

## COMPARISON OF OMAN SEISMIC CODE WITH INTERNATIONAL COUNTERPARTS BASED ON REGIONAL SEISMIC HAZARD

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**ABSTRACT:** This study compares the Oman Seismic Code (OSC) developed in 2013 with the Uniform Building Code 1997 (UBC) and the International Building Code 2006 (IBC) that are frequently used for seismic analysis and design in Oman. Base shear, story shear force distribution, and story drift ratios are compared using the equivalent static load and the response spectrum analysis methods. The discussion considers reinforced concrete buildings having a footprint of 25 m × 40 m with heights of 10 m, 19 m, 40 m, and 58 m having 3-, 6-, 13- and 19-stories, respectively. The buildings are considered as supported on very dense soil (type C) and have normal occupancy conditions. The Zone-1 of OSC is compared with the Zone-1 of UBC and IBC considering the low and the normal ductility class definitions of OSC. For the low ductility class, the values of design base shear for different building heights from IBC are 82% for the equivalent static method and ranged between 83%-85% for the response spectrum method compared to OSC. The base shear values by UBC are 73%-81% and 75%-78% for the equivalent static and the response spectrum methods, respectively, in comparison to OSC. For normal ductility class, IBC and UBC estimates are higher than OSC for all building heights except for the 3-story building. The story shear forces and story drift ratios from OSC also compared well with the international counterparts. The comparison indicates that Zone-1 in OSC is well matched to Zone-1 of UBC and IBC.

**Keywords:** Oman seismic code; Equivalent static load method; Response spectrum analysis; International Building Code (IBC); Uniform Building Code (UBC).

### مقارنة بين الكود العماني لتصميم المباني ضد مخاطر الزلازل مع نظيراتها الدولية بناءً على المخاطر الزلزالية الإقليمية

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**الملخص:** تقارن هذه الدراسة بين الكود العماني لتصميم المباني ضد الزلازل (OSC 2013) - والذي تم تطويره في عام 2013 - مع كود البناء الموحد (UBC 1997) وكود البناء الدولي (IBC 2006) والذين يستخدمان بشكل شائع في تصميم المباني لمقاومة الزلازل في سلطنة عمان. ولتحقيق اهداف الدراسة، تم تحليل مبانٍ مشيدة من الخرسانة المسلحة باستخدام طريقي الحمل الثابت المكافئ وتحليل طيف الاستجابة. تبلغ مساحة المباني تحت الدراسة 25م × 40م بارتفاع 10م و19م و40م و58م وتتكون من 3 و6 و13 و19 طابقاً، على التوالي. كذلك تم افتراض أن المباني مشيدة على تربة شديدة الكثافة (نوع C) وفي ظروف إشغال عادية ومقارنة المنطقة 1 من الكود العماني بالمنطقة 1 في كل من كود البناء الموحد وكود البناء الدولي، مع الأخذ في الاعتبار تعريفات فئة اللدونة المنخفضة والعادية في الكود العماني. شملت الدراسة مقارنة قوة القص عند القاعدة، وتوزيع قوى القص بين الطوابق المختلفة، ونسب الازاحة للطوابق المختلفة. وقد بينت نتائج الدراسة، أنه بالنسبة لفئة اللبونة المنخفضة، فإن قيم قوى القص عند القاعدة لارتفاعات المباني المختلفة المحسوبة باستخدام كود البناء الدولي بلغت 82% للطريقة الثابتة المكافئة وتراوح بين 83%-85% لطريقة طيف الاستجابة مقارنةً بالكود العماني. وقد بلغت 73%-81% و75%-78% للطريقة الثابتة وطيف الاستجابة، على التوالي، عند استخدام كود البناء الموحد بالمقارنة مع الكود العماني. وفيما يخص فئة اللبونة العادية، فإن نتائج كود البناء الدولي وكود البناء الموحد أعلى من الكود العماني لجميع ارتفاعات المباني باستثناء المبنى المكون من 3 طوابق. وعند مقارنة نتائج قوى القص ونسب الازاحة بين الطوابق المختلفة من الكود العماني فإنها تتطابق بشكل جيد مع نظيراتها الدولية. وقد خلصت الدراسة الى أن المنطقة 1 في الكود العماني مطابقة بشكل جيد مع المنطقة 1 من كود البناء الموحد وكود البناء الدولي.

**الكلمات المفتاحية:** الكود الزلزالي العماني؛ طريقة الحمل الثابت المكافئ؛ تحليل طيف الاستجابة؛ كود البناء الدولي؛ كود البناء الموحد.

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## NOMENCLATURE

$C_a$	Acceleration coefficient for calculation of base shear in UBC
$C_d$	Deflection amplification factor in IBC
$C_s$	Coefficient for calculation of base shear in IBC
$C_t$	Coefficient for calculation of natural period 'T' in OSC
$C_u$	Limiting factor for the natural period in UBC
$C_v$	Velocity coefficient for calculation of base shear in UBC
$F_a$	Acceleration factor based on the type of soil and seismic zonation in IBC.
$F_v$	Velocity factor based on the type of soil and seismic zonation in IBC.
$F_t$	Additional force at the top story to account for higher modes (kN)
$h_i$	Height of the $i^{\text{th}}$ -story above ground (m)
$H_n$	Total building height (m)
$I$	Importance factor
$N$	Number of stories in the building
$R$	Response modification factor in IBC or Over-strength and ductility factor in UBC
$Q$	Behavior factor
$q_R(T)$	Seismic load reduction factor for period 'T'
$S_{1D}$	1.0s elastic spectral acceleration (g)
$S_{AE}$	Elastic spectral acceleration (g)
$S_{AR}$	Design (reduced) spectral acceleration (g)
$S_{D1}$	1.0s design spectral acceleration in IBC (g)
$S_{DS}$	0.20s design spectral acceleration in IBC (g)
$S_{SD}$	Short period elastic spectral acceleration (g)
$T$	Prominent natural period of the building (s)
$T_0$	Initial Spectral period (s)
$T_L$	Long spectral period (s)
$T_S$	Short spectral period (s)
$v_i$	Shear force at the $i^{\text{th}}$ -story
$V$	Base shear (kN)
$w_i$	Weight of the $i^{\text{th}}$ -story (kN)
$W$	Total seismic weight of the structure (kN)
$\Delta F_N$	Additional force at the top story to account for higher modes in OSC (kN)
$\Omega_0$	System over-strength factor in IBC
$\Omega_o$	Seismic force amplification factor in UBC

## 1. INTRODUCTION

Lateral loads due to earthquakes pose a challenge to the structural design of buildings that principally carry gravity loads. Seismic events induce forces that are proportional to the structure's mass, act over a short duration, and must be resisted by the building without collapse. Further, minor excitation should not cause any damage to minimize maintenance costs. The lateral forces due to earthquakes have a major effect on the structural integrity that must be ensured under all circumstances. Experience and research have provided technical solutions that can minimize loss of life and damage associated with earthquakes. To ensure desired behaviour, seismic codes lay down the essential requirements and procedures for seismic analysis and

structural design. Due to a wide spectrum of civil infrastructure, specialized regulations are available for each category. The highest emphasis is laid on the seismic design of buildings to avoid catastrophic loss of life. International and national guidelines are developed and enforced to ensure life safety and minimize damage to the building stock. Seismic loads are very sensitive to regional seismology and geography, but in the absence of a national code, designers rely on international guidelines. Once a national seismic design code is developed, a comparative study with international standards is essential to identify the shortcomings in past designs that are based on international counterparts while also calibrating the national code. Many countries have established their seismic specifications and compared those with international counterparts to investigate and quantify the differences (Nahhas 2011, Marino *et al.* 2005, Noor *et al.* 1997, Fenwick and Davidson 2002, McIntosh and Pezeshk 1997).

