Performance Based Seismic Design of Multistorey RCC Buildings with Diaphragm Discontinuity

Siddharth Y. Vekariya[1] Rajul K Gajjar[2]
[1]PG Student [2]Principal
[1,2]Department of Civil Engineering
[1]L.D. College of engineering, Ahmedabad [2]Vishwakarma Govt. Engg. College & Director of GTU

Abstract— A Performance Based Seismic Design is aimed at controlling the structural damage under the action of earthquake forces, based on precise estimation of proper response parameters using Nonlinear Pushover Analysis. It is a highly iterative process needed to meet designer specified and code requirements. Openings in the floors (diaphragm discontinuity) reduce the rigidity of the diaphragm and affect the distribution of lateral load to the lateral load resisting element and causes stress concentration near discontinued joints. The assessment of the seismic vulnerability of such structures is very complex. Hence, there is a need for an accurate evaluation of the seismic response beyond linear behavior. This paper presents a Performance Based Seismic Design of RCC Buildings with different shapes of opening Diaphragm under the Design Basis Earthquake (DBE) and Maximum considered Earthquake (MCE) by choosing performance criteria in terms of Inter-storey Drift (IDR) and Inelastic Displacement Demand Ratio (IDDR). The Capacity Spectrum Method of Pushover Analysis is performed in SAP 2000, based on FEMA 365 [4] and ATC 40 [3] guidelines, to study the performance of RC buildings designed as per IS 1893:2002 [1], with diaphragm discontinuity. The results shows that opening in diaphragm reduce the capacity and produce higher drift at performance point.

Key words: Performance Based Seismic Design, Pushover analysis, Diaphragm Discontinuity, Performance Objectives, RCC Buildings

I. INTRODUCTION

The promise of performance based seismic engineering is to produce structures with predictable seismic performance [5]. From the effects of past earthquakes, it is concluded that the seismic risks in urban areas are increasing and are far from socio-economically acceptable levels. Therefore there is an urgent need to reverse this situation and it is believed that one of the most effective ways of doing this is through the development of more reliable seismic standards and code provisions than those currently available and their stringent implementation for the complete engineering of new engineering facilities [7]. The maximum drift of the structure without total collapse under seismic loads is called the target displacement or Performance Point [3,4].

Pushover analysis is an estimated analysis method where the structure is subjected to different monolithically increasing lateral forces, with a distribution which is height wise invariant, until the target displacement is touched. The nonlinear static analysis procedure requires determination of three elements like capacity, demand and performance point. The capacity spectrum can be obtained through the pushover analysis, which is generally produced based on first mode response of structure assuming that the fundamental mode of vibration is predominant response of structure. The demand spectrum curve is normally estimated by reducing the standard elastic 5% damped design spectrum by spectral reduction method. The intersection of pushover capacity and demand spectrum curve defines the 'Performance point' of structure and should be checked using certain acceptability criteria. Pushover analysis comprises of a series of successive elastic analysis, superimposed to estimate a force-displacement curve of overall structure. Pushover analysis can be performed as force controlled and displacement controlled [3].

In force controlled, full load combination is applied as specified and this procedure should be used when the load is known. Also such procedure having some numerical problems that affect the accuracy of results occur since target displacement may be associated with a very small positive or negative lateral stiffness because of development of mechanisms and p-delta effects. Pushover analysis allows tracing the sequence of yielding and failure on member and structural level as well as progress of overall capacity of the structure.

Performance-based design begins with the selection of design criteria stated in the form of one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard. Losses can be associated with structural damage, non-structural damage, or both. They can be expressed in the form of casualties, direct economic costs, and downtime (time out of service), resulting from damage. Methods for estimating losses and communicating these losses to stakeholders are at the heart of the evolution of performance-based design [5]. Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events. If the simulated performance meets or exceeds the performance objectives, the design is complete. If not, the design is revised in an iterative process until the performance objectives are met. In some cases it may not be possible to meet the stated objective at reasonable cost, in which case, some relaxation of the original objectives may be appropriate [7].

