

Design Alternatives for Lateral Force-Resisting Systems of Tall Buildings in Dubai, UAE

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Abstract—Four design alternatives for lateral force-resisting systems of tall buildings in Dubai, UAE are presented. Quantitative comparisons between the different designs are also made. This paper is intended to provide different feasible lateral systems to be used in Dubai in light of the available seismic hazard studies of the UAE. The different lateral systems are chosen in conformance with the International Building Code (IBC). Moreover, the expected behavior of each system is highlighted and light is shed on some of the cost implications associated with lateral system selection.

Keywords—Concrete, Dual, Dubai UAE Seismicity, Special Moment-Resisting Frames (SMRF), Special Shear Wall, Steel

I. INTRODUCTION

OVER the past two decades, Dubai had undergone vast developments in the construction of high rise buildings due to its increase in population density and economic growth. Currently, there are several seismic hazard studies and seismic design guidelines available for the city of Dubai and UAE in general [1]-[4]. Upon review of such documents, one can readily appreciate the need for uniformity and consensus. The findings and conclusions of the studies are significantly different, and in some cases, contradicting. In the case of the US Army Corps of Engineers, the difference in the seismicity parameters between the 1998 edition [3] and the 2010 edition [4] is quite astonishing. Such diversity in technical opinions about the seismic hazard in Dubai has an influential impact on the selection of lateral load-resisting systems conforming to the 2009 International Building Code (IBC'09) [5]. The IBC is widely accepted as the design code for tall buildings in Dubai. The Seismic Design Category (SDC) and height limit are two examples of such impact. The SDC can vary from "A" to "D" while the height limit can vary from 49m (160ft) to "No Limit".

The significance of this paper is drawn from the fact that it provides quantitative comparison of four different lateral load-resisting systems for use in Dubai. The following systems are considered since they do not have a height limit in SDC "D": (1) Steel Special Moment-Resisting Frame (SMRF), (2) Concrete SMRF, (3) Steel Dual System (SMRF with Special Steel Plates Shear Wall, SPSW), (4) Concrete Dual System (SMRF with Special Concrete Shear Wall, SCSW). SMRFs are called *special* due to the special design and detailing criteria to which they conform in order to exhibit desirable

performance, such as energy dissipation during strong seismic events. According to the IBC'09, when SMRFs are utilized in dual systems, the frames should be capable of resisting at least 25% of the seismic forces. Some of the advantages and limitations for the considered systems are described below.

A. Special Moment-Resisting Frames

The SMRF system is used as lateral resisting system mainly to resist earthquakes with high energy dissipation. 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, through special design and detailing requirements, at the beam-column joints and column bases. In a SMRF, the main factors that affect the columns and beams size selection are the following: controlling drift below allowable limits, avoiding P-Delta instabilities, and proportioning the members based on strong column-weak beam criteria. When using SMRFs, allows unmatched architectural freedom, allowing more open interior and exterior spaces. Another advantage is that the smaller forces imposed on the foundation result in more economical systems. Some economical limitations arise occasionally due to the use of heavy sections. As a result, SMRFs are sometimes more expensive to build than shear wall or braced frame structures [6]-[7].

B. Dual Systems

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: Less detailing requirements are needed. In addition, fewer numbers of bays are needed to resist lateral forces, as well as, allowing a rapid construction pace. Moreover, the weight is relatively less than that of the concrete dual system. One major limitation for the SPSW, however, is that complex analysis techniques are needed to capture its nonlinear behavior; it is relatively softer in comparison to concrete shear walls [8].