The Sultanate of Oman is part of the Arabian plate, which includes the continent of Arabia and the oceanic regions of the Red Sea, the Arabian Sea, the Sea of Oman, and the Gulf of Aden. No major earthquakes have been instrumentally recorded in Oman. However, global databases list an earthquake of magnitude 5.1 (Richter scale) in the Al-Kamil area during 1971 (Qamaruddin and Al-Harthy 2000). Further, there have been numerous felt earthquakes that were reported by residents (Qamaruddin and Al-Harthy 2000). Most of these reports are related to strong earthquakes occurring at a teleseismic distance (more than 1000 km). Since 2003, the Earthquake Monitoring Center (EMC) at Sultan Qaboos University has been monitoring the seismic activity in Oman using the national seismological network. A summary of the available data from 2003 to 2017 indicates that on average 1292 earthquakes were recorded by the network annually, out of which, 398 were identified as regional (proximity to Oman). Further, annually an average of 66 earthquakes was recorded in the Oman mountains and/or the Gulf of Oman. Among the earthquakes that originated in the Oman mountains, the maximum magnitude recorded was 5.3 in the year 2015. Using this recorded data and the global catalogues of seismic records, EMC carried out extensive seismic hazard assessment studies for Oman (Deif *et al.* 2013, El-Hussain *et al.* 2012, El-Hussain *et al.* 2014). These studies were utilized to develop the first seismic code for the design of buildings in Oman to help achieve optimized design and performance of buildings with the desired level of performance and safety.

This research compares the Oman Seismic Code (OSC) with the international counterparts using the equivalent static method and the response spectrum analysis method. Based on the current national practice for seismic design of buildings, the International Building Code 2006 (IBC) and the Uniform Building Code 1997 (UBC) are considered for comparison. The

zone equivalence among the codes is based on the level of seismic hazard. Reinforced concrete moment-resisting frame buildings with heights of 10 m, 19 m, 40 m, and 58 m are considered with 3-, 6-, 13- and 19-stories, respectively. The study also compares the codes in terms of the two ductility classes defined in OSC.

## 2. OMAN SEISMIC CODE FOR BUILDINGS

The Oman Seismic Code (OSC) divides the Sultanate of Oman into two seismic zones, referred to as Zone-1 and Zone-2. The zones are defined based on the design Peak Ground Acceleration (PGA), where Zone-1 is the high seismic hazard zone ( $PGA \geq 50$  gals), which includes Muscat, Sohar, Diba, and Khasab. Zone-2 is the low seismic hazard zone ( $PGA < 50$  gals), which includes Nizwa, Sur, and Salalah. OSC defines elastic spectral accelerations  $S_{SD}$  and  $S_{1D}$  for the two zones depending on the type of soil as shown in Table 1. These parameters are the basis for the estimation of seismic action using the elastic response spectrum.

OSC provides detailed procedures for the seismic design of buildings based on equivalent static load, response spectrum, and response history analysis methods. The code divides buildings into the following three categories based on the total building height ' $H_n$ ':

- Low-rise Buildings:  $H_n \leq 20.0$  m.
- Med-rise Buildings:  $20.0 \text{ m} < H_n \leq 40.0$  m.
- High-rise Buildings:  $40.0 \text{ m} < H_n \leq 60.0$  m.

where the building height ' $H_n$ ' is to be measured from ground floor level and buildings with heights more than 60.0 m are not covered by the code. The code further provides guidelines for the detailing and design of reinforced concrete, steel, composite, and masonry structures that complement the respective design provision of the Eurocodes.

## 3. METHODOLOGY

This study considers zone equivalence among the codes based on seismic hazard, which aligns the Zone-1 of OSC with Zone-1 of both UBC and IBC. Though UBC identifies Muscat as a Zone-2A, Waris *et al.* (2017) reported that this definition greatly overestimates the seismic actions using UBC and IBC compared to OSC for the equivalent static load method. As Zone-1 is the lowest seismic zone in the respective international codes, Zone-2 of OSC falls below their minimum seismic hazard level definition. The study uses ordinary reinforced concrete moment resisting frame buildings with normal occupancy conditions with four building heights, assumed to be resting on very dense soil (Type-C). A single soil type is considered in the study as the goal is a comparison of

the codes and the building height and type-C is the most frequently encountered soil in Muscat (El-Hussain *et al.* 2013). For reinforced concrete buildings, OSC identifies two ductility classes, a Low Ductility Class (DCL) that represents buildings designed based on Eurocode (EC2) only without incorporating provisions of OSC, and a Normal Ductility Class (DCN) where the provisions of OSC are incorporated in the design and detailing to ensure proper energy dissipation and ductile behaviour.

### 3.1 Structural System

A simple building layout with a footprint of  $25 \text{ m} \times 40 \text{ m}$  is considered. Figure 1 shows the typical structural plan with a grid spacing of 5 m in either direction. The first story has a height of 4.0 m and all subsequent stories have a height of 3.0 m. The following four building heights are considered in this study:

- 03-Story Building: G + 02 floors,  $H_n = 10$  m.
- 06-Story Building: G + 05 floors,  $H_n = 19$  m.
- 13-Story Building: G + 12 floors,  $H_n = 40$  m.
- 19-Story Building: G + 18 floors,  $H_n = 58$  m.