II. PERFORMANCE BASED SEISMIC DESIGN

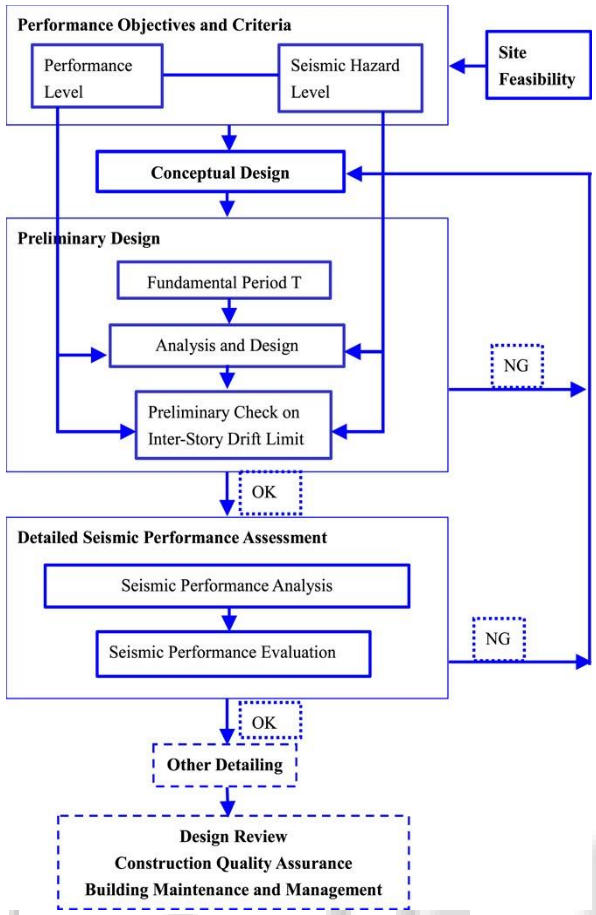


Fig. 1: Performance-based seismic design flowchart for new buildings [7].

A. *Performance Level*

Once pushover analysis is defined, the performance level can be determined using demand displacement. The performance verifies that the structure is adequate weather the acceptable limits of performance level.

Each performance level is quantified by parameters associated with strength, stiffness and ductility. Regarding strength, OP (Operational level) corresponds to an elastic behavior. Over-strength must be ensured for other performance levels and no large strength degradation can occur beyond the ductility limit. No weak story exists and the structure has enough vertical capacity.

According to ATC 40 and FEMA 356 [3,4], the performance levels of buildings are as shown in Table I.

Level	Description
Operational	Very light damage, no permanent drift, structure retains original strength and stiffness, all systems are normal
Immediate Occupancy	Light damage, no permanent drift, structure retains original strength and stiffness, elevator can be restarted, Fire protection operable
Life Safety	Moderate damage, some permanent drift, some residual strength and stiffness left in all stories, damage to partition, building may be beyond economical repair
Collapse Prevention	Severe damage, large displacement, little residual stiffness and strength but loading bearing column and wall function, building is near collapse

Table 1: Performance Level Of Building [3,4]

Regarding ductility, the concept of inelastic displacement demand ratio (IDDR) [7] is employed. IDDR represents the ratio of inelastic displacement demand over the ultimate inelastic displacement capacity. Acceptable values IDDR associated with structural system performance levels OP, IO, DC, LS, and CP are 0, 0.2, 0.4, 0.6 and 0.8, respectively. Subscript a stands for the allowable value.

Structural system	OP	IO	DC	LS	CP
Masonry shear wall system	0.005	0.007	0.007	0.007	0.009
Others	0.005	0.01	0.015	0.02	0.025

Table 2: Allowable Inter-Storey Drift Ratio (IDR)

Regarding stiffness, the maximum inter-story drift ratio (IDR) is considered to limit building lateral displacement. In this research, based on references such as the ATC 40 [3], FEMA 356 [4], SEAOC blue book and according to other literature studies, the IDR limits in Table III are preliminarily suggested. Structural systems are mainly classified into four types, namely, the load-bearing walls, the frame systems, the moment resisting frames and the dual systems.

Performance level	OP	IO	DC	LS	CP
IDDRa	0	0.2	0.4	0.6	0.8

Table 3: Allowable Inelastic Displacement Demand Ratio (IDDR)

III. STRUCTURAL MODELING

The 5x5 bays moment resisting frame (G+10 floors) is modeled using SAP2000. Dead and live loads of the sections were applied to slab and beam elements. Initially, static linear analysis is performed using only dead load of the member and live load with reduction factor of 0.25 with Lateral load applied to frame as per IS 1893:2002 [1].

