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Design Procedures of Reinforced Concrete Framed Buildings in Nepal and its Impact on Seismic Safety

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Abstract: The present paper analyses the design procedure and its impact on seismic safety of the structures. For this, a representative reinforced concrete frame building (WDS) is designed and the results are compared with similar buildings detailed with: *i*) Current Construction Practices (CCP); *ii*) the Nepal Building Code (NBC) and iii) the Modified Nepal Building Code (NBC+) recommendations. The seismic performance evaluation is done with global strength, inter-storey drift and displacement of the structures. Likewise, the sensitivity of the structural and geometrical parameters of the RC frame building is studied through nonlinear analysis. The study parameters considered for parametric analysis are column size, beam size, inter-storey height, bay length, bay width, and compressive strength of concrete. The results show that the influence on the structural behaviour, particularly by variation in column size and inter-storey height. Additionally, the influence of the seismic zone factor on reinforcement demand of the structure is studied. The result shows that structures designed for high to medium seismic hazard demands double the reinforcement in beams compared to structures in low seismic zone.

Key words: RC buildings, statistical analysis, adaptive pushover, seismic performance, sensitivity analysis.

1. INTRODUCTION

Nepal is located in a highly seismically active Himalayan belt. Over the last centuries, huge earthquakes occurring in 1803, 1833, 1897, 1905, 1934 and 1950 in the Himalayan region have resulted in a large number of casualties and caused extensive damage to structures (Bilhman *et al*. 2001). The great Gujarat earthquake in south-west India in 2001 revealed the vulnerability of non-earthquake proof cities and villages. Total casualties were estimated at 20,000 and more than 160,000 people injured (Genzano *et al*. 2007). Nepal is located in the subduction zone where the Indian plate passes under the Himalayas, and may actually be susceptible to an even larger scale earthquake than Gujarat. In 1934, an earthquake of magnitude 8.4 killed 8,519 people and damaged over 80,000 buildings in Nepal (Rana 1935). Later, the 1988 Udayapur earthquake also resulted in a heavy loss of life particularly in the eastern and western region of the country. Past earthquake records have shown that Nepal can expect two major earthquakes of magnitude 7.5–8 every 40 years (Table 1) (BCDP 1994). Thus, it has been the cause of great concern that the next great earthquake may occur at any time after around 80 years of silence.

Nowadays in Nepal a large percentage of the residential building is constructed with reinforced concrete frame structures. The majority of these buildings have only been designed for vertical loads without any seismic design criteria (Chaulagain *et al*. 2012).

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Table 1. Magnitude-frequency data on earthquakes in Nepal and the surrounding regions (1911–1991)

Earthquake magnitude (Richter scale)	5 – 6	6 – 7	7 – 7.5	7.5 – 8	> 8
Number of events	41	17	10	2	1
Approximate recurrence interval (years)	2	5	8	40	81

Source: Nepal National Building Code Development Project (1994)

However, since 2003 legal provisions were implemented in the Nepal Building Code to improve the seismic behaviour of RC buildings. The primary aim of this code is to improve the quality of the local building construction. In this context, this paper analysed the impact of Nepal Building Code recommendations on actual construction practices and safety. To accomplish this objective, four structures, designed and detailed according to: i) Current Construction Practices (CCP); ii) Nepal Building Code recommendations (NBC); iii) Modified Nepal Building Code (NBC+) recommendations and, iv) Well Designed Structures (WDS) are analysed and its performance is compared. Additionally, the influence of seismic zone factors on the reinforcement demand of the structure is analysed by designing the same WDS structure for seismic zones of low, medium and high seismic hazard.

Moreover, the impact of structural parameters on the behaviour of structure is evaluated through non-linear analysis. For this, a parametric analysis of the building structures is performed with variations in the beam and column sizes, inter-storey height, bay length, bay width and the compressive strength of concrete. The selections of parameters are based on Pereira *et al.* (2009), Muin (2011), Masi *et al.* (2008), D'Ambrisi *et al.* (2011), and Abdelouafi *et al.* (2010) study.

1.1. Building Typologies in Nepal

The information about the buildings typologies in Nepal was analyzed considering the information obtained during the National Population and Housing Census in 2011 (CBS 2012). The distribution of building structures throughout the country is presented in Figure 1(a). Based on this survey, buildings with similar characteristics, lateral load resisting systems, and diaphragms are classified in one group. The census survey data indicates that mud bonded brick/stone buildings are most common typology in Nepal for all the regions, representing about 44% of the total buildings. The wooden buildings are more popular in rural area of Terai region which represents around 25%. The Terai region is the southern part of country and is an extension of the Gangetic plains of India. It covers 17% of the total land area. Today, about 50% of the population lives in this region. Cement bounded brick/

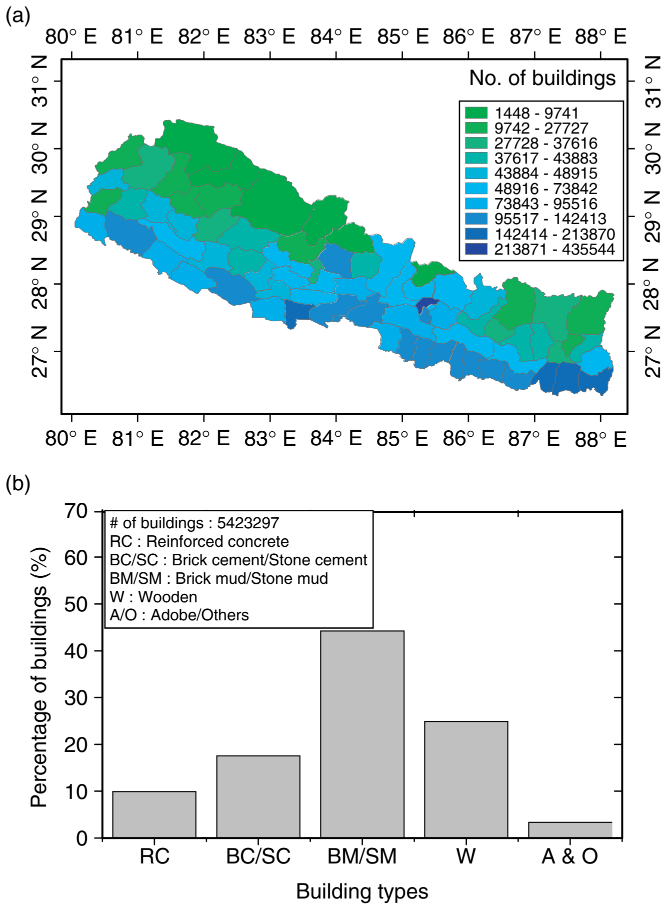


Figure 1. (a) District distribution of buildings; (b) Types of Nepalese building structure (NPHC 2011)

stone and reinforced concrete buildings are highly popular in urban area in most of the Terai region, Kathmandu Valley and some district headquarter of mountainous region. These buildings occupy 17% and 10% building stock in Nepal respectively [see Figure 1(b)]. The RC buildings are normally constructed with masonry infills, and the infill's are used for cladding and partitioning in the RC frame structures. The rest of the buildings are classified as others and not stated building typologies. These buildings are generally constructed with the combination of two or more than two different building materials. These are the mixed buildings like stone and adobe, stone and brick in mud, brick in mud and brick in cement, wooden and brick cement mortar.

1.2. Reinforced Concrete Building

Reinforced concrete building with masonry infills construction in Nepal has begun from late 1970s. And, in the last 3–4 decades has rapidly increased, replacing other construction materials and solutions like adobe, stone and brick masonry in Nepal. Brick masonry block is the most common infill material in Nepal because of its abundance, low cost, and the availability of labor skilled in this construction technique. Masonry infills are usually built up after the frames and floor structures have been constructed. These buildings are unlikely to act as moment-resisting frame buildings. The frame elements act as tie elements. There is a lack of structural design standards for masonry infill walls since they are normally treated as non-structural components. Therefore, reinforced concrete building structures are normally designed and analyzed as a bare frame without considering the contribution of the infill material to strength and stiffness. Based on design and construction process, RC buildings in Nepal can be classified as: (i) the first type corresponding to moment resisting frame design represent the current construction practices in Nepal (called CCP structure); (ii) the second design type is based on Nepal building code (called NBC structure); (iii) the third type of structure is the modified version of the Nepal building code (called as NBC+ structure) and the last type of RC frame represent the moment resisting frames which is designed based on Indian standard code with seismic provisions, namely seismic design with ductile detailing (called well designed structure, WDS) (Chaulagain *et al*. 2013). Most of the CCP buildings are based on non-engineered construction where as remaining building types (NBC, NBC+, and WDS) are engineered. Engineered buildings are designed and built with seismic provisions and in contrast, most of the non-engineered buildings are based on owner built construction, without the engineer participation. This category also includes the buildings that have architectural drawings prepared by engineers. The typical characteristics of each structure studied are discussed in the following sub-sections:

1.2.1. WDS Structure

The WDS building structure is designed based on the Indian standard code, considering seismic design with ductile detailing to the building located in seismic zone V and medium soil. Due to the low height, and regular plan and elevation, seismic analysis is performed using the seismic coefficient method (IS1893 2002). The effect of the finite size of joint widths (e.g. rigid offsets at member ends) is not considered in the analysis. However, the effect of shear deformation is considered. The detailed design of the beams and column sections are performed according to IS13920 (1993) recommendations. In fact, the NBC105 (1994) is the seismic loading standards for Nepal and provides all the seismic loading parameters; however, it relied on IS4326 (1993) for ductile detailing. These ductile detailing requirements for the reinforced concrete framed buildings was later elaborated and published in IS13920 (1993). The NBC105 (1994) still remains the valid loading standard, despite changes made to IS4326 (1993). The final results of the beam and column sections and detailing are presented in Tables 2 and 3.

1.2.2. NBC Structure

The NBC structure is designed with the Mandatory Rules of Thumb (MRT). MRT provides some ready-to-use provisions in terms of dimensions and details for structural and non-structural elements for up to three storeys with room sizes of no more than 4.5 m ∞ 3.0 m in RC framed, ordinary residential buildings commonly built by owner-builders in Nepal (NBC 205 1994). These guidelines are applicable to those buildings only which comply with the limitations set-out in the relevant documents. The recommended beam and column sizes, and the longitudinal steel in the beam and columns are presented in Tables 4 and 5.