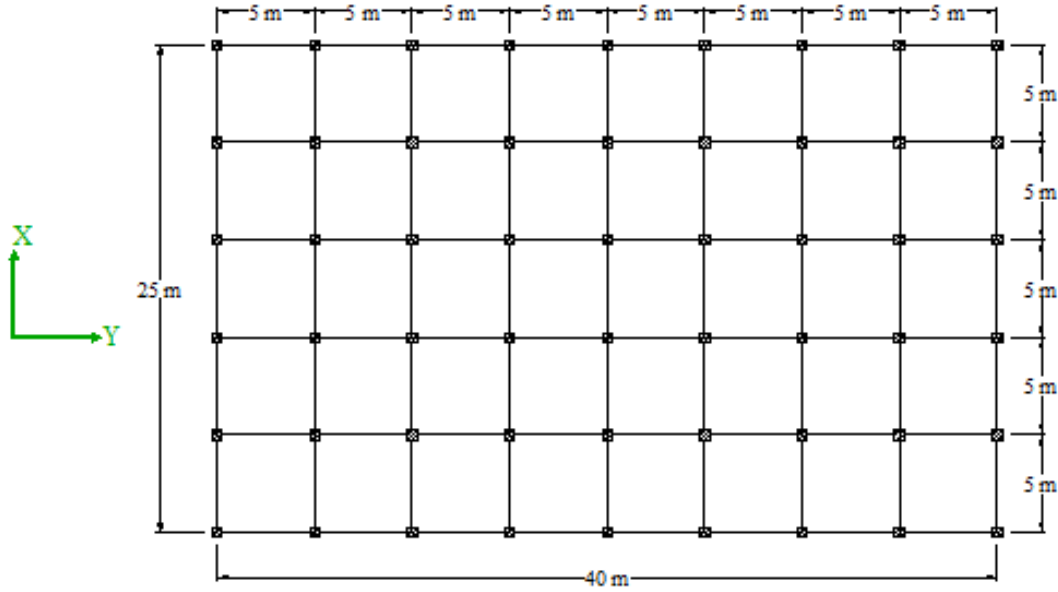
All beams have dimensions of  $600 \text{ mm} \times 200 \text{ mm}$ , while all columns are  $400 \text{ mm} \times 400 \text{ mm}$ . Concrete compressive strength and reinforcement yield strength are 35 MPa and 460 MPa, respectively. These dimensions and strength parameters are based on the norms in the construction industry in Oman. The structural elements are considered uncracked in all cases. Typical values of permanent and variable actions are considered as summarized in Table 2. ETABS software is used for the numerical modeling of the buildings. The floors are modeled as rigid diaphragms and P- $\Delta$  effects are considered in the analysis. As the buildings are symmetric and the principal goal of this study is to compare the three codes, the calculated story shear force is applied at the centre of mass for the respective story level and cases for  $\pm 5\%$  eccentricity are not included in the discussion.

**Table 1.** Elastic spectral accelerations and seismic zonation (OSC, 2013).

Local Soil Type	Seismic Zones			
	Zone-1		Zone-2	
	$S_{SD}$ (g)	$S_{1D}$ (g)	$S_{SD}$ (g)	$S_{1D}$ (g)
A	0.16	0.064	0.08	0.032
B	0.20	0.08	0.10	0.04
C	0.24	0.136	0.12	0.068
D	0.32	0.192	0.16	0.096
E	0.50	0.28	0.25	0.14
F	Site-specific geotechnical investigation and dynamic site response analysis required			

$S_{SD}$  - Short period elastic spectral acceleration.

$S_{1D}$  - 1.0-second elastic spectral acceleration.



**Figure 1.** Typical floor plan for all buildings with the definition of X- and Y-direction.

**Table 2.** Gravity loads acting on building.

Description	Typical Floor (kN/m <sup>2</sup> )	Roof (kN/m <sup>2</sup> )
-Self-weight of 150 mm thick slab	3.75	3.75
-Finishes and services	2.50	3.60
Total Permanent Action	<b>6.25</b>	<b>7.35</b>
Variable Action	3.0	3.0

$$q_R(T) = \begin{cases} 1 + \left(\frac{q}{I} - 1\right) \frac{T}{T_s} & 0 < T < T_s \\ \frac{q}{I} & T \geq T_s \end{cases} \quad (3)$$

### 3.2 Equivalent Static Load Method

OSC, IBC, and UBC each have their own set of specifications for the calculation of base shear ‘V’ and distribution of the lateral storey shear force along the building height. This section briefly reviews the equations used in the equivalent static load method by the three codes. The values of the different seismic parameters adopted in this study are indicated in their respective context.

#### a. Omani Seismic Code (OSC)

The total equivalent seismic load (base shear) – ‘V’ in the direction of the earthquake is calculated by Eqn. (1).

$$V = \frac{W}{g} S_{AR}(T) \geq 0.11 \frac{W}{g} S_{SD} I \quad (1)$$

where ‘W’ is the total seismic weight of the structure, ‘S<sub>AR</sub>’ represents design (reduced) spectral acceleration that is calculated as:

$$S_{AR}(T) = \frac{S_{AE}(T)}{q_R(T)} \quad (2)$$

q<sub>R</sub>(T) is the seismic load reduction factor given as:

Where ‘q’ is the behaviour factor that depends upon the ductility class of the reinforced concrete building. The importance factor ‘I’ is taken as 1.0 for normal occupancy. The code provides Eqn. (4) for calculation of the prominent natural period but recommends verification using the Rayleigh quotient method. The value of ‘C<sub>t</sub>’ is 0.075 for reinforced concrete moment-resisting frames. ‘S<sub>AE</sub>’ is the elastic spectral acceleration based on the prominent natural period ‘T’ that is calculated using Eqn. (5).

$$T = C_t (H_n)^{\frac{3}{4}} \quad (4)$$

$$S_{AE}(T) = \begin{cases} 0.4S_{SD} + 0.6S_{SD} \frac{T}{T_0} & T \leq T_0 \\ S_{SD} & T_0 < T \leq T_S \\ \frac{S_{1D}}{T} & T_S < T \leq T_L \\ \frac{S_{1D} T_L^2}{T} & T > T_L \end{cases} \quad (5)$$

$$T_S = \frac{S_{1D}}{S_{SD}}; \quad T_0 = 0.20T_S \quad (6)$$

where ‘S<sub>SD</sub>’ and ‘S<sub>1D</sub>’ are elastic spectral accelerations associated with short period ‘T<sub>S</sub>’ and one-second elastic spectral acceleration, respectively. ‘S<sub>SD</sub>’ and

'S<sub>1D</sub>' are based on the geographic location of the building (seismic zone) and the soil conditions at the site as shown in Table 1. 'T<sub>L</sub>' is the transition limit of the response spectrum to the long-period range that is taken as 8s in OSC. 'T<sub>0</sub>' defines the start of the plateau in the response spectrum and 'T<sub>S</sub>' defines its end, calculated using Eqn. (6) based on the zone and the soil type. A graphical representation of the parameters in the spectrum and its distinct regions are presented in Fig. 2. The lateral force 'v<sub>i</sub>' on the i<sup>th</sup>-story of the building is calculated using Eqn. (7) and (8).

$$v_i = (V - \Delta F_N) \frac{w_i h_i}{\sum_{i=1}^N w_i h_i} \quad (7)$$

$$\Delta F_N = 0.0075NV \quad (8)$$

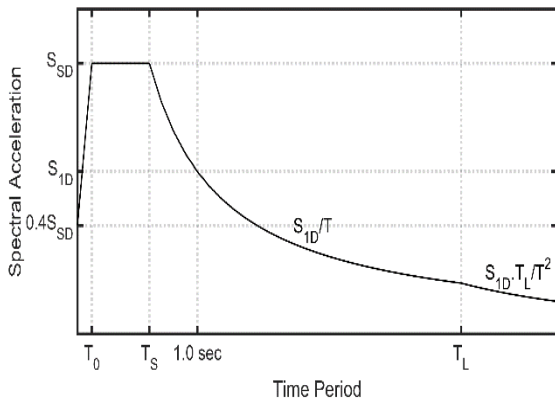
'w<sub>i</sub>', 'h<sub>i</sub>' are the seismic weight and overall height of the i<sup>th</sup>-story, respectively. The seismic mass typically includes the total weight of the floor, plus half of the weight of the vertical elements (walls; columns) located immediately above and below that floor. An additional seismic force 'ΔF<sub>N</sub>' should be considered to act at the top floor (roof-level) of the building to account for the contribution of higher modes of vibration. 'ΔF<sub>N</sub>' is estimated using Eqn. (8) and is based on the total number of stories in the building 'N' and the total base shear 'V'.

