

Impact of lateral force-resisting system and design/construction practices on seismic performance and cost of tall buildings in Dubai, UAE

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Abstract: The local design and construction practices in the United Arab Emirates (UAE), together with Dubai's unique rate of development, warrant special attention to the selection of Lateral Force-Resisting Systems (LFRS). This research proposes four different feasible solutions for the selection of the LFRS for tall buildings and quantifies the impact of these selections on seismic performance and cost. The systems considered are: Steel Special Moment-Resisting Frame (SMRF), Concrete SMRF, Steel Dual System (SMRF with Special Steel Plates Shear Wall, SPSW), and Concrete Dual System (SMRF with Special Concrete Shear Wall, SCSW). The LFRS selection is driven by seismic setup as well as the adopted design and construction practices in Dubai. It is found that the concrete design alternatives are consistently less expensive than their steel counterparts. The steel dual system is expected to have the least damage based on its relatively lesser interstory drifts. However, this preferred performance comes at a higher initial construction cost. Conversely, the steel SMRF system is expected to have the most damage and associated repair cost due to its excessive flexibility. The two concrete alternatives are expected to have relatively moderate damage and repair costs in addition to their lesser initial construction cost.

Keywords: special moment-resisting frames (SMRF); special shear wall; Dubai, UAE seismicity; steel; concrete; dual system

1 Introduction and background

Over the past three decades, the United Arab Emirates (UAE) has undergone vast development in the construction of high-rise buildings, particularly in Dubai, due to increased population density and economic growth. Due to this rapid development of high-rise construction, significant attention has been given to the seismic risk to the country's buildings and infrastructure (Barakat *et al.*, 2008). UAE, in general, is not an exceptionally seismically active area, especially when compared to its neighbor, Iran (Fig. 1). However, it can be seen that UAE is in relative proximity to the highly active area of southern Iran. This potentially impacts the northern parts of UAE, especially the locations that are on the Gulf shore, such as Ras Al-Khaimah and Dubai. This study focuses on tall buildings constructed in Dubai. Tall buildings are particularly vulnerable to strong ground motions propagating from

relatively long distances with high energy levels at low predominant frequencies. Therefore, the lateral design of tall buildings in Dubai is very important.

When selecting a lateral force-resisting system, the main concern of the Structural Engineer of Record (SEOR) is to achieve desirable seismic performance. Routinely, the SEOR devises multiple structural system solutions, from which the client selects the most favorable one. Many factors may influence the client's decision, such as functionality or cost of maintenance and repair, etc. In many instances, the selection is cost driven.

1.1 UAE seismic studies

Since the mid-1990's, the UAE has been the subject of several seismic hazard studies despite the paucity of major seismic activity (e.g., Al-Haddad *et al.*, 1994; Pieris *et al.*, 2006; Sigbjornsson and ElNashai, 2006; Aldama-Bustos *et al.*, 2009; Shama, 2011). Upon review of available seismic hazard studies, the need for uniformity and consensus is readily appreciated. This is due to the relative infancy of the pertinent research for this part of the world; thus, there is a shortage of detailed seismological information such as annual slip rates of fault systems, etc. As has been the case with other

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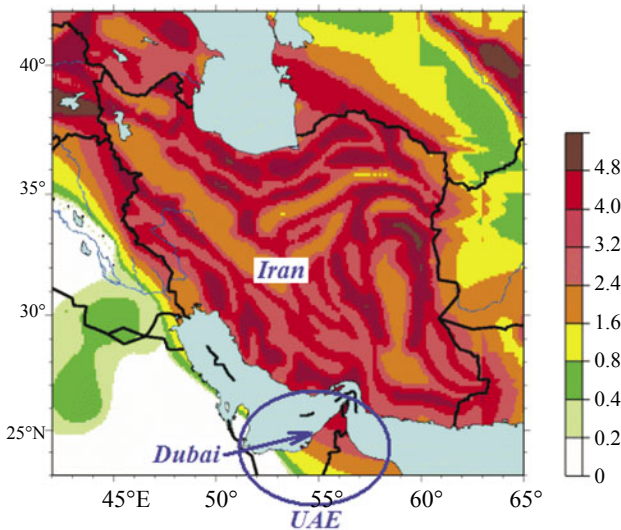


Fig. 1 Peak ground acceleration (m/s^2) with 10% probability of exceedance in 50 years (adopted from USGS, 2012)

well-developed seismic hazard studies in other regions, most of the seismological information issues will be resolved as more research is carried out in this area. The diversity in the estimates of the seismic hazard in Dubai has a significant impact on the selection of lateral load-resisting systems.

Given its wide acceptance among engineers, the International Building Code [IBC'12] (ICC, 2012) is used in this study as a model building code. In the IBC'12, the Seismic Design Category (SDC) and height limit are two examples of such impact. Based on different estimates of the spectral accelerations S_s and S_1 , the SDC can vary from "B" to "D" while the height limit can vary from "No Limit" to a mere 49 m (160 ft). Table 1 summarizes the spectral parameters and the corresponding SDCs from three recent studies, namely: Sigbjornsson and Elnashai (2006), Aldama-Bustos *et al.* (2009) and Shama (2011).

The SDC "D" will restrict the use of certain lateral systems and impose height limitations on others, while requiring a certain level of special detailing that promotes desirable ductile behavior. Although adopting a SDC "D" might be arguably overly conservative, the structural safety implications are justifiable considering the responsibility towards the public safety. In this investigation, the seismic parameters are adopted from the first study since it represents sound structural design considerations given the uncertainty associated with the seismic hazard in Dubai. The same seismic hazard study has been adopted in several recent studies (e.g., Mwafy

et al., 2006; Mwafy, 2010; AlHamaydeh *et al.*, 2011; Jeong *et al.*, 2012) and is widely accepted as a rational estimate of the local and regional seismic hazard.

Among the many lateral force-resisting systems that are described in the IBC'12, only a partial sub-group of systems are usable and/or preferable in the UAE, given the state-of-the-practice and the mandated SDC (governed by S_s and S_1 estimates).