1.2.3. NBC+ Structure

In 2010, the Department of Urban Development and Building Construction published additional recommendations for the construction of Earthquake Safer Buildings in Nepal with the assistance of UNDP

Table 2. Longitudinal steel in beams (230 mm × 325 mm) in WDS structure

		Exterior beam				Interior beam			
		Support		Mid-span		Support		Mid-span	
Location	Storey	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Long.	1^{st}&2^{nd}	5ϕ16	3ϕ16	2ϕ16	3ϕ16	5ϕ16	3ϕ16	2ϕ16	3ϕ16
Long.	3^{rd}	2ϕ12+1ϕ16	2ϕ12	2ϕ12	2ϕ12	2ϕ12+1ϕ16	2ϕ12	2ϕ12	2ϕ12
Trans.	1^{st}&2^{nd}	5ϕ16	3ϕ16	2ϕ16	2ϕ16	5ϕ16	3ϕ16	2ϕ16	2ϕ16
Trans.	3^{rd}	2ϕ12+1ϕ16	2ϕ12	2ϕ12	2ϕ12	3ϕ12	2ϕ12	2ϕ12	2ϕ12

Table 3. Columns size and longitudinal steel in WDS structure

	Corner column		Facade column		Interior column	
Storey	**Size (mm)**	**Reinf. (As)**	**Size(mm)**	**Reinf. (As)**	**Size (mm)**	**Reinf. (As)**
3rd	300 × 300	8ϕ16	300 × 300	8ϕ16	300 × 300	8ϕ16
2nd	350 × 350	8ϕ16	300 × 300	8ϕ16	350 × 350	8ϕ16
1st	350 × 350	8ϕ16	300 × 300	8ϕ16	350 × 350	8ϕ16

Table 4. Longitudinal steel in beams (230 mm × 325 mm) in NBC structure

		Exterior beam				Interior beam			
		Support		Mid-span		Support		Mid-span	
Location	**Storey**	**Top**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**
Long.	1st	2ϕ16+2ϕ12	2ϕ16+1ϕ16	2ϕ16	2ϕ16	2ϕ16+2ϕ12	2ϕ16+1ϕ16	2ϕ16	2ϕ16
Long.	2nd	2ϕ16+1ϕ12	2ϕ16+1ϕ10	2ϕ16	2ϕ16	2ϕ16+1ϕ12	2ϕ16+1ϕ10	2ϕ16	2ϕ16
Long.	3rd	3ϕ12	2ϕ12+1ϕ10	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12
Trans.	1st	2ϕ16+1ϕ12	2ϕ16+1ϕ12	2ϕ16	2ϕ16	2ϕ16+1ϕ12	2ϕ16+1ϕ12	2ϕ16	2ϕ16
Trans.	2nd	2ϕ12+1ϕ16	3ϕ12	2ϕ12	2ϕ12	2ϕ12+1ϕ16	3ϕ12	2ϕ12	2ϕ12
Trans.	3rd	2ϕ12+1ϕ10	2ϕ12	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12

Table 5. Columns size and longitudinal steel in NBC structure

	Corner column		Facade column		Interior column	
Storey	**Size**	**Reinf. (As)**	**Size**	**Reinf. (As)**	**Size**	**Reinf. (As)**
3rd	230 × 230	4 ϕ 16	230 × 230	4 ϕ 12	230 × 230	4 ϕ 12
2nd	230 × 230	4 ϕ 16	230 × 230	4 ϕ 16	230 × 230	8 ϕ 12
1st	270 × 270	4 ϕ 16	270 × 270	4 ϕ 16	270 × 270	8 ϕ 112

(UNDP 2010). This document is an improvement on the NBC, and specifies that the minimum sizes of columns for up to three storeys with room sizes of no more than 4.5 m × 3.0 m should be 300 mm × 300 mm or 75 mm more than the width of the beam. There should be a minimum of 4 and 8 nos. of 16 mm dia. reinforcement bars in columns located in the outer faces and centre of the building structure. The detailing of the beam is the same as specified in the NBC document.

1.2.4. CCP Structure

Finally, an additional building is defined to represent the current construction practices (CPP) in Nepal. The structures use light reinforced concrete frames with masonry infill. Most of these residential buildings are between 2 to 6 storeys high, with the majority of them being three storeys. However, these structures are not constructed with proper seismic detailing. In urban areas of Nepal, majority of existing RC buildings are under this category (Shrestha and Dixit 2008; UNDP 1994).

The detailing of the beams and columns of these structures are tabulated in Tables 6 and 7.

1.2.5. Comparison of Study Building Structures

The beam reinforcement quantity at the support and mid-span for the WDS, NBC+, NBC, and CCP structures are presented in Tables 2, 4 and 6. The CCP structure uses the same amount of reinforcement for negative and positive bending moments throughout the entire span of the beam. This amount is the lowest among all structures. There is a clear improvement in the beam detailing of the NBC and NBC+ structures. In these structures, the amount of support reinforcement is relatively larger than the CCP structure. Moreover, in NBC and NBC+ structures more reinforcement is provided in the first and second storey beams compared to top floor beam. In contrast, as expected, the WDS structure demands more reinforcement to withstand ground shaking.

The provisions of the columns and its reinforcement in the corners, the façade and the interior columns in the study building structures are presented in Tables 3, 5, and 7. The CCP structure uses the same column size of 230 × 230 with same amount of reinforcement in all the columns. There are some improvements in the size and reinforcement amount in the corner, façade and interior columns in the NBC structures. A larger size of columns (270 × 270) is used in the first storey and the same smaller size of columns (230 × 230) is used in the second and third storeys. In the NBC+ structure, a minimum size of 300 × 300 column is used for the whole structure. In contrast, as expected, the WDS structure demands more reinforcement with larger column sizes to withstand expected ground shaking. This amount is significantly higher than CCP, NBC and NBC+ structures.

1.3. Common Problems in RC Building Construction in Nepal

The RC building construction in Nepal only dates to 30–40 years ago. Due to their short history, these structures have faced very few earthquakes, with low intensity. As so, the earthquake damage scenarios in RC buildings can only be extracted from surrounding countries with similar construction trends, practices and seismic hazard levels. Based on a literature review (Arslan and Korkmaz 2007; Bothara and Hicyilmaz 2008; Bothara *et al*. 2010; Jain *et al*. 2001; Dogangun 2004; Ghobarah *et al*. 2006; Sezen *et al*. 2003; Thapa

Table 6. Longitudinal steel in beams (230 mm × 325 mm) in CCP structure

		Exterior beam				Interior beam			
		Support		Mid-span		Support		Mid-span	
Location	**Storey**	**Top**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**
Long.	1st	3ϕ12	3ϕ12	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12
Long.	2nd	3ϕ12	3ϕ12	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12
Long.	3rd	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12
Trans.	1st	3ϕ12	3ϕ12	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12
Trans.	2nd	3ϕ12	3ϕ12	2ϕ12	2ϕ12	3ϕ12	3ϕ12	2ϕ12	2ϕ12
Trans.	3rd	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12	2ϕ12

Table 7. Column size and longitudinal steel in CCP structure

	Corner column		Facade column		Interior column	
Storey	**Size (mm)**	**Reinf. (As)**	**Size(mm)**	**Reinf. (As)**	**Size (mm)**	**Reinf. (As)**
3rd	230 × 230	4ϕ16	230 × 230	4ϕ16	230 × 230	4ϕ16
2nd	230 × 230	4ϕ16	230 × 230	4ϕ16	230 × 230	4ϕ16
1st	230 × 230	4ϕ16	230 × 230	4ϕ16	230 × 230	4ϕ16

1988) on RC building construction trends and practices in India, Pakistan, Indonesia and Turkey, many common points and problems can be identified with the reality in Nepal. Structural deficiencies associated with the absence of ties in beam column joints, inadequate confinement near beam column joints, inadequate lap lengths, low concrete strength, improperly anchored ties, irregularities in plan and elevations**,** irregular distribution of loads and structural elements**,** soft storey effects, short column effects, strong beam-weak column connections, etc. are common in RC structures in Nepal and the surrounding areas. Some of the structural deficiencies in Nepalese construction are presented in Figures 2 to 6.

1.4. Evolution of the Nepal Building Code

Nepal is considered one of the most vulnerable countries for earthquakes. The earthquake in 1988 prompted serious concerns for the earthquake safety of the infrastructure. Following the major earthquake event of 1988, the Department of Urban Development and Building Construction (DUDBC) of the Ministry of Physical Planning and Works (MPPW) developed the Nepal National Building Code (NBC) in 1994, with the assistance of the United Nations Development Programme and United Nations Centre for Human Settlement (UN-HABITAT). NBC came into force when the Building Construction System Improvement Committee (established by the Building Act 1998) authorised MPPW to implement the code. The Ministry published a notice in the Gazette in 2003, and the implementation of NBC became mandatory in all municipalities and in some Village Development Committees (VDCs) in Nepal.

In Nepal Building Code, there are the provisions for four different levels of building construction namely: (a) International state-of-art, (b) Professionally engineered structures, (c) Buildings of restricted size designed with simple rules-of-thumb, and (d) Guidelines for remote rural buildings depending on the sophistication of design and construction. The present study also investigates an example building from Mandatory Rule of Thumb (see subsection 1.2.2 and 1.2.3 for more details).

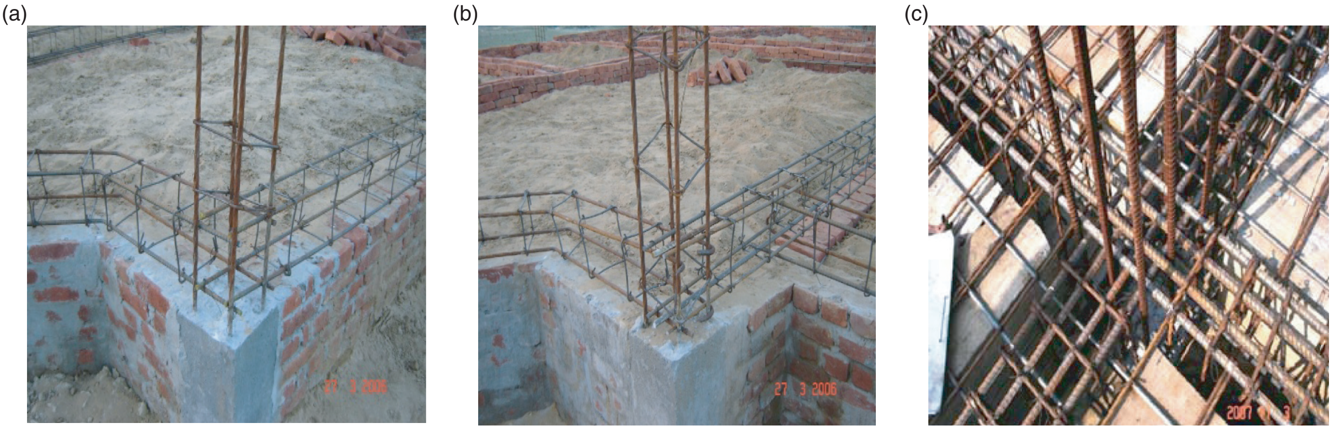


Figure 2. (a) No anchorage of beam bars in column; (b) Beam reinforcement hooking into column reinforcement; and (c) No stirrups in beam-column joint (Marhatta *et al*. 2007)

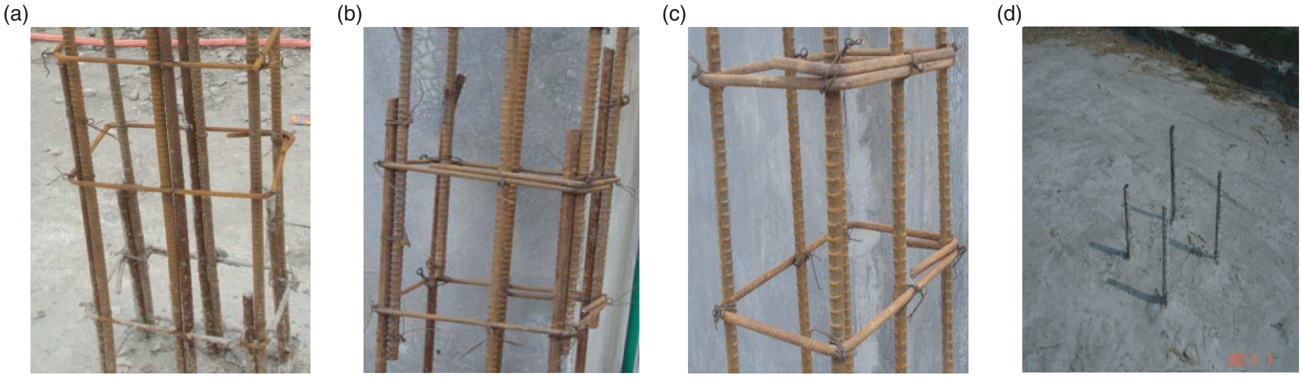


Figure 3. (a) Defective stirrups due to 90^o bend joints; (b) Inadequate lap length; (c) Large spacing of lateral tires in column with 90^o bend; and (d) Column reinforcement is too short for the continuity of the column

