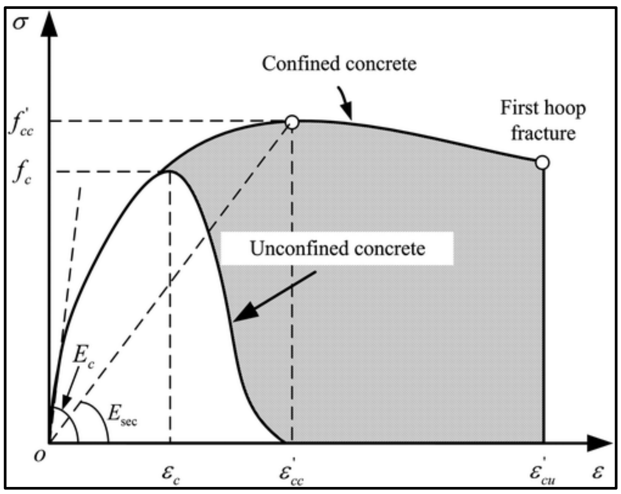
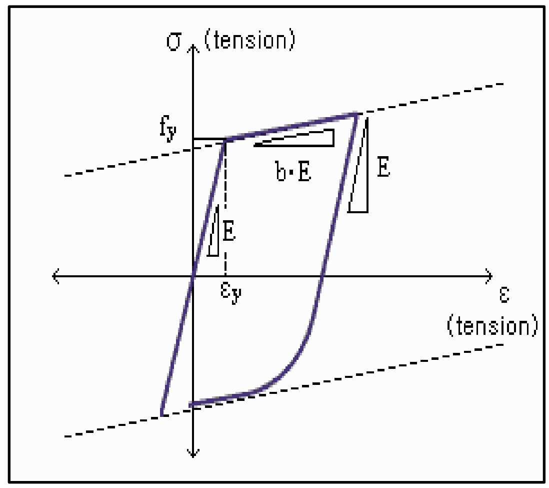


Fig.3. Design moments for strong column -weak beam (SCWB) principle as per IS: 13920:2016

Modelling approach for material inelasticity

Three cases of a G+3 storey RC building frame are designed as per IS 456:2000 with ductile detailing as per IS 13920:2016 for seismic zone IV. Earthquake forces are calculated according to IS 1893:2016, and the design and analysis. Inelastic material properties are assigned using the Mander (1988) confined model for concrete (Fig.4.) and the Menegotto-Pinto (1973) model for steel (Fig.4.) to assess material nonlinearity.





(a) **(b)**

Fig.4. (a) Stress-strain relationship of Mander's (1988) model for confined concrete and (b) Stress-strain relationship of Menegotto and Pinto (1973) steel model

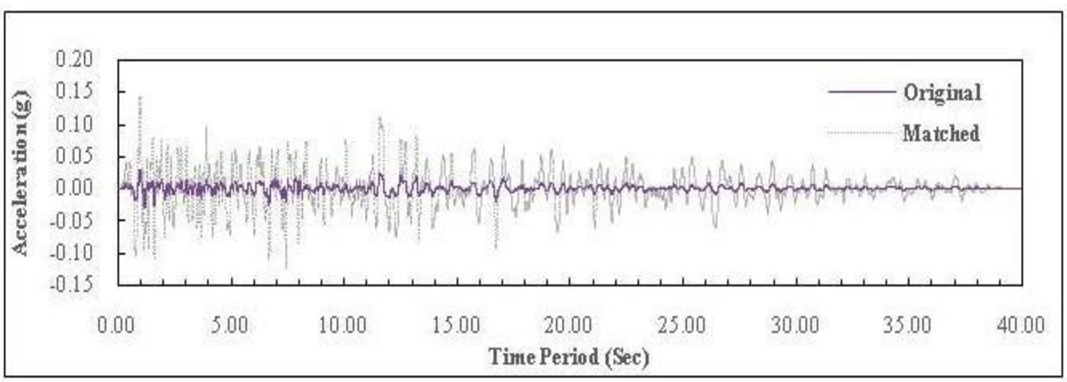
Ground Motion Selection

In selecting ground motion records shown in Fig.5 for dynamic analysis, similarity of soil type to the building site and matching response spectra to the target design spectrum are important considerations. Five natural ground motion records Table 6 were chosen based on event magnitude (5.40 to 6.00) and soil site consistency. The selected records were scaled to produce design and rare earthquakes at maximum PGA levels of 0.12g and 0.24g, corresponding to probabilities of exceedance of about 10% and 2% in 50 years, respectively, according to IS 1893:2016. Response spectra for the five records, scaled to a PGA of 0.24g, and the target design spectrum are shown in Fig. 6.