1.2 Lateral systems

IBC'12 defines several lateral load resisting systems that can be considered in the design of a tall building. Among these are: Special Moment Resisting Frames (SMRF); Special Shear Wall; and Dual systems which are combinations of both. Many of the defined systems have height limitations when used for Seismic Design Category "D." However, the following thirteen systems can be adopted with no height limitations:

• Moment-Resisting Frame Systems

(1) Steel special moment frames

(2) Special reinforced concrete moment frames

• Dual Systems with Special Moment Frames capable of resisting at least 25% of prescribed seismic forces

(3) Steel eccentrically braced frames

(4) Steel special concentrically braced frames

(5) Special reinforced concrete shear walls

(6) Steel special plate shear walls

(7) Steel and concrete composite eccentrically braced frames

(8) Steel and concrete composite special concentrically braced frames

(9) Steel and concrete composite plate shear walls

(10) Steel and concrete composite special shear walls

(11) Special reinforced masonry shear walls

(12) Steel buckling-restrained braced frames

(13) Steel special plate shear walls

Under the *Moment-Resisting Frame Systems* category, only two systems are available for use with SDC "D". Therefore, these two systems and their counterparts from the Dual Systems category are considered as the lateral load-resisting systems in the current study. The shear wall system and the dual system are the most commonly used in UAE. The main lateral load-resisting system can be made of concrete or steel. Although steel construction is available in UAE, RC is the most commonly used construction material.

SMRFs are called special due to the special design and detailing criteria to which they conform in order

Table 1 Seismic design category conforming to IBC'12

Seismic hazard study	S_s (g)	S_1 (g)	S_{DS} (g)	S_{D1} (g)	SDC
(Sigbjornsson and Elnashai, 2006)	0.71	0.59	0.59	0.59	D
(Aldama-Bustos <i>et al.</i> , 2009)	0.18	0.06	0.20	0.10	B
(Shama, 2011)	0.28	0.57	0.51	0.34	D

to exhibit desirable performance, such as energy dissipation during strong seismic events. The basic components of SMRFs are: beams, columns, and beam-column connections. SMRFs are designed to resist earthquakes based on their inelastic behavior, which is developed through the formation of plastic hinges. Plastic hinges are formed at the beam-column joints and column bases. In a SMRF, the main factors that affect the selection of the size of the columns and beams are the following: controlling drift below allowable limits, avoiding P-Delta instabilities, and proportioning the members based on strong column-weak beam criteria. Using SMRFs allows unmatched architectural freedom, resulting in more open interior and exterior spaces. Another advantage is that the smaller forces imposed on the foundation result in systems that are more economical. Some economical limitations occasionally arise from the use of heavy sections. As a result, SMRFs are sometimes more expensive to build than shear wall or braced frame structures (Moehle *et al.*, 2008; Hamburger *et al.*, 2009).

The dual systems adopt a belt and suspenders philosophy, by requiring the SMRF strength capacity to meet at least 25% of the seismic forces. The shear walls function as vertical cantilever beams that develop the needed stiffness, strength, and ductility to resist the majority of the lateral forces. Mostly, the design of the shear wall is controlled by the flexural requirements rather than shear requirements. In the case of the steel plate shear walls, SPSW, they consist of two vertical columns called Vertical Boundary Elements (VBE), and two horizontal beams called Horizontal Boundary Elements (HBE) surrounding an infill steel plate. The steel plate undergoes large inelastic deformations while the boundary elements are designed to remain elastic under the lateral forces resulting from earthquake actions. Using SMRF with SPSW has many advantages, primarily because less detailing requirements are needed. In addition, fewer numbers of bays are needed to resist lateral forces, and construction can be achieved at a rapid pace. Moreover, the weight is relatively less than that of the concrete dual system. Some of the major limitations of the SPSW, however, are the complex analysis techniques needed to capture its nonlinear behavior and the fact that they are relatively softer in comparison to concrete shear walls (Sabelli and Bruneau, 2007).

1.3 Seismic performance

The seismic performance (performance level) is described by designating the maximum allowable damage state (damage parameter) for an identified seismic hazard (hazard level). Performance levels describe the state of a structure after it is subjected to a certain hazard level as: Fully Operational (FO), Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP), or Collapse (C) (SEACO, 1995; FEMA, 1997). Overall lateral deflection, ductility demand, and interstory drift are the most commonly used damage parameters. The

five qualitative performance levels are related to the corresponding five quantitative maximum interstory drift limits (as a damage parameter), and are: < 0.2 , < 0.5 , < 1.5 , < 2.5 , and $> 2.5\%$, respectively. The hazard level can be presented by the probability of exceedance of 50, 10, and 2% in 50 years for low, medium, and high intensities of ground motions, respectively. Figure 2 shows the typical seismic performance objectives as defined by the SEAOC Blue Book (SEAOC, 1999). This performance-based seismic design and evaluation is now routinely performed for new and existing projects in the region (e.g., Berahman, 2010). In this study, the interstory drift is taken as a representative measure of the seismic performance of the studied buildings.

The significance of this study is drawn from the fact that it provides a quantitative comparison of four different LFRSs that are feasible for use in tall buildings in Dubai. The comparison includes the expected seismic performance along with the projected cost of the four structural systems. An understanding of the suitability and feasibility of the different systems given the standard local practices for design and construction is also provided. Furthermore, alternative thought processes and rationales involved in the selection of LFRSs are presented based on the specific objectives of the project.

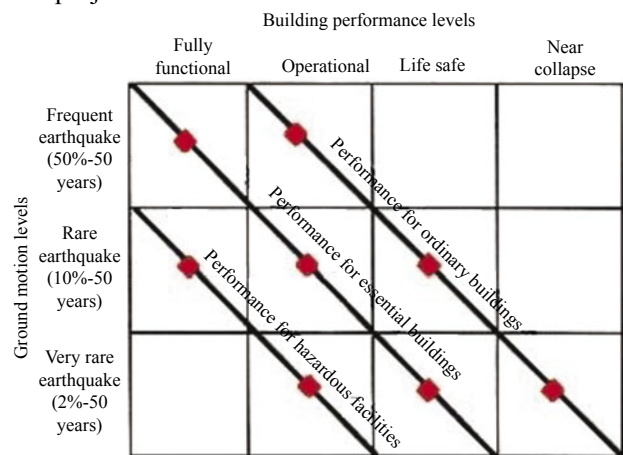


Fig. 2 Expected performance as related to building type and level of ground motion (adopted from SEAOC vision 2000, 1995)

2 Structural design and performance parameters

This study focuses on four structural systems; two reinforced concrete (RC) and two steel structures. The considered systems are: Steel Special Moment-Resisting Frame (SMRF), Concrete SMRF, Steel Dual System (SMRF with Special Steel Plates Shear Wall, SPSW), and Concrete Dual System (SMRF with Special Concrete Shear Wall, SCSW). These systems have no height limits in SDC "D," thus have been selected as feasible solutions for many tall buildings with different heights. Three response parameters are used for differential

inspection amongst the four lateral force-resisting systems, namely: the interstory drift ratio, the story shear and the story overturning moment. The interstory drift ratio is selected as a major and direct response indicator for expected seismic performance and damage. On the other hand, the story shear and overturning moment are directly proportional to the superstructural (columns, beams, and shear walls) and substructural (foundation) construction costs.