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II. SEISMICITY IN UAE

The seismic hazard map of Iran is shown in Figure 1 [9]. It can be seen that UAE is in relative proximity of the highly active southern Iran. This is especially true for the northern parts of UAE. Tall buildings in the northern emirates and are on the Gulf shore, such as Dubai, are particularly vulnerable to strong ground motions propagating from Iran with high energy levels at predominant low frequency ground motions. Therefore, the lateral design of buildings in Dubai is very crucial; partly due to the high uncertainty in the seismicity parameters used to determine the SDC. Among the many lateral force-resisting systems that are described in the IBC/ASCE, only a handful of systems are usable in UAE given the state-of-the-practice and the mandated SDC. Table I summarizes the spectral accelerations and the corresponding SDCs from four studies/design guidelines, namely: Aldama-Bustos *et al.* [1], Sigbjornsson and Elnashai [2], and the US Army Corps of Engineers [3],[4]. One of the main reasons for diversity in UAE seismic hazard estimates is the debatable existence of the West Coast Fault (WCF). Other reasons include the adopted seismic source models and attenuation relationships. The seismic hazard estimates from the Sigbjornsson and Elnashai include the WCF as an active local source in UAE, and thus from a structural safety point of view, the higher estimates are adopted for the obvious conservatism. Consequently, the adopted spectral accelerations, S_s and S_y , are 0.71g and 0.59g, respectively. The SDC "D" will restrict the use of certain lateral systems and impose height limitations on others, whereas 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 as far as public safety is concerned.

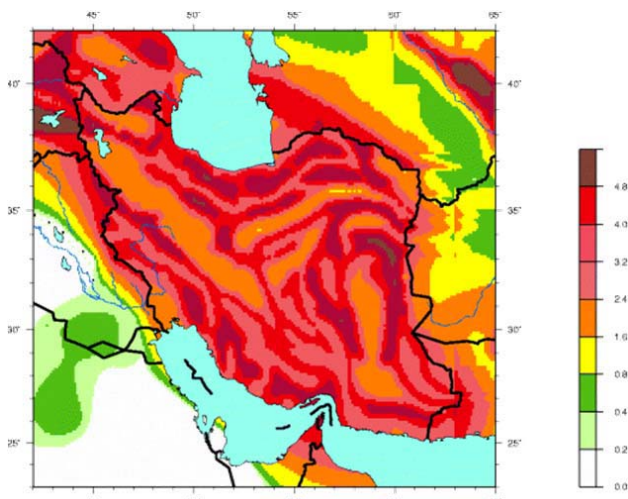


Fig. 1 Peak ground acceleration (m/s^2) with 10% probability of exceedance in 50 years [9]

III. BUILDING DESCRIPTION AND DESIGN APPROACH

The building considered is 20-storey office building to be constructed in downtown Dubai. The total height is 79.25m

(260ft) plus a 1.07m (3.5ft) high parapet. There are 6 bays, 6.1m (20ft) in length each in the East-West direction and 5 bays, 6.1m (20ft) in length each in the North-South direction. On the roof, a penthouse is located which is 3.66m (12ft) high, 12.2m (40ft) in length and 6.1m (20ft) 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 modeling technique using ETABS commercial package [10]. The buildings are designed to meet requirements of the IBC'09 which refers to the following standards for minimum design loads and design/detailing requirements: ASCE7-05 [11], ACI318-08 [12], AISC360-05 [13], AISC341-05 [14], AISC358-05 [15]. The strength and drift design of the frame elements is done using ETABS, whereas the shear wall strength design is done using in-house spreadsheets.

TABLE I
SEISMIC DESIGN CATEGORIES

Study/Design Guidelines	S_s (g)	S_1 (g)	S_{DS} (g)	S_{D1} (g)	SDC
US Army Corps of Engineers [4]	0.06	0.06	0.06	0.10	A
Sigbjornsson and Elnashai [2]	0.71	0.59	0.59	0.59	D
Aldama-Bustos <i>et al.</i> [1]	0.18	0.06	0.20	0.10	B
US Army Corps of Engineers [3]	1.68	0.67	1.12	0.67	D

IV. DETAILS OF STRUCTURAL SYSTEMS

Since the considered alternative systems are for the lateral systems on the peripheral 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 systems have been optimized every two floors, except for the RC shear walls which had the same design throughout the building height. This is opted to represent the state-of-the-practice for conventional construction in Dubai. The gravity systems for the steel/concrete alternatives are presented in Table II. The lateral systems are described in Tables III and IV 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 floor of interest.

