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Seismic performance of high-rise buildings in selected regions in Saudi Arabia according to different seismic codes

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Abstract: The design code for each country is revised and updated based on an expected zone's seismic intensities, geotechnical site classifications, structural systems, construction materials and methods of construction in order to provide more realistic considerations of seismic demand, seismic response, and seismic capacity. Based on the aforementioned provisions, structures designed according to different seismic codes may yield different performances for the same level of hazard. This study aims to investigate and compare the induced responses related to the earthquake-resistant design of reinforced concrete (RC) buildings according to the Saudi building code (SBC-301), American code (ASCE-7), uniform building code (UBC-97), and European code (EC-8). In order to account for the provision regarding the hazard specification and its effect on the induced seismic responses, four regions in the Kingdom of Saudi Arabia with different seismic levels are selected. The code provisions related to the specification of site classification and its effect on the induced design base shear are investigated as well. Significant differences are observed in the induced responses with the variation in seismic design codes for the considered seismic hazards and site classifications.

Keywords: high-rise building; SBC-301; international seismic codes; seismic zones; site classifications

1 Introduction

Design codes for buildings are defined as the sets of regulations that control the design and construction process and regular maintenance of a structure. These regulations provide the necessary requirements for saving the lives of occupants and to sustain operations of important structures for civil protection. The seismic design codes vary significantly in defining the limits of the parameters that control the design process of structures against earthquakes. Unifying the international seismic design codes may be considered impossible. However, it may be possible to achieve harmonization among such international codes through comparative studies. This may also be considered as a step toward producing a new generation of seismic design codes that may fulfill the harmonization requirements (Taranath, 2010). Design seismic codes are updated through addition, modification, or elimination of some specific regulations mainly based on research works.

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Khose *et al*. (2012) performed a comparative study of different seismic design codes, namely, ASCE 7, EC-8, New Zealand Standard (NZS, 1170.5), and Indian Standard (IS, 1893), for controlling the design shear force at the bases of reinforced concrete (RC) buildings. For all the codes considered in the study, elastic analysis was employed. Although the stated approaches of design seem to be similar, the study clearly indicated the existence of several fundamental differences. In another study, the Algerian Code for seismic design was compared to the UBC-97 and EC-8 by employing the dynamic RS analysis for investigating the differences between the RS curves recommended by the considered codes (Chebihi and Laouami, 2014). The EC-8 induced the maximum shear force at the base and peak displacement for all ground types considered. Imashi and Massumi (2011) conducted a comparative study between the IBC issued in 2003 and Iranian seismic code (IS, 2800-05) to calculate the induced seismic forces using the equivalent static force procedure. The study also investigated the differences between the factors that affect the shear values obtained using the two codes. The obtained simulation results clearly indicated the need to update the IS 2800-05 for achieving the functional and economic objectives of seismic design codes. Wang (2010) performed a revision of Chinese seismic design codes GB 50011-2001 and Standard for classification of seismic protection of building constructions GB 50223-2008 corresponding to building damages in the "5.12" Wenchuan earthquake in order to upgrade the classification of buildings that hold large populations such as buildings and hospitals. Beneldjouzi and Laouami (2015) followed a stochastic approach to propose a formulation for characterizing design sites according to the Algerian seismic design code. Comparison with the Eurocode-8 (EC-8) was done in the performed study. Abou-Elfath (2019) conducted a series of elastic and inelastic time-history analyses on moment resisting steel frames with 2, 4, 8 and 12 stories designed following Egyptian code requirements in order to estimate the ρ-ratio. The used excitation records were scaled such that targeted different peak drift ratios of are obtained.

The two international codes IBC and ASCE-7 were considered as the basis for evaluating the SBC-301 specified for the design loads for buildings and structures. However, extensive changes have been carried out to ensure compatibility with the different regions of the Kingdom of Saudi Arabia. The level of seismicity, structural system chosen for seismic resistance, and the construction materials used are some of the parameters considered when modifying the source codes and the code associated for the Kingdom (Shuraim *et al*., 2007). For improving the seismic provisions of the national building code of the Kingdom, comparisons were made with well-known international seismic codes. Nahhas (2011) employed the modal RS analysis to perform a comparative study between the IBC-2009 and the UBC-97 using a residential building in the standard occupancy category. The comparative analysis indicated that the UBC-97 is significantly more conservative than the IBC. Again Nahhas (2017) employed the procedure of one RS analysis to compare the SBC-301 and UBC-97 using the results of a sample of four buildings using software package ETABS for modeling and seismic analysis. The study pointed out that the SBC-301 cannot be considered as more conservative than UBC for all performed scenarios. In order to investigate the seismic performance of RC buildings located in Jazan city, the seismic analysis of a multi-story reinforced concrete building was performed using the equivalent static force analysis in compliance with the provisions of SBC-301 (Hassaballa *et al*., 2017). The simulation results proved the importance of considering the SBC-301 in the analysis and design of buildings in Jazan city.

This research paper presents a comparative study on the seismic response of RC buildings based on SBC-301, ASCE-07, UBC-97, and EC-8. An RC high-rise building located in different regions in Saudi Arabia was selected for the study. The locations chosen ensure different seismic intensities. The induced seismic responses in terms of shear forces, overturning moments, lateral drifts, and lateral displacements are obtained to explore the variation in results based on the requirements of the four selected codes. To investigate the effect of sub-base soil on the obtained design base shear, different soil profiles were selected according to the considered seismic design codes.

2 Building models

The building model was selected to ensure regularity in both plan and elevation to facilitate the comparison. The RC shear walls building chosen was assumed to be located in different cities in the Kingdom, Dammam, Jazan, Fifa, and Haql. These cities are located in different regions with different levels of seismicity. The considered building consists of 20 typical stories designed as a two-way solid slab system with a thickness of 14 cm carried by beams in both directions. The supporting beam dimensions are 25 cm × 50 cm with spacings of 5.0 m (see Fig. 1). The typical floor height is 3.0 m.

In terms of designing a high-rise building for gravitational and seismic loads, the basic design criteria that need to be satisfied are strength, serviceability, stability and human comfort. The strength is satisfied through assigning reinforced concrete with characteristic compressive strength f_c' = 28 MPa for all footings, slabs, and beams. f_c' = 35 MPa for columns and RC walls. The modulus of elasticity can be calculated in terms of the characteristic compressive strength f_c as $E = 4700\sqrt{f_c}$. Steel reinforcement with yield strength f_y = 420 MPa have been utilized in the design process. Serviceability is satisfied through keeping the overall deflection of the superstructure or structural member to remain within acceptable limits, conservative values, recommended by considered codes. The various loads in terms of dead, live and seismic loads are applied to the structures in combination with factors as indicated in ASCE-&, SBC-301, EC-8 & UBC-97. Each of the loads will be calculated and the combination producing the largest resultant forces and moments will be used in the design in order to satisfy the stability. All reinforced concrete elements are designed employing the ultimate strength method. The human comfort aspects are satisfied by minimizing the induced accelerations.

