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A STUDY ON CRITICAL SEISMIC DEMAND PARAMETERS OF REINFORCED CONCRETE BUILDING USING NONLINEAR STATIC ANALYSIS

ISTRAŽIVANJE KRITIČNIH POTREBNIH SEIZMIČKIH PARAMETARA ZGRADE OD OJAČANOG BETONA PRIMENOM NELINEARNE STATIČKE ANALIZE

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Keywords
- reinforced concrete building
- pushover analysis
- aspect ratio
- interstorey drift
- ductility

Abstract

Nonlinear static analysis of structures has become a profession of structural engineering due to its simplicity and ease. Nonlinear analysis gives more accurate results than linear analysis because inherently all structures have material and geometric nonlinearity. Nonlinear static analysis is a technique which is used to estimate seismic demands of structures under excitation. When lateral loads are applied on structures continuously throughout height of structures, the stiffness of some element in the structure decreases and starts failing. In this paper, there is an attempt to get the performance characteristics of RC buildings using nonlinear static (pushover) analysis. The selected models are rectangular in plan and have varying aspect ratio (H/B). Base width is constant, but height varies accordingly. The aspect ratio varies from 2.03 to 4.03. Some of the critical seismic parameters such as interstorey drift percentage, ductility and stiffness ratio of the building have been analysed and compared. The base shear and roof displacement corresponding to performance point that gives the seismic response of the structure are evaluated using pushover analysis and the results are compared. The performance of the structure is also influenced by aspect ratio. Ductility is more in the high aspect ratio compared to lesser one. The stiffness ratio of a different aspect ratio has been worked with respect to ductility. Complete nonlinear static analysis is done by using default hinges which are in line with the modern code compliant buildings.

Ključne reči
- zgrada od ojačanog betona
- analiza postupnog guranja - *pushover* analiza
- odnos dimenzija
- međuspratno pomeranje
- duktilnost

Izvod

Nelinearna statička analiza konstrukcija je postala deo profesije projektovanja konstrukcija usled svoje jednostavnosti i lakoće primene. Nelinearna analiza daje tačnije rezultate od linearne analize, jer suštinski, sve konstrukcije poseduju materijalnu i geometrijsku nelinearnost. Nelinearna statička analiza je metoda koja se koristi za procenu seizmičkih zahteva konstrukcije. Kada se pojavljuju bočna opterećenja u konstrukcijama, kontinualno po visini konstrukcije, tada opada krutost pojedinih elemenata i dolazi do razaranja. U ovom radu, predstavljeno je dobijanje karakteristika performansi zgrade od ojačanog betona, primenom nelinearne analize postupnog guranja - pushover analizom. Odabrani modeli su pravougaone projekcije sa promenljivim odnosom dimenzija (H/B). Širina osnove je konstantna, a visina promenljiva. Odnos dimenzija se menja od 2,03 do 4,03. Pojedini kritični seizmički parametri, na primer, procentualno međuspratno pomeranje, duktilnost i odnos krutosti zgrade, su analizirani i upoređivani. Pushover analizom je procenjeno i upoređeno smicanje osnove i pomeranje krova, koji se odnose na performanse koje definišu seizmički odziv konstrukcije. Na performanse konstrukcije takođe utiče odnos dimenzija. Duktilnost je više izražena kod većeg odnosa dimenzija. Odnos krutosti kod različitih odnosa dimenzija je obrađen s obzirom na duktilnost. Kompletna nelinearna statička analiza je izvedena korišćenjem tipičnih zglobova koji su usaglašeni sa standardom za moderne zgrade.

INTRODUCTION

Earthquake is a natural disaster which takes place continuously in different parts of the world. Recently in April 2015, Nepal got struck with a major earthquake of magnitude 7.8 M. It affected northern part of India. Many people have lost their lives. Many buildings collapsed because they were not designed as per earthquake code IS 1893:2002. However, buildings have a nonlinearity and are inelastic, and one cannot obtain exact structural behaviour using linear analysis. So, the use of nonlinear analysis has become most prominent to obtain inelastic behaviour of structures under seismic loads. Pushover analysis is widely used which provides useful data that cannot be acquired by linear static or dynamic analysis procedure. Structural engineering has started using the nonlinear static procedure (NSP), or pushover analysis, professionally due to its simplicity in nature and ease in calculation, described in FEMA-356 and ATC-40.