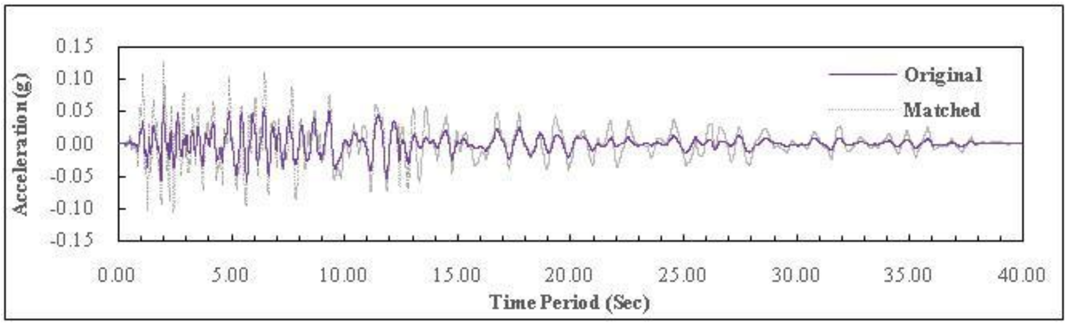
Table 6: selecting ground motion records for dynamic analysis

Small magnitude-short distance bin (SMSR: 5.4 <Mw ≤ 6.0, 12 km < R ≤ 40 km)						
Earthquake Name	**Year**	**Station Name**	**Country**	**PGA(g)**	**M**	**R(km)**
Imperial Valley-03	1951	El Centro Array #9	Mexico	0.031	5.60	25.24
Hollister-01	1961	Hollister City Hall	United States	0.059	5.60	19.56
Point Mugu	1973	Port Hueneme	United States	0.128	5.65	17.71
Umbria-03_ Italy	1984	Umber tide	Italy	0.035	5.60	26.98
Umbria Marche Italy	1997	Norcia	Italy	0.095	5.60	19.06

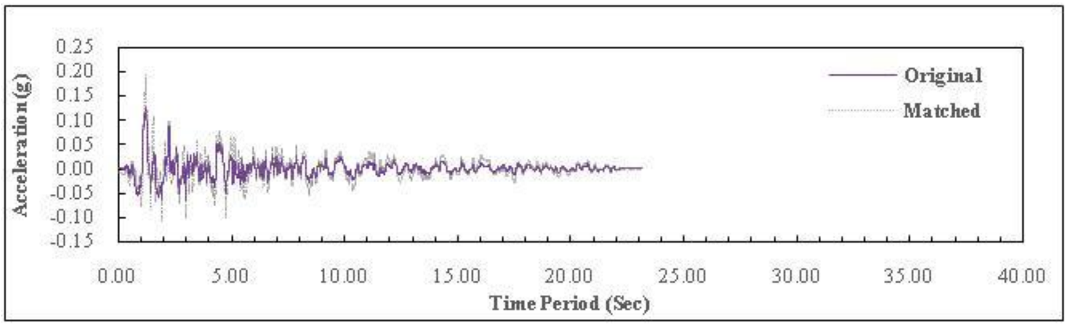
Nonlinear static analysis is done to determine the structure's performance, resulting in the development of a Pushover curve. Response spectrum curves are generated from time history data for five earthquakes. FEMA 356 is used to determine member-level performance based on plastic rotation, and ATC-40 is used to determine the performance of the structure as a whole based on maximum total drift limits. The target displacement is calculated from the earthquake data.