The cross sections of the columns and steel reinforcements designed to resist the applied gravitational and seismic loads according to the different codes and cities are listed in Table 1. Similarly, the dimensions of the sections and vertical reinforcements for shear walls designed to resist the applied gravitational and seismic loads are listed in Table 2. The dynamic RS analysis was performed using the ETABS program by specifying the cross sections, bar reinforcements, and properties of the designed structural elements. Beams as horizontal elements and columns as vertical elements were modeled as the frame element, which opposes axial and bending stiffness. The shell element, which can be realized as a three- or four-node formulation and which combines both membrane and plate-bending behavior, was used to model shear walls and slabs. This way of modeling ensured that the slab mass was transferred to the supporting elements and provided stiffness in all directions considered in the analysis. Each floor level was assigned to act as a semi-rigid diaphragm to simulate the actual in-plane stiffness properties and slab behavior. Moreover, the vast majority of RC slab systems, for which the membrane deformation due to the applied seismic loading as a lateral load is insignificant, both rigid and semi-rigid diaphragms induce almost identical results. Modeling a floor slab as a semi-rigid diaphragm, however, helps in accelerating the computation. In addition, for slabs modeled as rigid diaphragms, the applied seismic loads act at the center of the mass of the slabs. On the other hand, for slabs modeled as semi-rigid diaphragms, the applied seismic loads act at every node.

For considering the effect of modal damping, the complete quadratic combination technique was employed to analyze the modal combination. The supports and connections of the developed building model were defined by choosing the appropriate restraints. The building supports, in particular, were modeled as fixed. The maximum and minimum number of modes required to achieve the acceptable percentage of mass participation can be assigned in ETABS. Further, either the Eigen mode or Ritz mode methods too are available in the modal case function. The ETABS structural package also enables a user to define the mass source required to calculate the building weight and, consequently, the shear at the base. The shear walls and slabs were meshed automatically with meshes of approximately 0.5 m × 0.5 m for each mesh. The *P-Δ* effect was introduced during the analysis of the building model. The developed RC building model was loaded with both gravitational and seismic loads. The equivalent static procedure and RS analysis methods were applied to the building model to represent the seismic load and to calibrate the computed dynamic shear at the base with the static one. The developed three-dimensional building model used in study is shown in Fig. 1.

3 Response spectrum analysis method

The linear static analysis, which is commonly known as the equivalent static lateral-force procedure, is the simplest method for performing seismic analyses. This method involves low computational efforts. Seismic design codes permit the use of this method for the class of structures that are located in low seismic intensity zones, are regular in shapes with heights below specified limits, and are irregular in shapes with low heights. However, for regular structures with the total heights exceeding certain limits, with a fundamental period longer than 2 s, or located in an active seismic zone, the dynamic analysis is more accurate than the equivalent static one; the dynamic analysis, therefore, can be considered a mandatory procedure for the aforementioned cases. Similarly, for irregular buildings with either heights greater than 20 m or with a natural period longer than 0.5 s, the dynamic RS is mandatory for the analysis. Moreover, for most of the seismic design codes, it is preferable to obtain the seismic design forces using the dynamic analysis procedures, regardless of the structural configuration. Two types of dynamic analysis, namely, time-history and RS analyses, are available in the seismic design codes for realizing earthquake-resistant design. Time-history analysis, which is a nonlinear dynamic analysis, is the best technique for evaluating the structural response under earthquake motions. However, this type of analysis requires significant computational effort and is considered to be time consuming. The dynamic RS analysis of a structure employs the peak dynamic responses of all modes that make considerable contributions to the total structural response. The peak modal responses are calculated using the ordinates of the appropriate RS curve, which corresponds to the modal periods. In order to perform an RS analysis, idealized spectrum curves provided by design codes are selected based on the seismic zone coefficients, soil type, and damping ratio of the structure. These spectrum curves represent the peak response values of an idealized, single-degree-of-freedom model under seismic excitation versus time periods. The spectrum curve developed is divided into different ranges. Each range in the spectrum is defined using a specific equation derived according to the design code. The typical shape of an RS curve is drawn for time period T versus spectral acceleration S_a. The typical curve always has two ordinate values, namely, design spectral response acceleration at short period S_{DS} and 1-s period S_{D1}, as in the SBC-301 and the ASCE-7. The acceleration response coefficient C_a is used to define the two ordinates, following the UBC-97 (see Fig. 2). The EC-8 defines these two ordinates as S

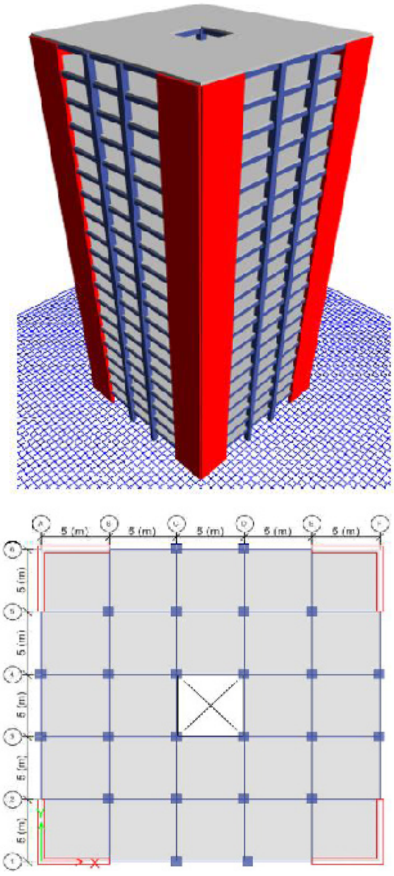

Fig. 1 Three-dimensional building model

and $2.5S\eta$ where S and η are the soil factor and damping ratio, respectively. The periods T_0 and T_S (called T_B and T_C for EC-8) limit the branch of constant spectral acceleration. T_D is the period at which the range of constant acceleration response starts.

The established expressions for the ordinates of inelastic design spectra vary depending on the seismic design code. Among the different codes considered in this study, two divide the spectrum into four parts, and the other two divide it into three. The ASCE-7 and EC-8 seismic codes define the ordinates of the spectrum curve as shown in Eq. (1) and Eq. (2), respectively. Note that the EC-8 defines two types of spectra: Type 1 is applicable to the zones of high seismicity, and Type 2 to those of low seismicity.

$$
\begin{aligned}
S_d(T) &= \left[0.4S_{DS} + \frac{0.6S_{DS}\cdot T}{T_0}\right]\cdot g\cdot\frac{1}{R} && \text{for } 0 \le T \le T_0 \\
S_d(T) &= S_{DS}\cdot g\cdot\frac{1}{R} && \text{for } T_0 \le T \le T_S \\
S_d(T) &= \frac{S_{D1}}{T}\cdot g\cdot\frac{1}{R} && \text{for } T_S \le T \le T_L \\
S_d(T) &= \frac{S_{D1}T_L}{T^2}\cdot g\cdot\frac{1}{R} && \text{for } T_L \le T
\end{aligned}
\qquad (1)
$$