2.1 Building descriptions and design criteria

The building considered is a 20-story office building to be constructed in downtown Dubai, UAE. The total height of the building is 79.25 m plus a 1.07 m high parapet. The building footprint is rectangular with six bays of 6.1 m in the East-West direction, and five bays of 6.1 m in the North-South direction. The building has a 3.66 m high penthouse on the roof, covering 2-bays (12.2 m, in length) and one bay (6.1 m, in width). For maximum torsional resistance, the lateral resisting system is located at the perimeter of the building. P-Delta secondary effects were included via a leaning

column modelling technique (Geschwindner, 2002) using ETABS commercial package (CSI, 2012). The buildings are designed to meet the requirements of the IBC'12 (2012), which refers to the following standards for minimum design loads and design/detailing requirements: ASCE7-10 (ASCE/SEI, 2010), ACI318-11 (ACI, 2011), AISC360-10 (AISC, 2010), AISC341-10 (AISC, 2010), AISC358-10 (AISC, 2010). The strength and drift design of the frame elements was conducted using ETABS (CSI, 2012), whereas the shear wall strength design was done using in-house spreadsheets following the applicable ACI and AISC standards.

2.2 Structural systems and details

Figure 3 shows the plan views and the structural system of the four designed buildings, and Fig. 4 shows their elevations. As the considered alternative systems are for the lateral load-resisting systems on the periphery of the building, the two steel/concrete options share the same interior gravity system. For economical designs and ease of constructability, all gravity and lateral system sections were the same size every two floors, except for

