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Research Article

Lateral Load Resisting Systems in High-Rise Reinforced Concrete Buildings

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Abstract

An efficient and economical tall building cannot be designed without a thorough understanding of the significant factors affecting the selection of the structural system and knowledge of how the structural system will interrelate with architectural, mechanical and other aspects. In this study, structural analyses were performed to compare the structural response of different types of lateral load resisting systems (moment-resisting frame system, shear wall system, dual system and framed tube system) under effect of seismic and wind loads using the structural program ETABS. The building consists of 28 stories with area of 625m² (25m x 25m). Storey displacements were evaluated for all lateral load resisting systems. Among the types of lateral load resisting systems, dual system showed a very suitable structural response for this height and did not exceed the limitation values.

Keywords: lateral load resisting system, high rise buildings, earthquake load, wind load, displacements.

Yüksek Katlı Betonarme Binalarda Yanal Yük Dayanım Sistemleri

Özet

Verimli ve ekonomik bir yüksek bina, yapısal sistemin seçimini etkileyen önemli faktörler tam olarak anlaşılmadan ve bu sistemin mimari, mekanik ve diğer yönlerle nasıl bir ilişki içinde olacağı bilgisi olmadan tasarlanamaz. Bu çalışmada, farklı tipteki yanal yük dirençli sistemlerin (moment çerçeve sistem, perde duvarlı sistem, perdeli-çerçeveli sistem ve tüplü çerçeve sistemler) sismik yükler ve rüzgâr yükleri altında yapısal tepkilerini karşılaştırmak için bir yapısal analiz programı olan ETABS kullanılarak yapısal analizler yapılmıştır. Bina 625m² (25m x 25m) alana sahip 28 kattan oluşmaktadır. Tüm yanal yük dirençli sistemler için kat deplasmanları hesaplanmıştır. Yanal yük dirençli sistem tipleri arasında perdeli-çerçeveli sistem, bu yükseklik için çok uygun bir yapısal tepki göstermiş ve sınır değerlerini aşmamıştır.

Anahtar Kelimeler: yanal yük dirençli sistem, yüksek binalar, deprem yükü, rüzgâr yükü, deplasmanlar.

1. Introduction

High-rise structure is defined as a structure of thirty-five meters' height or greater that is divided at regular intervals into occupiable levels [1]. The main aim of all types of structural models used in structures is to support gravity loads. Dead load, live load, rain load, and snow load are the most used loads resulted from the gravity effects. Additional to vertical loads, structures are exposed to lateral forces due to winds and earthquakes. Lateral forces cause very high stresses and deflections. So that, structures should have the adequate strength to resist vertical forces together with required stiffness against horizontal loads [2].

Increasing in population in most countries raises land area prices, so tall building has been growth and number of stories increases and reaches 100 to 200 stories and will increase to more for high rise towers. Structures in seismic zones could be exposed to high stresses and deflections. Along with vertical loads, structures have to resist the lateral loads which could develop a severe damage. The earthquake and wind loads can develop a lot of results like (ground shaking, ground displacement, fire, and flood); therefore, it is very important to prevent the negative results which are coming from earthquake. The main purpose of seismic design is to resist the lateral forces during the earthquake thus reducing the possibilty of death or injuries to people in the earthquake zone. Because severe earthquake is rare, engineers expect that structure damage is possible and acceptable but collapse should be prevented [3].

In seismic design of reinforced concrete (RC) multistoried structures, determination of the lateral load-resisting model is a very important issue. Specific structural members are designed to resist the lateral loads that raised during strong earthquake and wind loading. Stiffnesses and configuration of these identified members have a major role to determine the design load level in the members. Buildings are identified as rigid or flexible structures. High-rise buildings are more flexible and exposed to vibration due to earthquake and wind loads [4].

William Jenney's Home Insurance Building of 1879 is considered the first extensive application of the internal skeleton and curtain wall to a high office building. The Chicago School of Architecture refined the use of beams and columns in steel and subsequently frame construction became widespread. Also at this time concrete slabs and columns were develop [5]. The architect Perret designed the Rue Franklin Apartment Buildings in 1903 which was the first use of a reinforced concrete skeleton structural system [6].

