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# Evaluation of the Cost Effectiveness of Three Different Structural Systems for Tall Buildings

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**ABSTRACT**

New tall building developments of ever-increasing heights have been taking place around the world. The structural system of a high-rise building is designed to withstand vertical gravity loads as well as lateral forces induced by wind or seismic activity. The structural system consists only of the members designed to carry the loads, and all other members are referred to as non-structural. The structural system for a high-rise structure is determined by the selection and arrangement of the primary structural elements to withstand the different combinations of gravity and lateral loads as effectively as possible. A high-rise building needs to be stabilized for horizontal loads, and to achieve this; several different structural systems can be chosen. All the different systems have evolved from the traditional rigidly jointed structural frame. The fundamental design for all these structural systems has been to place as much of the load-carrying material as possible around the building's external fringe to maximize its flexural rigidity. This study has concentrated on three of these structural systems: the rigid frame system, the dual system, and the shear wall system. These systems were chosen because of their common use in the region. This study aims to evaluate the three structural systems and figure out which system is the most cost-effective to utilize based on the number of floors (10, 20, and 30) as well as the minimum element cross-section and reinforcement ratio. This will be provided by static checking (dynamical is required) of the results obtained from ETABS. Following the completion of the work using ETABS 2016 and comparing the systems in terms of strength and economy, the findings were as follows: the most economical system for 10 floors is the rigid frame system, the shear wall system for 20 floors, and the shear wall system for 30 floors.

**KEYWORDS:** high-rise buildings, structural systems, rigid frame system, dual system, shear wall system

## 1 INTRODUCTION

From the famous Tower of Babel in antiquity, reputedly meant to reach heaven, to today's highest skyscraper, humans have always struggled to push the boundaries of nature in their age-old search for height [1]. Case studies of some of the world's most renowned structures, illustrated in full color, will bring to life the architectural issues that architects and structural engineers have dealt with. The Empire State Building, the Burj Khalifa, Taipei 101, and the Pirelli Building are just a few instances of real-life specifications used to teach and exemplify basic design ideas and their subsequent influence on the final construction [1, 2].

There is no clear definition of what a high-rise building is. However, according to the Council of High-rise Buildings and Urban Habitat, it should have one of the following elements to be considered a high-rise building: (i) Height relative to context: when a building is distinctly taller than an urban norm, (ii) Proportion: a building that is slender enough to give an appearance of a high-rise building, and (iii) High-rise building technologies: the building contains technologies that are a product of the building's height, such as specific vertical transportation technologies and structural wind bracing [3].

Tall building design entails a conceptual design, approximate analysis, preliminary design, and optimization to properly carry gravity and lateral loads. Strength, serviceability, stability, and human comfort are the design targets. Limit stresses satisfy the strength, whereas drift limitations in the range of H/500 to H/1000 satisfy the serviceability. A suitable factor of safety against buckling and P-delta effects ensures stability. The safety factor ranges from 1.67 to 1.92. Human comfort is satisfied by accelerations ranging from 10 to 25 milli-g, where gravity's acceleration is around 981 $cms/sec^2$ [4].

Philosophy In contrast to vertical load, the effects of lateral load on structures are extremely diverse and rise rapidly with height. Under wind load, for instance, the overturning moment at the base of the structure changes in proportion to the square of the building's height, and lateral deflection varies as the fourth power of the building's height, everything else being equal [3]. The necessity for strength is the most important issue in the construction of low-height buildings. Nevertheless, as height grows, the requirements for stiffness and stability become more critical, and they are often the deciding considerations in the design. There are two options for meeting these needs in a framework. The first is to raise the size of the members beyond what is required for strength. However, this strategy has its limitations, beyond which increasing the sizes becomes either unfeasible or uneconomical [5]. The second and more efficient strategy is to modify the structure's shape to make it stiffer and more stable to contain the deformation and boost stability. There have been no cases of completed tall structures collapsing due to wind load. Through analysis, it can be shown that a tall structure subjected to wind pressure would collapse due to the so-called P-delta effect, in which the eccentricity of the gravity load grows to such a magnitude that it causes the columns to collapse because of axial stresses [5]. As a result, ensuring that expected wind loads are less than the load corresponding to the stability limit is an essential stability requirement. The second issue is to keep the lateral displacement to a level that will not harm architectural finishes or walls. Although less severe than the collapse of the main structure, the floor-to-floor displacement known as the inter-story drift must be controlled due to the expense of restoring the windows and the danger of falling glass to pedestrians [5, 6].