Table 1 Concrete dimensions and reinforcement for columns

Column location	Floor level							
	Foundation to 5th		6th to 10th		11th to 15th		16th to 20th	
	b×*t*	Raft.	*b*×*t*	Raft.	*b*×*t*	Raft.	*b*×*t*	Raft.
Interior columns	85×85	24Φ25	70×70	20Φ25	60×60	20Φ25	50×50	16Φ25
Exterior columns	70×70	20Φ25	60×60	20Φ25	50×50	16Φ25	45×45	16Φ25

b = column width in mm; *t* = column thickness in mm; Raft. = vertical reinforcement

Table 2 Thickness and vertical reinforcement for shear walls

City	Soil type B		Soil type C		Soil type D		Soil type E	
	t (mm)	Raft.	*t* (mm)	Raft.	*t* (mm)	Raft.	*t* (mm)	Raft.
Dammam	250	5Φ16	250	5Φ16	250	6Φ16	250	7Φ20
Jazan	300	5Φ16	300	8Φ18	300	8Φ22	300	10Φ25
Fifa	300	8Φ18	300	8Φ22	400	10Φ25	400	10Φ32
Haql	300	10Φ25	450	10Φ25	500	10Φ28	500	10Φ32

t = thickness of wall; Raft. = vertical reinforcement per meter

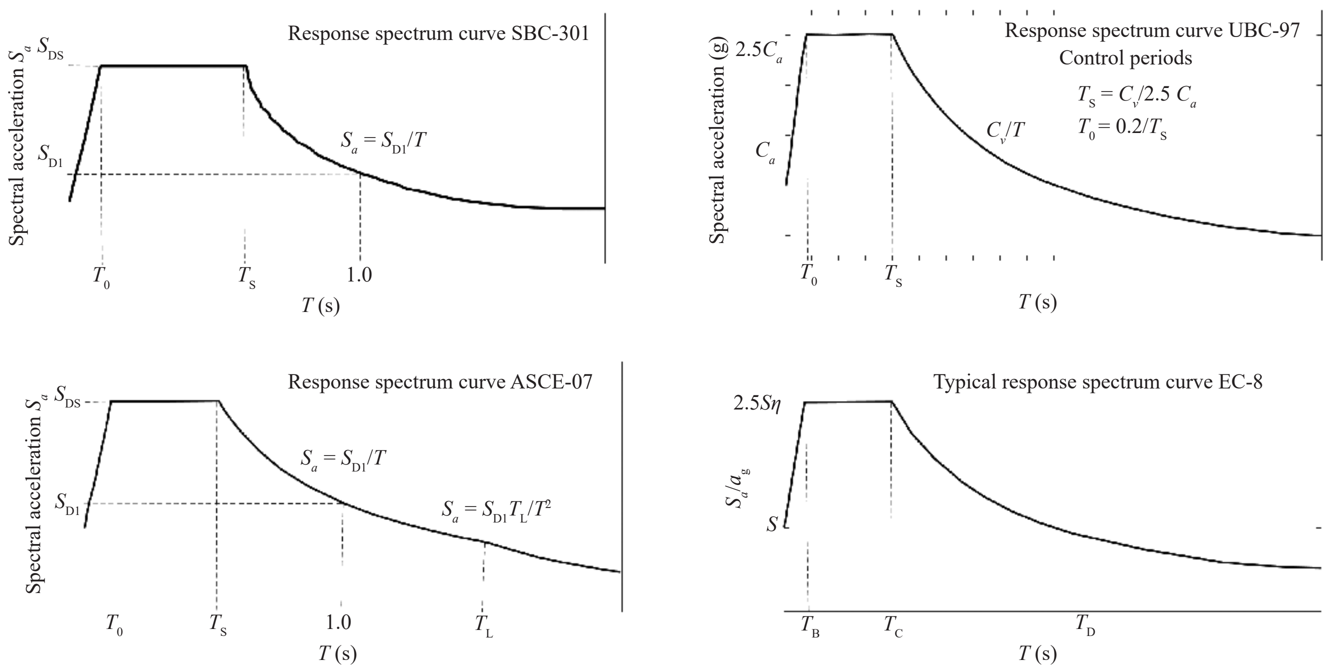

Fig. 2 Spectrum curves obtained according the different standards

$$S_d(T) = a_g S\left[\frac{2}{3}+\frac{T}{T_B}\left(\frac{2.5}{q}-\frac{2}{3}\right)\right] \quad \text{for } 0 \le T \le T_B$$
$$S_d(T) = a_g \cdot S\frac{2.5}{q} \quad \text{for } T_B \le T \le T_C$$
$$S_d(T) = a_g \cdot S\frac{2.5}{q}\left[\frac{T_C}{T}\right] \ge \beta a_g \quad \text{for } T_C \le T \le T_D$$
$$S_d(T) = a_g \cdot S\frac{2.5}{q}\left[\frac{T_C T_D}{T}\right] \ge \beta a_g \quad \text{for } T_D \le T \le 4 \quad (2)$$

Meanwhile, the UBC-97 and SBC-301 divide the spectrum into three regions, forming the inelastic design spectrum curve, as shown in Eq. (3) and Eq. (4), respectively:

$$S_d(T) = \left[C_a + \frac{1.5C_a \cdot T}{T_0}\right]\cdot \text{g} \cdot \frac{1}{R} \quad \text{for } 0 \le T \le T_0$$
$$S_d(T) = 2.5C_a \cdot \text{g} \cdot \frac{1}{R} \quad \text{for } T_0 \le T \le T_S$$
$$S_d(T) = \frac{C_v}{T} \cdot \text{g} \cdot \frac{1}{R} \quad \text{for } T_S \le T \quad (3)$$

$$S_d(T) = \left[0.4S_{DS} + \frac{0.6S_{DS} \cdot T}{T_0}\right]\cdot \text{g} \cdot \frac{1}{R} \quad \text{for } 0 \le T \le T_0$$
$$S_d(T) = S_{DS} \cdot \text{g} \cdot \frac{1}{R} \quad \text{for } T_0 \le T \le T_S$$
$$S_d(T) = \frac{S_{D1}}{T} \cdot \text{g} \cdot \frac{1}{R} \quad \text{for } T_S \le T \quad (4)$$

For the ASCE-7 and SBC-301, the design spectral response acceleration parameters at short periods SDS and at 1-s period SD1 can be determined in terms of the acceleration and velocity related site coefficients F_a and F_v as well as the mapped maximum considered earthquake (MCE) spectral response accelerations at short periods (S_S) and at the 1-second period (S_1):

$$S_{DS} = \frac{2}{3}\left(F_a \cdot S_S\right) \quad (5)$$

$$S_{D1} = \frac{2}{3}\left(F_v . S_1\right) \quad (6)$$

T and T_L refer to the fundamental period of the structure and long-period transition period.