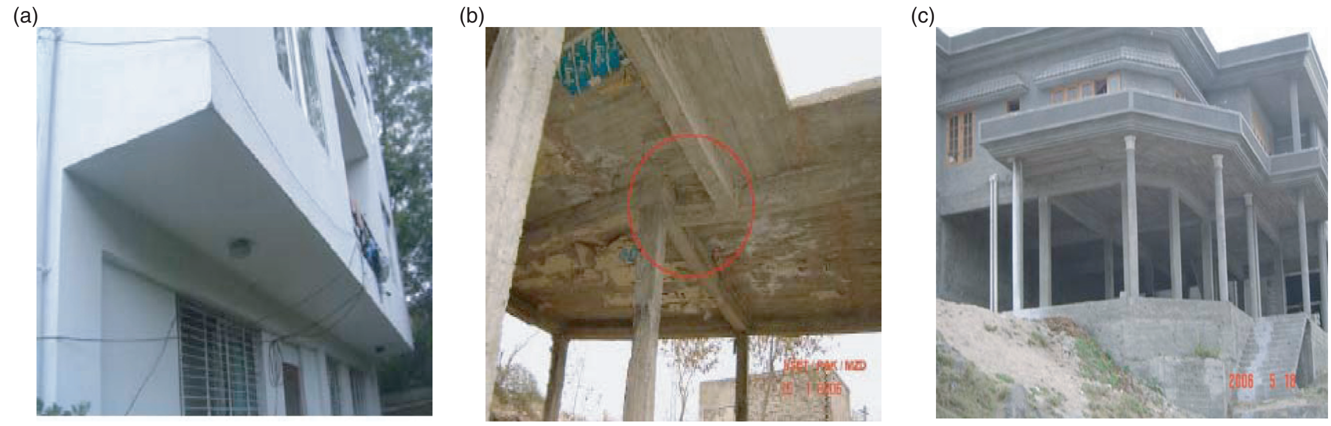


Figure 4. (a) Load path problem due to external wall; (b) Load path problem due to improper beam column connection; and (c) Soft storey problems (NSET 2009)

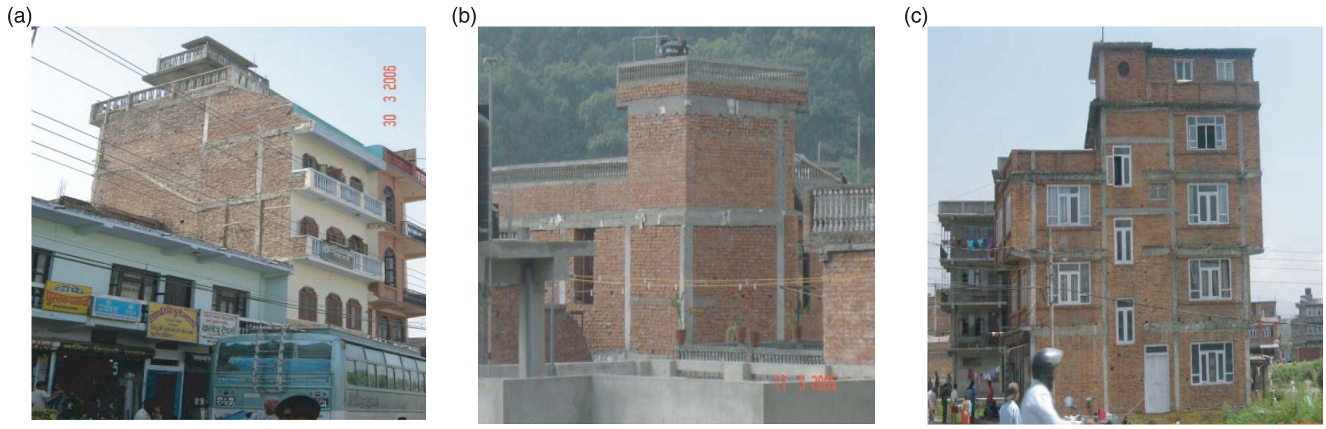


Figure 5. (a) Column starting from fifth storey; (b) Missing column in top storey; and (c) Missing beam (Marhatta *et al*. 2007)

Figure 6. Existing RC building construction practices in Nepal (NSET 2009)

2. CASE STUDY

2.1. Statistical Analysis of RC Buildings in Nepal

The statistical analysis was based on data from consultancy drawings, municipality drawings, and a field survey of current construction and existing buildings in different localities in Nepal (Chaulagain *et al*. 2010; JICA 2002; NSET 1999). The information collected during different surveys includes the size and detailing of RC elements (beams and columns), inter-storey height, numbers of bays and dimensions, years of construction, and quality of concrete. All the reinforced concrete buildings are constructed with brick masonry infills. The thickness of 230 mm and 115 mm normally exist on periphery and internal brick masonry infill panels respectively. Results from the statistical analysis are applicable for the buildings up to 5 storeys. The additional results from the statistical analysis of beams and column sections and the static of survey building structures are presented in Tables 8 to 10.

The maximum (max.), minimum (min.), and average (avg.) sizes of beam elements for the surveyed buildings are 250 × 380, 230 × 230 and 236 × 320 respectively. The max., avg. and min. amount of reinforcement for the top and bottom of the beam elements are 1.17%, 0.68% and 0.45%, and 0.87%, 0.47% and 0.33% respectively. The maximum covariance is for the top steel reinforcement in beam elements (29%) whereas the minimum is for the width of beams (4%). A result from the statistical analysis of beam section is presented in Table 8.

The max., min., and avg. sizes of column sections for the surveyed buildings are 300 × 300, 230 × 230 and 241 × 245 respectively. The max., avg. and min. amount of reinforcement for exterior and interior column sections are 1.95%, 1.18%, and 0.86% and 1.95%, 1.31%, and 0.86% respectively. The maximum covariance is for the moment of inertia of column sections (35%) whereas the minimum is for the width and depth of column elements (13% and 14% respectively). The detailed results of the statistical analysis on column elements are presented in Table 9.

Furthermore, the max., avg. and min. value of inter-storey height, bay length and bay width of the studied buildings are 3300, 3000 and 2850; 4500, 3950, and 2625; and 4100, 3150 and 2625 respectively. The variations in bay length in the X and Y directions are 12% and 7% respectively, whereas the value is limited to 7% for inter-storey height. The results from the analysis are presented in Table 10.

2.2. Description of the 3-Storey Prototype RC Building

The sample 3-storey regular RC building was developed to represent a typical residential RC building in Nepal. The global dimensions of the prototype building, namely storey height, number of storeys, and bay spacing, are based on the statistical analysis of the relevant data. The geometry of the

Table 8. Statistical analysis of beam sections

S.N	B (mm)	D (mm)	MoI (mm^4)	Top steel (%)	Bottom steel (%)
Max.	250	380	1143166667	1.17	0.87
Min.	230	230	233200833	0.45	0.33
Avg.	236	320	646598848	0.68	0.47
Std dev	9	59	174581689	0.20	0.10
CoV	4	19	27	29	22

Table 9. Statistical analysis of column sections

S.N	B (mm)	D (mm)	MoI (mm^4)	Ext. col. steel (%)	Int. col. steel (%)
Max.	300	300	873350493	1.95	1.95
Min.	230	230	233200833	0.86	0.86
Avg.	241	245	295295883	1.18	1.31
Std dev	32	35	103353559	0.41	0.42
CoV	13	14	35	35	32

Table 10. Statistical analysis of surveyed building structures

S.N	Bays- X nos.	Bays-Y nos	Avg. C/C in X mm	Avg. C/C in Y mm	Storey Ht. mm
Max.	4	4	4500	4100	3300
Min.	2	2	2625	2625	2850
Avg.	3	2	3950	3150	3000
Std dev	1	1	474	221	210
CoV	23	28	12	7	7

study building structure is presented in Figure 7. The building has two and three bays of 3 m and 4 m in the X and Y directions respectively. The inter-storey height is taken as 3 m. The material properties are assumed to be identical for the four structures throughout the height of the structure. The material properties and loading on the building structures are presented in Tables 11 and 12.

2.3. Influence of Zone Factor on Reinforcement Demand of the Structure

The influence of seismic zone factor on reinforcement demand of the structure is the interesting issue to the general people. Therefore, in this section, the requirement of beam reinforcement in different seismic zones is studied. For this, the same WDS structures with three different seismic hazard zones are designed and compared with the structure designed for gravity load. Due to similarity in seismic hazard in the northern India and Nepal along the Himalayan belt and similar soil types, the zone factors indicated in Indian seismic code (IS1893 2002) is used in this study. The zone factor of 0.36 is used for regions liable to shaking intensities of IX and higher (seismic zone V), similarly zone factors of 0.24 and 0.16 are used for intensities of VIII (seismic zone IV) and VII (seismic zone III) respectively (IS1893 2002). The results are presented in Tables 13 to 16.

In the longitudinal beam, the building structures designed for seismic zones V, IV and III demand 2, 1.5 and 1.25 times respectively, more reinforcement compared to the gravity load design structure (GLD). In the transverse beam, the structures designed for seismic zone III and GLD demand the same amount of reinforcement. The amount of reinforcement is more than 3.5 and 2.5 times in seismic zones V and IV respectively. In all the seismic zones, it is seen that longitudinal beams demand higher reinforcement compared to the transverse beams. Regarding the gravity loading condition, it is seen that longitudinal beams demand double amount of reinforcement than the respective transverse beams.

Table 11. Properties of materials used in this research

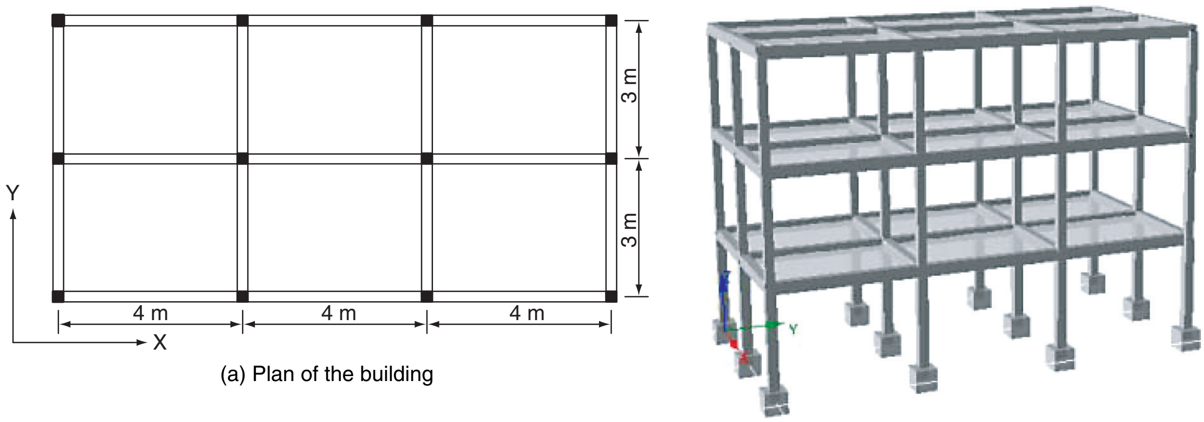
Materials	Characteristics
Reinforcing steel yield strength, f_y	415 MPa
Concrete compressive strength, f'_c	20 MPa
Brick on peripheral beams	230 mm thick
Brick wall on internal beams	115 mm thick
Density of brick masonry including plaster	20 kN/m^3
Density of reinforced concrete	25 kN/m^3

Table 12. Loading for numerical analysis of structure

Loading characteristics	Loading
live load on roof	1.5 kN/m^2
live load on floors	2 kN/m^2
roof and floor finishing	1 kN/m^2

Table 13. Comparison of reinforcement in exterior longitudinal beams

IS zone	Zone factor	Support, –ve (%)	Centre, +ve (%)
V	0.36	1.59	0.68
IV	0.24	1.33	0.45
III	0.16	1.15	0.41
GLD		0.85	0.40



(a) Plan of the building

(b) 3-D model of the building

Figure 7. Geometry of three-storey reinforced concrete building structure

Table 14. Comparison of reinforcement in interior longitudinal beams

IS zone	Zone factor	Support, –ve (%)	Centre, +ve (%)
V	0.36	1.53	0.64
IV	0.24	1.26	0.41
III	0.16	1.07	0.38
GLD		0.74	0.35

Table 15. Comparison of reinforcement in exterior transverse beams

IS zone	Zone factor	Support, –ve (%)	Centre, +ve (%)
V	0.36	1.39	0.54
IV	0.24	1.05	0.32
III	0.16	0.44	0.21
GLD		0.41	0.20

Table 16. Comparison of reinforcement in interior transverse beams

IS zone	Zone factor	Support, –ve (%)	Centre, +ve (%)
V	0.36	1.38	0.54
IV	0.24	1.04	0.32
III	0.16	0.36	0.18
GLD		0.35	0.17

Note: support, -ve and centre, +ve stand for the amount of reinforcement required for negative moments at the support and positive moments at the centre.