Multiple numbers of pushover load cases are defined. The first pushover load case was used to apply gravity load case (which is force controlled) and then subsequent lateral pushover load cases (which is displacement controlled) were specified. In Pushover analysis the iteration is done using Newton-Raphson method. In this case a Gravity load combination of DL+0.25LL has been used and for pushover case, lateral load are based on acceleration.

A. *Non-Linear Plastic Hinge*

In frame structures plastic hinges usually formed at the ends of beams and columns under earthquake action. For beam elements, plastic hinges are mostly caused by uniaxial bending moments, whereas for column elements, plastic hinges are mostly caused by axial loads and biaxial bending moments. Therefore, in push-over analysis different types of plastic hinges should be applied for the beam elements and the column elements separately.

In SAP2000, hinge properties can be assigned to members using options of default hinge properties and user-defined hinge properties. The built-in default hinge properties are typically based on FEMA-356 and ATC-40 criteria.

The M3 hinge is used to simulate the plastic hinge caused by uniaxial moment, so default M_3 hinges are applied at both ends of the beams and the PMM hinge is used to simulate the plastic hinge caused by axial load and biaxial bending moments, Thus PM_2M_3 hinges are applied at both ends of the columns at relative distance 0 & 1.

Five points labeled A (unloaded condition), B (effective yield), C (ultimate strength), D (residual strength), and E (failure) are used to define the force deformation behavior of the plastic hinge. These points are specified to determine hinge rotation behavior of RC members. The points between B and C represent acceptance criteria for the hinge, which may be any of the 3 conditions of Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) [4].

IV. PROBLEM DEFINITION

There are 5 types of buildings selected to study the effect of diaphragm discontinuity on non-linear response parameters and based on that, performance based seismic design is carried out ti meet predefined performance criteria in terms of IDR and IDDR. Model I is taken as building without opening as shown in figure I. Model II, III, IV and V are building with different shapes of opening as shown in figure 3, 4, 5 and 6 respectively. The prototype buildings are G+10-storied reinforced concrete buildings consisting of five bays in both the directions. The spacing along X and Y directions is 5m and the story height is taken as 3m. So the overall plan is 25m X 25m. Primary Beam size is 230mm x 450mm and columns are 425mm x 425mm (For Model I) & 400mm X 400mm (For Model II, III, IV & V) with fixed support at base. To achieve the performance objective size of beam and column are increased until required performance is not met. Slab thickness is 150mm.

A. *Design Data:*

Live load	3.0 kN/m^2 at typical floor
	1.5 kN/m^2 on terrace
Floor finish	1.0 kN/m^2
Water proofing	2.0 kN/m^2
Terrace finish	1.0 kN/m^2
Wall Load	230 mm thick brick masonry walls only at periphery (4.9 kN/m^2)
Earthquake load	As per IS-1893 (Part 1) – 2002
Zone factor, Z	0.16
Importance factor	1
Response reduction factor	5
Type of soil	Type II, Medium as per IS:1893
Grade of concrete	M30
Grade of steel	fe 415 (HYSD)

Table 1: Design data

B. *Plan and Elevation of the Building models*

The plan and elevation of models are shown in figure 2 to 7.

