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THE MOST SUITABLE SEISMIC STRUCTURAL SYSTEMS IN HIGH-RISE REINFORCED CONCRETE BUILDINGS

*Odai Hasan Fawzi Masheh[1], and Mohammed Salman Al-lami[2]

[1,2] Civil Engineering Department, Faculty of Engineering, Al-Isra University, Jordan

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ABSTRACT: Many lateral force resisting systems are used in the structures, but no definite answer implies how the most suitable earthquake-resistant structural system is to be chosen for each type of earthquake severity, type of soil, and height of buildings. This research was conducted to choose the most suitable seismic structural system for different cases. The parameters being studied were seismic hazard level, soil classification, and structure height. Three lateral force resisting systems were tested, the bearing wall system using special reinforced concrete shear walls, the dual system of special reinforced concrete shear walls and moment-resisting frames, and the special reinforced concrete moment-resisting frame system. The dynamic and static analysis methods were applied using (ETABS) software to check the responses of the structures for 243 cases. Responses to critical values were grouped, compared, and checked according to code limitations. The special reinforced concrete-moment resisting frame system tends to be the most suitable in most of the cases except in soft clay soil sites for structures of risk category 4 in high seismic hazard sites as it did not satisfy the drift limitation. The duel can still be the most suitable system, but it needs to be modified by raising the stiffness or using bracing members. The dual system tends to be the most suitable in all cases and especially in soft clay soil sites and high seismic hazards and for the structures of risk category 4.

Keywords: High-Rise Buildings, Seismic Structural Systems, Reinforced Concrete, Response

1. INTRODUCTION

The construction of high-rise buildings increased the need to have more stable and safely designed structures during the action of earthquakes. As a result, it became the preliminary motive of researchers and designers to reach the best performance of these buildings under the action of different types of loads. The advancement in modern tall building construction, which began in the 1880s, has been directed largely to commercial and residential purposes [1], and this can be justified due to the noticeable increase in floor area ratio (FAR) in the big cities as stated by Gupta and Neeraja [2].

Responses of the structures under seismic loads depend on many parameters previously studied and analyzed by many researchers. The responses considered are the displacement, drift, shear force, bending moment, and stiffness of the structures. Choosing a suitable lateral force resisting system is essential to seek the allowable responses according to the design code’s limitations and have a well-designed structure that can withstand earthquakes

Thorat and Salunke [3] found the use of a single shear wall in frames is better than multiple shear walls, and if multiple shear walls should be used, then it is preferable to locate them in the internal bays. Moreover, the drift in the braced concrete frame system is less than that of the shear wall but with more axial load, less bending moment, and less shear force in columns. Also, it was found that the bracing frames were better located in adjacent bays.

Somasekharaiah et al. [4] carried out a study on a structure of 30 m × 30 m dimensions elevated 20 stories using static and dynamic analysis methods and (ETABS) software, according to IS:1893–2002 part 1. The results showed that the shear walls added more stability and degraded the structure period. Moreover, a structure with a shear wall system has the least lateral displacement

Rasool and Ahmad [5] covered the analysis of a structure of 12 m × 12 m elevated 9 stories using (Staad-Pro V8i) software. They concluded that the bracing frame system's bending moments and shear forces are less than the shear walls. Moreover, the relative displacement was found to be lesser in the bracing lateral load resisting system than in the shear wall and Moment Resisting Frame, and finally, the result showed that the bracing type of lateral load resisting system is most effective in reducing displacements ahasave more economical sections

Gupta and Neeraja [2] analyzed six types of resisting systems by dynamic analysis using (ETABS) software according to IS: 1893–2002. According to the cost perspective, they found that using the bracing at the periphery as inverted V bracing (IV) is effective and economical.

Bhuta and Pareekh [6] analyzed a structure elevated 40 stories by static and dynamic analysis using (ETABS) software according to IS: 1893–

2002 and IS: 800–2000. Three types of resisting systems were used: shear wall, outrigger, and diagrid. The results showed that using the diagrid system model shows the minimum displacement compared to other time history analysis models.