### b. International Building Code 2006 (IBC)

According to IBC, the base shear is calculated based on the natural period of the building 'T' and is given as:

$$V = C_s W \quad (9)$$

$$C_s = \left. \begin{array}{l} \min \left( \frac{S_{DS}}{R/I}, \frac{S_{D1}}{(R/I)T}, 0.01 \right) \quad T \leq T_L \\ \frac{S_{D1}}{(R/I)T^2} \quad T_L < T \end{array} \right\} \quad (10)$$



**Figure 2.** Elastic response spectrum in omani seismic code (OSC, 2013).

where 'W' is the building's seismic weight. 'S<sub>DS</sub>' and 'S<sub>D1</sub>' represent design spectral response accelerations for short period (0.2-seconds) and a longer period (1.0-second), respectively. These are based on spectral response accelerations 'S<sub>S</sub>' and 'S<sub>1</sub>' associated with the geographic location of the building and the soil conditions at the site using Eqn. (11) and (12).

$$S_{DS} = \frac{2}{3} F_a S_S \quad (11)$$

$$S_{D1} = \frac{2}{3} F_v S_1 \quad (12)$$

'F<sub>a</sub>' and 'F<sub>v</sub>' are based on the type of soil and seismic zonation. For this study, as per IBC, S<sub>S</sub>=0.25, S<sub>1</sub>=0.10 for Zone-I. This gives a value of F<sub>a</sub>=1.20 and F<sub>v</sub>=1.70. In IBC, the natural period of a building can be estimated by:

$$T = C_t (H_n)^x \quad (13)$$

where C<sub>t</sub>=0.0466 and x=0.9 for moment resisting reinforced concrete structures, 'H<sub>n</sub>' represents the total height of the building. The response modification factor 'R' depends upon the ductility characteristics of the building and the importance factor 'I' depends upon the type of occupancy. I=1.0 for normal occupancy. The lateral force 'v<sub>i</sub>' for the i<sup>th</sup>-story is determined using Eqn. (14):

$$v_i = V \cdot \frac{w_i h_i^k}{\sum_{i=1}^n w_i h_i^k} \quad (14)$$

'w<sub>i</sub>', 'h<sub>i</sub>' are the seismic weight and overall height of the i<sup>th</sup>-story, In Eqn. (14), the coefficient k=1.0 for structures with a fundamental period T ≤ 0.50 s, and k=2.0 for a fundamental period T ≥ 2.50 s. For structures having a period between 0.5 and 2.5 s, coefficient k shall be 2.0 or can be determined by linear interpolation between 1 and 2.

### c. Uniform Building Code 1997 (UBC)

In UBC, the calculation of base shear 'V' on a building is done using Eqn. (15), which also defines upper and lower bound for the value:

$$\left. \begin{array}{l} V = \frac{C_v I W}{R T} \Delta y \\ 0.11 C_a I W \leq V \leq \frac{2.5 C_a I W}{R} \end{array} \right\} \quad (15)$$

where 'W' is the seismic weight of the structure, 'I' is the Importance factor that depends on occupancy and usage of the building, 'R' is ductility and overstrength factor that depends on the basic structural system, and the lateral-force resisting system of the building. 'C<sub>v</sub>' and 'C<sub>a</sub>' are seismic coefficients associated with the structure's sensitivity to the velocity and acceleration

of ground motion, respectively. These are based on the geographic location of the structure (seismic zone) and soil conditions at the site.  $C_v=0.13$  and  $C_a=0.09$  are used for Zone-1 and soil type-C.

The over-strength factor ‘R’ depends upon the structural ductility and the Importance factor  $I=1.0$  for normal occupancy. In Eqn. (15), the upper bound for base shear tends to govern for stiff structures while the lower bound is applicable for flexible structures. In UBC, the prominent natural period of a building with height ‘ $H_n$ ’ can be calculated as:

$$T = C_t(H_n)^{3/4} \tag{16}$$

$C_t=0.0731$  is used to reinforce concrete moment-resisting frames. The lateral force ‘ $v_i$ ’ for the  $i^{\text{th}}$ -story of the building is estimated using Eqn. (17):

$$v_i = (V - F_t) \frac{w_i h_i}{\sum_{i=1}^n w_i h_i} \tag{17}$$

‘ $w_i$ ’, ‘ $h_i$ ’ are the seismic weight and overall height of the  $i^{\text{th}}$ -story, respectively. ‘ $F_t$ ’ is an additional lateral force assumed to act at the top of the structure. This force is used to approximate the effect of higher modes of vibration. The magnitude of ‘ $F_t$ ’ is determined based on the natural period of the building ‘ $T$ ’ and the base shear ‘ $V$ ’, as given in Eqn. (18).

$$F_t = \left. \begin{array}{ll} 0 & T < 0.70 \text{sec} \\ 0.07TV & 0.70 \text{sec} \leq T \leq 3.6 \text{sec} \\ 0.25V & T > 3.6 \text{sec} \end{array} \right\} \tag{18}$$

### 3.3 Response Spectrum Method

Each code defines an elastic response spectrum for use in the response spectrum analysis. The spectrum is based on the relationships defined in Eqn. (5), (10), and (15) for OSC, IBC, and UBC, respectively. Fig. 3 shows the comparison of the elastic response spectrum for the three codes considering the zone and soil type considered in the study. The comparison shows that the selection of zone definitions for international codes (UBC and IBC) are closely matched with Zone-1 of OSC. The spectrums as defined in Fig. 3 for the respective code are employed in the response spectrum analysis considering the first 30 modes of vibration to ensure more than 99% modal participation for all building heights. Direct spectral input using the parameters of this study is made in ETABS for UBC and IBC codes, while the spectrum of OSC is generated using Eqn. (5). The base shear, story shear forces, and displacements are obtained employing modal response spectrum analysis in ETABS.