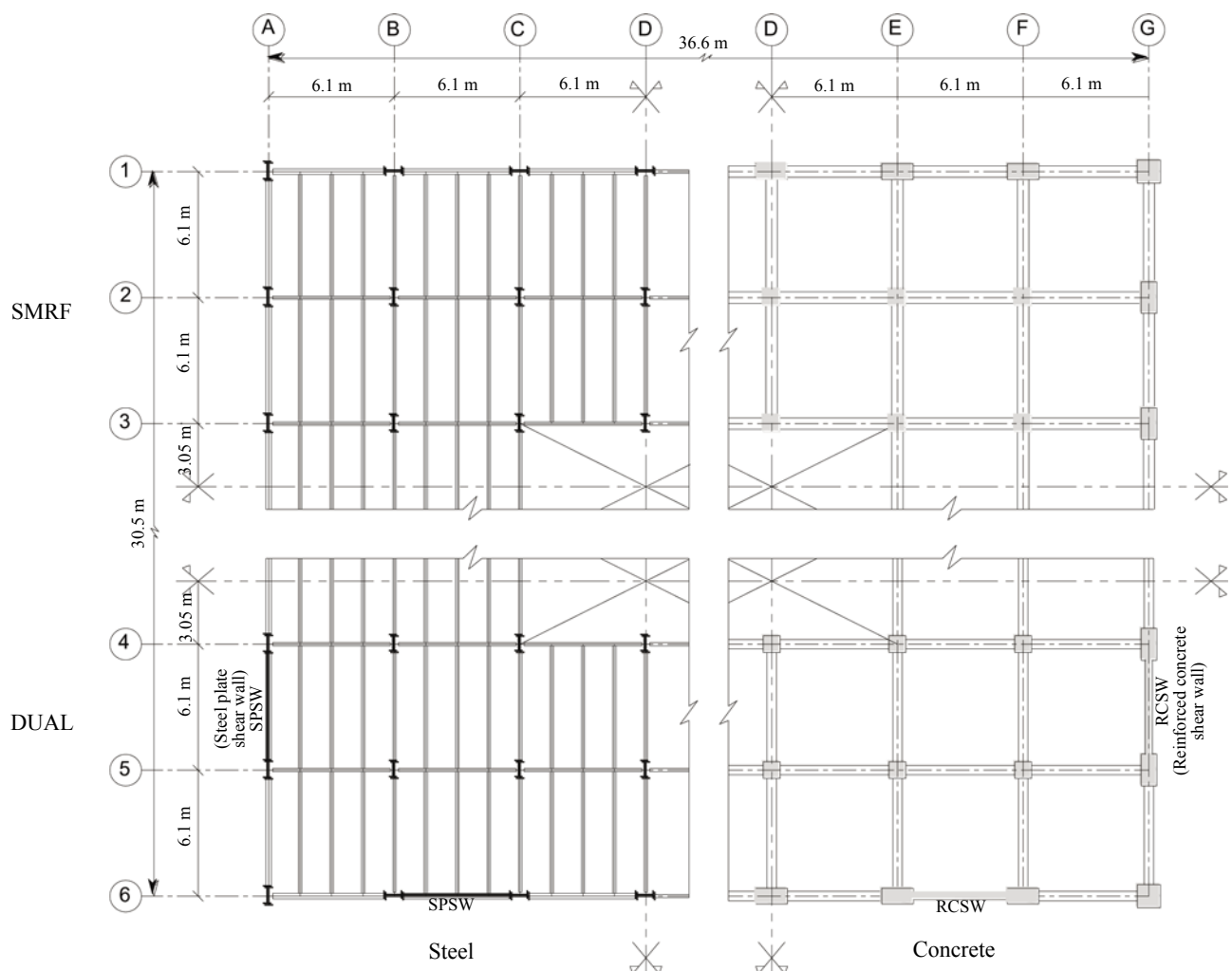


Fig. 3 Plan view showing the four studied structural systems of the buildings

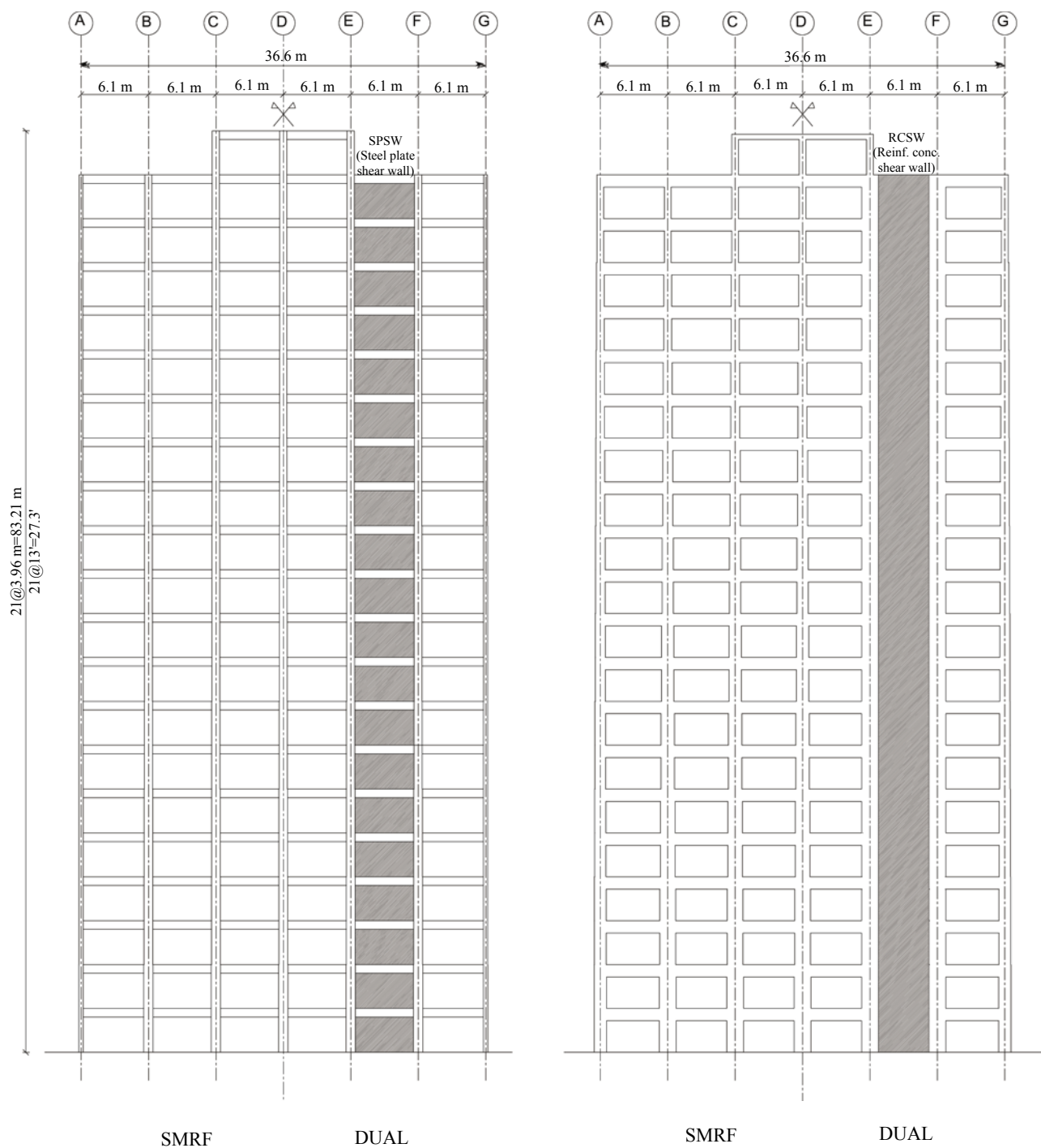


Fig. 4 Elevations of the four 20-story buildings

the RC shear walls, which had the same dimensions throughout the building height but with varying steel reinforcement. This option is adopted to represent the state-of-the-practice for conventional construction in Dubai. The number and layout of the shearwalls have been selected based on common structural engineering practice and conventional wisdom. Different shearwall configurations could potentially produce different structural behavior and construction cost. The proposed shearwall configuration is a valid practical and common design alternative. Therefore, it is deemed acceptable for

the purpose of this research, since it aims at evaluating the performance of a class of buildings, rather than a specific building that is sensitive to its particular design. Furthermore, the same shearwall configuration is used in the considered systems, thus the relative structural behavior comparisons are valid. The gravity systems for the steel/concrete alternatives are presented in Table 2. The lateral systems are described in Tables 3 and 4 for the different alternatives. Typically, the lateral systems are designed to resist the story forces resulting from the seismic and wind loads, whichever is controlling at the

Table 2 Sizes of the internal gravity systems of the SMRF and Dual structures

Story	Steel column ^a	Concrete column ^b
19-20	W254×101	406×406
17-18	W254×115	406×406
15-16	W356×110	457×457
13-14	W356×112	508×508
11-12	W406×149	559×559
9-10	W457×117	610×610
7-8	W457×213	660×660
5-6	W610×241	711×711
3-4	W686×265	762×762
1-2	W762×284	813×813
Beam	W457×60	254×508

Note: ^a SI conversion of AISC standard sections: W $i \times j$; wide-flange steel section with depth i (mm) and weight j (9.8 N/m);

^b SI conversion of $b \times h$; rectangular concrete section with width b (mm) and depth h (mm).

floor of interest.

It is found that the adopted seismic parameters produce controlling load cases over the wind cases for all the considered systems. The concrete shear walls required boundary elements at their ends with special confinement reinforcement. For the steel shear walls to exhibit ductile behavior, specially designed and detailed horizontal and vertical boundary elements are required. Further details of the four designs can be found in AlHamaydeh *et al.* (2012).

2.3 Seismic performance of the considered alternatives

The building design alternatives are considered feasible in Dubai and conform to the local construction industry standards. Some key aspects of the designs are tabulated as a measure of the main static (gravity load) and dynamic (period, base shear, and overturning moment) characteristics of each alternative. Table 5 summarizes the building weight, natural period of

Table 3 Sizes of lateral load resisting systems: SMRF elements

Story	Steel column ^a		Concrete column ^b			
	SMRF	Dual	SMRF		Dual	
			Middle	Corner	Middle	Corner
19-20	W610×308	W305×312	305×610	610×610	356×864	610×610
17-18	W610×341	W356×287	356×711	711×711	406×813	711×711
15-16	W610×372	W356×314	406×813	762×762	457×914	762×762
13-14	W610×415	W457×260	457×914	813×813	457×965	813×813
11-12	W686×289	W533×247	508×1016	864×864	508×1016	864×864
9-10	W686×323	W610×241	559×1118	914×914	559×1118	914×914
7-8	W686×418	W610×262	610×1220	965×965	610×1219	965×965
5-6	W762×314	W610×286	660×1321	1016×1016	660×1321	1016×1016
3-4	W762×350	W610×308	711×1422	1068×1068	711×1422	1068×1068
1-2	W762×582	W610×341	762×1524	1118×1118	762×1542	1118×1118
Beam ^b	W762×220	W533×219	559×1118		457×914	

Note: ^a SI conversion of AISC standard sections: W $i \times j$; wide-flange steel section with depth i (mm) and weight j (9.8 N/m);

^b SI conversion of $b \times h$; rectangular concrete section with width b (mm) and depth h (mm)