Shubham et al. [7] showed that the structure with a diagrid system gives a better response than other systems. Diagrid system has a good aesthetic appearance and effectiveness in performance compared with frame tube system and beam-column system for a structure of 36 m × 36 m dimensions and elevated 40 stories when applying dynamic analysis using (ETABS) software. According to the seismic hazard, the zone was defined as zone 2 and the soil classification was not specified.

Janakkumar [8] analyzed a structure of 25 m × 25 m dimensions and elevated 20 stories by static analysis using (ETABS) software according to IS:1893–2002. Their results showed that the lateral displacements and drift are significantly lower after inserting the shear wall in the bare frame and through the comparison of story drift values, they observed that the maximum reduction in drift values was obtained when the shear walls were provided at the center as a core.

Wiyono et al. [9] analyzed a hotel of 33 m × 30 m dimensions elevated 11 stories by dynamic analysis using (ETABS) software according to SNI1 726:2012 code. The results assured that a two-sided shear wall in the X direction and a two-sided shear wall in the Y direction at the center of the building are recommended because it has the best seismic performance than the bare system, the period is less than the minimum, story drift is acceptable, the dynamic lateral load has met the minimum requirement, which should be at least 85% of the Static Load, and frame structure carried more than 25% lateral load in dual system building.

2. RESEARCH OBJECTIVE

Several types of research have been carried out on the subject related to this paper, but most of them focused on changing the lateral force-resisting system without seeking the simultaneous effects of soil classification and seismic hazard.

This research aims to have a more comprehensive study on three lateral force resisting systems used by many researchers and cover the parameters that were not taken into consideration. Static and dynamic analysis using the response spectrum method was used to analyze buildings with five, fifteen, and twenty-five stories designated as short, tall, and high buildings, respectively. Three lateral force resisting systems were used as follows:

1- Bearing wall system by providing (L) shaped special reinforced concrete shear walls at corners, at the center as a tube, and the periphery too.

2- The dual system uses special moment resisting frames with special reinforced concrete shear walls. Assuring that the moment resisting frames carry more than 25% of the shear force.

3- Special reinforced concrete moment resisting frames, they are without bracing or masonry infill. The two-dimensional plans for the three systems are shown in Figures 1, 2, and 3, respectively.

Soil interference was considered to seek three types of soil were used, soil class (B) rock characteristics; soil class (C) stiff soil, and soil class (E) soft clay soil according to the classification in the 2012 international building code (IBC) and (ASCE 7–10, 2010). Moreover, three-building heights (5, 15, and 25 floors), three seismic hazard levels (low, medium, and high), and three risk categories (1, 2, 3, and 4) were taken into consideration.