S_{D1} and S_{DS} are defined as:

$$T_0 = 0.2\left(\frac{S_{D1}}{S_{DS}}\right) \text{ and } T_S = \frac{S_{D1}}{S_{DS}} \quad (7)$$

For the UBC-97, once the seismic zone factor and the soil profile type are known, the acceleration response coefficient C_a and velocity response coefficient C_v can be assigned. The values of T_S and T_0 can be calculated in terms of C_a and C_v as:

$$T_S = \frac{C_v}{2.5C_a} \text{ and } T_0 = \frac{0.2}{T_S} \quad (8)$$

Similarly, the soil factor *S*, required to define the response spectrum curves of the EC-8, needs the seismicity level and the soil type. η is the damping correction factor with a reference value of $\eta = 1$ for 5% viscous damping. Recommended constant values describing the parameters T_B, T_C and T_D are provided in the EC-8.

For the seismic codes, the dynamic base shear should be scaled to ensure that the structure designed using the RS analysis method has a minimum strength; this is similar to the requirement arising when a structure is designed using static analysis. Scaling of the calculated dynamic base shear using the RS procedure is a requirement in accordance with the design codes. For regular structures, if the induced base shear employing the RS is a value of less than 85% of the induced value employing the equivalent static force (ESF) procedure, it should be scaled to 85% of the calculated static value following the requirement of ASCE-7. For irregular structures, the required scaling percentage is 100% of the static base shear. The other codes specify percentages almost similar to that in the ASCE-7; the exception is the EC-8, which does not require base shear scaling.

Note that the site class influences the design acceleration response spectra values in different ways according to the seismic design codes considered. In the seismic design codes ASCE-7 and SBC-301, the effect of the site class is expressed in terms of acceleration and velocity related site coefficients F_a and F_v. These two coefficients are functions of the mapped maximum considered earthquake (MCE) spectral response accelerations at short periods (S_S) and at the 1-second period (S_1) and site class. In UBC-97, the soil profile type together with the seismic zone factor provide seismic coefficients; namely, the acceleration response coefficient Ca and velocity response coefficient C_v. The soil factor S or sometimes called site coefficient of EC-8 is defined for type 1 spectra associated with the areas of high seismicity and type 2 spectra associated with the areas of moderate seismicity for each soil type.

4 Seismic parameters

In order to compare the aforementioned seismic design codes, different locations with different levels of seismicity were carefully chosen. Scenarios in which the target high-rise building was located in Dammam, Jazan, Fifa, and Haql cities were considered. Most of the seismic design codes use a specific parameter to represent the peak ground acceleration (PGA) to identify the seismic hazard. The EC-8 and UBC-97 follow the aforementioned trend, with the EC-8 using specific design ground acceleration and the UBC-97 using a zone factor that refers to the effective PGA. However, the ASCE-7 and SBC-301 use two spectral ordinates, namely, short-period spectral acceleration at 0.2 s and spectral acceleration at 1 s. The chosen locations have approximately design ground accelerations in between 0.03 g and 0.3 g, which can be considered as the lowest and highest levels of seismicity, respectively, in the Saudi Arabia standard. The spectra values presented following the different codes are compatible with the level of seismicity of the considered locations and the supporting soil types. Further, the design spectrum values presented by the SBC-301 and ASCE-7 are also compatible with the corresponding ground acceleration levels provided by the other codes. The supporting soil of the building was first assumed to be very dense soil and soft rock; later, it was changed as per the SBC-301 and the other selected codes to examine the effect of the soil on the induced shear forces at the base of the building model. Its importance factor was assigned as 1. A damping ratio of 5% was used in the analysis. The seismic parameters used according to the different seismic design codes considered for the Dammam, Jazan, Fifa and Haql regions are listed in Table 3. All the stated seismic parameter values in the table have been calculated for very dense and soft rock supporting soil. For the purpose of investigating the effect of changing the supporting soil type on the induced shear forces at the base of the building, new seismic parameters have been assigned to fit the site conditions and the varied seismic levels following the requirements and guidelines of the different seismic codes considered.

5 Numerical results and discussions

Dynamic RS analysis was performed to obtain the structural response of a reinforced concrete building following the application of seismic loads according to the guidelines of SBC-301 and other international seismic design codes. The structural system of the chosen RC high-rise building consists of structural walls in both directions of loading. As mentioned earlier, regions with different seismic intensities were selected. The dynamic software ETABS was employed for the analysis, and the design spectra recommended according to the selected seismic design codes, locations, and soil profiles were used. The target building was assumed to be located at sites in different seismicity zones based on the chosen cities. The reference peak ground accelerations of these zones vary from low to high, with the maximum value of 0.30 g. The seismic loads produced by ETABS are equivalent to the recorded seismic intensity of each city considered herein and are in accordance with the studied codes. The calculated seismic weight of the building has been found to be of 145000 kN. A damping ratio of 0.05 was considered during the dynamic analysis. The captured natural periods corresponding to the 1st, 2nd, and 3rd modes are 2.352 s, 2.347 s and 1.439 s, respectively. The cumulative sum of the modal participation mass ratio in the global *X*-direction for the last three modes, namely 18th, 19th, and 20th, are 99.4%, 99.8%, and 100%, respectively. Similarly, the captured values for the global *Y*-direction for the 18th, 19th, and 20th modes are 95.4%, 96.8%, and 98.8%, respectively.

The induced shear forces and moments at each story, which are considered the most useful responses for earthquake-resistant design strategy, were obtained along the height of the building model. These parameters were compared among the codes considered for the given seismic loads and seismic regions. Similarly, floor displacements were considered a measure of building deflection and were compared. The drift parameter was also predicted and compared among the regions and codes considered in the study.

The earthquake design codes classify site conditions into different categories, sometimes called soil profile types or ground types. In order to investigate the effect of the soil profile on induced seismic shear at the base, four soil profile types, namely, rock, very dense and soft rock, stiff soil, and soft soils, were selected in accordance with the considered seismic design codes. The corresponding RS curves were used to seismically excite the building model. Seismic analyses of the building were performed separately for the *X* and *Y* directions. Because of the symmetry of the considered structure and for the sake of brevity, only the seismic responses in the *X*-direction are compared herein.

5.1 Story response results

Figures 3 through 6 present the results for the aforementioned responses under the applied dynamic spectrum loads equivalent to the specified codes in the study. The distribution of the captured shear forces at each story level due to the applied seismic loads corresponding to different regions and seismic design codes are presented in Fig. 3.