3. STRUCTURAL MODELLING

The finite element analysis program SeismoStruct (2009), was used to perform the numerical analysis. Seismostruct is able to evaluate the behaviour of space frames under static or dynamic loading, taking into account the inelastic behaviour of the material as well as the geometric nonlinearities of the elements. It accepts static loads (either forces or displacements) as well as dynamic (accelerations) actions and has the ability to perform eigenvalues, non-linear static pushover (conventional and adaptive), nonlinear static time history analysis, nonlinear dynamic analysis and incremental dynamic analysis.

A mathematical model of the structures with lumped plastic hinges at both ends of each element has been used for the nonlinear analysis. The three dimensional building is represented with a space frame model assuming the centrelines dimensions. In the analyses, half of the larger dimension of the cross-section is considered as the plastic hinge length, with fibre discretization at the section level. The consideration of non-linear material behaviour in the prediction of the RC columns' response requires accurate modelling of the uniaxial material stress-strain cyclic response.

Concrete modelling is based on the Madas uniaxial model (Madas and Elnashai 1992), which follows the constitutive law proposed by Mander *et al.* (1988). The cyclic rules included in the model for the confined and unconfined concrete were proposed by Martinez-Rueda (1997), and Elnashai and Elghazouli (1993). The confinement effects provided by the transverse reinforcement were considered through the rules proposed by Mander *et al.* (1988), whereby constant confining pressure is assumed throughout the entire stress-strain range, this effect increases the peak value of the compression strength and reduces the stiffness of the unloading branch.

The uniaxial model proposed by Menegotto and Pinto (1973), coupled with the isotropic hardening rules proposed by Filippou *et al.* (1983), is adopted for the steel reinforcement representation in these analyses. This steel model does not represent the yielding plateau characteristic of the mild steel virgin curve. The model takes into account the Bauschinger effect, which is relevant for the representation of the columns' stiffness degradation under cyclic loading. The model adopted for numerical analysis in this study is represented in Figure 7.

The analysis of Nepalese RC buildings were performed with adaptive pushover analysis to estimate the capacity of a structure, taking full account of the effect that the deformation of the structure and the frequency content of input motion have on its dynamic response characteristic (Antoniou and Pinho 2006). The lateral load distribution is not kept constant but rather continuously updated during the analysis, according to the modal shapes and participation factors divided by eigen-values analysis carried out at each analysis step (Ghobarah *et al.* 2006). It provides the accurate method for evaluating the inelastic seismic response of structures. The results from adaptive pushover are close to the ones obtained with dynamic time history analysis. For adaptive pushover analysis, response spectrum provided in Indian seismic code is used (IS1893 2002).

4. RESULTS DISCUSSION

In this section the results from nonlinear analysis is presented and discussed. In the first section, the obtained results are presented in terms of capacity curves and inter-storey drift. In the middle section, the allocation of various performance levels in buildings with different design and construction practices are presented. In last section, the results from the sensitivity analyses are discussed. The parametric analysis of the structure is based on the variation of column size (C), beam size (B), inter-storey height (IH), bay length (BL), bay width (BW) and compressive strength of concrete (f_{ck}).

4.1. Capacity Curves

The plotting of maximum shear resisted by the different building structures in both directions (X and Y) during nonlinear analyses is plotted in Figure 8. As observed in figure, structures having different design consideration show the different behaviour. CCP structure has lower level of performance in terms of base shear capacity and maximum inter-storey drift. On the contrary, the shear strength capacity and stiffness of WDS structure is nearly one and a half, two and three times the values obtained with the NBC+, NBC and CCP structures respectively. The NBC+ structure shows the better performance in terms of strength, stiffness, deformation and inter-storey drift compared to the CCP and NBC structures. The NBC recommendations present poorer performance in terms of strength, tangent stiffness and deformation compared to NBC+ and WDS. The WDS structure has the maximum inter-storey drift of around 3.5%. The CCP and NBC structures have the inter-storey drift of around 5%. Due to the change of column size, there is a remarkable change of inter-storey drift between first and second storey in NBC structure.

4.2. Bilinear Idealisation of Capacity Curve

In this study, the yielding of structure is determined with the method proposed by Eurocode 8 (2004). For this purpose, a bi-linear curve is fitted to the capacity curve. In bilinear idealisation of the capacity curve, it is necessary to simplify the capacity curve for an elastic perfectly plastic regime. In the capacity curve, F_y^* represents the resistance capacity of the system with an equivalent SDOF and d_y^* represents the idealised yield displacement of the equivalent single degree of freedom

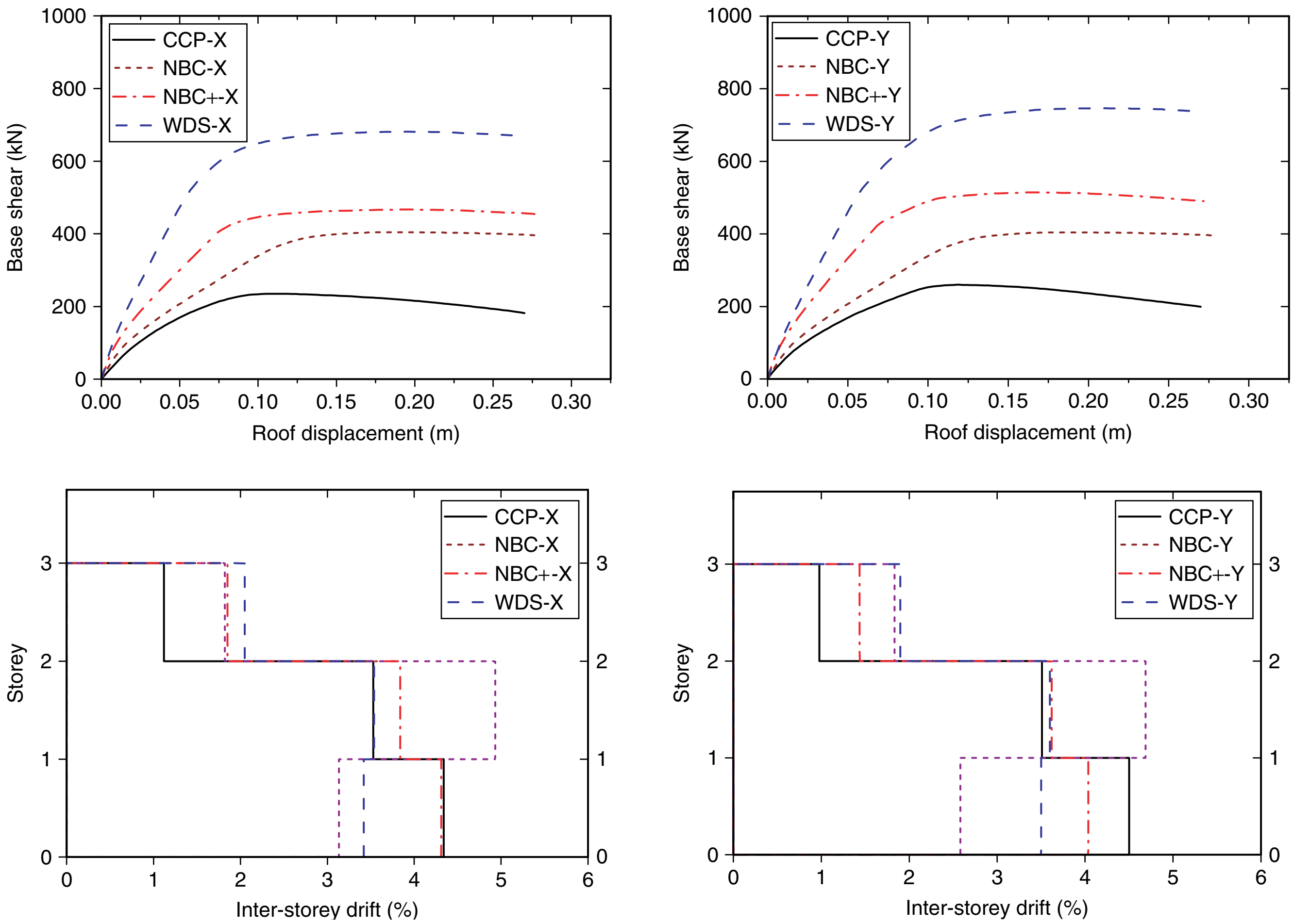


Figure 8. Capacity curves and corresponding inter-storey drift for study building structures
Note: CCP-X, NBC-X, NBC+-X, WDS-X and CCP-Y, NBC-Y, NBC+-Y and WDS-Y represent the capacity curve and corresponding IS-drift for CCP, NBC, NBC+ and WDS structures for both X and Y directions of loading respectively.

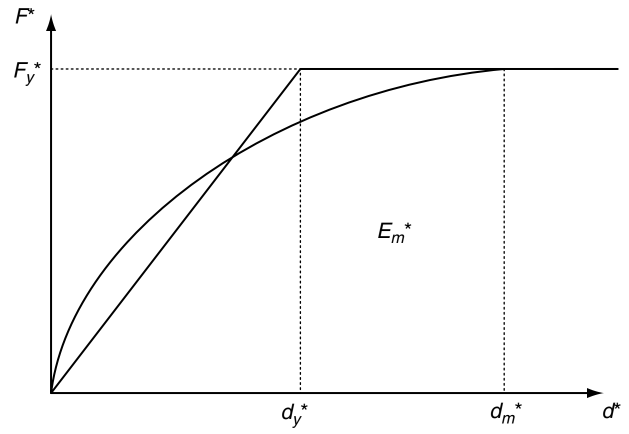


Figure 9. Determination of the idealized elastic-perfectly plastic force-displacement relationship

system (SDOF). The yield displacement is given by Eqn 1, where E_m^* is the deformation energy up to the point the plastic hinge is formed and d_m^* is the displacement at that point (see Figure 9). The initial stiffness of the idealised system is determined in such a way that the areas under the actual and the idealised force-deformation curves are equal. As per Eurocode 8 (2004) the yield displacement of the idealized SDOF system d_y^* is given by the relation:

$$d_y^* = 2\left(d_m{}^* - \frac{E_m^*}{F_y^*}\right) \tag{1}$$

4.3. Performance of the Structures

The nonlinear behaviour of the structures are assessed based on the material strains implemented in the SeismoStruct (2009). For this, the values of cracking of steel elements, spalling of cover concrete (crush_unc), crushing of core concrete (crush_conf), yielding of steel (yield) and fracture of steel (fracture) are taken as +0.0001, –0.0035, –0.008, +0.0025 and +0.060 respectively. The different performance criteria of the structures are summarized as:

- Cracking of structural elements can be detected by checking for (positive) concrete strains larger than the ratio between the tension strength and the initial stiffness of the concrete material.
- Spalling of cover concrete (crush_unc) can be recognised by checking for (negative) cover concrete strains larger than the ultimate crushing strain of unconfined concrete material.
- Crushing of core concrete (crush_conf) can be verified by checking for (negative) core concrete strains larger than the ultimate crushing strain of confined concrete material.
- Yielding of steel (yield) can be identified by checking for (positive) steel strains larger than the ratio between yield strength and modulus of elasticity of the steel material.
- Fracture of steel (fracture) can be established by checking for (positive) steel strains larger than the fracture strain.