### 3.4 Structural Ductility

OSC defines two ductility classes; the Low Ductility Class (DCL) and the Normal Ductility Class (DCN)

based on the energy dissipation ability of the structure. If the structural design incorporates the detailing and structural requirements outlined in the OSC code, the structure is classified as normal ductility class (DCN), otherwise, it is considered as the low ductility class (DCL). The behaviour factor ‘q’ in Eqn. (3) is used to account for the ductility class. The UBC and IBC define Ordinary Moment Resisting Frames (OMRF) and Special Moment Resisting Frames (SMRF) using the same criterion. UBC uses over-strength and ductility factor ‘R’ and seismic force amplification factor ‘ $\Omega_o$ ’, while IBC uses response modification coefficient ‘R’, system over-strength factor ‘ $\Omega_o$ ’ and deflection amplification factor ‘ $C_d$ ’. The factor ‘R’ is employed to distinguish structural behaviour as given in Eqn. (10) and (15) for IBC and UBC, respectively. The values of all these factors for the two classes are summarized in Table 3. The subsequent discussion uses low ductility class to refer to DCL and OMRF, and normal ductility class to indicate DCN and SMRF.

## 4. RESULTS AND DISCUSSION

This section first compares the buildings considered in the study in terms of their prominent period and how this may affect their behaviour. The results for the equivalent static and the response spectrum analysis methods are then discussed in terms of base shear, lateral force distribution, and story drift ratios.

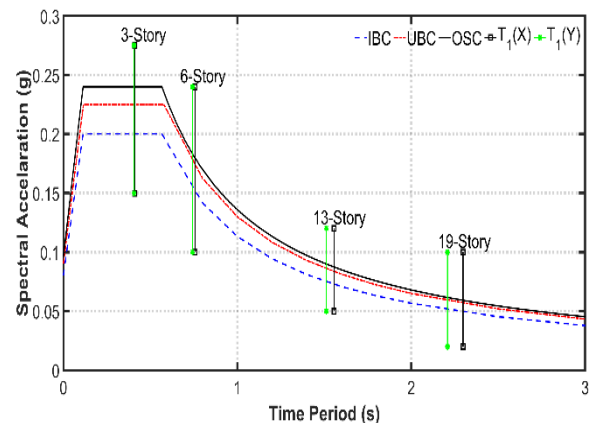


Figure 3. Comparison of elastic response spectrum.

Table 3. Behaviour/ductility factors for ductility classes.

Ductility Class	Behaviour / Ductility Factor					
	IBC			UBC		OSC
	R	$\Omega_o$	$C_d$	R	$\Omega_o$	q
Low Ductility Class (OMRF/ DCL)	3	3	2.5	3.5	2.8	1.0
Normal Ductility Class (SMRF/ DCN)	8	3	5.5	8.5	2.8	3.5

**4.1. Natural Period and Spectral Acceleration**

Table 4 lists the estimated natural periods for the four building heights based on OSC, IBC, and UBC using Eqn. (4), (13), and (16), respectively. Rayleigh’s quotient method is used in ETABS for the estimation of the natural period. The natural period in the two directions is nearly the same with the X-direction being marginally higher. Figure 3 shows these values on the response spectrum, making it clear that the selected building heights cover a broad range of the spectrum. Periods estimated using the codes are very close to the values using ETABS for small building heights (10 m and 19 m) but underestimate the period for tall buildings (40 m and 58 m). It is because this study has not considered any shear walls that are common in tall buildings. As the natural period in the two directions is very close, the subsequent discussion only considers results for the X-direction.

Table 4 also lists the spectral acceleration to be used in the equivalent static load method for the respective building height and code. The spectral accelerations obtained from UBC are 94%-96% compared to OSC, while values from IBC are 83% of OSC for all the building heights. This is because both IBC and OSC have  $T_S=0.567s$  while for UBC, the value of  $T_S=0.58s$ . Therefore, the response spectrum of OSC is quantitatively closer to UBC while qualitatively it resembles IBC.

**4.2 Base Shear**

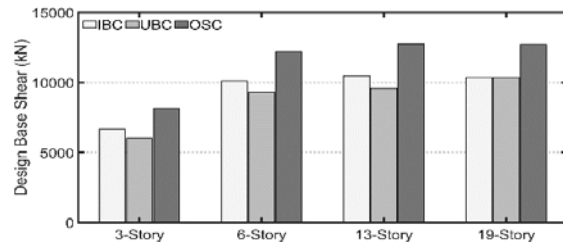
Due to the difference in definition, the base shear calculated using the equivalent static load method or response spectrum analysis method cannot be directly compared among the codes. In OSC, Eqn. (1) or the spectrum is used to directly estimate the design seismic actions, while in UBC and IBC, the values are calculated using Eqn. (15) and (10) must be amplified using  $\Omega_o$  and  $\Omega_o'$ , respectively. Therefore, the comparison is presented in terms of the design base shear.

**a. Equivalent Static Load Method**

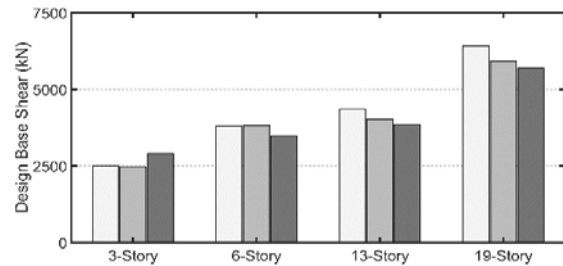
The comparison of the design base shear in X-direction for the two ductility classes using the equivalent static load method is summarized in Fig. 4. Since the natural period obtained from the detailed numerical model differs from the code provided estimate, additional code provisions must be considered. UBC recommends that the period should not exceed 1.4 times the ‘T’ as

defined by Eqn. (16), while IBC recommends a limit of  $C_uT$  for ‘T’ as defined in Eqn. (13). The factor ‘ $C_u$ ’ depends upon the ‘ $S_{D1}$ ’ value and is estimated as 1.67 for this study. OSC does not define any such limit and recommends using the value estimated by Rayleigh’s Quotient method. In this study, the base shear calculation using UBC for the 19-story building is the only case governed by this provision.

For the low ductility class, the design base shear is nearly constant for 6-, 13- and 19- story buildings, while the value for the 3-story building is almost 2/3 of these values. This is due to the small value of ‘R’ (UBC, IBC) and ‘q’ (OSC). The base shear value is governed by ‘ $C_v$ ’ for UBC, ‘ $C_s$ ’ for IBC, and ‘ $S_{AR}(T)$ ’ in the case of OSC. For the normal ductility class, a continuous increase in base shear with building height is observed. The base shear for the 3-story building is still nearly 2/3 (~67%) for UBC and IBC, but for OSC it is 83% of the value for the 6-story building. The base shear increased by 15%, 5%, and 10% for 6-story to 13-story buildings in IBC, UBC, and OSC respectively. For, 13-story to 19-story buildings, all the codes showed an increase of 47%. Due to a large ‘R’ and ‘q’ factor, the base shear for 13- and 19-story buildings are governed by the minimum limits in the respective codes, which causes the jump in base shear for the 19-story building due to larger seismic weight.



(a) Low Ductility Class.



(b) Normal Ductility Class.