As seen from the figure, the distribution of shear forces against stories varies significantly with changes in the seismic code for all the considered regions. Differences among story shear values associated with different codes are highly pronounced for the lower stories. As expected, the shear force values at each story level increase with the seismicity level. For Dammam, the minimum base shear requirements of the SBC-301 and ASCE-7 are the governing requirements, and hence, the plotted base shear force values are identical to the minimum design base shear recommended by the two codes. Similarly, the EC-8 produces lower shear forces than those obtained by the other codes for the region with the lowest seismicity level. This also can be attributed to the fact that the EC-8 does not specify a minimum value for the shear forces at bases. In contrast to the results for the low seismicity regions, for regions with higher seismic levels than those for Dammam, the EC-8 produces higher story shear forces compared to those induced following the other codes, particularly, for Fifa and Haql, the latter having the highest seismicity level in Saudi Arabia. Although the ASCE-7 is considered as the basis of the SBC-301, the SBC-301 produces story shear values significantly higher than those obtained using the

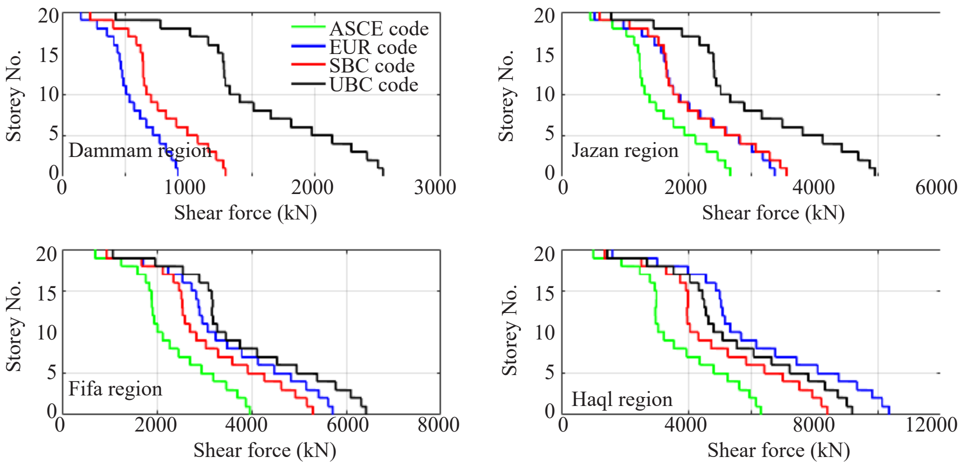

Fig. 3 Story shear forces distribution due the applied dynamic spectrum loads equivalent to the ASCE-7, EC-8, SBC-301 and UBC-97 for different regions in Saudi Arabia

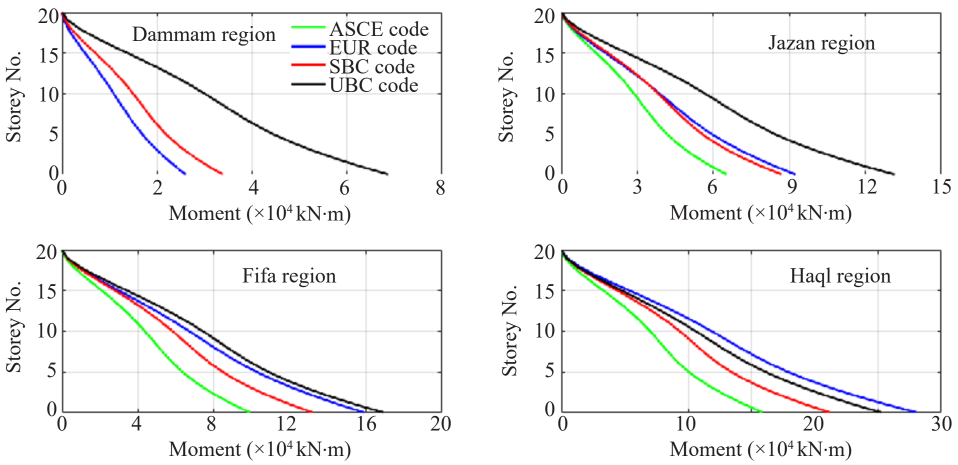

Fig. 4 Story moments distribution due the applied dynamic spectrum loads equivalent to the ASCE-7, EC-8, SBC-301 and UBC-97 for different regions in Saudi Arabia

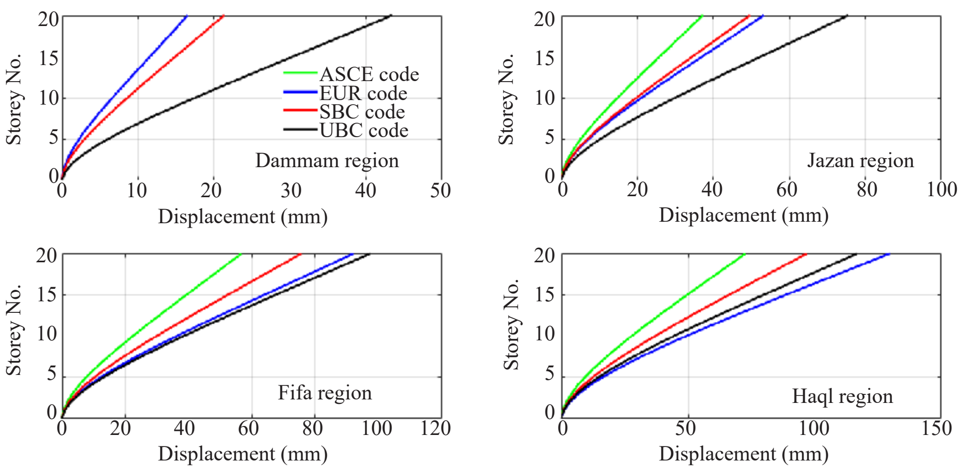

Fig. 5 Story displacement distribution due the applied dynamic spectrum loads equivalent to the ASCE-7, EC-8, SBC-301 and UBC-97 for different regions in Saudi Arabia

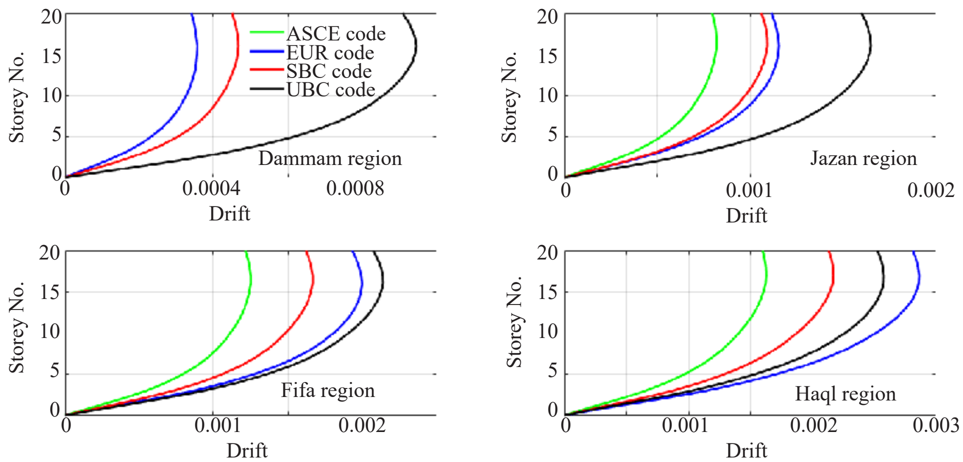

Fig. 6 Story drift distribution due applied dynamic spectrum loads equivalent to the ASCE-7, EC-8, SBC-301 and UBC-97 for different regions in Saudi Arabia

Table 3 Seismic parameters for the considered different regions and seismic codes