In Figure 10(a), the various performance criteria namely: (a) yielding of first column, (b) yielding of first beam, (c) yielding and (d) crushing of concrete are allocated in capacity curves. The values of yielding of first column, yielding of first beam, and crushing of concrete are determined from the numerical models, while the value of yielding is determined by the procedure as indicated in section 4.2. Similarly, the deflection of structures during nonlinear analysis at 0.25 m roof displacement and deflection of structures at the beginning of crushing of concrete is presented in Figures 10(b) and (c).

From Figure 10, it can be seen that the structures with different design standards have varied performance level. It also provides the information regarding local and global failure mechanisms to study building structures. In CCP, NBC and NBC+ structures, the yielding starts with column at lower stories, then propagates to upper stories, and continuous with yielding of beams. In contrast, in WDS structure, first yielding occurs at the first floor beam and propagates to other beams and columns [see Figure 10(a)]. The distribution of yielding, crush_unc and crush_conf as shown in Figures 10(b) and (c) indicate that local failure mechanism exists in CCP and NBC structure. In these structures, local damage will induce severe damage or even collapse of the whole structure system. The crushing of concrete in second storey column (NBC structure) indicates that there may be the chance of the soft storey failure mechanism, such as the structures with light columns. Soft storey column suffer from severe damage under large deformation. It is as a result of variation of column size between first and second storey of the building. The WDS structure, the crushing of core concrete starts from the columns in the first storey and propagates to the other stories. Such failure at the bottom of the columns is almost inevitable even if the "strong column-weak beam design" is adopted. Thus, the designed "strong column-weak beam" cannot prevent the occurrence of the soft storey failure mechanism in the column for first storey (Lieping *et al.* 2006). It is due to the fact that the current "strong column-weak beam" design is merely based on joint equilibriums without taking into account the system concept (Dooley and Bracci 2001). Form the overall structural analysis, the global failure mechanism

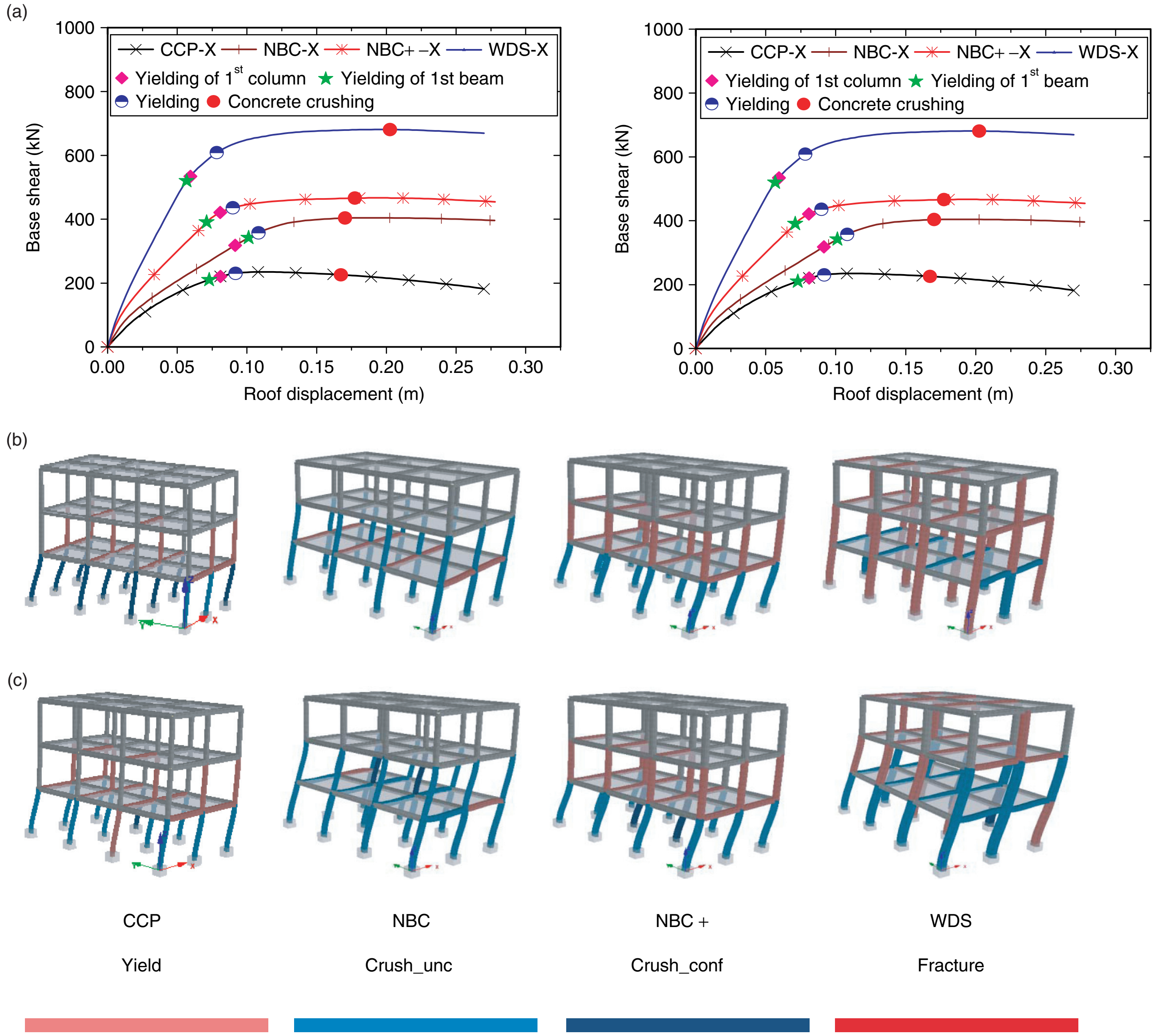


Figure 10. Performance of structures: (a) allocation of performance criteria in CCP, NBC, NBC+ and WDS structures; (b) deflection of structures during nonlinear analysis at 0.25 m roof displacement; and (c) deflection of structures at the beginning of crushing of concrete core

occurred in the WDS building structures. In such a mechanism, the structural damage progress gradually without sudden collapse in case of the failure of some local elements. In this failure mechanism, the plastic deformabilites and thus the energy dissipating capacities of the structural components can be fully developed before the failure of structure (Lieping and Zhe 2009).

4.4. Sensitivity Analysis

The sensitivity of the structural and geometrical parameters of the RC building structure is studied through nonlinear analysis. The study parameters considered in this study are column size, beam size, inter-storey height, bay length, bay width, and compressive strength of concrete. From the statistical analysis, the covariance of the moment of inertia of beam and column sections are found to be 27% and 35%, whereas the covariance in inter-storey height, bay length and width of the building structure are 7%, 12% and 7% respectively. The variation of compressive strength of concrete is based on available literature review (D'Ambrisi 2013). Statistical properties of these random variables are taken from Tables 8 to 10, and are summarized in Table 17. The evaluation of output variability of all the structural parameters in all the building structure is based on the variation of one design

Table 17. Statistical property of random variables

Random variables	Mean	Standard deviation	COV (%)
MoI of column (mm^4)	295295883	103353559	35
MoI of beam (mm^4)	646598848	174581689	27
Inter-storey height (mm)	3000	210	7
Bay length (mm)	3950	474	12
Bay width (mm)	3150	220	7
Compressive strength of concrete (MPa)	30	9	30

* MoI=Moment of Inertia of section

parameter, while all other design parameters are held constant.

In Figures 11 to 18, + and – symbols are used to represent the capacity curve and inter-storey drift as a result of increased and decreased values of random variable with the respective covariance. All the analysis results are in the order of increased, original and decreased value based on the covariance of the parameters (random variables). Due to similarity in the structural response in both direction (X and Y), the plotting of results of sensitivity analysis is only presented in X direction in all the building models. The structural behaviours due to variation in column size (C), beam size (B), inter-storey height (IH), bay length (BL), bay width (BL) and compressive strength of concrete (fck) in both directions of loadings are discussed in the following sub-sections:

4.4.1. CCP structure

CCP structures are the most common structures in Nepal. Due to the low level of base shear capacity and high value of inter-storey (IS) drift, the overall performance of these structures is very poor. As expected, it is due to the small column sizes with a low amount of reinforcement. The effects of the variation in column size, inter-storey height, and compressive strength of concrete and beam size are significant on CCP structure. Bay length and width do not affect on capacity curves. The variation in beam section has less control on structural behaviour compared to the column section. The results are presented in Figures 11 and 12. The key findings are summarised as:

- The column size variation has the maximum influence on the inter-storey drift profile. The value increases from 4.34% to 5.23% in the X and 4.50% to 5.39% in the Y direction of loading. The rate of change of IS-drift and base shear capacity are also significantly affected by variations in column size. Moreover, in CCP structures, the ultimate shear strength is also highly dependent on column size. The value increases from 434.97 kN to 261 kN in the X and 259.62 kN to 293 kN in the Y directions of loading.
- The effect of change in bay length is minimal in this structure. Its effect on the rate of change in inter-storey drift, base shear capacity and yield displacement are less than 3% in both the X and Y directions of loading.
- Variation of beam size has a significant influence on the rate of change of inter-storey, base shear capacity and yield displacement (9%, 6% and 7%) in the structures.
- When the inter-storey height is decreased, the inter-storey drift increases from 4.34% to 4.49% in the X and 4.81% to 5.39% in the Y directions of loading.