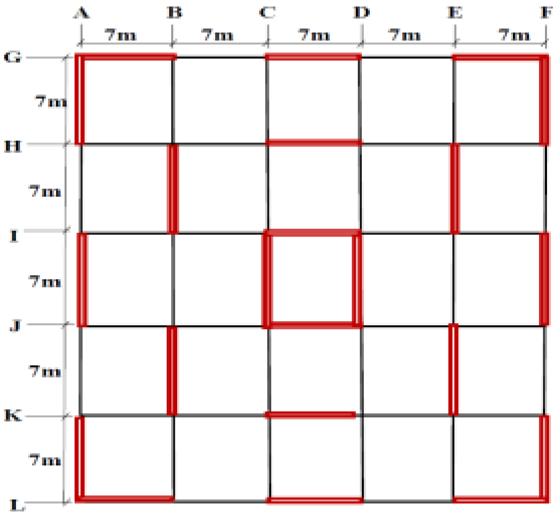

Fig.1 Building plan with special reinforced concrete shear wall resisting system

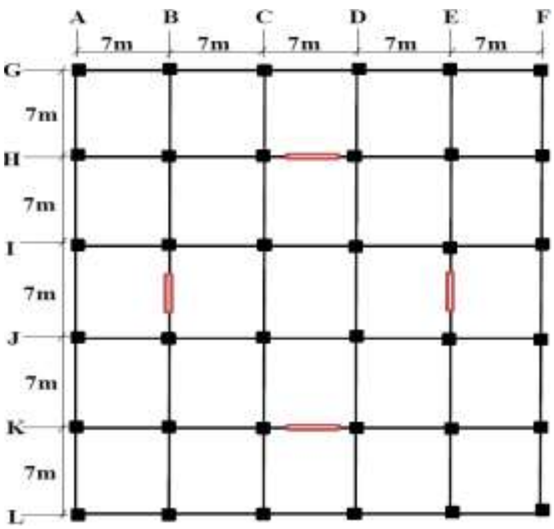

Fig.2 Building Plan with Duel resisting system

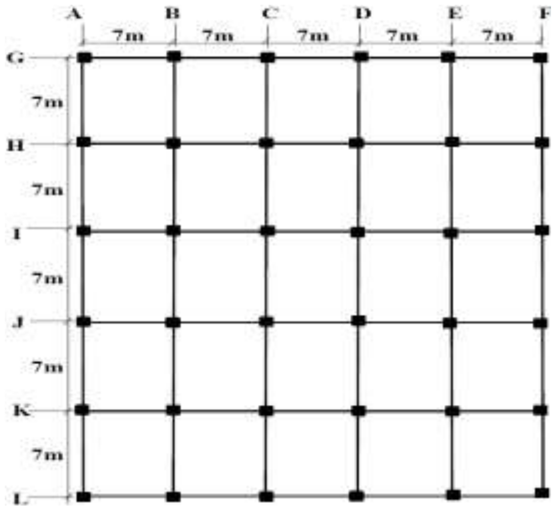

Fig.3 Building plan with special reinforced concrete moment resisting frame system

As a result, seismic resisting systems were taken into consideration in the analysis by changing the parameters of the 9 buildings and analyzing each time. The results of responses such as displacement, drift, shear force, bending moment, and stiffness were grouped and compared between the three different lateral force resisting systems to choose the most suitable one for each case.

3. ANALYSIS

In this research, nine models of structures with plan dimensions of 35 m × 35 m were modeled using three-dimensional analysis of building systems (ETABS) software. The structures were analyzed using dynamic analysis, which was scaled by the static analysis according to ASCE 7–10.

The buildings were regular with a floor area of 1225 m2 and a story height equal to 3 m. The cross-section dimensions of all columns were 80 cm × 80 cm, and they were 70 cm × 31 cm and 30 cm × 31 cm for interior, and exterior beams respectively. The compressive strength of the concrete used was 25 MPa, and the yield stress was 420 MPa and 280 MPa for main reinforcement and shear reinforcement, respectively. The thickness of the slab was set at 31 cm and the thickness of the shear walls was selected to be 30 cm. The gravity loads were considered 7 kN/m^2 for superimposed dead load, and 2 kN/m^2 for live load and own weight, which was calculated by the software.

The response spectrum was defined using the function type ASCE7-10 in (ETABS) software. According to table 12.6–1 of (ASCE 7–10, 2010), it is permitted to use the design response spectrum which was suggested in this research instead of the site-specific response spectrum. The values of (Ss) and (S_1), were taken using the world seismic hazard map, which is provided by the Global Seismic Hazard Assessment Program (GSHAP), previously suggested by Lubkowski and Aluisi [10]. This map was introduced to the study along with the database of (ETABS) for (S_S) and (S_1) values for the United States of America and Canada to validate the aspect of variety in seismic hazards.

Fortunately, the United States of America and Canada region show this variety in seismic hazards. The samples which were taken are illustrated in Table 1. So, as the data needed to be filled in (ETABS) became available, the (ETABS) software automatically determined the design values of spectral response acceleration coefficients according to the (IBC, 2012) Code. 243 cases were taken into consideration in the analysis by changing the parameters of the 9 buildings and analyzing each time.

Table 1 Zones of study

Country	Latitude	Longitude	Seismic hazard
United States of America	40.73061	-73.93524	Low
Canada	45.50888	-73.56166	Medium
United States of America	34.05223	-118.2436	High

Dynamic analysis was used. The response spectrum for each case was defined, and the analysis was done accordingly. The responses of each case were extracted from (ETABS) software as reports. In this research, 405 reports were extracted. The reports showed displacement, drift, shear force, bending moment, and stiffness values.

4. RESULTS AND DISCUSSION

The design response spectrum for the 243 cases was grouped into twenty-seven comparisons between the three structural systems. These comparisons paved the way for results showing the most suitable system in each case after applying drift limitations specified by table 12.12–1 of ASCE-10, 2010.