Shear walls in the connection with concrete slabs were first utilized on the Lake Meadows Housing Project in Chicago 1949. The structure became very common for residential constructions due to the reason that walls can be utilized to separate rooms. Architectural communities encouraged the designers to develop the design ingenuity. Later, shear wall-frame connections were the development of using shear walls with simply supported exterior framing. The thirty-eight floor Brunswick Building (1962) is considered as first structure using the shear wall-frame system.

During the structural design innovation period, many lateral load resisting models have been developed like the outrigger braced structures in connection with surrounding belt truss and many different framed tube models like tube-in-tube, partially braced tube-tube, and bundled tube models which provide an economical high-rise structure designs with different height-width ratios [7-10].

Development of high strength and light concrete materials, good connecting and construction techniques, and accurate methods to predict the structural performance of buildings due to loads, and practical applications of those innovations. Jinghai and Xinhua [11] conducted a study about latticed shell tube–reinforced concrete core wall structures. Authors used two types of structures systems in same building, one of them was located in the interior which is RC core wall and the other was located in the exterior faces of building, and concluded that arranging a number of diagonal braces reasonably can enhance the lateral resisting capability of latticed shell tube effectively.

Massumi and Absalan [12] conducted a study about interaction between bracing system and moment resisting frame in braced RC frames. The authors investigated the results of two experimental models of reinforced concrete frames and developed a new numerical model. They concluded that the interactions between RC frames and bracing systems have a significant and good effect on developing the performance of dual model. The result of numerical analysis indicates a raise of 18% in the ultimate strengths of the dual model, which results from the interactions between the two models.

Sadjadia et al., [13] conducted a study about seismic performance of reinforced concrete RC moment resisting frames. He conducted four structural cases which are (ductile, nominally ductile, gravity loaded design- and retrofitted gravity loaded design), In the study, a typical 5-story frame is designed for all cases and presents an analytical study for the earthquake effect on reinforced concrete structures using time history analyses and push-over analyses. It is figured out that the ductile and nominally ductile structures performed perfectly under the studied earthquakes, while performances of the gravity loaded design frames were not good. After the damaged gravity loaded design frames were strengthened, the earthquake resistances were developed.

Patil et al., [1] studied the structural behavior high-rise structures using the equivalent static analysis method. The authors evaluated different horizontal load resisting models. The different horizontal load resisting models are: moment frames, braced frames, and shear wall frames. The effect of horizontal load resisting models is evaluated under the seismic loadings. The major factors considered in this research are: storey drifts, base shear, story deflections, time period, shear forces, bending moments, and axial forces. Design results showed obvious improvements in all parameters particularly in the braced and shear wall frames.

The main purpose of the present study is to show the structural response of moment-resisting frame system, shear wall system, dual system and frame tube system due to seismic and wind loads by evaluating storey displacements of each system using structural program ETABS [14].

2. Types of Structural Systems

The selection of the lateral load resisting system (LLRS) for s specific building is clearly a design decision of fundamental importance, yet there is no system that is best for all buildings

[15]. Factors to consider when selecting a seismic force resisting system include: performance, architectural and nonstructural coordination, construction cost, and design budget. Acceptable earthquake performance is a function of more than the selected structural system [15]. Configuration of the LLRS within the building is fundamental to good design, concerning such issues as structural irregularities, torsion, redundancy, and the combination of systems.

The most commonly used structural systems have been classified by Khan [16]. They are broadly defined as follows: moment resisting frames, shear wall system, dual system, shear truss-outrigger braced systems, framed-tubes, Tube-in-tube systems with interior columns, and bundled tubes and modular tubes.

A brief explanation to the types of lateral load resisting systems used in this research are presented.

2.1 Moment resisting frames

Moment resisting frames are normal frame with beams, columns and fixed or semi-rigid connections. The stiffness and strength are proportional to the height of story and column spacing. Moment resisting frames could also be built with columns connected to flat slab or flat plate. This type is without shear walls so the number of stories are limited depending on the bay spans between columns and story height [16].