4.4.2. NBC structure

NBC structures are built as per the NBC recommendations. The guidelines mentioned in the code is applicable to those buildings only which comply with the limitations set out in the relevant documents. These structures also offer low performance due to smaller column sections with low amounts of reinforcement. The effect of variation in column section and inter-storey height are highly significant in terms of the maximum inter-storey drift, base shear capacity and yield displacement in NBC structures. The variation in beam size and compressive strength of concrete reflect intermediate effects. The change of bay length and width has the negligible influence on performance of structure. The effect on variation of study parameters on building response is presented in Figures 13 and 14. The additional results are summarised as:

- Due to changes in column size between the first and second storeys in NBC structures, the maximum inter-storey drift (5.38%) is observed in the second storey.
- The decrease in inter-storey height has the greatest influence on inter-storey drift. The

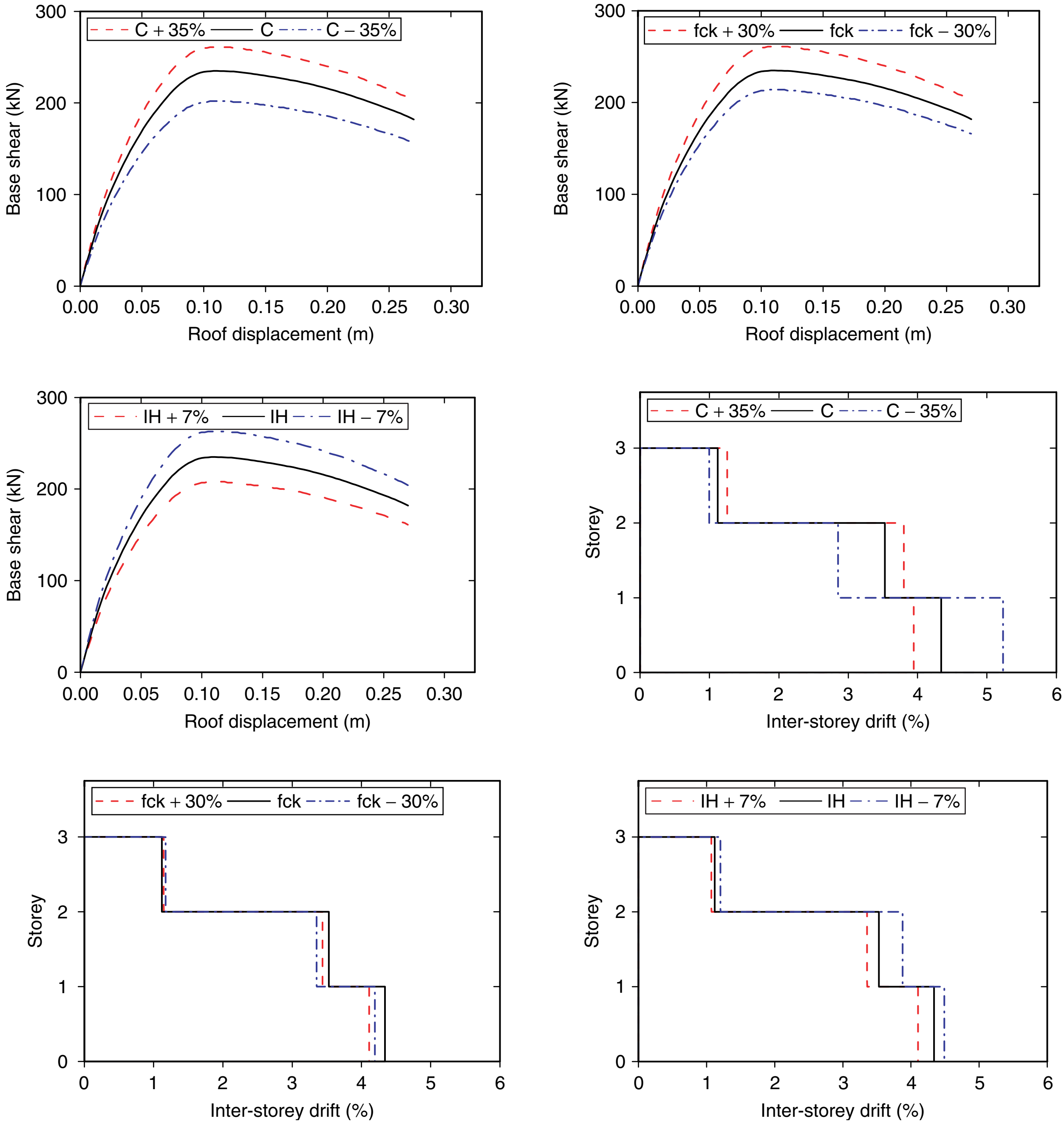


Figure 11. Capacity curve and corresponding inter-storey drift of CCP structure due to variation of column size, compressive strength of concrete and inter-storey height respectively

value increases from 4.93% to 5.38% in the X and 4.68 to 5.07% in the Y directions of loading. In contrast, the inter-storey drift values are limited to 4.56% and 4.39% when the inter-storey height is increased.

- The maximum variation in base shear capacity is due to the change in column size. When the column size is increased, the base shear capacity is increased from 404.14 kN to 442.40 kN in the X and 426.49 kN to 474.94 kN in the Y directions of loading.

4.4.3. NBC+ structure

The NBC+ structure offers better performance in terms of base shear capacity, inter-storey drift and yield displacement. The structure is different from the NBC

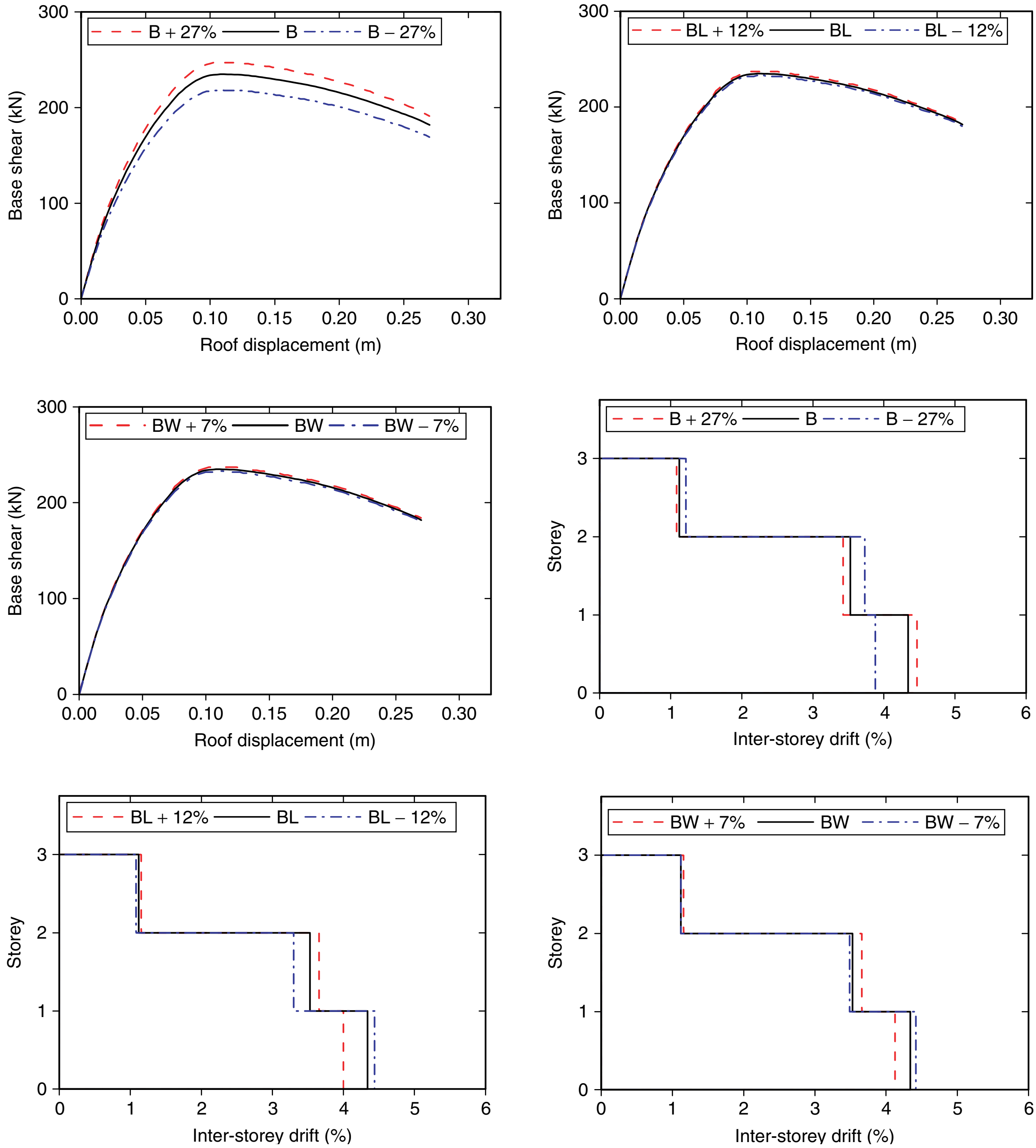


Figure 12. Capacity curve and corresponding inter-storey drift of CCP structure due to variation of beam size, bay length and bay width respectively

structure due to its improved column sections. This improvement in column elements finally results the better performance in structures. Inter-storey height is highly influential on structural performance compared to the other parameters. The RC element size (beam and column size) and compressive strength of concrete also have a significant effect on the response of the structure. The effect of parametric variation on performance of NBC+ structure is presented in Figures 15 and 16. The additional outcomes from the analysis are summarised as:

- The maximum IS-drift increases from 4.31% to 4.58% and decreases from 4.31% to 3.97% in the X, and increases from 4.03% to 4.25% and decreases from 4.03% to 3.73% in the Y directions of loading for decreases and increases

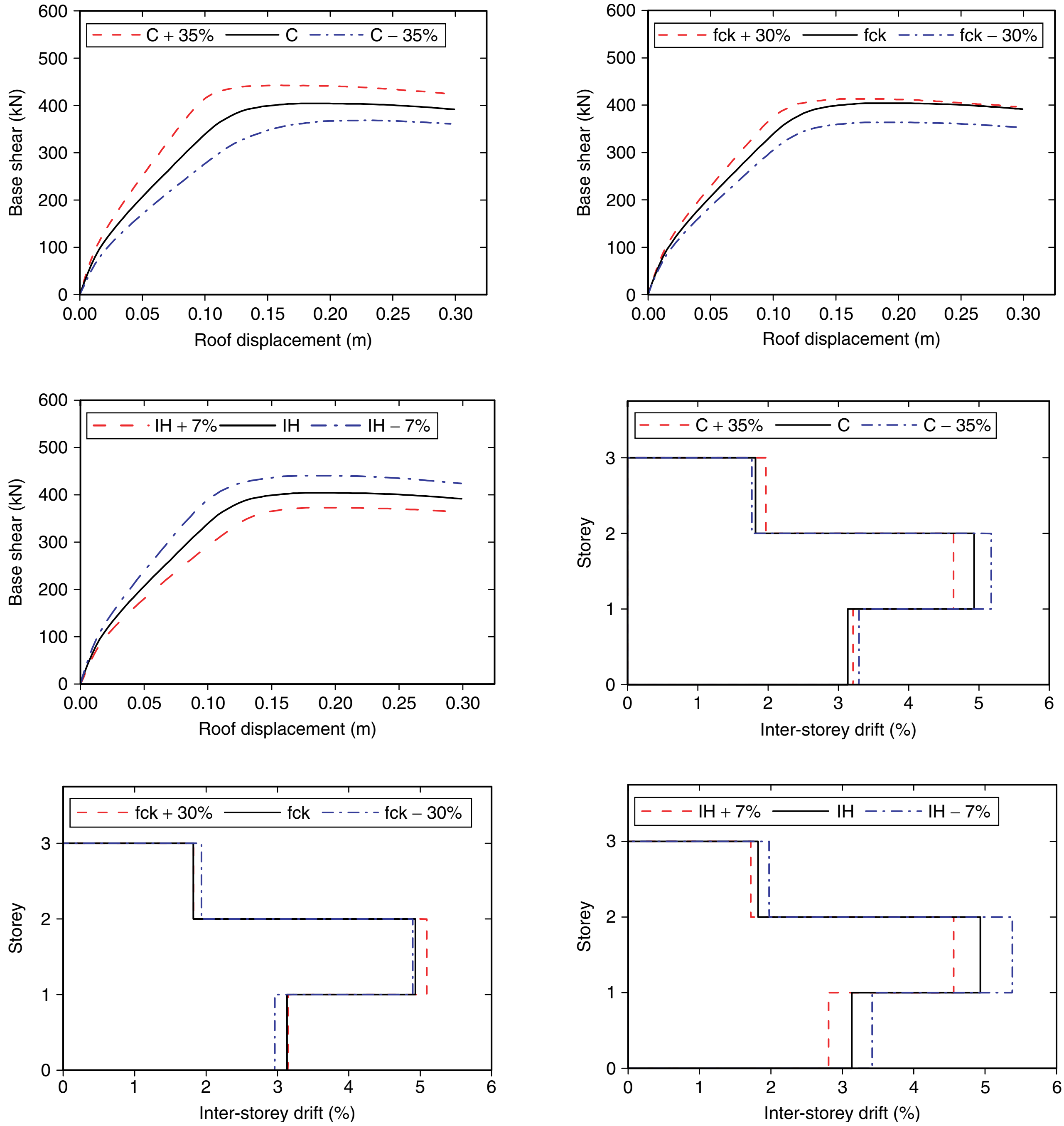


Figure 13. Capacity curve and corresponding inter-storey drift of NBC structure due to variation of column size, compressive strength of concrete and inter-storey height respectively in X direction of loading

in the inter-storey height of the structure. Moreover, NBC+ structures offer the maximum base shear capacity value when the storey height is decreased.