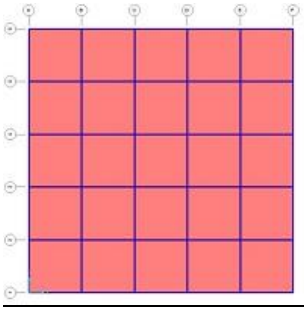


Fig. 2: model I

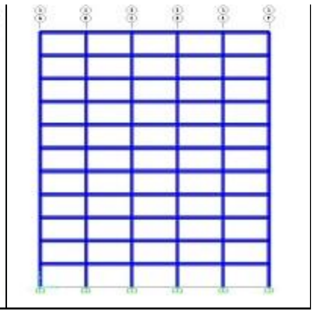


Fig. 3: Elevation of building

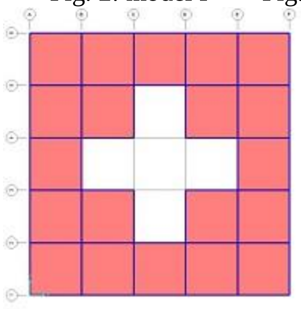


Fig. 4: model II

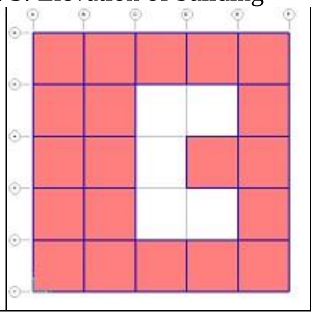


Fig. 5: model III

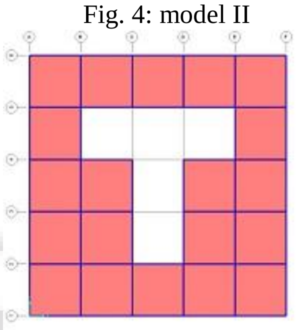


Fig. 6: Model IV

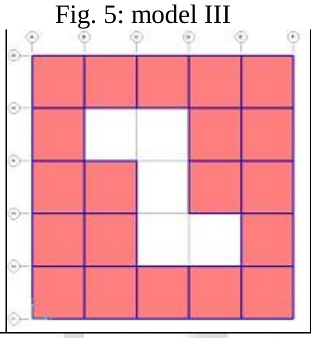


Fig 7. Model V

- Model I: Building without opening
- Model II: Building with + shape opening
- Model III: Building with C shape opening
- Model IV: Building with T shape opening
- Model V: Building with Z shape opening

V. ANALYSIS AND RESULTS

The performance point of the structure that responds to the considered hazard level is evaluated through the capacity-spectrum method [3]. The structure is pushed again to the target displacement associated with the performance point to access the behavior of both the structural system and the elements if such a hazard level occurs.

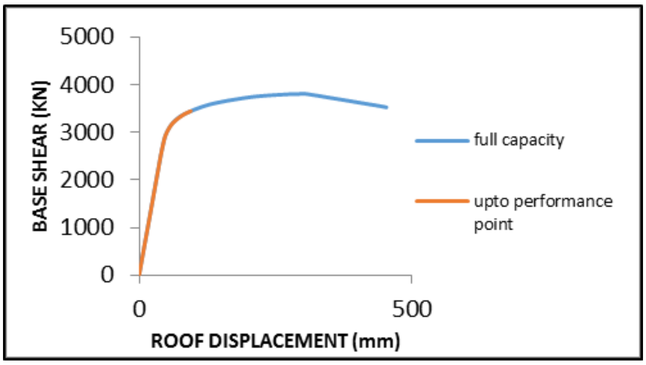
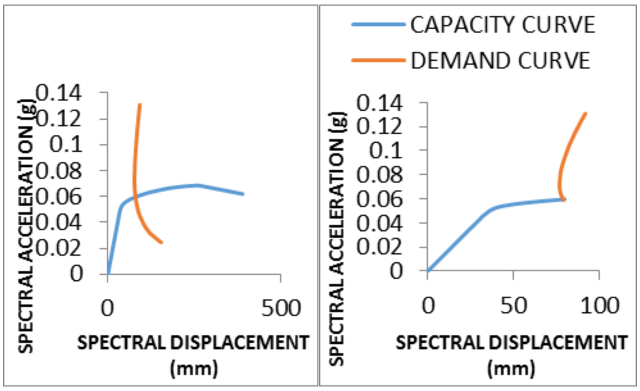


Fig. 8: Overlap of pushover curve for full capacity and upto performance point



(a) ADRS conversion for full capacity (b) ADRS conversion upto Performance Point

Fig. 9: ADRS Conversion

The result shows that, whenever there is opening present in diaphragm is considerably lower down the capacity of building. Also, to achieve the performance objectives, the model with opening required higher section (Beam, Column) size compared to model without opening in diaphragm. Also performance points shows that for same section size of members, base shear observed is lesser and displacement is higher in case of buildings with opening in diaphragm compared to model I.