2.2 Shear wall system

A shear wall system is defined by ASCE 7-05 [17] as “a structural system with shear walls providing support for all or major portions of the vertical loads. Shear walls provide seismic resistance”. Shear walls will be added due to the structural type, size, loads and number of stories. And depend on property of material, geometry, stiffness, symmetry and center of rigidity.

2.3 Dual system

A dual system is defined by ASCE 7-05 [17] as “a structural system with a complete space frame providing support for vertical loads and capable of resisting at least 25% of prescribed seismic forces.

2.4 Framed tubes

The framed tube structural system is the most modern type developments in high-rise structural buildings. The framed tube system consists of very closely spaced (between 2-3 meters) exterior columns are joined in each floor level with deep edge beams (with depth usually 0.5-1.5meters). Like other structure of this form, the exterior tube or columns is designed to resist the entire lateral loading. Vertical gravitational forces are resisted partly by the exterior frames and partly by some inner structure such as interior columns or an interior core. Sometimes the closely spaced column arrangement makes access difficult to the public area at the base. It can be avoided by using a large transfer girder to collect the vertical loads from the closely spaced columns and distribute them to a smaller number of larger more widely spaced columns at the base [18]. The framed tube allows the core framing to be constructed independently therefore the exterior can be constructed while the interior layout is being finalized [16].

3. Description of the Analytical Models

The structure considered in this study was reinforced concrete building with 28 storeys. The building area is 625m² (25 x 25 m) and consist of five bays in both directions. The floor plans for the different types of lateral load resisting systems are shown in Fig.1, Fig.2, Fig.3 and Fig.4. The storey height of the building is 3.4 m for all floors except the first floor in which the storey height is 4.4 m and thickness of slab is 0.2 m.

Regarding the moment-resisting frame system, the beam cross section B is 0.65 x 0.75m and the column section C is 0.65 x 0.65m. Regarding the shear wall system, the thickness of shear wall is 0.4 m. Regarding the dual system, the beam cross section B is 0.40 x 0.50m, the column section C is 0.40 x 0.40m and the thickness of shear wall is 0.4 m. Regarding the tube system, the beam cross section B1 is 0.40 x 0.50 m, B2 is 0.40 x 1.20 m, the column section C1 is 0.40 x 0.40 m, C2 is 0.4 x 120 m and the thickness of shear wall is 0.4 m. In the design of the buildings, a uniform mass distribution over the height of the structure was assumed. The design of the structures was performed according to the lateral load distribution specified in International Building Code IBC [19] and American Society of Civil Engineering ASCE [17].

In order to investigate the effect of the different types of lateral load resisting systems, equivalent static analysis was performed to compare the structural response of moment-resisting frame system, shear wall system, dual system and frame tube system under effect of earthquake and wind loads.

The modulus of elasticity of concrete is E = 26000 MPa, the compressive strength is F’c = 30 MPa and Poisson’s Ratio = 0.2.

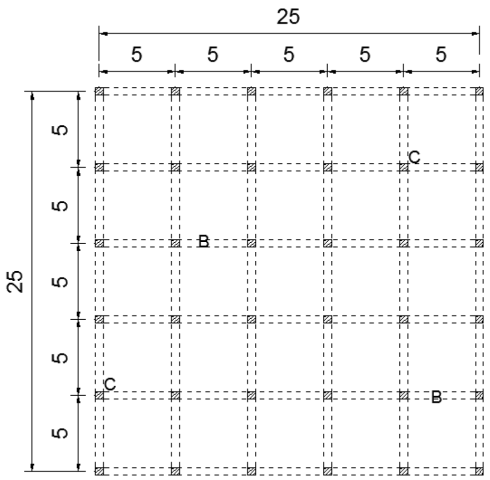

Figure 1. Typical floor plan of moment-resisting frame system (units in meter).