Some investigations have been done in the field of pushover analysis by Moroni /17/, Inel and Ozmen /15/, Lakshmanan /18/, Duan and Hueste /10/, Ismail /13/, Koçak et al.

/2/, Sameh A. El-Betar /20/, Danish and Aruna /7/, Kamath et al. /14/, and Ismaeil et al. /16/. Seismic performance and check vulnerability of masonry house which is situated in Chile /17/, the effect of plastic hinge properties in low and mid-rise RC buildings with changing the transverse reinforcement spacing using pushover analysis shows difference in capacity or strength of structure /15/. Pushover analysis of RC buildings and a retrofitted member with CFRP material has checked their capacity /18/. Due to continuously applied imposed lateral loads on structures, the stiffness of some elements of the structure decreases and starts losing its performance. The different lateral loads pattern is applied on the structure to see the variation in capacity of the structure and interstorey drift percentage /10/. Structural assessment of irregular RC building after earthquake were considered and applied pushover analysis to determine the capacity and nonlinear time history analysis to determine the drifts /2/. The existing low, mid, and high-rise buildings are considered for analysis and check of performance /20/. The masonry infill RC building with bracing fixed on soft storey level had been checked in performance by fragility curve and an inter-storey drift percentage was found as a seismic demand parameter /7/. Pushover analysis has been in vogue for many structures like steel frame structures, diagrid structures to get capacity, ductility demand and performance /14/. Finally, Ismail /13/ and Ismaeil et al. /16/ have assessed the reinforced concrete building using different materials as steel plating, CFRP and reinforced concrete jacket, and checked the strength and compared with the original structure.

Reinforced concrete models presented here have practical utility. The default properties have been provided due to convenience and simplicity as per the FEMA-356, ASCE 41 and ATC-40 documents. Due to its simplicity, the default hinge properties which built into some software package (i.e., SAP2000), can be used without taking any considerations. FEMA-356 and ATC-40 guidelines are prepared based on some assumptions related to typical reinforced concrete structures. The documents provide the hinge properties for several ranges of detail, since programmes (i.e. SAP2000) may implement averaged values. Seismic demand parameters discussed in this paper are the capacity, storey displacement, interstorey drift percentage, ductility, and storey stiffness for different aspect ratios.

DESCRIPTION OF STRUCTURAL MODELS

Dimension

The model considered in the present study is rectangular by plan of residential building. The typical plan of reinforced concrete structure is shown in Fig. 1. Four cases of RC buildings with 6, 8, 10, and 12 stories are considered for study. The buildings are composed of moment resisting RC frames which are situated in zone IV. The plan dimension is 9*16 m in the X and Y direction, in respect. The typical bay width in X direction and storey height of the four models are 3.0 and 3.0 m, respectively, and ground floor height is 3.3 m.

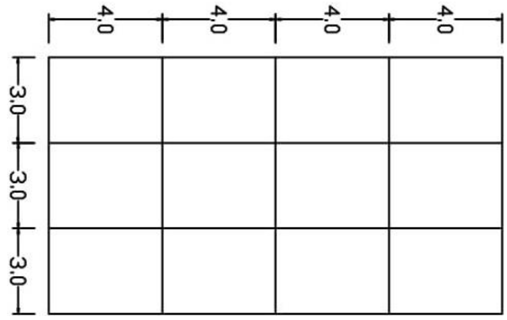

Figure 1. Plan of the building (in m).