Table 4 Sizes of the lateral load resisting systems: shear wall elements

Story	Steel shear wall			Concrete shear wall	
	VBE ^a	HBE ^a	t_w^b	Length	7900
19-20	W610×140	W457×213	2.7	Thickness	300
17-18	W131×195	W457×213	3.2	L_{BE}	460
15-16	W610×217	W457×213	3.4	R_{BE}	16T36
13-14	W610×241	W457×213	4.8	$C_{BE,w}$	3T16@100mm
11-12	W610×308	W457×213	6.4	$C_{BE,L}$	5T16@100mm
9-10	W610×341	W457×213	8	R_{HW}	2T22@300mm
7-8	W610×415	W457×213	8	R_{VW}	2T22@300mm
5-6	W610×455	W457×213	10		
3-4	W610×551	W457×213	11		
1-2	W762×582	W838×473	13		

Note: ^a SI conversion of AISC standard sections: W $i \times j$; wide-flange steel section with depth i (mm) and weight j (9.8 N/m); ^b Web thickness (mm); L_{BE} : boundary element length; R_{BE} : boundary element reinf.; $C_{BE,w}$: boundary element confin. Reinf. perpendicular to wall; $C_{BE,L}$: boundary element confin. Reinf. parallel to wall; R_{HW} : shear wall horz. reinf.; R_{VW} : shear wall vert. reinf

Table 5 Comparison of key structural design parameters

	Steel		Concrete	
	SMRF	Dual	SMRF	Dual
Building weight (kN)	106,618	108,127	196,313	200,481
Natural period (s)	3.72	2.67	3.83	2.88
Base shear (kN)	4,842	5,822	7,039	7,575
Overturning moment (MN.m)	3,826	3,944	5,674	5,703

vibration, seismic base shear and base overturning moment. All of the reported results are obtained from the Static Equivalent Lateral Force (SELF) method. Upon inspection of the key parameters, the following is noted:

- The dual systems are slightly heavier, have shorter natural periods and attract higher base shears compared to their SMRF counterparts.
- The added weight due to the use of dual systems (vs. SMRF) is negligible and does not significantly impact materials cost for both steel and concrete.
- The steel alternatives tend to weigh less (less material quantities) than their concrete counterparts but have higher cost due to the necessary skilled labor installation, fire proofing and material price differences.
- The steel systems have smaller overturning moment compared to their concrete counterparts, which translates into footing design savings.
- The faster erection time for the steel buildings can partially offset the cost increase with earlier revenue generation and quicker capital return.

3 Time-history analysis (THA)

3.1 Selection and scaling of ground motion records

Due to the scarcity of local strong ground motion records in some regions, such as in the UAE, selection of representative earthquakes for structural analysis and design is not a trivial task. To overcome this obstacle, some researchers revert to simulated ground motions. For instance, AlHamaydeh *et al.* (2011) implemented the simulated earthquake records from the seismic hazard study by Sigbjornsson and ElNashai (2006) in a series of elaborate nonlinear analyses. Other researchers revert to selected *real* recorded ground motions that represent the site hazard and are pertinent to the structural systems considered (e.g., Azimi *et al.*, 2009; Galal and Naimi, 2008).

Although both approaches have merit and are widely accepted in the seismic engineering arena, uniformity and consistency are yet to be achieved. Recently, the FEMA-P695 document (FEMA, 2009) introduced a systematic approach for quantification of structural seismic performance and collapse evaluation. As an integral part of the seismic evaluation process, a set of 22 Far-Field (> 10 km distances) ground motion records was compiled. The carefully selected records are

viewed as appropriate for nonlinear structural dynamic analysis since they conform to a number of sometimes conflicting objectives: (a) *Very strong ground motions*: representing the Maximum Considered Earthquake (MCE) level events; (b) *Site hazard independent*: independent of hazard deaggregation, source type and condition or site-specifics to be broadly appropriate; (c) *Structural type independent*: independent of structural period, lateral load-resisting system or properties to be broadly appropriate; (d) *Large number of records*: enough records to be “statistically” sufficient in describing median values as well as Record-To-Record (RTR) variability; and (e) *Consistent with the “ASCE7” standard*: for three-dimensional analysis of structures, the ground motion record *pairs* conform to section 16.1.3.2 of ASCE7-10 (ASCE/SEI, 2010). The details of FEMA-P695 Far-Field ensemble of selected records are summarized in Table 6, and their response spectrum is shown in Fig. 5. The earthquake records were acquired through the Pacific Earthquake Engineering Research [PEER] Center database (PEER, 2012). The table also shows the Acceleration/Velocity (A/V) ratio for the selected ensemble of ground motions. Tso *et al.* (1992) examined the significance of A/V ratio of the ground motion record as a parameter to indicate the dynamic characteristics of earthquakes. It was found that the A/V ratio can be used as a simple indicator for the frequency content of the ground motion. In this study, the A/V ratio of the 22 records range from 0.38 to 1.51 g.s/m, representing earthquakes with low, medium and high frequency contents.

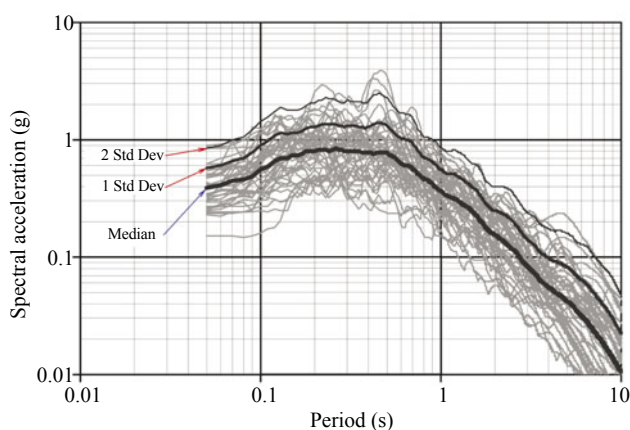
The FEMA-P695 procedure specifies the scaling requirements of the records in order to match specific target response spectra representing the appropriate SDC (B, C or D) criteria. Alternatively, the ASCE7-10 (section 16.1.3.2) scaling procedure can be utilized. In this study, the latter procedure is adopted through the use of the commercial software package *RspMatchEDT* (GeoMotions, 2012). The response spectrum of the scaled ensemble is illustrated in Fig. 6.