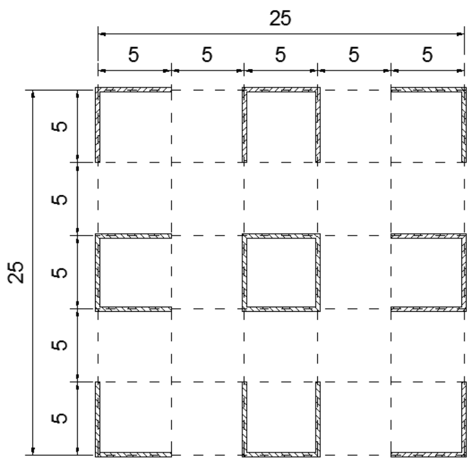

Figure 2. Typical floor plan of shear wall system (units in meter).

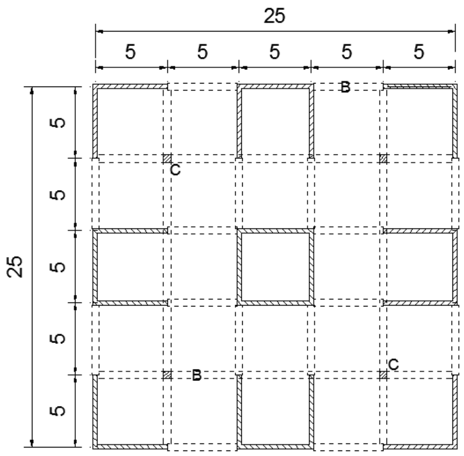

Figure 3. Typical floor plan of dual system (units in meter).

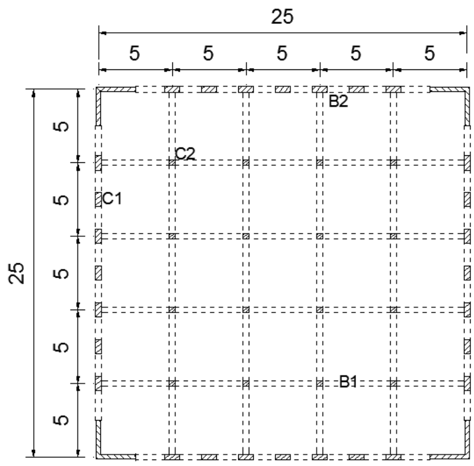

Figure 4. Typical floor plan of frame tube system (units in meter).

4. Analysis Method

The latest National Earthquake Hazards Reduction Program (NEHRP) guidelines such as FEMA 273 [20] and FEMA 356 [21] show that, for a specific earthquake, the building should have adequate capacity to resist a specified roof displacement which is called as target displacement.

In the current study, equivalent static analysis was performed to determine the structural behavior of 28-storey building with moment-resisting frame system, shear wall system, dual system and frame tube system due to seismic and wind loads. The analyses of the frames were carried out through a well-known computer program ETABS.

4.1 Seismic load coefficients and factors:

- Time period = 0. 028, 0.8
- Ecc. Ratio = 0.5
- Response modification, R;
- For moment resisting system = 3
- For shear wall system = 4.5
- For dual system = 6
- For frame tube system = 6
- Occupancy importance, I =1
- Ss =2.29
- S1 = 0.869
- Long- period transition period = 8
- Site class = B
- SDs = 1.5267
- SD1 = 0.5793

4. 2 Wind load coefficients and factors:

- Wind speed (mph) = 110
- Exposure type = C
- Importance factor = 1
- Topographical Factor, Kzt = 1
- Gust Factor = 0.85
- Directionally Factor, Kd = 0.85
- Windward Coeff. =0.8
- Leeward Coeff. = 0.5
- Exposure height from base to story 28

5. Results and Discussion

The four models are analyzed in the same situations and the same properties, either the material properties or the factors which have relations with lateral loads (quake and wind). Meanwhile, they were analyzed in the same (seismic zone, type class, wind speed, exposure type,…etc). They were analyzed in so symmetrical plane, homogeneous vertical height, and there is no weak floor from the base floor up to upper floor, it means the models have been analyzed in an ideal case.

The results of this study showed that the displacements in all structural systems are in the permitted limitation according to the international codes except moment resisting that the results show that it is not possible for this level (28 floors).