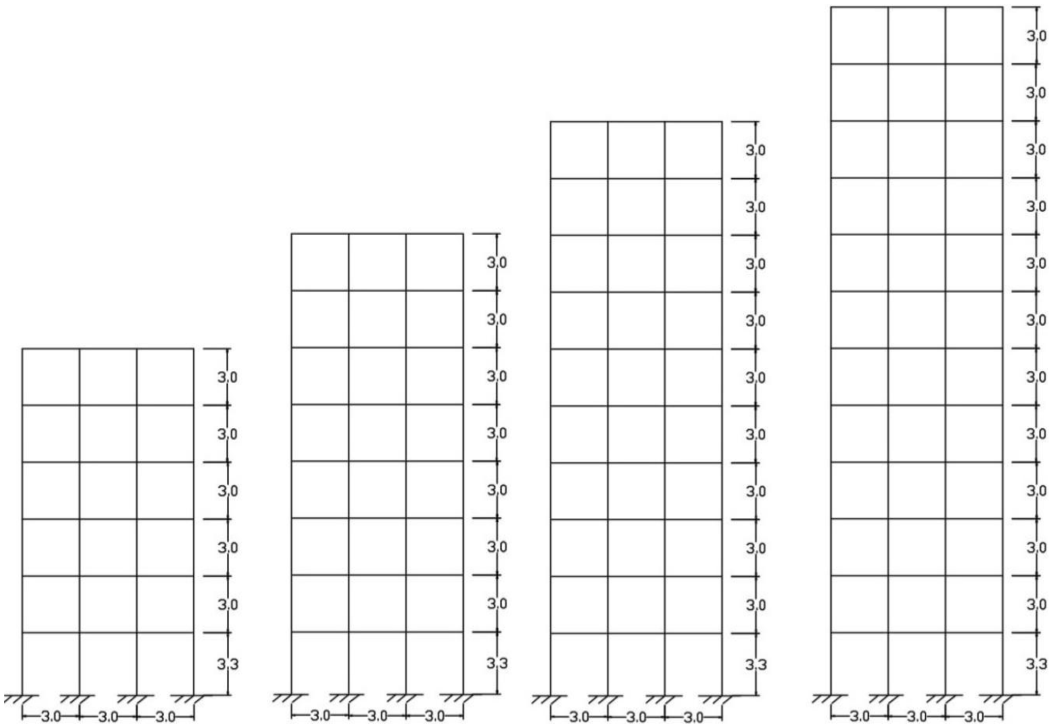

Figure 2. Elevation of models for different aspect ratio as: (i) 2.03; (ii) 2.7; (iii) 3.36; (iv) 4.03, (unit: m).

Figure 2 shows the elevation of models for different aspect ratios with constant base width 9 m and varied height, in respect. Reinforcement details of major structural components as columns and beams in different levels are given in Table 1. Columns are assumed to be fixed at base. The building is analysed and designed as per seismic provisions by IS 456:2000 and IS 1893:2002 Part-I. The unit weight of concrete and steel is 25 kN/m^3 and 78.5 kN/m^3, respectively. Slab thickness is taken as 125 mm. The spacing of transverse reinforcement is to be taken as 150 mm for all cases. The dimension of columns and beams are assumed first, while modelling in all AR. Then all members are verified, either they are passed or not after designing the structure as per IS 456:2000 through finite element software SAP2000. Square columns have been taken for this study. The size of beams and columns are kept different as the level is increased in all AR as per requirements which are clearly shown in Table 1. The elevation of models considered for all AR is shown in Fig. 2.

Table 1. Size of major components of structure for different levels with reinforcement details.

Aspect ratio	Columns size (mm)	Levels	Beams size (mm)	Longitudinal reinforcement of column
2.03	500*500 450*450	1st to 4th 5th to 6th	230*450 230*450	8-16# 8-16#
2.7	500*500 450*450	1st to 5th 6th to 8th	230*450 230*450	8-16# 8-16#
3.36	500*500 450*450	1st to 5th 6th to 10th	230*450 230*450	8-16# 8-16#
4.03	500*500 450*450 400*400	1st to 4th 5th to 8th 9th to 12th	230*450 230*450 230*400	8-25# 8-20# 8-16#

The aspect ratio of the building can be computed as,
Aspect ratio (AR) = Total height / Full width (shorter direct.)
i.e., for 6 stories: AR = (3.3+3.0+3.0+3.0+3.0+3.0)/9 = 2.03
8 stories: AR = (3.3+3.0+3.0+3.0+3.0+3.0+3.0+3.0)/9 = 2.7
10 stories: AR = (3.3+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0)/9 = 3.36
12 stories: AR = (3.3+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0+3.0)/9 = 4.07.