TABLE II
GRAVITY SYSTEMS

Story	Steel Column ^a	Concrete Column ^b
19-20	W254x101	406x406
17-18	W254x115	406x406
15-16	W356x110	457x457
13-14	W356x112	508x508
11-12	W406x149	559x559
9-10	W457x117	610x610
7-8	W457x213	660x660
5-6	W610x241	711x711
3-4	W686x265	762x762
1-2	W762x284	813x813
Beam	W457x60	254x508

^aSI conversion of AISC standard sections: W $i \times j$; wide-flange steel section with depth i (mm) and weight j (kgf/m); ^b SI conversion of $b \times h$; rectangular concrete section with width b (mm) and depth h (mm).

It is found that the adopted seismic parameters produce controlling load cases over the wind cases for all the considered buildings. 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.

TABLE III
LATERAL SYSTEMS: SMRF ELEMENTS

Story	Steel Column ^a		Concrete Column ^b			
	SMRF	Dual	SMRF		Dual	
			Middle	Corner	Middle	Corner
19-20	W610x308	W305x312	305x610	610x610	356x864	610x610
17-18	W610x341	W356x287	356x711	711x711	406x813	711x711
15-16	W610x372	W356x314	406x813	762x762	457x914	762x762
13-14	W610x415	W457x260	457x914	813x813	457x965	813x813
11-12	W686x289	W533x247	508x1016	864x864	508x1016	864x864
9-10	W686x323	W610x241	559x1118	914x914	559x1118	914x914
7-8	W686x418	W610x262	610x1220	965x965	610x1219	965x965
5-6	W762x314	W610x286	660x1321	1016x1016	660x1321	1016x1016
3-4	W762x350	W610x308	711x1422	1068x1068	711x1422	1068x1068
1-2	W762x582	W610x341	762x1524	1118x1118	762x1542	1118x1118
Beam ^b	W762x220	W533x219	559x1118		457x914	

^aSI conversion of AISC standard sections: $W i x j$; wide-flange steel section with depth i (mm) and weight j (kgf/m); ^b SI conversion of $b x h$; rectangular concrete section with width b (mm) and depth h (mm).

TABLE IV
LATERAL SYSTEMS: SHEAR WALL ELEMENTS

Story	Steel Shear Wall			Concrete Shear Wall	
	VBE ^a	HBE ^a	t_w^b	Length	7900mm
				Thickness	300mm
19-20	W610x140	W457x213	2.7	L_{BE}	460mm
17-18	W131x195	W457x213	3.2	R_{BE}	16T36
15-16	W610x217	W457x213	3.4	$C_{BE,w}$	3T16@100mm
13-14	W610x241	W457x213	4.8	$C_{BE,L}$	5T16@100mm
11-12	W610x308	W457x213	6.4	R_{HW}	2T22@300mm
9-10	W610x341	W457x213	8	R_{VW}	2T22@300mm
7-8	W610x415	W457x213	8		
5-6	W610x455	W457x213	10		
3-4	W610x551	W457x213	11		
1-2	W762x582	W838x473	13		

^aSI conversion of AISC standard sections: $W i x j$; wide-flange steel section with depth i (mm) and weight j (kgf/m); ^bWeb 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.

V. PERFORMANCE OF STRUCTURAL SYSTEMS

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 in order to give the reader a measure of the appropriateness of each alternative. Table V summarizes the building weight, natural period of 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 is not expected to 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 and material price differences.

- The faster erection time for the steel buildings can offset the cost increase with earlier revenue generation and quicker capital return.