**Figure 4.** Design Base Shear using Equivalent Static Method.

**Table 4.** Prominent natural period of the buildings and spectral acceleration.

Model	$H_n$ (m)	Natural Period (s)					Spectral Acceleration (g)		
		IBC Eqn. (13)	UBC Eqn. (16)	OSC Eqn. (4)	ETABS		IBC	UBC	OSC
					X	Y			
3-Story	10.0	0.37	0.41	0.42	0.41	0.41	0.200	0.225	0.240
6-Story	19.0	0.66	0.67	0.68	0.76	0.74	0.149	0.171	0.179
13-Story	40.0	1.29	1.16	1.19	1.56	1.51	0.073	0.083	0.087
19-Story	58.0	1.80	1.54	1.58	2.30	2.21	0.049	0.057	0.059



As the spectral accelerations for the OSC are higher than the other codes, its base shear values should be higher than UBC and IBC. This is true in Fig. 4(a) for the low ductility class, where values of base shear from OSC are higher for all the building heights. The values from IBC are nearly 82% of OSC for the respective building height, which is the same as the ratio of spectral acceleration among the two codes. For UBC this value varies between 73%-76% for the 3- to 13-story buildings and is 81% for the 19-story building, which are lower compared to the ratio of spectral accelerations discussed earlier. For the normal ductility class in Fig. 4(b), OSC provides marginally smaller base shear except for the 3-story building, where values of UBC and IBC are nearly 85% of OSC. For the 6-story, both codes provide 10% higher estimates, while for the 13- and 19-story, IBC and UBC estimates are 13% and 4% higher than OSC, respectively. This is due to provisions in OSC that relate 'q' to the member design through local ductility requirements thus ensuring better energy dissipation and higher reduction in base shear for longer periods.

#### b. Response Spectrum Method

The base shear using modal response spectrum analysis for the three codes is shown in Fig. 5. The values are lower compared to the equivalent static method for both the ductility classes. In the case of the low ductility class, the values range between 90%-94% for IBC, 84%-94% for UBC, and 88%-92% for OSC compared to the equivalent static method. UBC shows the largest drop of 84% for the 19-story building because the base shear in the equivalent static method is controlled by the limit of  $1.4T$  as defined by Eqn. (16). The base shear using the response spectrum analysis gets smaller due to the increased contribution of higher modes that is overestimated by the equivalent static load method. For the normal ductility class, the ratio for the 3- and 6-story values are the same as observed in the low ductility class. The ratios reduced to 81%, 88%, and 85% for IBC, UBC, and OSC, respectively, for 13-story buildings, and 55%, 60%, and 57% for IBC, UBC, and OSC, respectively, for the 19-story building. This is because base shear in the equivalent static method is governed by the minimum limit rather than the response spectrum values for the 19-story building. All the codes (OSC, IBC, UBC) recommend that the values of base shear calculated using modal response spectrum method (Figure 5) should not be less than a certain fraction of the value calculated using equivalent static method (Figure 4). The fraction is 0.85 for OSC and IBC, and 0.90 for UBC. As per OSC, if the ratio is not satisfied, the response quantities (displacement and internal forces) should be scaled up corresponding to this factor. A lighter shade is used in Fig. 5 to extend the bars to this limit as required. This limit has a significant influence on the 19-story building for the normal ductility class only. For the low ductility class, the factor is 1.07 with UBC for the 19-story building. In the normal ductility

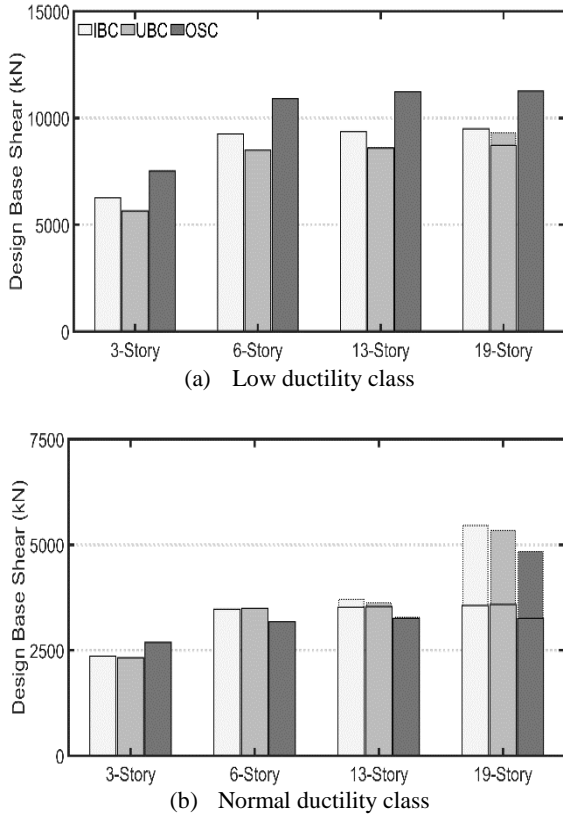
class, for 13-story building factors are 1.05, 1.02, and 1.003, and for the 19-story building, the factors are 1.53, 1.49, and 1.49 for IBC, UBC, and OSC, respectively.

#### 4.3. Lateral Force Distribution

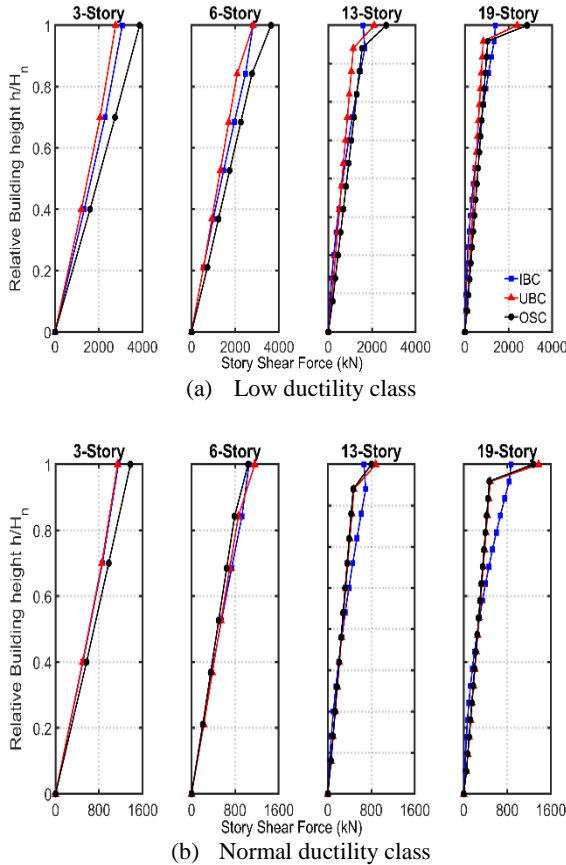
Figure 6 presents the story shear force distribution calculated using Eqn. (7), (14), and (17) for OSC, IBC, and UBC, respectively. The values from Eqn. (14) and (17) are scaled using ' $\Omega_0$ ' and ' $\Omega_o$ ' factors, respectively, as listed in Table 3. To facilitate the comparison among building heights, the vertical axis is normalized using the total building height ' $H_n$ ', which is 10 m, 19 m, 40 m, and 58 m for the 3-, 6-, 13- and 19-story buildings, respectively. Since the story force distribution for the three codes does not consider ductility classes (Eqn. (7), (14), and (17)), the distributions only differ in terms of values. For the 3-story building, the three codes have almost linear force distribution, which indicates that the contribution of higher modes is negligible. The lateral force from UBC and IBC for intermediate stories has the same constant ratio with the OSC counterpart as observed for base shear, while the ratio is different for the top story (roof). This is due to the similar story shear distribution model in OSC (Eqn. (7)) and UBC [Eqn. (17)], while for IBC (Eqn. (14)), the value of 'k' is 1.0 for the 3-story building. For the 6-story building, only a slight deviation is observed for the top story in the case of OSC and UBC, which indicates that for low-rise buildings  $h_n \leq 20m$ , the additional force at the top story is insignificant in both the codes. For IBC, the ratios of individual story shear force relative to OSC increase with story height reflecting the nonlinear distribution ( $k > 1.0$ ) being utilized in IBC (Eqn. (14)) in contrast to the linear pattern of OSC and UBC.