- The change in the compressive strength of concrete also has a significant effect on the yield strength of the structures (8%).

4.4.4. WDS structure

As expected, WDS structures have better performance in terms of base shear capacity and inter-storey drift. In this structure, the influence of parametric variations (changes in capacity curve and inter-storey drift) is very minimal. However, all the parameters have some influence in modifying the

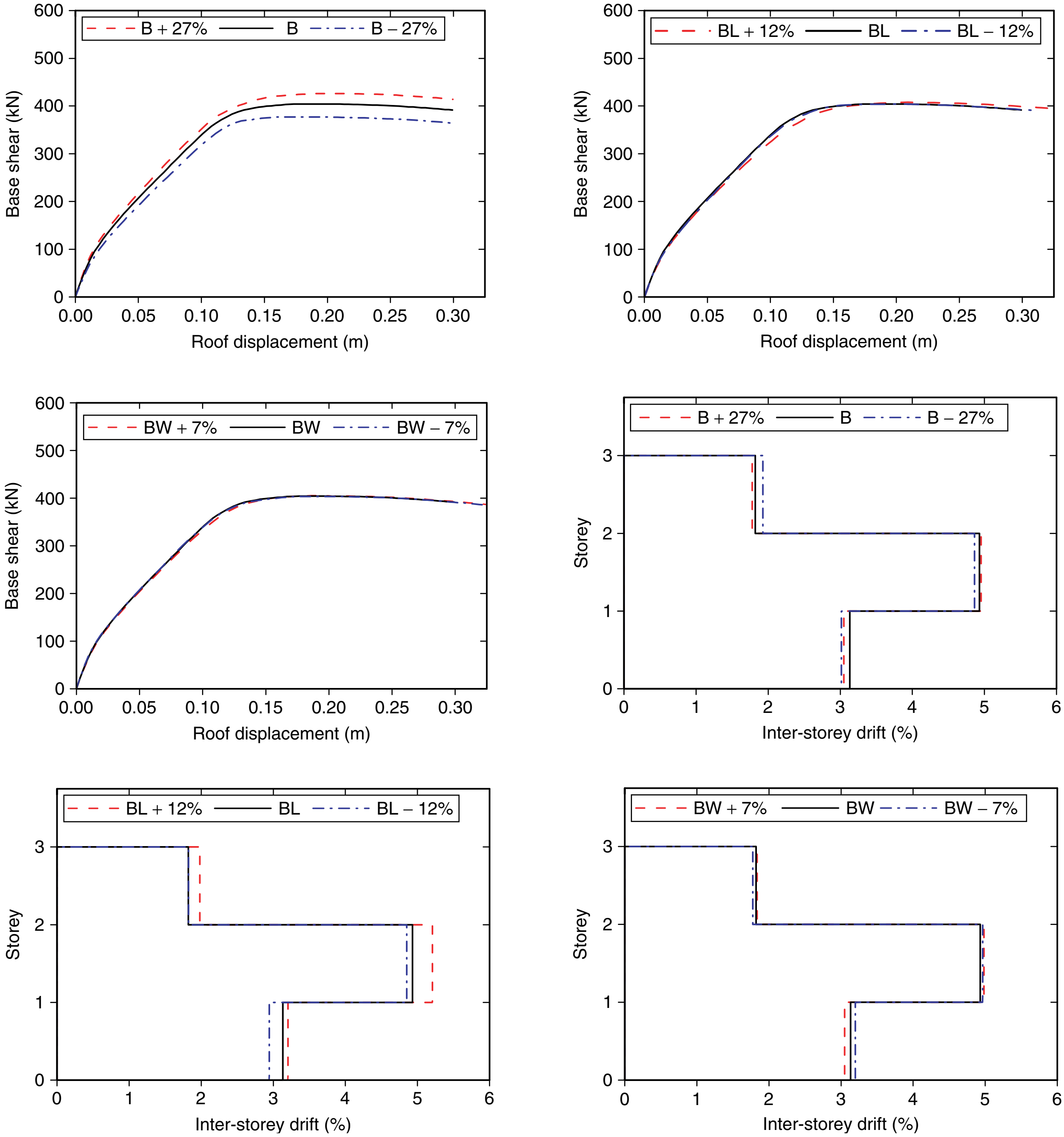


Figure 14. Capacity curve and corresponding inter-storey drift of NBC structure due to variation of beam size, bay length and bay width respectively

overall performance of the structure. The structural behaviour of these structures predominantly depends upon the column and beam sections, storey height, and the compressive strength of concrete. There is a consistency in the rate of change in IS-drift, maximum shear strength, and yield displacement of the structure. The effects of variations in column size, compressive strength, inter-storey height, beam size, bay length and bay width on the WDS structure are presented in Figures 17 and 18. Further results are summarised as:

- The maximum inter-storey drift in the X and Y directions of loading are 3.61% and 3.72% respectively

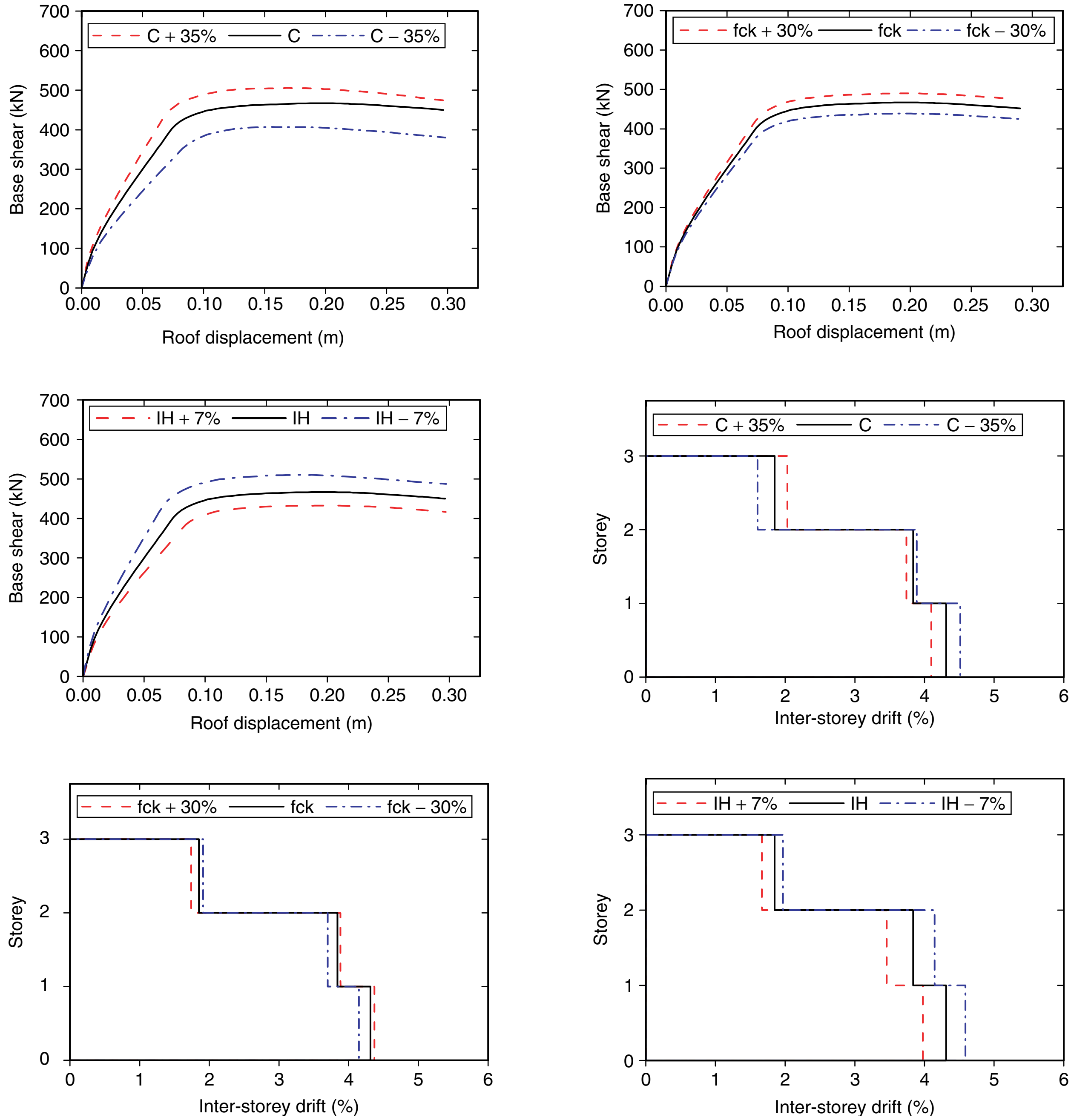


Figure 15. Capacity curve and corresponding inter-storey drift of NBC+ structure due to variation of column size, compressive strength of concrete and inter-storey height respectively in X direction of loading

- The rate of change in IS-drift, base shear capacity, and yield displacement due to the variations in column size, beam size, inter-storey height and compressive strength of concrete are significant.
- The variations of bay length and width have negligible influence on capacity curves.

5. CONCLUDING REMARKS

The present paper presents the study of the code based design procedure and its impact on seismic safety in RC buildings in Nepal. For this, four types of representative RC framed buildings were considered. From the global comparison of the structures, a low amount of reinforcement in both the beam and column sections is