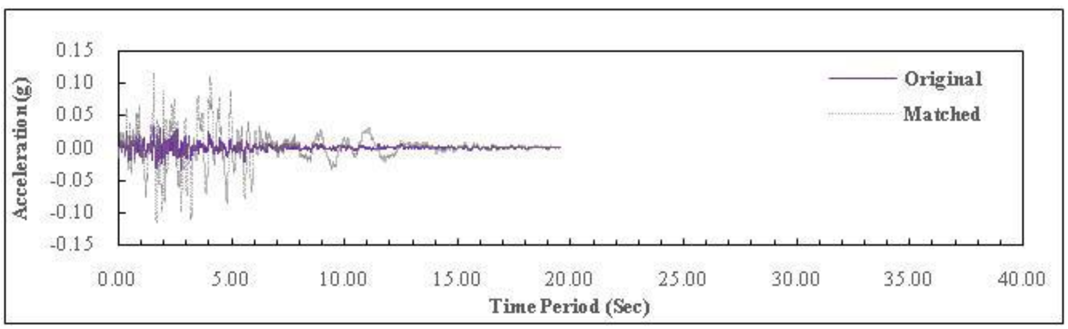
a) Imperial Valley-03



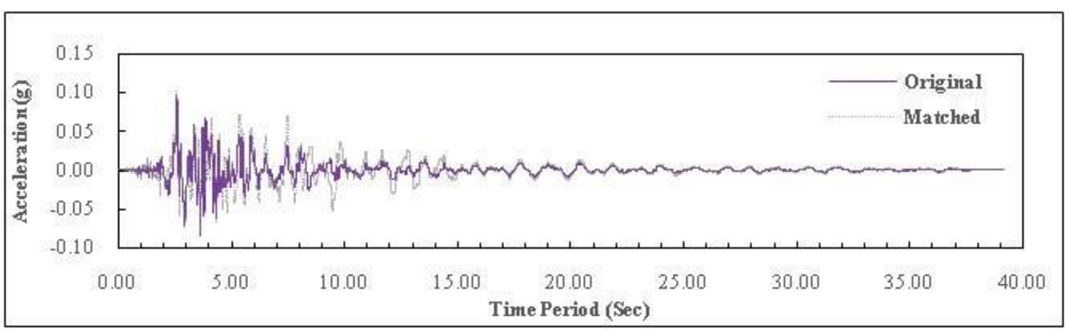
b) Hollister-01



c) Point Mugu



d) Umbria-03_ Italy

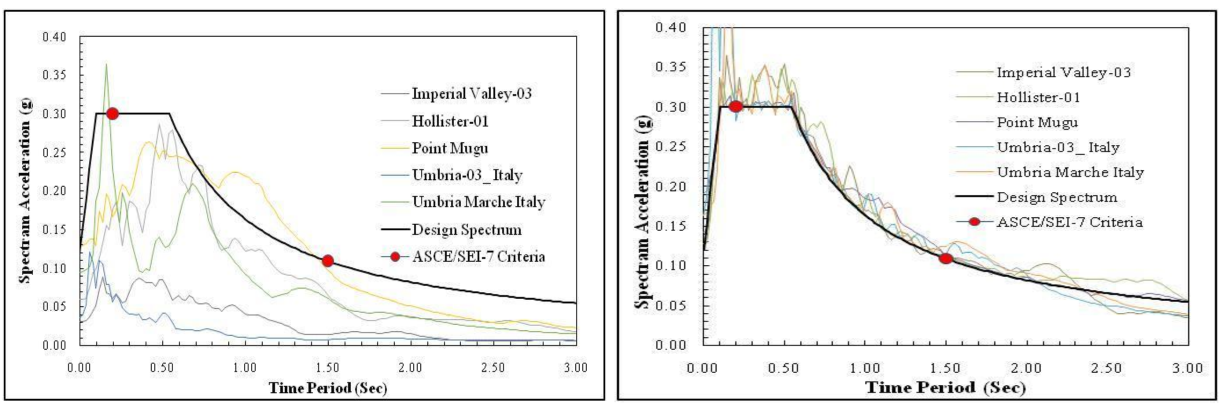


e) Umbria Marche Italy

Fig. 5. Five Small magnitude–short distance bin time history original compared with Scaled time history

Failure criteria

The failure criteria for evaluating seismic performance in a building are based on the ASCE/SEI 41 standard used. Two types of limits are accept: global-level limits and member-level limits. The goal was to assess the likelihood of exceeding a specific performance level in each story and individual member of the structure. ASCE/SEI 41 defines three performance levels for seismic evaluation: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). For the global-level evaluation, the maximum inter-story drifts obtained from nonlinear analysis are compared against suggested limiting values for inter-story drift. This comparison helped determine if the building met the desired performance levels. Additionally, a member-level evaluation is performing using plastic rotation limits specified in ASCE/SEI 41. This detailed assessment provided insights into the structural behavior and seismic performance of individual members within the building. By considering both global and member-level limits, a comprehensive evaluation of the building's seismic performance is achieve.