3.2 Discussion of THA results

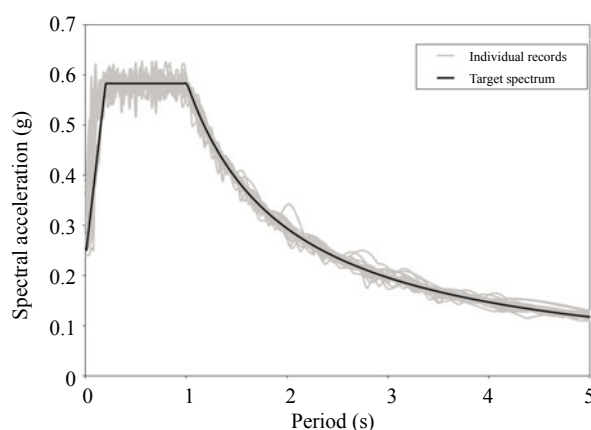
The four buildings are modeled using the commercial software package ETABS (CSI, 2012). The THA is limited to linear elastic behavior for simplicity and conformance with common state-of-the-practice in design firms. This simplification is justifiable based on the widely accepted Equal-Displacement rule (Veletsos

Table 6 Earthquake records recommended by FEMA-P695 [Adapted from PEER, 2012]

ID No.	M	Year	Name	Station	Site class	Fault type	Epicentral distance	PGA (g)	PGV (cm/s)	A/V (g.s/m)
1	6.7	1994	Northridge	Beverly Hills - Mulhol	D	Thrust	13.3	0.52	63	0.83
2	6.7	1994	Northridge	Canyon Country-WLC	D	Thrust	26.5	0.48	45	1.07
3	7.1	1999	Duzce, Turkey	Bolu	D	Strike-slip	41.3	0.82	62	1.32
4	7.1	1999	Hector Mine	Hector	C	Strike-slip	26.5	0.34	42	0.81
5	6.5	1979	Imperial Valley	Delta	D	Strike-slip	33.7	0.35	33	1.06
6	6.5	1979	Imperial Valley	El Centro Array #11	D	Strike-slip	29.4	0.38	42	0.90
7	6.9	1995	Kobe, Japan	Nishi-Akashi	C	Strike-slip	8.7	0.51	37	1.38
8	6.9	1995	Kobe, Japan	Shin-Osaka	D	Strike-slip	46.0	0.24	38	0.63
9	7.5	1999	Kocaeli, Turkey	Duzce	D	Strike-slip	98.2	0.36	59	0.61
10	7.5	1999	Kocaeli, Turkey	Arcelik	C	Strike-slip	53.7	0.22	40	0.55
11	7.3	1992	Landers	Yermo Fire Station	D	Strike-slip	86.0	0.24	52	0.46
12	7.3	1992	Landers	Coolwater	D	Strike-slip	82.1	0.42	42	1.00
13	6.9	1989	Loma Prieta	Capitola	D	Strike-slip	9.8	0.53	35	1.51
14	6.9	1989	Loma Prieta	Gilroy Array #3	D	Strike-slip	31.4	0.56	45	1.24
15	7.4	1990	Manjil, Iran	Abbar	C	Strike-slip	40.4	0.51	54	0.94
16	6.5	1987	Superstition Hills	El Centro Imp. Co.	D	Strike-slip	35.8	0.36	46	0.78
17	6.5	1987	Superstition Hills	Poe Road (temp)	D	Strike-slip	11.2	0.45	36	1.25
18	7.0	1992	Cape Mendocino	Rio Dell Overpass	D	Thrust	22.7	0.55	44	1.25
19	7.6	1999	Chi-Chi, Taiwan	CHY101	D	Thrust	32.0	0.44	115	0.38
20	7.6	1999	Chi-Chi, Taiwan	TCU045	C	Thrust	77.5	0.51	39	1.31
21	6.6	1971	San Fernando	LA - Hollywood Stor	D	Thrust	39.5	0.21	19	1.11
22	6.5	1976	Friuli, Italy	Tolmezzo	C	Thrust	20.2	0.35	31	1.13

**Fig. 5 Response spectra of forty-four individual components of the normalized far-field record set (adopted from FEMA-P695, 2009)**

and Newmark, 1960). The inelastic displacements and drifts are obtained by reducing the elastic-level drift into design-level drifts [via dividing by the *Response Modification Factor* (R -Factor)], then magnifying them to the inelastic-level [via multiplying by the *Deflection Amplification Factor* (C_d -Factor)]. The code-assigned values of the R -Factor are: 7 for the concrete dual system, and 8 for all the other systems. The code-assigned values of the C_d -Factor are: 6.5 for the steel dual system, and 5.5

**Fig. 6 Response spectra of scaled earthquake records**

for all the other systems. The THA analysis conforms to the procedure prescribed in section 16.1.3.2 of ASCE7-10 where the two horizontal components of each of the 22 earthquake records are simultaneously applied. In order to envelope the peak structural response, both major and minor record components are rotated horizontally such that the two principal directions of the buildings have equal opportunity of exposure to both earthquake components. The envelope of both horizontal cases is

recorded at every floor for both principal directions of the buildings. As a sample, Fig. 7 shows the interstory drift response of the steel SMRF building for individual records as well as the *mean* (μ) and the *mean plus/minus standard deviation* ($\mu \pm \sigma$). For brevity, henceforth, the peak responses of the buildings in the East-West and North-South directions are combined using the Square Root of the Sum of the Squares (SRSS) rule and only the *mean plus standard deviation* ($\mu + \sigma$) quantities are shown.

Figure 8 illustrates the inelastic interstory drift response along the height of the four systems to the ensemble of earthquake records. To allow for direct comparison of the individual buildings responses, the seismic performance criteria are superimposed into the figure. All four systems exhibit desirable seismic performance ranging from IO and LS. Typical trends of relative flexibility are observed; for example, the SMRF systems exhibit higher drift ratios than their dual systems counterparts. The steel dual system is observed to be stiffer than the concrete dual system, which can be attributed to the stiffening effect of the HBES. Typical lower soft story (relatively excessive drifts) behavior is evident in the SMRF systems, whereas intermediate

soft story behavior is demonstrated by the dual systems. The upwards shift in the soft story location at the dual systems is a consequence of the cantilever effect of the walls. The concrete SMRF system drift ratios are almost constant along most of the mid-height, indicating that the design is drift-controlled at those locations. It is worth mentioning that the two concrete systems (SMRF and Dual) appear to produce comparable inelastic code-specified drifts in Fig. 8. This apparent match is due to the inelastic drift calculation procedure, and should not be construed as a design flaw. The two systems produce different elastic-level displacements and drifts that reflect the relative stiffness of the systems; the Dual system is inherently stiffer and thus exhibits about 14% (on average) lesser displacements than the SMRF system. However, these elastic-level displacements are divided by different *R-Factors* (7 for Dual; 8 for SMRF), then multiplied by the same *C_d-Factor* (5.5 for Dual/SMRF), resulting in comparable outcomes.