In all models, there are not any problems with the rotation displacements because the symmetric is available in all models. The outputs of these models are too much because the structure is high-rise building and contains many points in every floor, therefore, there is no need to show all of these outputs. For instance, in every floor, point number one was selected for comparison when dealing with displacement, but for story drift, the researcher showed the maximum value in each floor.

5. 1 Moment Resisting System

Table 1 and Figure 5 show the displacements versus the storey number due to Earthquake (Qx) in moment resisting system.

Table 1. Displacements versus the storey number due to Earthquake (Qx).

Story number	point	Displacement Ux (mm)
Story 28	1	840.2
Story 27	1	821.8
Story 26	1	801.4
Story 25	1	779
Story 24	1	754.7
Story 23	1	728.7
Story 22	1	701.1
Story 21	1	672.1
Story 20	1	641.9
Story 19	1	610.6
Story 18	1	578.4
Story 17	1	545.4
Story 16	1	511.9
Story 15	1	477.8
Story 14	1	443.5
Story 13	1	409
Story 12	1	374.5
Story 11	1	340.1
Story 10	1	306.1
Story 9	1	272.4
Story 8	1	239.3
Story 7	1	206.9
Story 6	1	175.2
Story 5	1	144.5
Story 4	1	114.9
Story 3	1	86.5
Story 2	1	59.3
Story 1	1	33.2

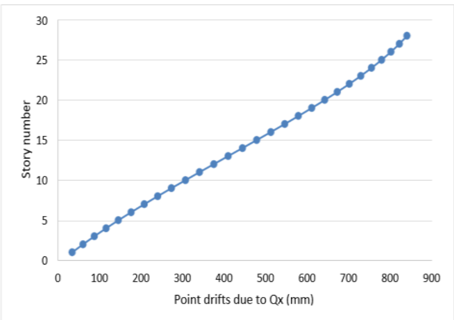

Figure 5 Point drifts due to Qx

Table 2 and Figure 6 show the displacements in (mm) versus the storey number due to wind load (Wx).

Table 2. Displacements versus the storey number due to wind load (Wx).

Story number	point	Displacement Ux (mm)
Story 28	1	61.6
Story 27	1	60.5
Story 26	1	59.4
Story 25	1	58.1
Story 24	1	56.7
Story 23	1	55.2
Story 22	1	53.6
Story 21	1	51.9
Story 20	1	50.2
Story 19	1	48.3
Story 18	1	46.3
Story 17	1	44.3
Story 16	1	42.1
Story 15	1	39.9
Story 14	1	37.6
Story 13	1	35.2
Story 12	1	32.8
Story 11	1	30.3
Story 10	1	27.7
Story 9	1	25.1
Story 8	1	22.5
Story 7	1	19.8
Story 6	1	17.1
Story 5	1	14.4
Story 4	1	11.7
Story 3	1	9
Story 2	1	6.3
Story 1	1	3.6

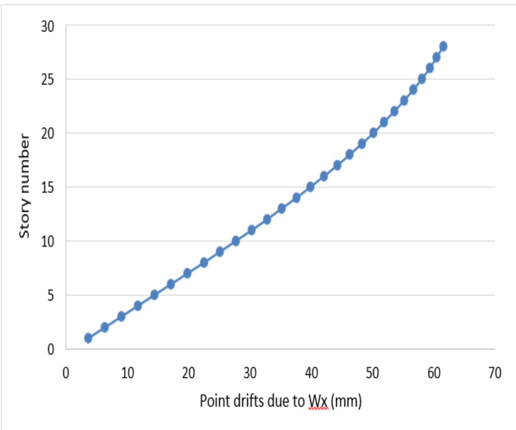

Figure 6. Point drifts due to Wx

It has been noted that the displacements values for both loads (Qx and Wx) were decreased from the moment resisting system to the shear wall system, and the dual frame has less values than moment resisting and shear wall. It was also shown that the tube system has the least values from the other systems. From the mentioned results, the researcher found out these points:

- The first system, which is (moment resisting system), is not possible for this height (28 floors) because the values of all floors that were obtained were very high and exceed the limitation values which were in the (UBC 97) code.
- The results of the two systems (shear wall system and dual system) showed that they were very suitable for this height and did not exceed the limitation values which were in the (UBC 97) code.
- The results of the fourth system (tube system) showed that they were very low and were in the limitations but it is not recommended to be used in this height because it is too costly.