Loads

Wall loads are considered on exterior and interior beams for this building. The wall thicknesses provided on exterior and interior beams are 230 mm and 115 mm on all intermediate floors, respectively. The surrounding parapet wall has been provided on terrace. Live loads on the floor are taken as 3 kN/m^2 and on roof 1.5 kN/m^2. The model location is considered as seismic Zone IV and type of soil is medium. Earthquake loading is combined with gravity loads, i.e., G + 0.25Q, where: G denotes permanent loads that include exterior walls, interior walls; and Q are live loads as per IS875 Part-II. The total seismic weight is calculated based on IS 1893:2002. A typical three-dimensional rendered view of the structure is shown in Fig. 3.

Modelling approach

The general finite element package SAP2000 (version 19) was used for pushover analysis. The three-dimensional model of each aspect ratio is created in SAP2000 to carry out nonlinear static analysis. Beams and columns are modelled as nonlinear frame elements. SAP2000 provides default hinge properties and recommends P-M2-M3 hinges for columns and M3 hinges for beams, as described in FEMA 356. There is no extensive calculation due to considering default hinge properties. The performance of the structure is evaluated by varying C_a and C_v coefficients as per ATC 40. These two coefficients depend on the type of soil, seismic zone, distance, and type of seismic source.

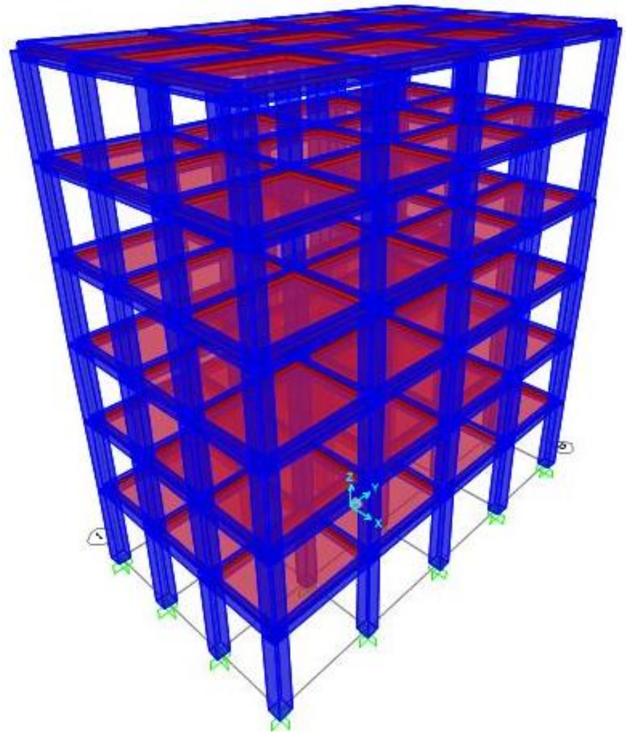

Figure 3. Three-dimensional model of structure.

Pushover analysis is a static nonlinear analysis method where the structure is subjected to gravity loads and a monotonically increased lateral load pattern which continuously increases with elastic and inelastic behaviour until an ultimate condition is reached. It also allows a sequence of yielding and failure on members and progress of overall capacity curve in the structure. The lateral load pattern for all cases is the same, which is an inverted triangle representing the first mode shape for pushover analysis. At the end of the analysis, the capacity curve and a plastic hinge model can be produced which give a general idea of the behaviour of the building.

Figure 4 shows the capacity curve with five points A, B, C, D, and E that define the behaviour of plastic hinges in the structure. These points will be varying, depending on the type of element, material properties, axial load level on an element, longitudinal and transverse steel contents. All points shown in Fig. 4, i.e., B, C, D, and E represent effective yield, peak strength, residual strength, and ultimate deformation. The segment A-B represents the elastic region; the segment B-C represents the strain hardening region, and the segment C-D represents loss of strength which may be sudden, or in some cases somewhat gradual, and the segment D-E represents substantially reduced strength. Also, based on service requirements, the performance levels for Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) can be expressed in terms of deformation levels.