The distribution of the story shears and story overturning moments along the systems heights are shown in Fig. 9 and Fig. 10, respectively. The response of individual systems demonstrate the typical trends of relative stiffness and weight; for instance, the concrete

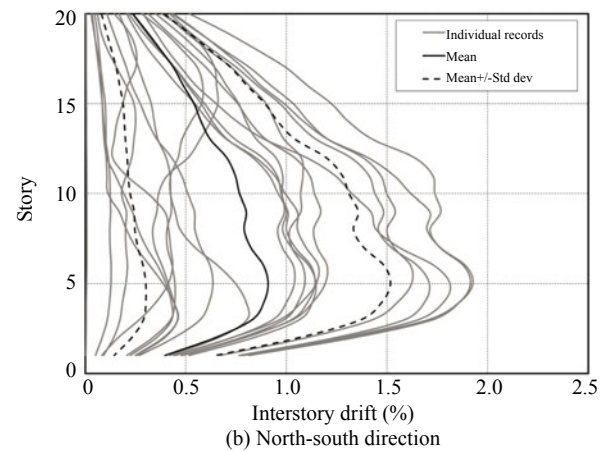
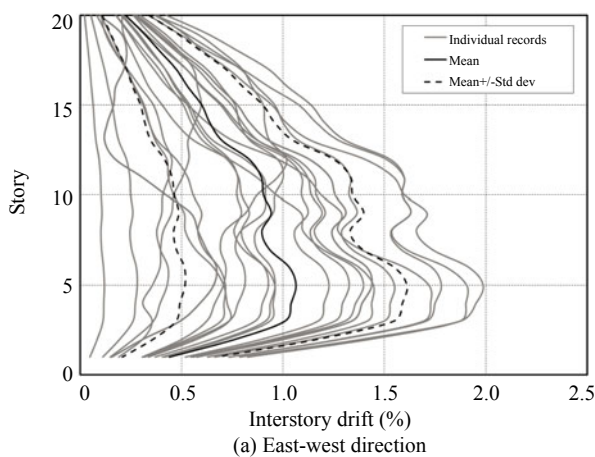


Fig. 7 Interstory drift response of the steel SMRF building to the earthquake records

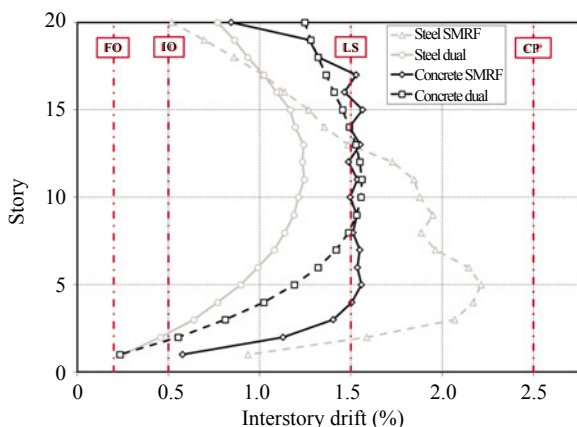


Fig. 8 Four buildings inelastic interstory drift response to the earthquake records

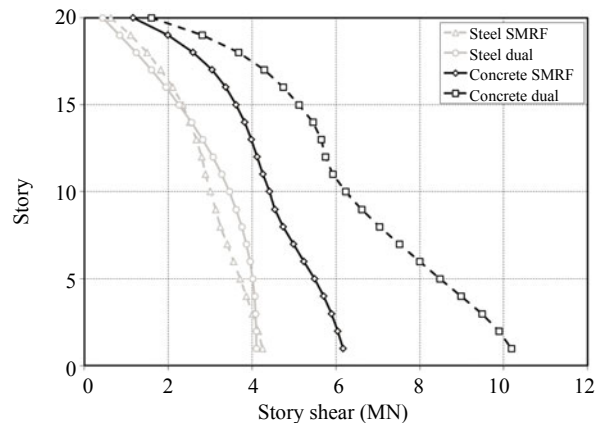


Fig. 9 Four buildings design-level story shear response to the earthquake records

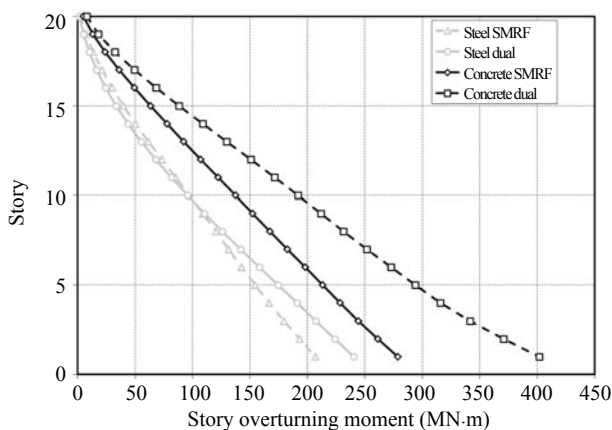


Fig. 10 Four buildings design-level overturning moment response to the earthquake records

systems are heavier than their steel counterparts and thus experience higher inertial forces resulting in higher overturning moments as well. Similarly, the dual systems are stiffer and tend to develop higher spring forces as they deflect. The increased spring forces are manifested through increased overturning moments. The story forces and overturning moments are not to be construed as elastic demands, as they are design-level actions reflecting the corresponding *R-Factors*; this allows for realistic comparisons of the produced designs. The selected systems have comparable inherent desirable performance that is intended by the code-assigned *R-Factors*.

4 Quantities and associated cost estimation methodology

Due to the rapid urban development and the harsh climate environment, the structural life-span cycle is relatively short in the UAE. Local maintenance costs do not vary significantly between the concrete and steel buildings and are not expected to influence any differential cost analysis. Consequently, the buildings' construction cost, excluding lifetime maintenance costs, is of interest here. For the two buildings to be constructed with either steel or concrete, the gravity system is identical and will not be a differentiating factor in the construction cost of the lateral systems. The

construction cost for concrete is significantly lower than that for steel in the UAE. However, steel construction speed allows for rapid scheduling as well as early project completion and delivery. This is translated into direct cost reductions associated with early real estate revenue generation and accelerated capital return. This type of economical investigation is routinely included in decision-making strategies for real estate developers. Consequently, the construction costs of the two steel options are augmented with cost reductions that are representative of projected early revenue.

Table 7 summarizes the bill-of-quantities for the lateral force-resisting systems as well as the associated construction cost and projected early revenue. Construction cost and scheduling estimates presented herein reflect realistic local UAE market trends and prices obtained through published surveys (e.g., Bruce Shaw handbook, 2012) as well as personal communications with regional offices of major consulting firms and major local contracting companies. Since steel prices are typically expressed per ton and concrete prices are typically expressed per cubic meters, all quantities and unit prices are converted to volumetric representations including the incurred labor cost. Footing construction cost is directly associated with the selected lateral force-resisting system and thus the reported values reflect the relatively higher overturning forces in dual systems as compared to SMRF systems. The additional materials due to utilizing the dual systems are not significant when compared to their SMRF counterparts (2% in steel and 1.5% in concrete, by weight). However, the dual systems would incur additional costs due to larger required footing sizes. Consequently, system differentiation is not a trivial task and will not depend solely on the superstructure bill-of-quantities. A holistic system differentiation approach, including the direct and indirect costs and their implications in each system, is presented in the following section.