5. 2 Shear Wall System

Figure 7 shows the displacements in (mm) versus the storey number due to Earthquake (Qx) in shear wall system.

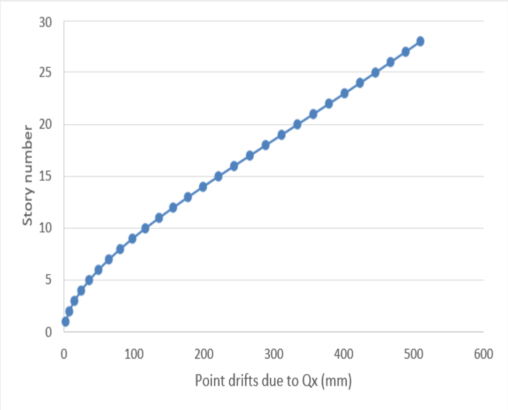

Figure 7 Point drifts due to Qx

Figure 8 shows the displacements in (mm) versus the storey number due to wind load (Wx).

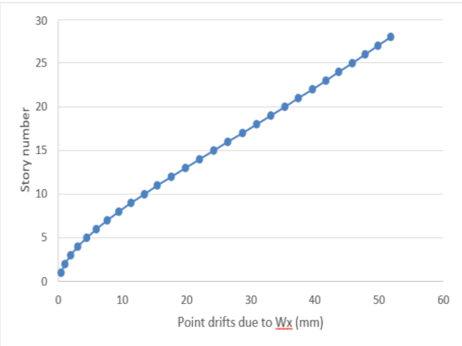

Figure 8. Point drifts due to Wx

From figures 7 and 8 above, the displacements due to earthquake did not exceed the limited values according to the international codes except two upper floors were critical and these floors needed to be braced just due to earthquake and it is safe due to wind load Wx.

5. 3 Dual System

Figure 9 shows the displacements in (mm) versus the storey number due to Earthquake (Qx) in dual system.

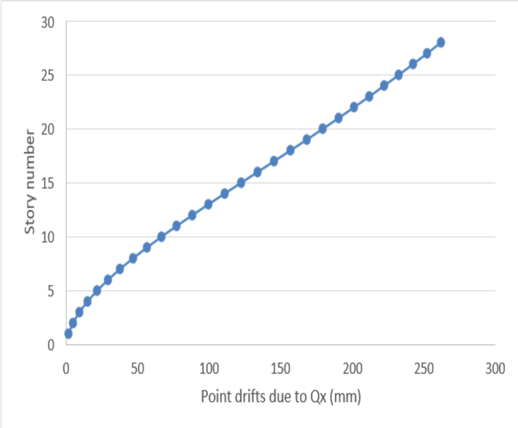

Figure 9 Point drifts due to Qx

Figure 10 shows the displacements in (mm) versus the storey number due to wind load (Wx).

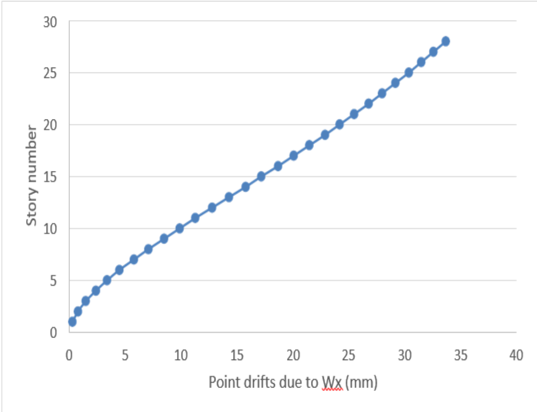

Figure 10. Point drifts due to Wx

From figures 9 and 10 above, it showed that there is no problem due to earthquake and wind load to construct a building with this height and with these factors and situations. The stiffness of this structure has been improved due to the use of this system with ratio about 48% for earthquake load and about 35% for wind load if it compared with the shear wall system.