Generally, in the first expected behavior, the shear wall resisting system showed more stiffness, shear, moment values, and less displacement and drift values than other systems. While the frame would show less stiffness, shear, moment values, and more drift and displacement values than other systems. However, the dual system would show values between the values of the shear wall and moment-resisting frame systems. And that is illustrated in the tables of comparison 2 to 6 for soil class B, Low seismic risk, and five floors of height presented as a typical example of the results of the analysis.

Table 2 Displacement comparison at the top of the 5 floors-Low seismic risk-Soil class B

Story	Shear wall system (mm)	Frame system (mm)	Dual system (mm)
Story5	0.641	4.319	2.823
Story4	0.493	3.289	2.109
Story3	0.339	2.253	1.398
Story2	0.193	1.273	0.743
Story1	0.072	0.456	0.227
Base	0	0	0

Table 3 Drift ratio comparison at the top of the 5 floors-Low seismic risk-Soil class B

Story	Shear wall system (mm)	Frame system (mm)	Dual system (mm)
Story5	0.1548	1.089	0.750
Story4	0.1482	1.089	0.741
Story3	0.1470	1.008	0.669
Story2	0.1212	0.825	0.515
Story1	0.0720	0.456	0.228
Base	0	0	0

Table 4 Stiffness comparison at the top of the 5 floors-Low seismic risk-Soil class B

Story	Shear wall system (kN/m)	Frame system (kN/m)	Dual system (kN/m)
Story5	6914903	160798	423067
Story4	11288514	162097	450954
Story3	15219466	192968	541169
Story2	21213157	303724	990237
Story	37798092	732835	2813050
Base	0	0	0

In this comparison, the shear wall was dominant with a value less than other systems in displacement and drift to be 0.6406 mm, and 0.1548 mm, respectively, and to have the highest stiffness, which is expected as well. The value of stiffness (K) reduces the higher stories. The reason beyond that is the non-linearity in our structures where the ductility is introduced to have more displacement with fewer values of K when going to the upper floors because of the first mode shape effect factor (R).

Table 5 Shear comparison at the top and bottom of the 5 floors-Low seismic risk-Soil class B

Story (top/ bottom)	Shear wall kN	Frame system kN	Dual system kN
Story5	953	175	316
	1025	175	316
Story4	1698	176	334
	1746	176	334
Story3	2203	194	364
	2237	194	364
Story2	2545	250	514
	2566	250	514
Story1	2723	334	639
	2729	334	639
Base	0	0	0
	0	0	0

Table 6 Moment comparison at the top of the 5 floors-Low seismic risk-Soil class B

Story	Shear wall system (kN.m)	Frame system (kN.m)	Dual system (kN.m)
Story5	0	0	0
Story4	2974	525	950
Story3	8110	954	1836
Story2	14643	1272	2482
Story1	22071	1633	3297
Base	29984	2259	4643

According to these tables, the frame is dominating with small values of shear and moment due to its ductility, less stiffness, and less mass. it would be more economical when use smaller sections to resist these stresses than other systems. Hereby the approach, which will be taken into consideration after applying the drift control limitation, is to try using the frame as much as it can satisfy the drift limitations as a bare system. If the frame system cannot check the drift control limitation, the second system would be the dual system with higher stiffness and less displacement can be used. The shear wall can be applied if the dual system does not satisfy the drift control limitation.

The rule in this research is to take the building frame system as the most suitable resisting system to be used if it satisfies the drift limits because of its more ductility leading to more dissipation of energy, its low shear force, and bending moment values, and the good of R-value, which can be raised to be equal to 8 when using special moment-resisting frames. Moreover, its low stiffness would have a lower frequency, which implies a long period. Long periods in the response spectrum curve would lead to smaller values of acceleration, less shear, less bending moment, and an economical design as a result.

The choice of the most suitable structural system approach using the procedure of applying drift limitations for the three structural systems is shown in the figures from 4 to 6 for risk categories 1& 2 as an example. According to the risk category, all cases are compared to the drift control limitation. Choosing the most suitable system can be done by taking the systems with drift values below the drift limits for a specific case and with the least stiffness value.