Code	ASCE-7				SBC-301				UBC-97				EC-8			
City	Dammam	Jazan	Fifia	Haql	Dammam	Jazan	Fifia	Haql	Dammam	Jazan	Fifia	Haql	Dammam	Jazan	Fifia	Haql
R	4				3				4.5				3			
S_S (g)	0.083	0.435	0.616	0.866	0.083	0.435	0.616	0.866	$a_g/g=$ 0.075	$a_g/g=$ 0.150	$a_g/g=$ 0.200	$a_g/g=$ 0.300	$a_g/g=$ 0.030	$a_g/g=$ 0.124	$a_g/g=$ 0.176	$a_g/g=$ 0.281
S_1(g)	0.03	0.124	0.176	0.281	0.03	0.124	0.176	0.281								
F_a	1.2	1.2	1.15	1.05	1.2	1.2	1.15	1.05	0.09	0.18	0.24	0.33	$S=1.0$	$S=$ 1.20	$S=$ 1.15	$S=$ 1.20
F_v	1.7	1.68	1.62	1.52	1.7	1.68	1.62	1.52	0.13	0.25	0.32	0.45				

R = over strength reduction factor; S_1 = maximum spectral acceleration at 1 s; S_S = maximum spectral acceleration at 0.2 s;
S = soil factor; a_g = design ground acceleration; F_a = a parameter relates site class and mapped short period S_S.
F_v = a parameter relates site class and mapped 1 s period S_1

ASCE-7. This result is attributed to the fact that the SBC-301 provides a lower response modification factor than that in the ASCE-7. Among all the considered seismic codes, the story shear forces generated employing the American code ASCE-7 are, in general, smaller than those induced under application of dynamic seismic loads following the guidelines of the other codes. With an increase in the seismicity level, the story shear forces induced by the SBC-301 increase and exceed those produced by the UBC-97, which is also considered as a basis in the evolution process of the SBC-301. The comparison shows that buildings designed according to different codes do not exhibit similar performance for the same level of hazard. Since earthquake-resistant design considers the shear at the base as a governing parameter, changing the design code can significantly affect the design strategy of the structure.

Results of the story moment patterns for the high-rise building model under dynamic response spectrum load for the different codes considered herein are presented in Fig. 4. The portion F_i of the seismic base shear induced at story level located at height h_i from the base can be used to calculate the overturning moments using the code formula:

$$M_x = \sum_{i=x}^{n} F_i \left(h_i - h_x\right) \tag{9}$$

The induced story moment values vary remarkably as the level of seismicity changes. In addition, the story moments computed using different codes for the same seismic level exhibit drastic differences. For all the considered regions, the ASCE-7 code of seismic design provides the lowest story moments. Although the EC-8 provides the lowest story moments for a low level of seismicity, it yields higher values that exceed the other codes, particularly for the Haql region, with the increase in level of seismicity. For the other two regions, the values produced exceed those induced by ASCE-7 and SBC-301. The story moment values obtained using the SBC-301 are higher than those obtained using the ASCE-7 for all the considered regions except for the one with the lowest seismic level, for which the values obtained using the two codes are identical. For regions with low and moderate seismic levels, the UBC-97 produces higher story moments as compared to the values by the other codes.

Figure 5 shows the story lateral displacements under the applied dynamic response spectrum for different seismic codes according to the seismicity levels. In general, regardless of the seismic intensity, the upper stories of the structural model produce greater lateral displacements than the induced lateral displacements of the lower stories for all the considered design codes. As shown in the figure, the change in the seismicity level causes significant change in the obtained story displacements, and this change is highly pronounced for the top stories. Similar to the induced story moments and shear forces, the ASCE-7 induces lower story displacements than those obtained using other codes, except for the region with the lowest seismic intensity. The induced displacement responses obtained using the SBC-301 are always higher than those induced by the ASCE-7, regardless of the seismic intensity except for Dammam where the induced values are identical. The UBC-97 provides the higher story displacements for almost all the seismic regions considered herein except for Haql. However, with the increase in seismic intensity, the EC-8 produces story displacement values of slightly higher values as compared to the induced values obtained using the UBC-97 (see plots for Haql region). Overestimation of story displacements greatly influences the P-Δ effect, which may result in an instability in the building structure and potentially lead to the collapse of the building. From the viewpoint of earthquake-resistant design, unexpected story deflections of a building structure under lateral seismic actions arising from the use of seismic codes that underestimate the actual deflections, may lead to collisions between insufficiently separated neighboring structures. Such collisions may not only cause damage to the colliding portions, but also result in an increase in the induced story accelerations.

Figure 6 shows the results of the story drift ratio of the building model under the dynamic response spectrum curves specified by different codes for the four regions. The plotted curves demonstrate the differences among the drift profiles of the building structure using different seismic codes and for different seismic levels. The UBC-97 provides the highest drift ratios, except for Haql. However, with the increase in the seismicity, the EC-8 produces the highest drift ratio values (see Haql region of 0.3 g level). Similar to the obtained displacement response, the ASCE-7 shows lower drift ratio profiles comparable to the other profiles produced by the other selected codes, except for the Dammam where the two profiles obtained using the ASCE-7 and SBC-301 are identical. In addition, the drift ratios obtained using the SBC-301 exceed those obtained considering the building structure is excited using the ASCE-7 spectrum. This increase in the drift ratio is more pronounced with the increase in the seismicity level. The divergence among the drift values obtained using different codes is more pronounced at top stories, regardless of the seismicity level. The change in design codes seems to have a slight effect on the induced story drift ratios at lower stories. From the viewpoint of seismic design, the higher values of induced drift can significantly affect the structural and nonstructural elements. Consequently, design codes that overestimate the drift values compared to the others may be considered cost effective because the structural elements need to be strengthened to withstand overestimated values. On the other hand, the codes that underestimate the drift values may result in structural damage to the structural and nonstructural elements that are not designed to withstand the actual induced drifts.

The acceleration response quantities are important since the accelerations that developed in the floors are proportional to the forces exerted due to the applied dynamic load. The results of the story accelerations of the building model under the dynamic response spectrum curves specified by different codes for the four regions are presented in Fig. 7. As shown in the figure, the building experiences a much higher maximum acceleration at the top levels than at the lower floors of the building regardless of the code followed and seismic intensity of the region. The figure clearly indicates the variances among the plotted acceleration profiles considering different seismic levels and seismic codes as well. The ASCE-7 provides the lowest acceleration values for all the considered regions and seismic codes except for the Dammam region, where the EC-8 provides the lowest acceleration values. However, with the increase in the seismicity, the EC-8 produces the highest acceleration values. The acceleration profiles obtained using the SBC-301 exceed those obtained considering the building structure is excited using the ASCE-7 spectrum as the seismicity level increases.