For the 13-story building (Fig. 6), an additional force on the top floor to account for higher modes is observed in UBC and OSC, while the distribution for IBC becomes nonlinear to account for higher modes. Compared to OSC, the intermediate story force in UBC is 74% and 103%, while for the roof level force is 79% and 110% in low and normal ductility classes, respectively. For IBC, the shear force for intermediate floors increases with an increase in building height but shows a drop at the top due to the additional force (Eqn. (8)) considered in OSC. The trend for the 19-story building is the same as the 13-story but the ratio of the lateral force from UBC is 84% and 108% of the OSC values for the roof and 81% and 103% for other floors in low and normal ductility classes, respectively. This indicates that both OSC and UBC account for the higher modes using a similar approach, but OSC has a smaller allowance for this additional force (Eqn. (8)) compared to UBC (Eqn. (18)). The allowance in OSC further does not follow the same trend as UBC with an increase in building height. For the response spectrum method, the values as obtained from ETABS are presented in Fig. 7, after scaling the values for IBC and UBC using ' $\Omega_0$ ' and ' $\Omega_o$ ' factors as listed in Table 3.





**Figure 5.** Design base shear using response spectrum method.



**Figure 6.** Shear force distribution along building height using equivalent static method.

The values are not corrected for the limit discussed previously, since it only applies to internal forces. For the 3- and 6-story buildings, the distribution is almost linear as observed in the case of the equivalent static method. This confirms the assumption of minimal contribution from higher modes in all the codes. OSC, therefore, rightly recommends only using the equivalent static method for low rise buildings ( $h_n \leq 20m$ ) that satisfy the structural regularity criterion outlined in the code. For 13- and 19-story buildings, the distribution is similar for the three codes having a clear nonlinear distribution, therefore using the response spectrum method is more appropriate and is correctly made mandatory by OSC for medium and high-rise buildings ( $20 m < h_n \leq 60m$ ).

#### 4.4 Story Drift Ratio

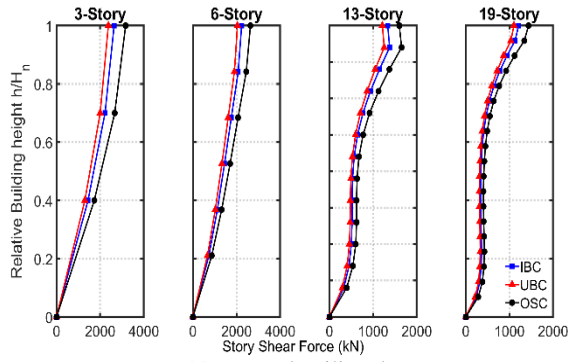
As discussed in the previous section, IBC, UBC, and OSC use different factors to account for ductility and inelastic behaviour of the buildings as listed in Table 3. This study compares the story drift ratio defined as the relative displacement of a story level/floor compared to the floor immediately below divided by the inter-story height as given in Eqn. (19).

$$\delta_i = \frac{\Delta_i - \Delta_{i-1}}{h_i} \quad (19)$$

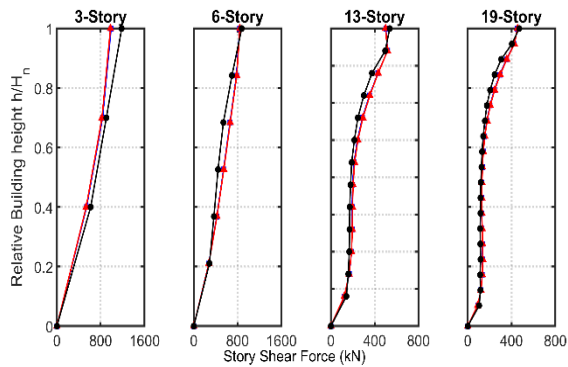
where ' $\Delta_i$ ', ' $\Delta_{i-1}$ ' are displacements of the  $i^{\text{th}}$  story and the story immediately below it and ' $h_i$ ' is the height of the  $i^{\text{th}}$ -story. The story drift ratios need to be modified using ' $C_d/I$ ', ' $0.7R$ ', and ' $q/I$ ' for IBC, UBC, and OSC, respectively. For the low ductility class, these factors are 2.5, 2.45, and 1.0, and for the normal ductility class, these are 5.5, 5.95, and 3.5 for IBC, UBC, and OSC, respectively.

The distribution of story drift ratios for the equivalent static method is shown in Fig. 8. The permissible limit set by the three codes is 2.0%, which is satisfied for all building heights. It can be observed that IBC and UBC provide very similar results in all the cases, while OSC provides higher values. Comparing the maximum drift ratio, for the low ductility class, the ratio of IBC/OSC is a constant 69% for all building heights while UBC/OSC ratio is 66% for 3-,6- and 13-story and 71% for the 19-story building. For normal ductility class, IBC/OSC ratio is 45%, 57%, 60% and 60%, and UBC/OSC ratio is 52%, 67%, 63% and 63% for 3-,6-,13- and 19-story buildings, respectively.

It is further observed that the drift ratios for the two ductility classes (Low/Normal) have a constant ratio for all stories in a building for a given code. These ratios are summarized in Table 5 for the two analysis methods. For the equivalent static method, this ratio stays constant for low-rise buildings in IBC and UBC at 1.21 and 1.00, respectively, and then decreases with the building height. This drop is because the design base shear is governed by minimum base shear criteria for these heights in the normal ductility class.