- The steel systems have smaller overturning moment compared to their concrete counterparts which translate into footing design savings.

TABLE V
KEY PARAMETERS COMPARISON

	Steel		Concrete	
	SMRF	Dual	SMRF	Dual
Building Weight (kN)	106,618	108,127	196,313	200,481
Natural Period (sec)	3.72	2.67	3.83	2.88
Base Shear (kN)	4,842	7,229	7,039	7,575
Overturning Moment (MN-m)	3,826	3,944	5,674	5,703

To evaluate the lateral systems performance under SELF seismic loads, the story drifts as well as the controlling design criteria (strength vs. drift) are reported in Table VI. It is noted that steel SMRF has several floors controlled by drift rather than strength requirements especially at the lower third of the building height. The concrete SMRF building has some floors governed by drift but not as many as the steel building and the distribution along the building height does not exhibit a clear pattern. Moreover, the dual systems do not have any floors governed by drift as the two systems inherently possess sufficient stiffness. The stiffer systems (steel/concrete dual) are more likely to experience higher accelerations and greater forces during seismic events. Conversely, the softer systems are more likely to exhibit higher story drifts and greater structural and/or nonstructural damage associated with excessive inelastic deformations.

TABLE VI
INELASTIC DRIFT RATIOS

Story	Steel			Concrete				
	SMRF	Design	Dual	Design	SMRF	Design	Dual	Design
20	0.58	S ^a	1.04 ^b	S	1.23	S	0.17	S
19	0.77	S	1.17	S	1.76	S	0.18	S
18	0.94	S	1.27	S	1.71	S	0.18	S
17	1.11	S	1.38	S	1.89	D	0.19	S
16	1.22	S	1.48	S	1.76	S	0.19	S
15	1.34	S	1.58	S	1.85	D	0.20	S
14	1.40	S	1.63	S	1.74	S	0.20	S
13	1.49	S	1.69	S	1.80	D	0.21	S
12	1.67	S	1.68	S	1.72	S	0.21	S
11	1.75	S	1.69	S	1.77	S	0.21	S
10	1.76	S	1.63	S	1.73	S	0.21	S
9	1.81	D	1.59	S	1.78	S	0.21	S
8	1.76	S	1.52	S	1.76	S	0.20	S
7	1.82	D	1.43	S	1.80	D	0.19	S
6	1.94	D	1.28	S	1.79	D	0.18	S
5	1.98	D	1.14	S	1.81	D	0.16	S
4	1.93	D	0.95	S	1.75	S	0.14	S
3	1.81	D	0.75	S	1.63	S	0.11	S
2	1.41	S	0.52	S	1.30	S	0.08	S
1	0.85	S	0.26	S	0.66	S	0.03	S

^a S: Strength criteria governs the design; D: Drift criteria governs the design.

^b Percentage of story height.

VI. CONCLUSIONS AND RECOMMENDATIONS

This study is motivated by the diversity in seismic hazard estimates for Dubai and the UAE in general. Among the many lateral systems prescribed in the IBC code, four feasible solutions are presented and compared, namely: steel and concrete SMRFs and dual systems of SMRFs and special shear walls. The four alternatives are designed in conformance to the IBC'09 code. The selection of the systems is driven by the fact that there is no height limit under the SDC "D" in the IBC'09 code. A quantitative comparison of the key parameters for the systems is presented. The four alternatives are formidable design solutions; however, their seismic performance during seismic events will vary. Although the four systems have different attributes, they all have acceptable predicted performance and are expected to behave desirably in seismic events. The cost implications of selecting one system over the others would be attributed to the different material quantities and unit prices, construction costs and erection rates which translate into earlier revenue generation and quicker capital return. Depending on the preferred performance, associated capital cost and expected repair cost, real-estate developers, with the help of a qualified structural consultant, can choose from the different alternatives based on detailed cost analyses that are routinely conducted in the projects' schematic stages.

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