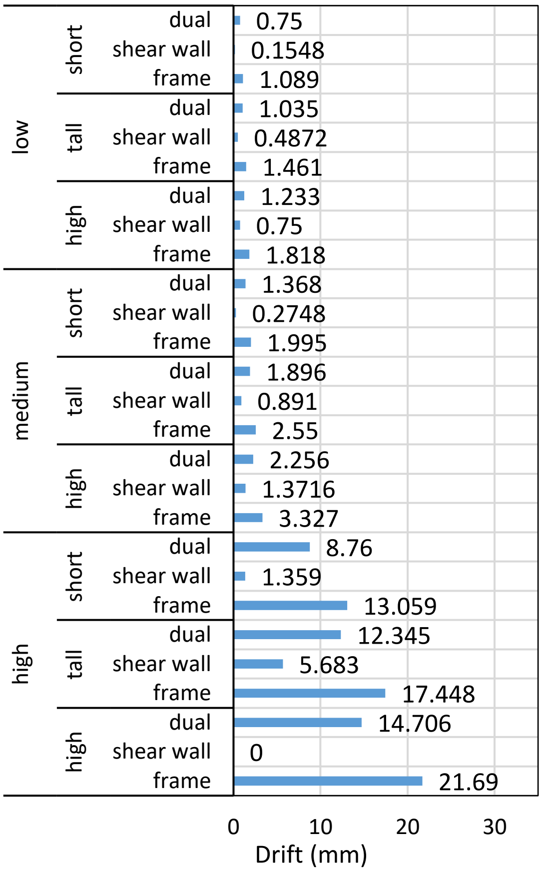

Fig.4 Drift for soil class B and risk categories 1 & 2

Figures 4 to 6 show the drift values in the three structural systems. The drift limitations are 60, 45, and 30 mm for risk categories 1, 2, 3, and 4, respectively. These limits were calculated according to Table 12.12-1 of ASCE7-10. According to the risk category, all cases are compared to the drift control limitation. Choosing the most suitable system can be done by taking the systems with drift values below the limit value for a specific case and with the least stiffness value. The (zero) value is given for shear walls with a high seismic risk of 25 floors structures because it is not permitted to use this system according to (ASCE 7–10, 2010).

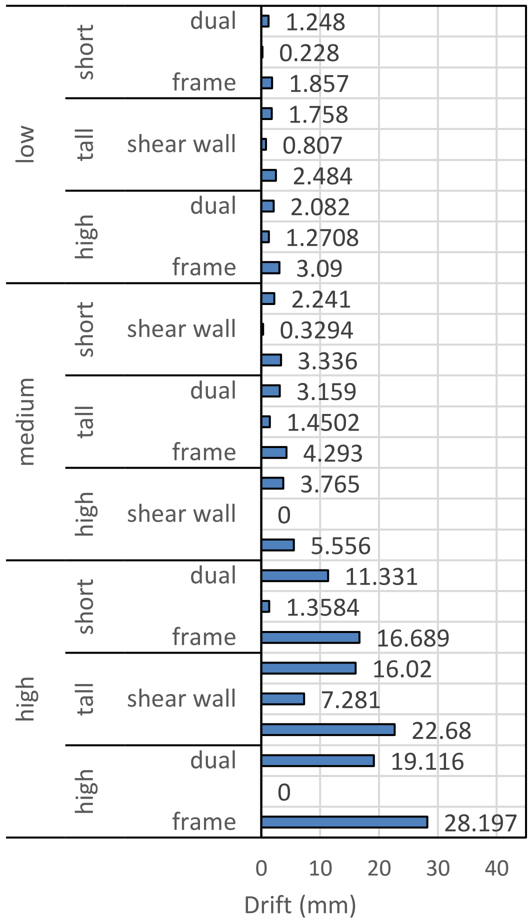

Fig.5 Drift for soil class C and risk categories 1&2

When the frame does not exceed the limits, it would be the most suitable system and economic one, if it has the lowest values of shear and bending moment according to many Tables exerted from analysis results for soil C and E, like that shown in Tables 2 to 6 for soil class B. If the frame exceeds the limits, the second alternative would be chosen with a commitment to (ASCE 7–10, 2010) permitted structural systems.