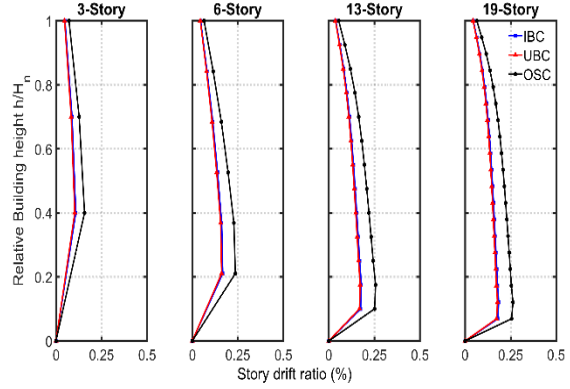


(a) Low ductility class

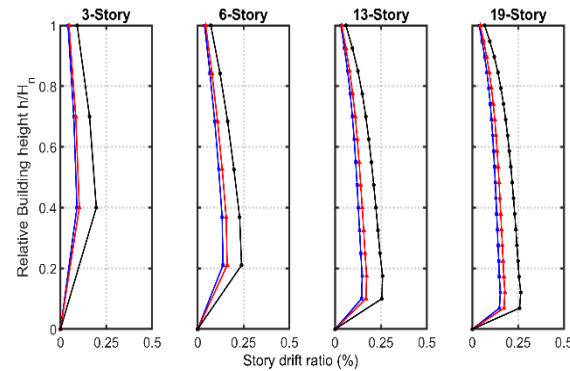


(b) Normal ductility class

**Figure 7.** Shear Force Distribution along building height using Response Spectrum Method.

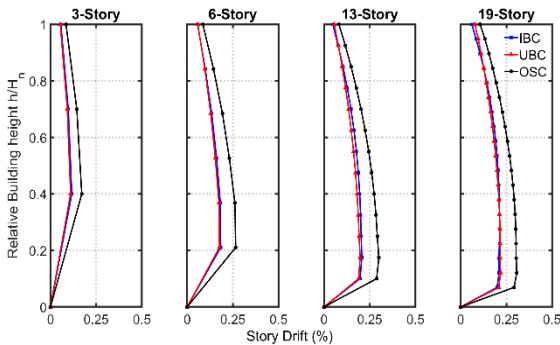


(a) Low ductility class

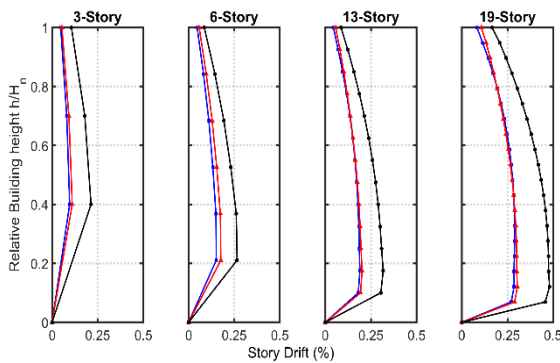


(b) Normal ductility class

**Figure 9.** Story Drift Distribution along building height using Response Spectrum Method



(a) Low ductility class



(c) Normal ductility class

**Figure 8.** Story drift distribution along building height using equivalent static method.

**Table 5.** Comparison of Story Drift ratio among Ductility Classes (Low/Normal)

Building	Equivalent Load Method			Response Spectrum Method		
	IBC	UBC	OSC	IBC	UBC	OSC
Story-03	1.21	1.00	0.80	1.21	1.00	0.80
Story-06	1.21	1.00	1.00			1.00
Story-13	1.09	0.98	0.95			1.00
Story-19	0.73	0.72	0.64			1.00

In OSC, the ratio first increases from 0.8 to 1.0 from 3-story to 6-story building and then start to decrease like IBC and UBC but at a higher rate. This is because OSC uses a variable value of  $q_R(T)$  for  $T < T_S$  as listed in Eqn. (3) and for the 3-story building  $q_R(T) = 0.80q$ .

Figure 9 shows the drift ratios using the response spectrum method. The response spectrum method provides similar drift values for the 3- and 6-story buildings, while it has smaller values for 13- and 19-story buildings, due to the smaller shear forces. The comparison of the two ductility classes remains the same as discussed for the equivalent static method, which further extends to 13- and 19-story buildings, as listed in Table 5. This verifies that the difference observed among the ductility classes in the equivalent static method for the 19-story building is due to the

minimum base shear criteria.

The drift ratios in OSC are higher because the same factor 'q' is used for response modification and deflection amplification ( $q/q = 1$ ). On the other hand, in IBC the  $C_d/R$  ratio is 0.833 and 0.688 for low and normal ductility classes, respectively, whereas in UBC the factor is 0.70 for both ductility classes. Therefore, the drift ratio estimated using OSC will always be higher compared to its counterparts. Since OSC uses the same allowable limit of 2%, it will require a stiffer design compared to IBC and UBC to satisfy this limit. A comparison of Fig. 8 and Fig. 9 shows that the equivalent static load method provides good agreement of drift ratios with the response spectrum method for 3- and 6-story buildings but higher estimates for 13- and 19-story buildings. This means that using an equivalent static method for medium and high-rise buildings will lead to stiffer designs in all the codes.

## 5. CONCLUSION

The study presented a comparison of the Oman Seismic Code (OSC) with international codes, Uniform Building Code-1997 (UBC) and International Building Code-2006 (IBC), based on the equivalence of seismic hazard. Base shear, lateral force distribution, and story-drift ratios are compared using the equivalent static method and the response spectrum method. Four building heights of 10 m, 19 m, 40 m, and 58 m are considered with 3-, 6-, 13- and 19- stories, respectively. Both low and normal ductility classes identified in OSC are compared and discussed. The following observations are made:

- The high seismic zone of OSC (Zone-1) is well-matched with Zone-1 of UBC and IBC in terms of seismic hazard.
- For the low ductility class, the base shear values for IBC are 83%-85% compared to OSC, using both the equivalent static load and response spectrum methods.
- For the low ductility class, the base shear values for UBC are 73%-81% and 75%-78% compared to OSC using the equivalent static load and the response spectrum methods, respectively.
- For the normal ductility class using the equivalent static method, the base shear value for IBC is 86%, 109%, 113%, and 113% of OSC for 3-, 6-, 13-, and 19- story buildings, respectively. The base shear value for UBC is 85%, 110%, 104%, and 104% of OSC for 3-, 6-, 13- and 19- story buildings, respectively.
- For the normal ductility class using the response spectrum method, the base shear value for IBC and UBC is 87% of OSC for the 3-story building and 110% of OSC for the other building heights.
- The story shear force distribution in the equivalent static method for OSC is similar to UBC, while it considers a marginally smaller allowance for the additional force at the top.
- The story shear force distribution in the 13- and 19-story buildings using the response spectrum method

showed the clear contribution of higher modes.

- Story drift ratios from the response spectrum method indicate that the two ductility classes in all codes provide the same deformation of the structure while the normal ductility class targets better energy dissipation through proper detailing.
- The use of the response spectrum method for medium and high-rise buildings suggested by OSC will lead to a better economy in design due to lower values of loads and smaller drift ratio estimates that control the stiffness of the structure.

The study concludes that the Zone-1 of OSC is closely matched to Zone-1 of UBC and IBC contrary to the recommendation of UBC that defines Muscat (Zone-1 of OSC) as Zone-2A.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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