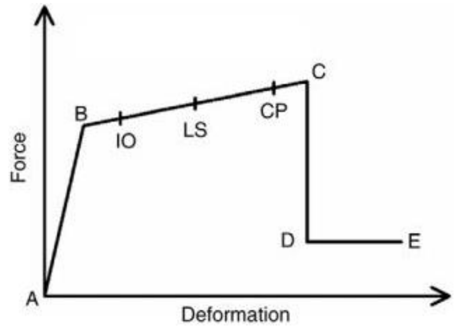

Figure 4. Capacity curve.

RESULTS AND DISCUSSION

The global response of a structure is represented by the pushover curve which is base shear vs. roof displacement shown in Fig. 4. The stage of plastic hinge formation at ultimate point for four models is shown in Fig. 5. For capacity curve, base shear is normalised with respect to total seismic weight of the structure and building drift is the ratio of roof displacement to the total height of structure, H. Inter-storey drift is the lateral displacement of one level of multistorey building relative to the lateral displacement for the level below it. It can be calculated as the difference in lateral displacements between two adjacent storey level normalised by corresponding storey height. ATC-40 suggests the use of normalised storey drift of 0.01 for IO level performance and a value of 0.02 for LS level performance. Structural damage is directly proportional to the inter-storey drift ratio, and so is critical for seismic evaluation.

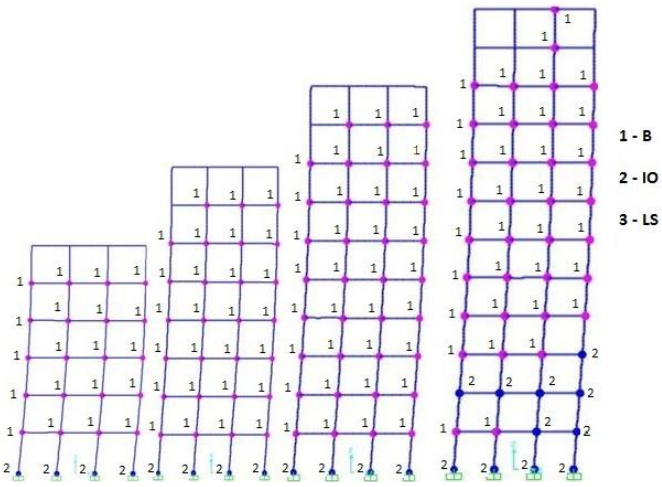

Figure 5. Stage of hinge rotation at ultimate point.

The results obtained from the analysis are compared as follows. Figure 6 demonstrates the pushover curve for aspect ratio values from 2.03 to 4.03. This curve clearly shows that aspect ratio (AR) of 2.03 has less building drift (%) at ultimate point, as compared to the other three aspect ratios. For any aspect ratio between 2.03 to 4.03, the base shear can be obtained for a given building drift. This capacity curve is transformed into capacity spectrum by SAP2000 as per ATC40 and the demand or response spectrum is also estimated for the structure for the required building performance level. The capacity spectrum represents the structure's ability to resist earthquake, and the demand spectrum represents earthquake ground motion. The intersection of demand and capacity spectrum gives the performance point of the structure. Performance point is also affected as the aspect ratio increased shown in Fig. 7. For aspect ratios of 2.03, 2.7, 3.36, and 4.03, the performance points have coordinates, S_a, S_d, as 0.405g, 0.032m; 0.292g, 0.048m; 0.224g, 0.062m; and 0.186g, 0.075m, respectively. Where S_a and S_d indicate spectral acceleration and spectral displacement. From Fig. 7, the S_a is lower, and S_d is higher in AR 4.03, compared to other three aspect ratios. This indicates the aspect ratio 2.03 is more critical during earthquake.