5. 4 Tube System

Figure 11 show the displacements in (mm) versus the storey number due to Earthquake (Qx).

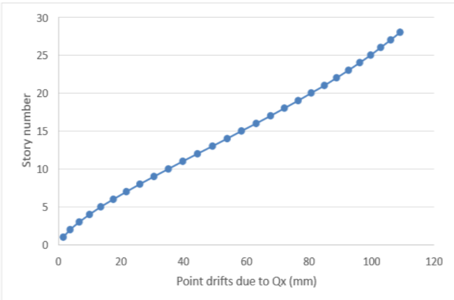

Figure 11 Point drifts due to Qx

Figure 12 show the displacements in (mm) versus the storey number due to wind load (Wx).

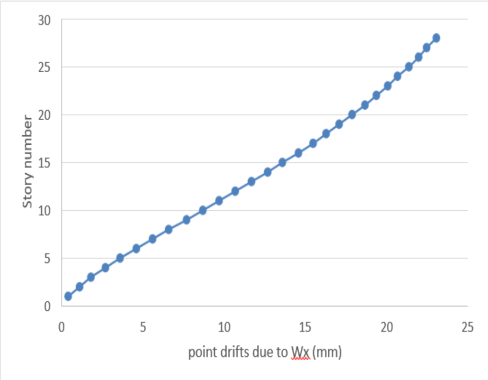

Figure 12. Point drifts due to Wx

Charts 11 and 12 showed that the displacement due to lateral loads (earthquake and wind) was decreased if they compare to the displacements of dual system. it has been a good improvement in the value of displacements, this due to exterior columns which located in the perimeter of the building and the ratio of decrease is about 62% for earthquake load and about 38 % for the wind load if it compared with dual system.

The following tables (table 3 and 4) and figures (figure 13 and 14) show the results of the earthquake Qx and wind Wx loadings of all the structure systems:

Table 3. Comparison between four systems of Qx in X direction

Story number	Point	Moment Resisting	Shear Wall	Shear Frame	Tube System
Story 28	1	840.2	509.7	262.4	109.2
Story 27	1	821.8	488.4	252.8	106.2
Story 26	1	801.4	466.9	242.9	103
Story 25	1	779	445.3	232.9	99.8
Story 24	1	754.7	423.4	222.7	96.3
Story 23	1	728.7	401.3	212.3	92.7
Story 22	1	701.1	379	201.6	88.9
Story 21	1	672.1	356.6	190.8	85
Story 20	1	641.9	333.9	179.7	80.8
Story 19	1	610.6	311.2	168.5	76.6
Story 18	1	578.4	288.5	157.1	72.2
Story 17	1	545.4	265.9	145.6	67.8
Story 16	1	511.9	243.3	134.1	63.2
Story 15	1	477.8	221	122.5	58.5
Story 14	1	443.5	199	111	53.9
Story 13	1	409	177.5	99.6	49.2
Story 12	1	374.5	156.5	88.4	44.4
Story 11	1	340.1	136.2	77.4	39.7
Story 10	1	306.1	116.7	66.8	35.1
Story 9	1	272.4	98.1	56.6	30.5
Story 8	1	239.3	80.7	46.9	26
Story 7	1	206.9	64.5	37.7	21.7
Story 6	1	175.2	49.6	29.3	17.5
Story 5	1	144.5	36.4	21.7	13.5
Story 4	1	114.9	24.9	15	9.9
Story 3	1	86.5	15.3	9.3	6.6
Story 2	1	59.3	7.9	4.9	3.7
Story 1	1	33.2	2.7	1.7	1.5