5.2 Design base shear results

The shear forces at the base of the high-rise building were acquired via seismic analysis using design spectra corresponding to 5% critical damping. Seismic analyses of the building were carried out for the four aforementioned ground types as defined in the response spectrum analysis and their equivalents in the SBC-301, ASCE-7, UBC-97, and EC-8. Figures 8 to 11 present the estimated base shear forces for the specified soils, regions, and design codes. The figures clearly show very different base forces for the different soil types and regions with different intensities. The softer the supporting soil, the higher the shear forces induced at the base, regardless of the seismic intensity level for the building considered herein and for buildings with similar dynamic characteristics. This is attributed to the fact that the change in site class significantly influences the values of the design spectral response acceleration. As the soil gets softer, the corresponding design spectral values increase, causing an increase in the calculated base shear where the elastic design spectral acceleration is directly proportional to the design base shear and controls the seismic lateral response of high-rise buildings. For the same level of hazard and soil base type, significant differences are observed in the computed shear forces at the base for different design codes. Such variations and differences among the obtained design shear values is due to differences in the design spectra of different seismic codes and response modification factors. In almost all the considered seismic codes and seismic levels, the design base shear of the ASCE-7 are the lowest. This is because the ASCE has the largest response reduction factors and considers soil nonlinearity, which results in the reduction in soil amplification, especially, at high seismicity levels. As the seismicity level increases, the values of the design base shear obtained using the SBC-301 exceed the values obtained using the ASCE-7. The difference in design base shear values is more pronounced in the case of buildings located in very low seismicity regions and sited on relatively weak supporting soils. The lack of the minimum base shear provision in the EC-8 results in a very low design base shear of high-rise buildings in low seismicity regions. However, the results show that the EC-8 provides the maximum shear forces at the base when the PGA level is relatively high, and the supporting soil type is rock and soft rock (see Figs. 10 and 11). This is attributed to the fact that the ordinate of the inelastic spectra of the fundamental period of the building is more important for the EC-8 Type 1, which is associated with relatively high seismicity levels.

The UBC-97 produces the highest shear values at the base for all the considered seismicity regions, provided that the soil at the base gets weaker. Similarly, the SBC–301 produces higher shear forces at the base; these values approach those induced by the UBC-97 as the soil gets weaker. From the viewpoint of the type of soil, the computed shear forces at the base show that the EC-8 yields the maximum base shear values for supporting subsoils with high shear velocity; that is, rock and very dense and soft rock soils for all regions, except for Dammam with the lowest PGA level.

The variation in the obtained response curves can be attributed to differences in design spectra which in turn depend on response reduction or behavior factor, MCE, site class, and damping ratio. Some of the codes used herein combine the effect of overstrength and ductility

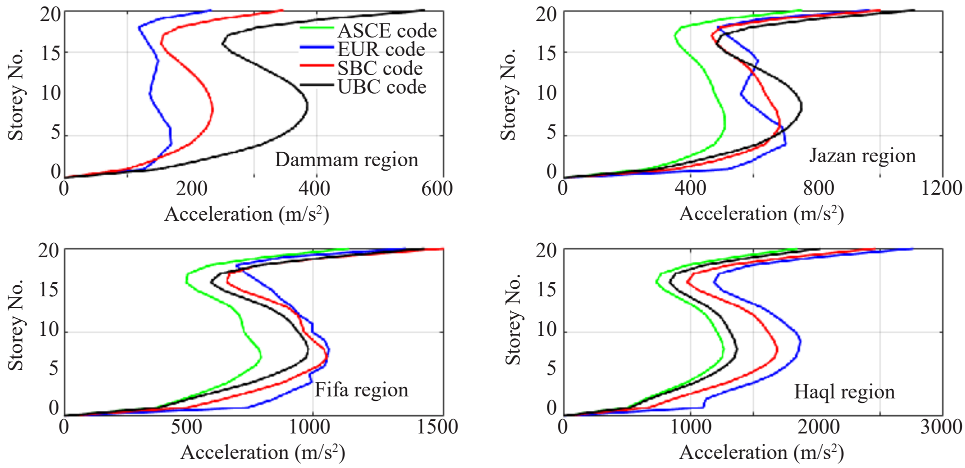

Fig. 7 Story accelerations distribution due the applied dynamic spectrum loads equivalent to the ASCE-7, EC-8, SBC-301 and UBC-97 for different regions in Saudi Arabia

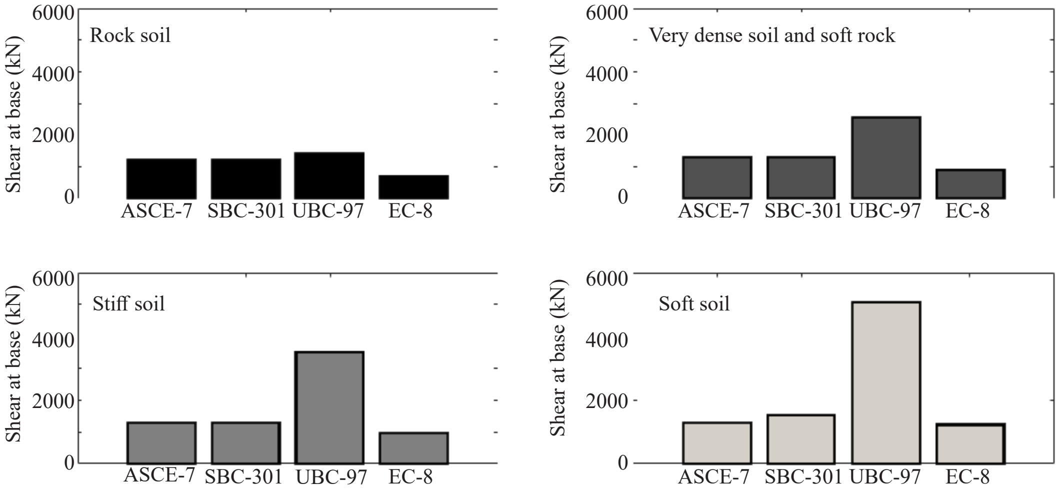

Fig. 8 Base shear computed according to the considered codes versus soil types for Dammam region

in a single response reduction and others consider the effect of overstrength separately through a ‘structural performance factor. Moreover, the response reduction values vary significantly from one code to another. The code values of the response reduction factor are 4, 3, 5.5, and 3 for the ASCE-7, SBC-301, UBC-97, and EC-8, respectively. Some codes use an MCE with a 2% probability of exceedance in 50 years with a return

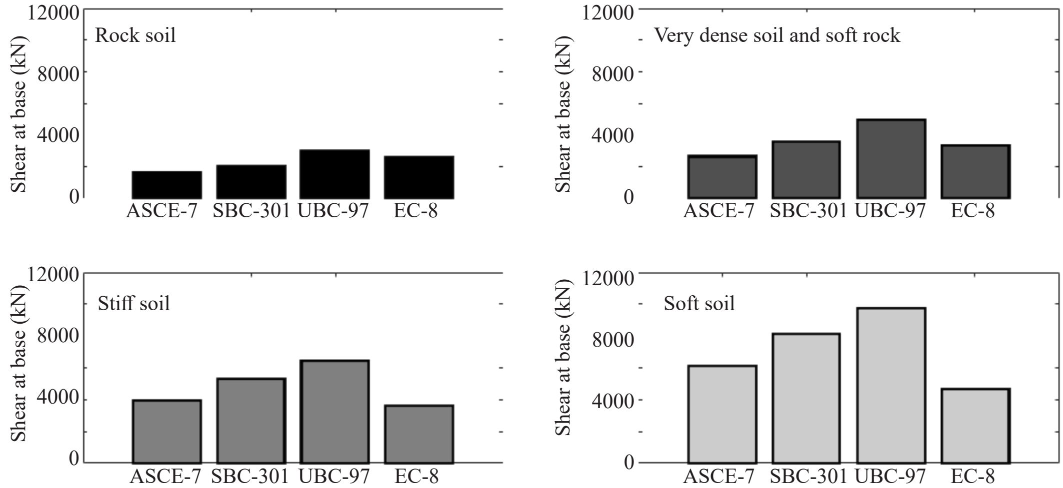

Fig. 9 Base shear computed according to the considered codes versus soil types for Jazan region