a) **b)**

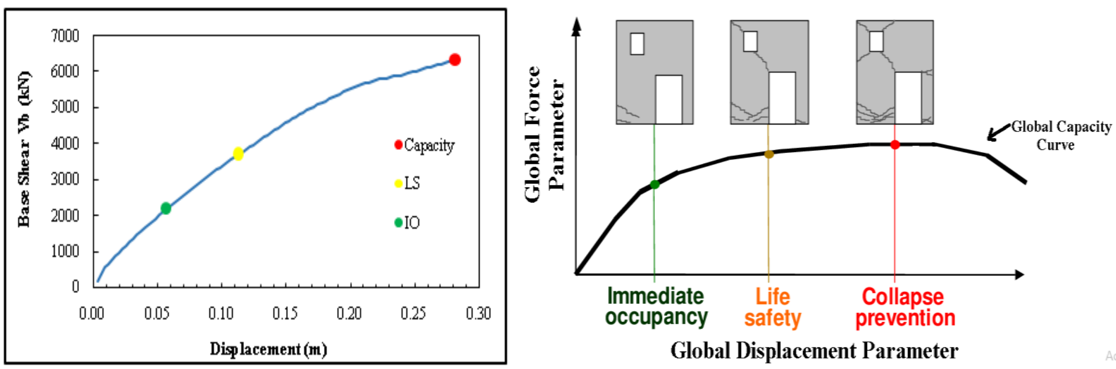
Fig. 6. a) Design response spectrum, actual response spectrum, **b)** Design response spectrum, matched response spectrum

Pushover Analysis

Pushover analysis is a progressive set of nonlinear static analyses used to study a structure's lateral deformation and damage pattern as it enters the inelastic range. It estimates the structural strength capacity beyond its elastic limit and into its post-elastic range. Static pushover analysis helps to exhibit the yielding sequences and provide an insight into structure's weak zone during its seismic event.

Global level performance:

Global structural response of the building based on base shear versus roof displacement; provide lateral load–displacement envelopes. The ATC- 40 deformation limits in terms of building drift are used to represent the global performance of the building where 0.1 represents Intermediate occupancy, range 0.1-0.2 represents Damage control and 0.2 represents Life safety. Along with this Inter-story drift limit criteria according to ASCE/SEI is also use for the global evaluation.



a) **b)**

Fig. 7. ATC-40 Capacity curve showcasing performance level of the building

Fig.7 represents the pushover curve of the building that denotes the ultimate capacity of the structure when pushed for the 2% building drift. The point on the pushover curves shows the performance level of the structure determined in the terms of drift (as per ATC-40) corresponding to the displacement values that took place in each pushover step.

The building has performance level of IO upto the base shear 2197.57 kN having drift value of 0.00968 (IO limit- 0.1), performance level of LS upto the base shear 3720.87 kN having drift value of 0.01947 (LS limit- 0.2) and at ultimate capacity of the building at 6338.68 kN the building performance level reaches way beyond LS.

In terms of inter-story drift limits:

The inter-story drift is calculated on the basis of story drift for 2% building drift along with this inter-story drift at different percentage (0.25%, 0.5%, 0.75%, 1% and 1.5%) of building drift is also evaluated. Inter-story drift of 2.551 is maximum on the story level 2 of the building shown in Fig. 8.