5 Impact of LFRS on seismic performance and cost

Since there are several, often contradicting, considerations that could influence the selection of the LFRS, the relative pros and cons of each system are presented. Several possible thought processes involved

Table 7 Summarized bill-of-quantities and associated cost for the lateral force-resisting systems

		Materials - Volume (m ³)				Cost (\$) ^a			
		Columns	Beams	Walls	Total	Structural system cost	Footing cost	Projected early revenue	Net cost
System	Steel	17	48	104	169	2,369,590	304,009	668,400	2,005,199
	Concrete	357	713	1135	2205	1,107,819	795,071	N/A	1,902,891
	Concrete	1128	1676	N/A	2804	793,308	551,118	N/A	1,344,427
	Steel	82	75	N/A	158	2,210,600	262,088	618,172	1,854,516

Note: ^aThe shown values are based on a survey of the 2012 construction cost in Dubai, UAE

in adopting specific solutions are also presented. It is recognized that often times, the selection of structural systems is not solely performance driven. Ultimately, the specific needs of the pertinent project would drive the decision in one direction or another.

The seismic performance of all the considered systems is found to be desirable and satisfies both the collapse-prevention as well as the life-safety design objectives as can be seen in Fig. 8. Thus, all four systems are deemed as acceptable design alternatives. The maximum interstory drift ratio along the building height is utilized as a direct measure to rank the systems in terms of seismic performance. Figure 11 is an attempt to quantify the trade-offs of cost versus seismic performance. Therefore, interstory drift, construction cost and net cost, including early revenue, are normalized relative to the respective minimum value; i.e. the system with the minimum parameter will be the benchmark for assessing the other systems. Due to the high local steel prices (material and labor), the concrete options are consistently less expensive. If material and cost were the only selection criteria, concrete construction would always be more attractive for the obvious economic benefits. However, the early revenue-generation associated with steel construction helps alleviate and offset considerable percentages of the additional cost (up to 25%, based on the UAE market survey). This is clear in the case of the dual systems, where the aggregation of the additional footing and superstructure bill-of-quantities are “paid-off” by the early real estate rental. The additional cost of the steel dual system is only 5% more than that of the concrete dual system. Although the concrete dual system is considered more economical, it exhibits 25% more drift than the steel dual system; an acceptable trade-off.

Due to their practicality and convenience, the SMRF systems are usually preferred over systems with shear walls. However, SMRF systems undergo higher drifts than dual systems; sometimes by a significant margin. This renders the SMRFs prone to suffering more complications associated with excessive structural and

nonstructural repairs subsequent to seismic events; another reasonable trade-off between initial capital cost and possible repair cost. When the considered SMRF systems are compared, the concrete system outperforms the steel system in performance and cost, making the concrete solution an obvious preference. The same cannot be said about the two dual systems, as demonstrated above.

If initial capital is the main concern and little regard is given to the possible cost of repairs and down-time due to seismic events, the two concrete systems would be most feasible over the steel systems. Both concrete systems are expected to have comparable performance, yet the SMRF would be the most attractive solution, even among all four systems. This type of selection would typically be made by the designers who choose to undermine the probability of experiencing a seismic event within the short life span of buildings in UAE. If seismic events are viewed by the decision makers as a formidable threat that would cause significant property damage, the system selection would be performance driven and the steel dual system would prevail. It offers substantial performance improvement, followed by the two concrete systems at a 25% increase in drift. The system that is expected to have the least favorable relative performance in terms of lateral drifts is the steel SMRF due to its excessive inherent flexibility. It is expected to experience 78% more drift than the steel dual system benchmark.

6 Summary and conclusions

Four different lateral force-resisting systems were investigated for feasibility of use in Dubai, UAE. The considered systems were two concrete systems: SMRF and dual (special shear walls with SMRF), as well as two steel counterparts. All designs were performed in conformance with the IBC'2012 code and the state-of-the-practice procedures in international design firms. Time-history analysis was performed in order to quantify the expected seismic performance of the four design alternatives. For seismic performance, several parameters were considered: (a) interstory drift, (b) story shear, and (c) story overturning moment. For economic differentiation, the lateral system cost was compared by taking into account the early real estate revenue generated by the faster steel construction.

Upon comparison of the four alternatives, it was found that they all have acceptable seismic behavior and that they are expected to have desirable performance (LS-level) during seismic events. The steel dual system is expected to have the least damage based on its relatively lesser interstory drifts. However, this preferred performance comes at a higher initial construction price. The steel SMRF system is expected to have the most damage and the associated repair cost due to its excessive flexibility. The two concrete alternatives are expected to have relatively moderate damage and repair

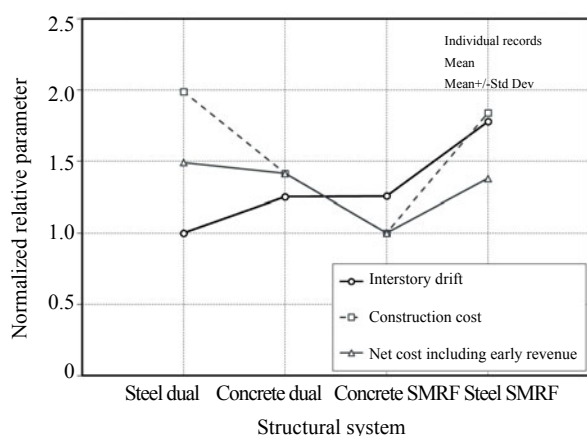


Fig. 11 Impact of lateral force-resisting system on seismic performance and cost

cost in addition to their lesser initial construction cost. Between the two concrete systems, the SMRF requires fewer materials, which is translated into lesser initial construction cost. However, it is more flexible and is expected to incur more repair cost after seismic events. Different real estate developers consider different risk factors affecting their investment plans, and as such, could use the devised framework for differential analysis. Real estate developers concerned only with initial cost will gravitate towards the use of the less expensive concrete alternatives. Developers that consider the seismic damage repair cost and the associated downtime cost (in the case of commercial buildings) will find the stiffer steel dual system more appealing.

Note that these conclusions are based on the findings of the dynamic analyses of the specified building systems along with their pertinent costs analysis. Further structural / cost analyses should be done considering other variables, such as building heights, etc., in order to generalize these conclusions.

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