Group	Group I		Group II	
Seismic hazard level	DBE	MCE	DBE	MCE
Selected section	C-425X425, B-230X450		C-450X450, B-230X450	
IDRa	1.5	2.5	1	2
IDR (%)	0.7	1.86	0.675	1.71
Check if IDR ≤ IDRa	Yes	Yes	Yes	Yes
IDDRa	0.4	0.8	0.2	0.6
IDDR (%)	0.12	0.76	0.09	0.52
Check if IDDR ≤ IDDRa	Yes	Yes	Yes	Yes

Table 4: System Performance Evaluation Regarding IDR and IDDR for Model I

Group	Group I		Group II	
Seismic hazard level	DBE	MCE	DBE	MCE
Selected section	C-450X450, B-230X450		C-500X500, B-230X500	
IDRa	1.5	2.5	1	2
IDR (%)	0.83	2.3	0.66	1.83
Check if IDR ≤ IDRa	Yes	Yes	Yes	Yes
IDDRa	0.4	0.8	0.2	0.6
IDDR (%)	0.18	0.73	0.13	0.54
Check if IDDR ≤ IDDRa	Yes	Yes	Yes	Yes

Table 5: System Performance Evaluation Regarding IDR and IDDR for Model II

Group	Group I		Group II	
Seismic hazard level	DBE	MCE	DBE	MCE
Selected section	C-450X450, B-230X500		C-500X500, B-230X600	
IDRa	1.5	2.5	1	2
IDR (%)$_{X\text{-Direction}}$	0.77	2.16	0.59	1.56
IDR (%)$_{Y\text{-Direction}}$	0.77	2.15	0.52	1.55
Check if IDR ≤ IDRa	Yes	Yes	Yes	Yes
IDDRa	0.4	0.8	0.2	0.6
IDDR (%)$_{X\text{-Direction}}$	0.17	0.71	0.12	0.52
IDDR (%)$_{Y\text{-Direction}}$	0.17	0.71	0.13	0.56
Check if IDDR ≤ IDDRa	Yes	Yes	Yes	Yes

Table 6: System Performance Evaluation Regarding IDR and IDDR for Model III

Group	Group I		Group II	
Seismic hazard level	DBE	MCE	DBE	MCE
Selected section	C-450X450, B-230X500		C-500X500, B-230X600	
IDRa	1.5	2.5	1	2
IDR (%)$_{X\text{-Direction}}$	0.78	2.17	0.58	1.59
IDR (%)$_{Y\text{-Direction}}$	0.77	2.16	0.58	1.55
Check if IDR ≤ IDRa	Yes	Yes	Yes	Yes
IDDRa	0.4	0.8	0.2	0.6
IDDR (%)$_{X\text{-Direction}}$	0.17	0.71	0.11	0.47
IDDR (%)$_{Y\text{-Direction}}$	0.16	0.66	0.1	0.42
Check if IDDR ≤ IDDRa	Yes	Yes	Yes	Yes

Table 7: System Performance Evaluation Regarding IDR and IDDR for Model IV

Group	Group I		Group II	
Seismic hazard level	DBE	MCE	DBE	MCE
Selected section	C-450X450, B-230X500		C-500X500, B-230X500	
IDRa	1.5	2.5	1	2
IDR (%)$_{X\text{-Direction}}$	0.77	2.17	0.61	1.56
IDR (%)$_{Y\text{-Direction}}$	0.77	2.17	0.59	1.56
Check if IDR ≤ IDRa	Yes	Yes	Yes	Yes
IDDRa	0.4	0.8	0.2	0.6
IDDR (%)$_{X\text{-Direction}}$	0.15	0.66	0.13	0.53
IDDR (%)$_{Y\text{-Direction}}$	0.15	0.62	0.13	0.56
Check if IDDR ≤ IDDRa	Yes	Yes	Yes	Yes

Table 8: System Performance Evaluation Regarding IDR and IDDR for Model IV

VI. CONCLUSION

In this work, Performance based seismic design of a G+10 storey buildings with and without opening in diaphragm has been done by evaluating their performance using pushover analysis. By varying member (Beam, Column) size in different combinations and their effect on the performance of the structure was studied.

1) Performance of building increase with increasing member size, by using these we can easily achieved pre-established performance objectives for PBSD of Buildings.
2) Results shows that, to achieve the same performance objective in terms of IDR and IDDR parameters, higher member size is required whenever there is opening present in building.

3) Pushover curve shows opening in Diaphragm decrease base shear capacity significantly. At performance point reduction of base shear is almost 55% in both directions for all the Models compared to model I (For Initial Section Size).
4) The increase in roof displacement at performance point are 34.35%, 35.11%, 36.21% and 35.13% in X direction & 36.99%, 37.70%, 36.25% and 37.78% in Y direction for model II, model III, model IV and model V respectively compared to model I.

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