Tables 7, 8, and 9 show the responses of the three structural systems. These tables can be used to specify the most suitable system when four parameters are specified. The parameters are the seismic hazard level, the soil classification, the building height, and the risk category. Some modifications may be needed after choosing the system from the tables. After choosing the system, the design category is essential to be specified, which has a reflection on the design and detailing of the structural members.

For example, if the building is with 13 floors, which is the case of tall buildings, the site is soil classification C, the seismic hazard is Medium, the building risk category is 3, and the design category was (D), then, the most suitable system to be used is the special reinforced concrete moment resisting frame system.

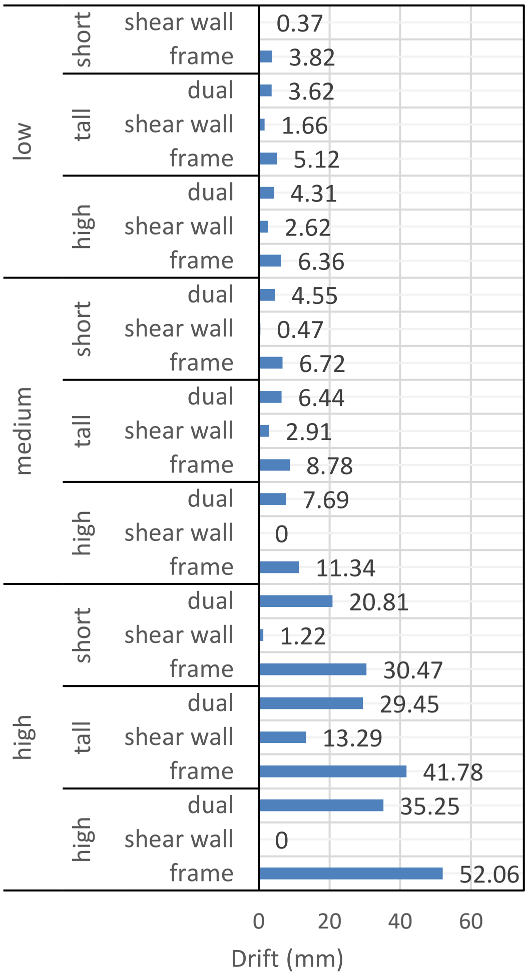

Fig.6 Drift for soil class E and risk categories 1& 2

The special reinforced concrete moment-resisting frame system is the most suitable system to start with when initiating a structural design since it is permitted for non-limited height (ASCE7-10). Moreover, it matched the drift limitations, but in the cases of risk category 4 for high-rise buildings, it did not match the drift limitations. So, a wise decision is to modify it by adding bracing for example, or any other system or to use a more stiff system such as the dual system, which shows effectiveness in high-rise buildings to control the drift values.

For the three tables of results, deep attention to be paid to the following:

1- When the seismic hazard increases the values of Ss and S_1 are higher so directly the values of SDS and S_{D1} would increase, which would uplift the design response spectrum upward, and periods (T) would have higher acceleration, then higher forces to be propagated, which implies more displacement. Therefore, when going from low to high seismic risk, the alternative is going from being a frame to a shear wall to have more stiffness with a smaller R-value to control the displacement and drift.

Table 7 Final results for soil B

Mapped spectral acceleration		High				Medium				Low			
structural system / height of building	R.C	SW	F	D	DC	SW	F	D	DC	SW	F	D	DC
Short building	1 or 2		✓		E		✓		B		✓		B
	3		✓		E		✓		B		✓		B
	4		✓		F		✓		C		✓		C
Tall buildings	1 or 2		✓		E		✓		B		✓		B
	3		✓		E		✓		B		✓		B
	4		✓		F		✓		C		✓		C
High rise buildings	1 or 2	NP	✓		E		✓		B		✓		B
	3		✓		E		✓		B		✓		B
	4		✓		F		✓		C		✓		C

Notations: NP: Not Permitted according to (ASCE 7-10), RC: Risk Category, SW: Shear Wall, F: Frame, D: Duel, and DC: Design Category

2- When the type of soil goes from bedrock to clay, i.e., from a stronger soil to a softer soil, the response spectrum curve would be uplifted, and the reason beyond that is the site classification factors (F_a), and (F_v) values. So, when the soil type becomes softer, displacements, accelerations, and forces increase.