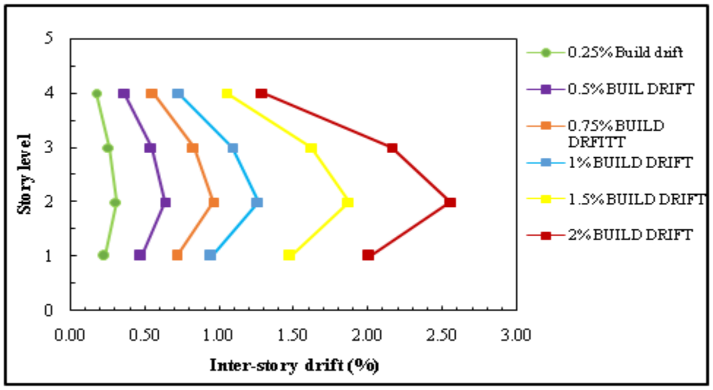


Fig. 8. Inter-story drift percentage at different percentage of building drift

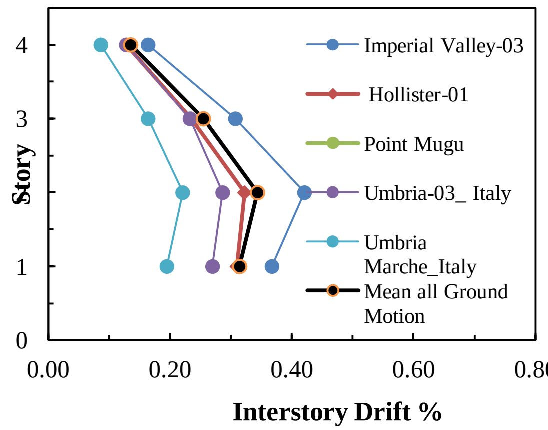
Member level rotation

On the basis of acceptance criteria of member level performance of beam and column respectively from plastic rotation of ASCE/SEI-41, maximum plastic rotation in beams is 0.02028 were exhibited in first story level which denotes performance level of LS (LS limit- 0.02) and maximum plastic rotation limits in columns is 0.0076 in first story level that lie between the performance level of IO-LS (IO limit- 0.005 and LS limit- 0.015).

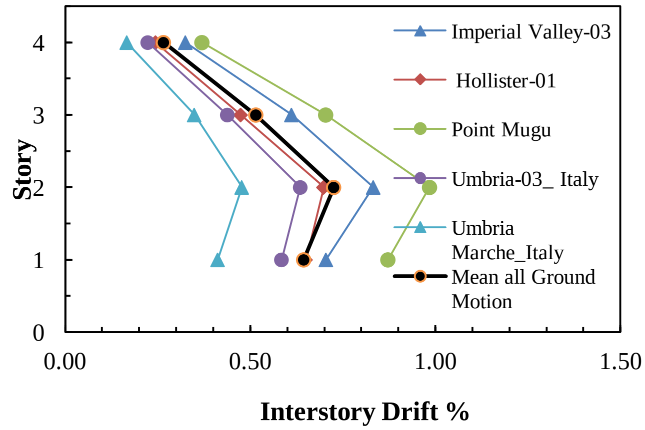
Global response

Based on the analysis of the tables and figures, the median interstory drift values for the design level earthquake with a peak ground acceleration (PGA) of 0.12g are below the ASCE/SEI 41 global-level limit of 2% for life safety (LS) performance. Similarly, for the collapse prevention (CP) level earthquake with a PGA of 0.24g, the median interstory drift values are significantly lower than the ASCE/SEI 41 global-level CP limit of 4%..

Imperial Valley-03, Hollister-01, Point Mugu, Umbria-03_ Italy, Umbria Marche_Italy Earthquake ground motion are used in this analysis out of which the maximum response in the form of building drift percentage and max interstory drift generated by Point Mugu Earthquake are 0.4687 %, 0.3544% for DBE and 0.7395 %, 0.9851% for MCE level earthquake respectively.



a)



b)

Fig. 9 . a) Interstory drift DBE (Design Based Earthquake) level. **b)** Interstory drift MCE (Maximum Credible Earthquake) level.

Based on these findings in Fig.9 a &b , it can be concluded that the case study building satisfies the recommended Basic Safety Objective (BSO) for LS performance during the design event, as well as CP performance for the rare event. This assessment is made using a general global-level evaluation and considering the suggested drift limits.

Conclusions:

- The inter- story drift measures are effective indicator of weak/soft story failure, from Pushover analysis results it can be concluded that the building does not show the potential of weak/ soft story failure mechanism as the inter-story drift at base floor is 2.005% and 2.551% at second floor level, but it certainly displays weak story failure in middle floors. As per ASCE/SEI-41 limits the performance level are exceeding Life safety limits of 2% but is under collapse prevention limits of 4%. The inter story drift limits were under Life safety limits for building drift of 1.5% having maximum inter story of 1.870% but exceed its LS limits for 2% building drift. These were not exhibited in dynamic analysis.

- From member level criteria in pushover analysis beam plastic rotation were more than column plastic rotations, 0.02028 and 0.0076 respectively, similarly in dynamic analysis beam plastic rotation is 0.00790 and column plastic rotations is 0.00480, it's very clear that the beam elements undergoes higher value of rotation as compared to column rotations and are more likely to reach there limiting values before column, as IS 13920:2016 suggests that at a joint where beam-column meets the column should resist lager moment as that of beam which is satisfied by the member level plastic rotation of beam and column hence criteria for strong column-weak beam through the design is fulfilled.

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