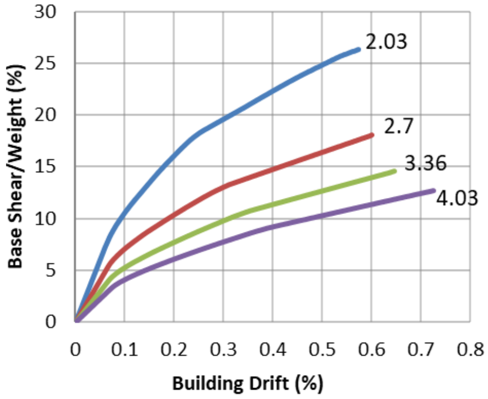

Figure 6. Pushover curve for different AR.

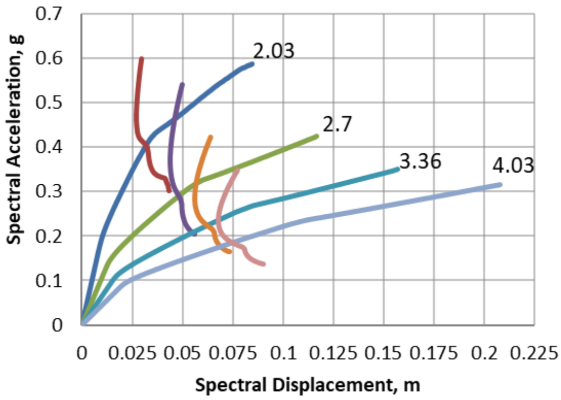

Figure 7. Performance point for different AR.

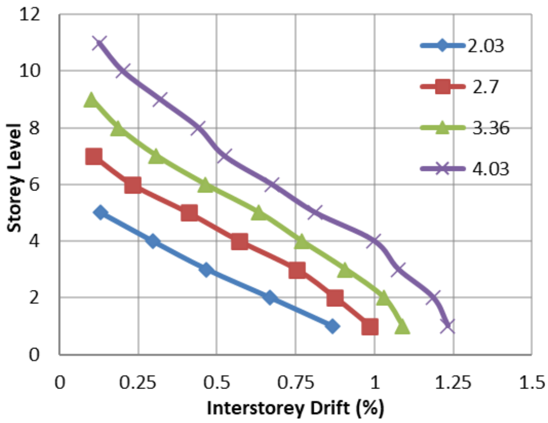

Figure 8. Variation of storey displacement for different AR.

Figure 8 represents the roof top displacement versus storey level for different aspect ratios at ultimate stage. Interstorey drift (ISD) is one of critical parameters in seismic analysis evaluation because it relates to the extent of non-structural damage. There are some limits for knowing ISD % as per code ATC 40. So, for all four models, ISD % is less than 1.4 %. As aspect ratio increases, ISD % increases, as shown in Fig. 9. All building models are situated within the life safety (LS) region of the capacity curve. Ductility is computed by given formula,

$$\mu = \frac{\delta_u}{\delta_y},$$

where: δ_u is ultimate displacement; and δ_y is yield displacement.

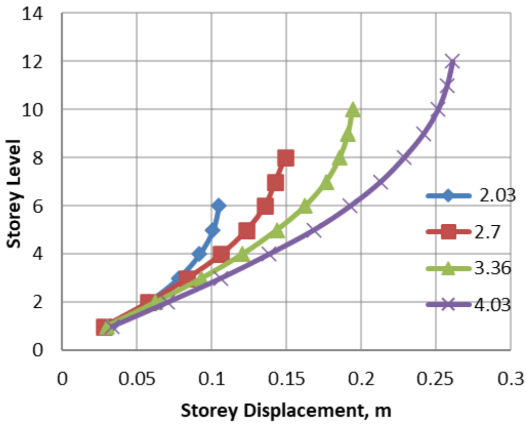

Figure 9. Variation of interstorey drift % for different AR.

Variations in ductility in different storeys for all aspect ratios are shown in Fig. 10. The variation of plastic hinges in yield and ultimate stage for different AR is displayed in Table 2. This table helps to know the number of plastic hinges formed in B to IO, IO to LS, etc. in yield and ultimate stage for different AR which gives the ductility of the structures.