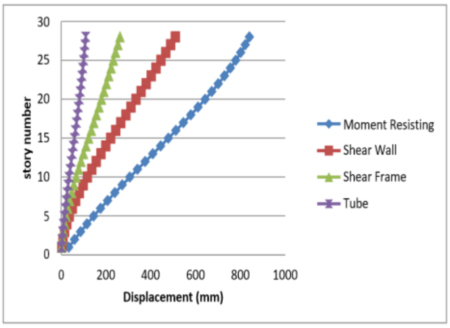

Figure 13. Comparison between four systems of Qx in X direction

Table 4 comparison between four systems of Wx in X direction

Story number	Moment Resisting	Shear Wall	Shear Frame	Tube System
Story 28	61.6	51.8	33.7	23.1
Story 27	60.5	49.8	32.6	22.5
Story 26	59.4	47.8	31.5	22
Story 25	58.1	45.8	30.4	21.4
Story 24	56.7	43.7	29.2	20.7
Story 23	55.2	41.7	28	20.1
Story 22	53.6	39.6	26.8	19.4
Story 21	51.9	37.4	25.5	18.7
Story 20	50.2	35.3	24.2	17.9
Story 19	48.3	33.1	22.9	17.1
Story 18	46.3	30.9	21.5	16.3
Story 17	44.3	28.7	20.1	15.5
Story 16	42.1	26.4	18.7	14.6
Story 15	39.9	24.2	17.2	13.6
Story 14	37.6	22	15.8	12.7
Story 13	35.2	19.8	14.3	11.7
Story 12	32.8	17.6	12.8	10.7
Story 11	30.3	15.4	11.3	9.7
Story 10	27.7	13.4	9.9	8.7
Story 9	25.1	11.3	8.5	7.7
Story 8	22.5	9.4	7.1	6.6
Story 7	19.8	7.6	5.8	5.6
Story 6	17.1	5.9	4.5	4.6
Story 5	14.4	4.4	3.4	3.6
Story 4	11.7	3	2.4	2.7
Story 3	9	1.9	1.5	1.8
Story 2	6.3	1	0.8	1.1
Story 1	3.6	0.4	0.3	0.4

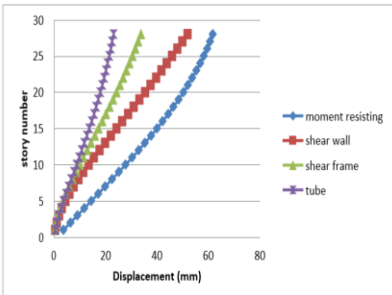

Figure 14. Comparison between four systems of Wx in X

direction

It has been noted that the displacements values for both loads (Qx and Wx) were decreased from the moment resisting system to the shear wall system, and the dual system has less values than moment resisting and shear wall. It was also shown that the tube system has the least values from the other systems.

The first system, which is (moment resisting system), is not possible for this height (28 floors) because the values of all floors that were obtained were very high and exceed the limitation values which were in the (UBC 97) code. The results of the two systems (shear wall system and dual system) showed that they were very suitable for this height and did not exceed the limitation values which were in the (UBC 97) code.

6. Conclusion

The building for all types of structures has been analyzed in the same situations and the plan is symmetric. Therefore, the study showed that the effect of earthquake on the structure was greater than the effect of wind on the building.

From the second type (shear wall system), the study noted that the maximum drift story due to earthquake load (Qx) in the X-direction for the two upper floors was critical, so there was more than one solution for this problem. This can change all the systems to another one or this can increase the stiffness of structure by increasing the compressive strength of concrete, but these two mentioned solutions were somehow costly, so the best solution is to make bracing only for weak two floors.

The study noted that the results of displacements from the type 4 (frame tube system) for all lateral loads (earthquake and wind) were decreased very much if it compared to the other structure systems because there were stiff columns with deep beams (spandrels) on the exterior of the building work as rigid members and connections and give the building a high stiffness against lateral loads, but this system is expensive (costly) for this heights and it is recommended to be used in higher buildings, for example more than 60 stories.

The main purpose of this study was to prove that the changing in the type of structural system from the moment resisting system to the tube system had positive results in the performance of the structure behavior, and this purpose is satisfied in this study as it was shown in tables (3 and 4) and charts (13 and 14). The researcher took the samples from these two tables randomly which were Qx and Wx in X-direction and the results showed that the deflections were decreased with changing the type of structure from the first system (moment resisting) to the fourth system (tube).

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