3- When the building is going higher in elevation, it implies that the mass of the building is increasing, and the frequency would be decreased, which implies a high period. The effect of frequency is very high and is illustrated in the decoupled equations of the dynamic equilibrium equation.

Table 8 Final results for soil C

Mapped spectral acceleration		High				Medium				Low			
structural system / height of building	R.C	SW	F	D	DC	SW	F	D	DC	SW	F	D	DC
Short building	1 or 2		✓		E		✓		D		✓		B
	3		✓		E		✓		D		✓		C
	4		✓		F		✓		D		✓		B
Tall Buildings	1 or 2		✓		E		✓		D		✓		B
	3		✓		E		✓		D		✓		B
	4		✓		F		✓		D		✓		C
High rise buildings	1 or 2	NP	✓		E	NP	✓		D		✓		B
	3		✓		E		✓		D		✓		B
	4		✓		F		✓		D		✓		C

Notations: NP: Not Permitted according to (ASCE 7-10), RC: Risk Category, SW: Shear Wall, F: Frame, D: Duel, and DC: Design Category

4- The frame has shear and moment values less than the dual system, where these values for the dual system are less than the shear wall too. From a static analysis approach, the reason is the (Cs) factor, which contains R in its denominator, which is reducing it. And the weight of the shear wall buildings is the highest, so more shear force would be propagated. And from the dynamic analysis approach, the mass of the floor is a parameter, and shear wall structures are more massive than their counterparts causing high shear and bending moment values.

5- For frames, the value of (R) was 5, and for the chosen dual system type R = 5.5. It is not a big difference, but the initial slope (K) for the dual system would be more than the one for the frame; that is why the frame propagates higher displacements. For the shear wall R = 4. On the other hand, the sheer wall has a high initial stiffness that leads to smaller values of displacement. Generally, the stiffness of the frame is less than the dual system, which is less than the shear wall. So, when stiffness decreases, the frequency decreases, and much displacement would occur. Therefore, the frame system always displaces more than its counterparts. And when the (R) value is becoming higher, the structure would be more ductile with fewer shear forces and more dissipation of energy.

Table 9 Final results for soil E

Mapped spectral acceleration		High				Medium				Low			
structural system / height of building	R.C	SW	F	D	DC	SW	F	D	DC	SW	F	D	DC
Short building	1 or 2		✓		E		✓		D		✓		C
	3		✓		E		✓		D		✓		C
	4		✓		F		✓		D		✓		D
Tall buildings	1 or 2		✓		E		✓		D		✓		C
	3		✓		E		✓		D		✓		C
	4		✓		F		✓		D		✓		D
High rise buildings	1 or 2	NP	✓		E	NP	✓		D		✓		C
	3		✓		E		✓		D		✓		C
	4		✓		F		✓		D	NP	✓		D

Notations: NP: Not Permitted according to (ASCE 7-10), RC: Risk Category, SW: Shear Wall, F: Frame, D: Duel, and DC: Design Category

So, this procedure which was illustrated in this research shows the approach which was taken and identifies the methodology since the start of defining 9 models of three structural systems with certain load patterns, load cases, and combinations. 81 models were analyzed using (ETABS) software seeking different elevations, different seismic hazards, and different soil classifications.

Dynamic analysis was performed using the design response spectrum method to have different responses of shear, moment, displacement, drift in addition to, and stiffness. The drift after illustrating the concept of ductility, elasticity, and non-linearity, was the first controller to make a benefit of using the most ductile system with the highest values of (R) with less shear and bending moment stresses to have a more economic system.

5. CONCLUSION

In this study, Eighty-one cases were carried out to have the final results of this research by changing different major parameters such as the height of the structure, the seismic hazard, and the soil classifications seeking three lateral force resisting systems: The bearing wall system using special reinforced concrete shear walls; the special reinforced concrete moment resisting frame system, and the dual system using special reinforced concrete and special reinforced concrete moment-resisting frames. The design categories were introduced, too, to have 243 cases which are summarized in three tables from Table 7 to Table 9.

Tables from 7 to 9 can be used to specify the most suitable system when the four parameters are specified. The parameters are the seismic hazard level, the soil classification, the building height, and the risk category. Some modifications may be needed after choosing the system from the tables. After choosing the system, the design category is essential to be specified, which has a reflection on the design and detailing of the structural members.

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