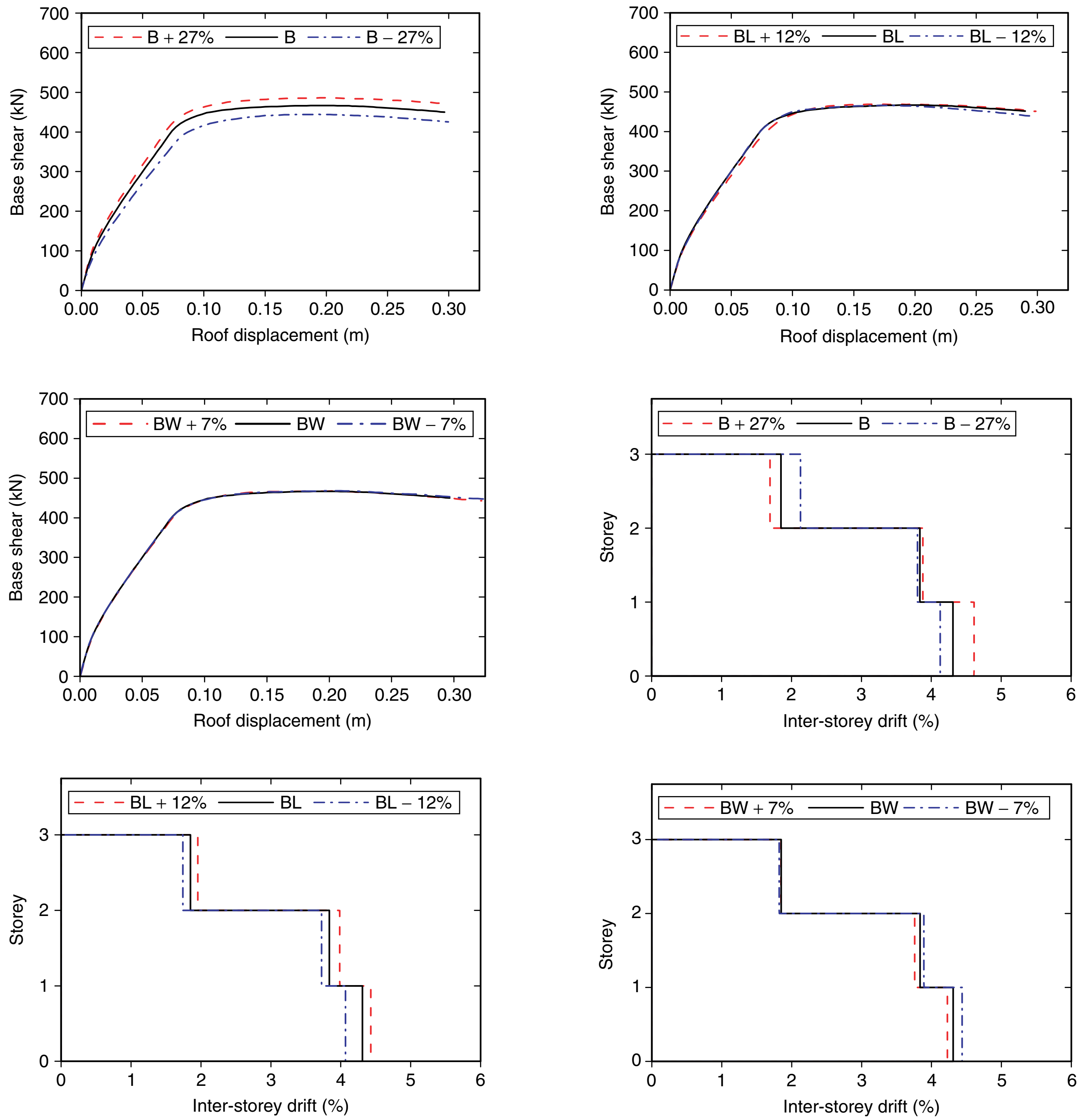


Figure 16. Capacity curve and corresponding inter-storey drift of NBC+ structure due to variation of beam size, bay length and bay width respectively

observed for the CCP structure when compared to WDS structure. For the structure designed according to NBC and NBC+ recommendations, the improvements are clear relative to the CCP structure, but it may be not sufficient for regions of medium/high seismic hazard. Similarly, the influence of seismic zone factor on the reinforcement demand of the structure is studied. The sensitivity of the structural and geometrical parameters of the RC building structure is studied through nonlinear analysis. The main conclusions from the analyses are summarised as:

- The structures designed for high and medium seismic hazard zones require double the amount of reinforcement in beams compared to the structures in zones of low seismicity.
- For the structure designed according to NBC and NBC+ recommendations, improvements are

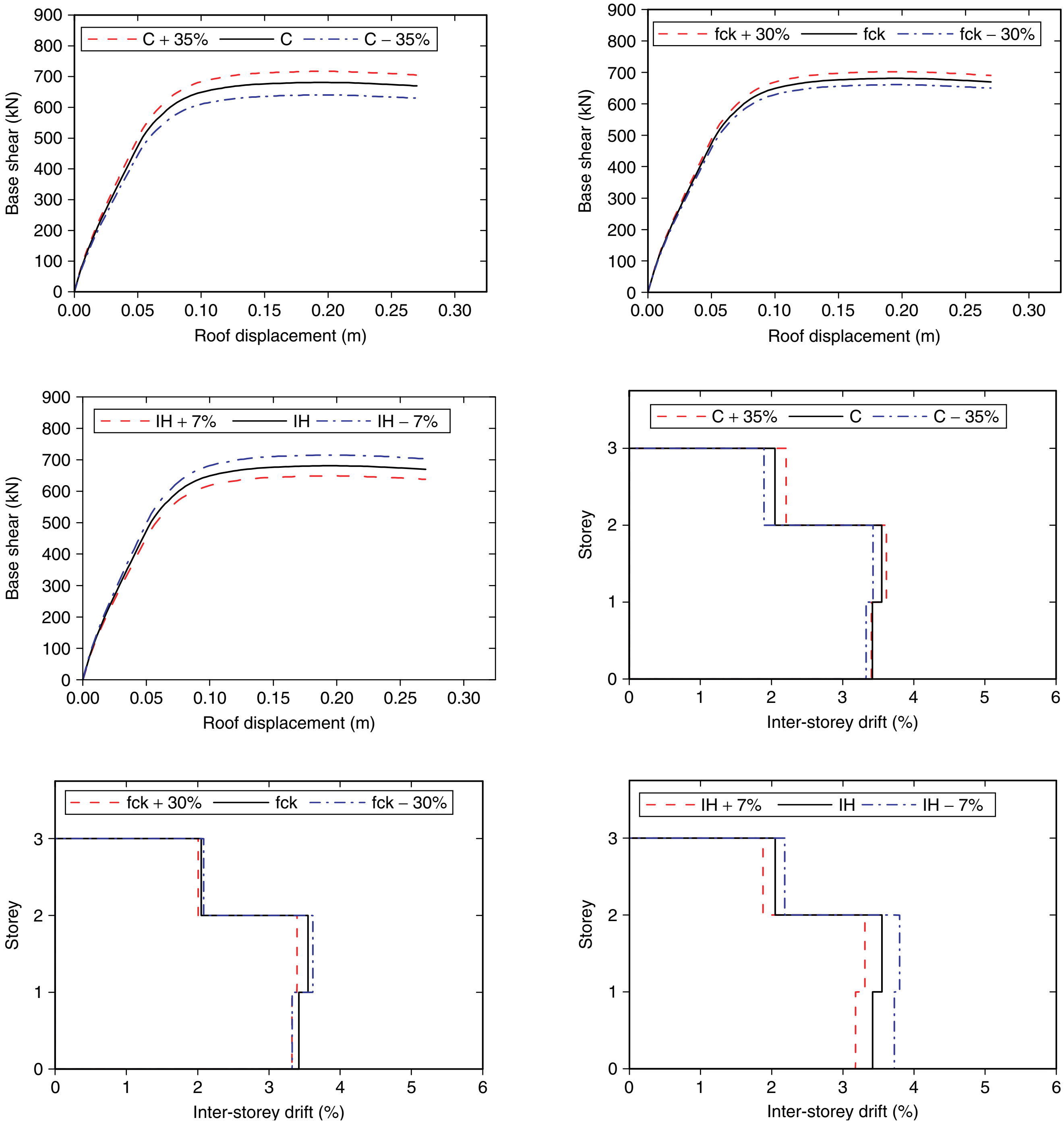


Figure 17. Capacity curve and corresponding inter-storey drift of WDS structure due to variation of column size, compressive strength of concrete and inter-storey height respectively in X direction of loading

clear relative to the CCP structure, but may be not sufficient for the demands of regions with medium/high seismic hazards.

- The shear strength and tangent stiffness of WDS are nearly one and a half, two and three times the values obtained with the NBC+, NBC and CCP structures respectively.
- The effect on structures due to variation of column size and inter-storey height is highly appeared in terms of base shear capacity and

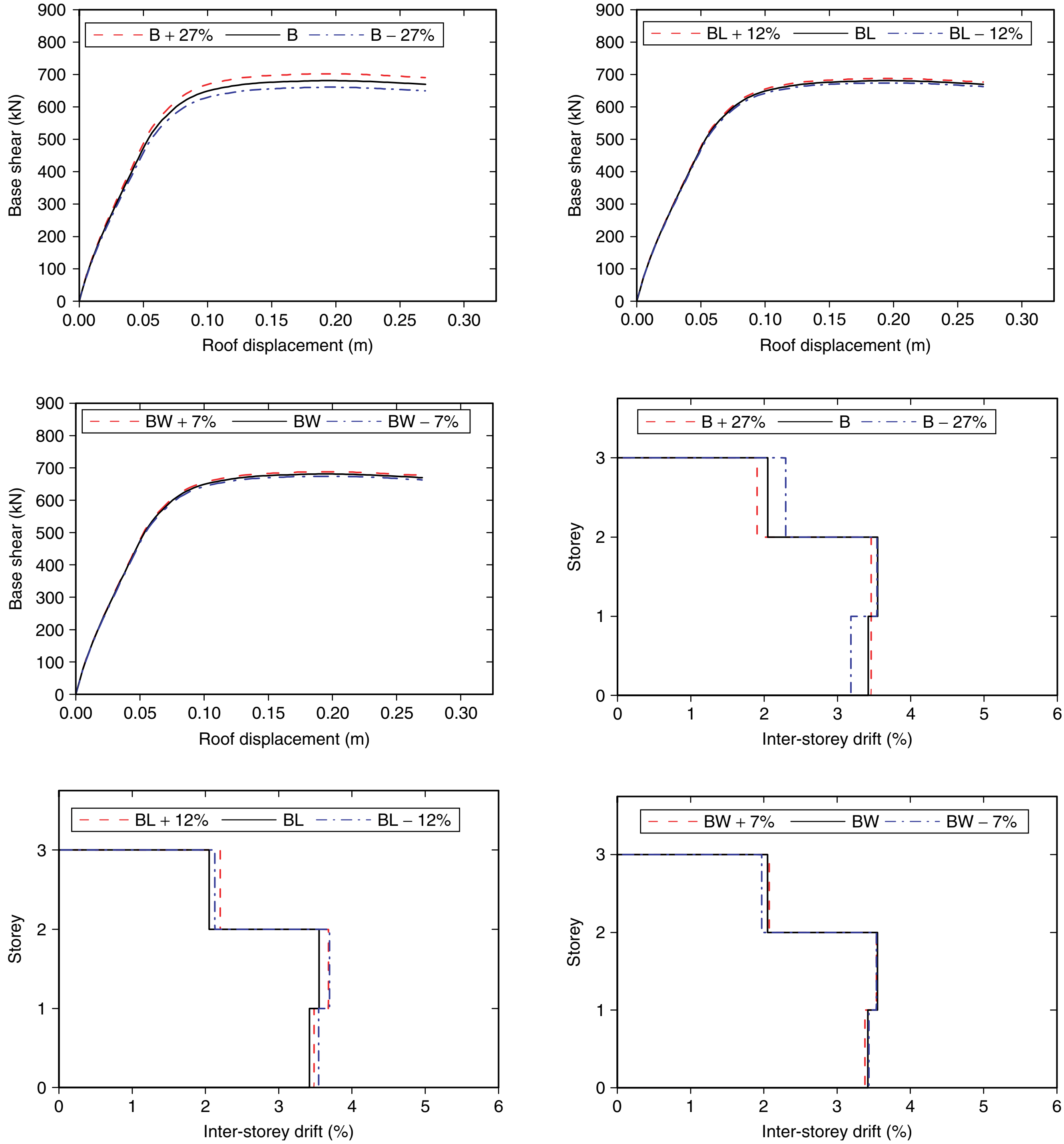


Figure 18. Capacity curve and corresponding inter-storey drift of WDS structure due to variation of beam size, bay length and bay width respectively

inter-storey drift compared to other parameters.

- The increases in column size, beam size and compressive strength of concrete increases base shear capacity of the structures, resulting the higher stiffness.
- The variation of bay length and bay width has negligible change in base shear capacity of the buildings.
- The variation of column size, beam size, compressive strength of concrete, bay length and bay width do not have the similar effect on the inter-storey drift.
- An increase in inter-storey height of the structures significantly reduces the base shear capacity and inter-storey drift of the building structures.

- The effect on variation of structural and geometrical parameters in WDS structure is minimal as compared to NBC+, NBC and CCP structures.

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