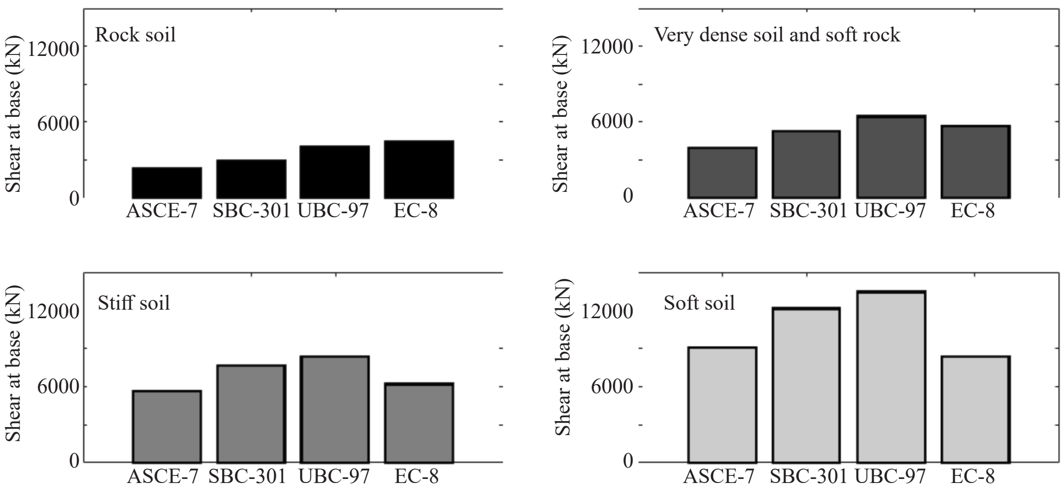

Fig. 10 Base shear computed according to the considered codes versus soil types for Fifa region

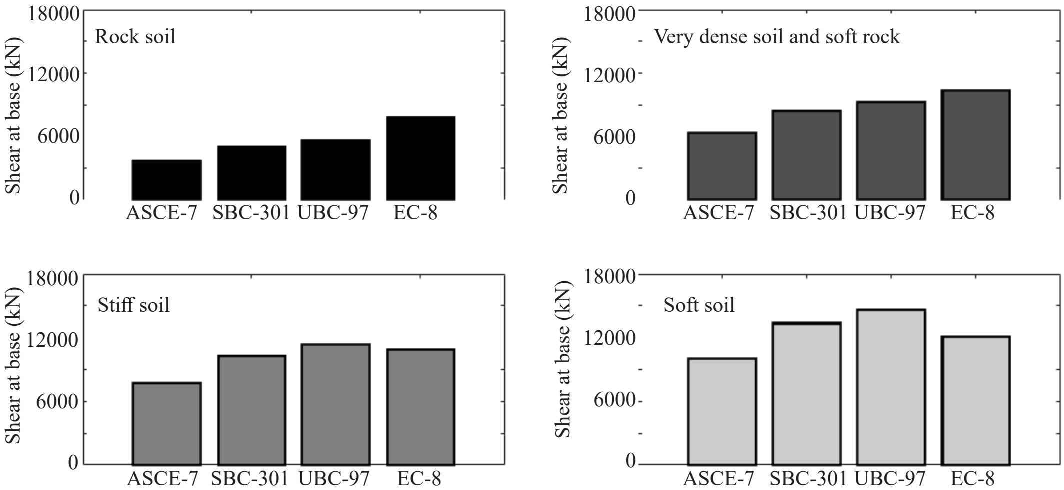

Fig. 11 Base shear computed according to the considered codes versus soil types for Haql region

period of around 2500 years such as ASCE and SBC. The UBC-97 seismic design code uses an MCE with a 10% probability of exceedance in 50 years with a return period of around 500 years. However, MCE is missing from the European code. Moreover, the established expressions for the ordinates of inelastic design spectra vary depending on the seismic design code. Among the different codes considered in this study, two divide the spectrum into four parts, ASCE-7 and EC-8, and the other two divide it into three parts, UBC-97 and SBC-301. In addition, the codes also differ significantly on the issue of minimum design base shear, where the EC-8 has no minimum limit on design base shear.

6 Conclusions

The present study is an attempt to evaluate the seismic performance of an RC high-rise building with shear walls designed following the national building code of Saudi Arabia and three other codes. The study, as a whole, identifies the influencing parameters in terms of seismic region intensity, response reduction factor, and site class, which can regulate the effect of changing the design code on the seismic behavior of high-rise buildings. The seismic responses of the selected buildings were investigated for several seismic levels ranging from 0.03 g to 0.3 g according to the regions in Saudi Arabia. The effect of site class on the design base shear for all the considered seismic regions was investigated to provide exhaustive guidelines regarding this issue. The following conclusions were drawn:

1. The effect of seismic level, which is the primary parameter that regulates the seismic response of the building, appreciably alters the seismic responses of a building structure.

2. The effect of site class, which is considered as one of the primary seismic provisions, appreciably alters the design base shear of a building structure. This effect is more pronounced with the decrease in the hardness of soil, regardless of the seismicity level. Thus, evaluation of the design base shear without assigning an accurate site class may cause serious errors in seismic design.

3. The effect of code change on the induced seismic responses is appreciably altered even for low PGA level. This is evident from the comparison of the results for the Dammam region, which has the lowest PGA, and the other regions.

4. If the effect of seismicity level is not considered while studying the seismic behavior of high-rise buildings, the difference between the SBC-301 and ASCE-7 may not be apparent as the two codes provide similar results for low PGA. However, the SBC-301 produces story responses significantly higher than those obtained using the ASCE-7 as the seismic intensity increases.

5. The higher the seismicity level, the higher the induced seismic responses obtained using the EC-8 as compared to the responses obtained using the other codes.

6. The lower the seismic level, the higher the induced seismic responses obtained using the UBC-97 as compared to those obtained using the other codes. In addition, the weaker the supporting soil, the higher the induced shear forces at the base as obtained using the UBC-97 as compared to the values obtained using the other codes.

7. Among all the considered seismic codes, the story responses generated employing the ASCE-7 are, in general, smaller than those induced for the dynamic seismic loads following the guidelines of the other codes.

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