Here we can observe the ductility on every storey of 4.03 aspect ratio which is more than for the other three. The reduction of stiffness ratio in the structure causes more ductility as shown in Fig. 8. Resistance offered by the material against displacement is called stiffness. The stiffness ratio is high in AR 2.03 than in AR 4.03 as shown in Fig. 11.

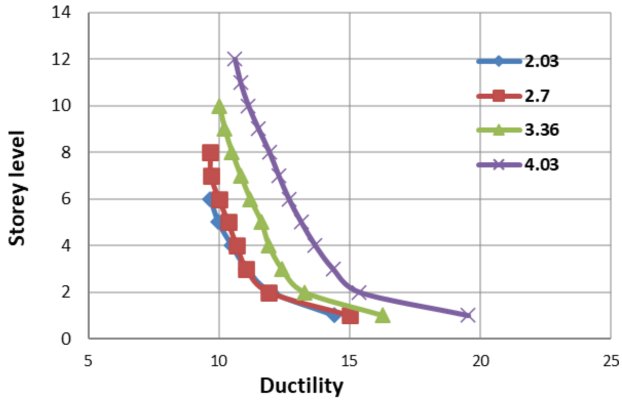

Figure 10. Variation of ductility in all storey level for different AR.

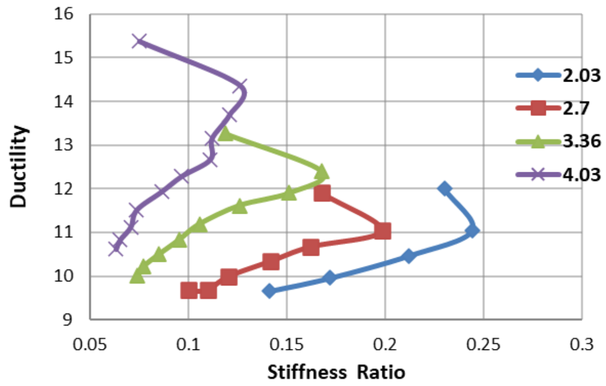

Figure 11. Variation of ductility vs. stiffness ratio for different AR.

Table 2. Variation of plastic hinges in yield and ultimate stage for given aspect ratio.

Aspect ratio	Stage	Top displacement (m)	Base shear (kN)	No. of plastic hinges formed								
				A to B	B to IO	IO to LS	LS to CP	CP to C	C to D	D to E	beyond E	Total
2.03	yield	0.010843	909.756	607	5	0	0	0	0	0	0	612
	ultimate	0.104749	3329.652	401	191	20	0	0	0	0	0	612
2.7	yield	0.015428	890.866	815	1	0	0	0	0	0	0	816
	ultimate	0.145944	3104.096	572	224	20	0	0	0	0	0	816
3.36	yield	0.019392	833.795	1019	1	0	0	0	0	0	0	1020
	ultimate	0.196078	3159.367	717	283	20	0	0	0	0	0	1020
4.03	yield	0.024597	791.02	1223	1	0	0	0	0	0	0	1224
	ultimate	0.263391	3253.793	848	328	48	0	0	0	0	0	1224

CONCLUSIONS

This paper discusses nonlinear static analysis of four models of reinforced concrete building using SAP2000. The parameters in the study are aspect ratio, capacity curve, performance point, interstorey drift, ductility, and stiffness ratio. The following conclusions are made from the present study.

- For any aspect ratio between 2.03 to 4.03, the base shear can be obtained for a given building drift.
- The performance of the structure is also influenced by aspect ratio. For all models, 4.03 aspect ratio has less base shear at performance compared to other three aspect ratios.
- Top storey displacement is increased by 26 % for all aspect ratios. Because all four AR are taken as equal difference of 0.67 with each other. The storey displacement is high as aspect ratio increases, and that provide excess time to be affected by seismic loads.
- The percentage of interstorey drift increases with a decrease in storey level. Among all aspect ratios, 2.03 has less interstorey drift than the other three. Even though AR 4.03 is under the category of life safety level, this is less than a 1.4 % interstorey drift. So all models considered above have not collapsed but have yielded by effect of earthquake.

- For higher aspect ratio, ductility is high and stiffness ratio is less which gives more clarity about the performance of the above structural models.

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