High-rise structures must have a high degree of flexibility because they are among the tallest buildings ever constructed. For this reason, high-rise structures require structural systems or structural frames-the collection of connected or dependent pieces that create a complex structure [7]. These structural systems were created and planned to withstand various loads. Take the human body as an illustration to learn more about how structural systems function. Human bones must be strong and properly positioned for the human body to function. Similar to mechanical systems, improperly constructed structural systems would not be able to support loads [7, 8].

For the first selection of systems, many distinct structural schemes are investigated. To achieve this balance in design, knowledge of the behavior of each structural system, quick preliminary design approaches, approximation analysis, and optimization techniques are required. Typically, 15 structural plans with different combinations of gravity and lateral systems are explored. Each concept is constructed with a candidate structural system, beginning with the basic plan size and height. Different column spacing, member sizes, truss, and other subsystem parameters such as outriggers and diagonal truss systems, should be carefully evaluated when comparing systems [9]. For a given drift, optimization may then be performed using one- or two-story sub-assemblies at various heights of the building in 2 to 3 iterative cycles. At intermediate levels, interpolation, frequently linear, might be built from these various level optimizations for member sizes and moments of inertia. This is then utilized in total stress analysis, which is done using big structural analysis software packages like Staad Pro, Sap2000, and ETABS. This will allow for faster final design and detailing [9]. Alternatively, the starting sizes may be inefficient, and reaching the drift and acceleration limitations may require many more iterative cycles [10]. The optimal design of a tall structure is an art and science, with structural engineers' years of knowledge, stress analysis, structural design, and detailed methods used wisely at the proper time and place [9, 11].

Extreme engineering procedures are necessary for extremely tall structures. The technological difficulties involved in building massive, highly inventive skyscrapers that ambitiously aim for the sky while defying the powerful natural forces of gravity, wind, and earthquake are what define extreme engineering for tall buildings [3]. Creativity in their structural design becomes essential to fulfill the demands placed on them by their enormous height as well as the difficulties brought on by higher gravity and lateral pressures applied to them.

The structural system should be able to withstand a variety of loads, including gravity, lateral, temperature, blast, and impact loads. The tower's drift should be controlled within restrictions, such as H/500 [9].

These three systems have been chosen for this study: (i) Steel and reinforced concrete structures employ rigid frame systems, also known as moment frame systems [4]. This system is made up of beams and columns. A rigid frame is an unbraced frame that can withstand vertical and lateral loads by bending beams and columns. (ii) A dual system is a structural system in which an essentially complete frame supports gravity loads while a specifically designed moment-resisting frame and shear walls or braced frames resist lateral stresses [12]. Shear walls and frames both assist in resisting lateral loads brought on by earthquakes, wind, or storms, and the number of forces that each can withstand depends on its stiffness, ductility, elastic modulus, and capacity to produce plastic hinges in its sections. Moment-resisting frames made of steel or concrete may be used, although concrete intermediate frames are not allowed in seismic zones 3 or 4. The two systems must be constructed to handle the entire lateral load by their respective rigidities, and the moment-resisting frame must be able to withstand at least 25% of the base shear [12]. (iii) Shear wall systems are employed in reinforced concrete structures [13]. This system is made up of perforated (with apertures) or solid reinforced concrete shear walls [4]. Shear wall systems, which can withstand all vertical and lateral stresses on a structure without columns, may be conceived of as a vertical cantilever permanently fastened at the base. Shear wall construction[14]. In structures with up to 35 floors, offer adequate stiffness to withstand wind and earthquake-induced lateral stresses effectively and inexpensively [10, 14].

## 2 SIGNIFICANCE OF THE STUDY

The objective of this research is to analyze three structural systems that are commonly used in the Duhok region, including the rigid frame system, the dual system, and the shear wall system, to discover which system is the most cost-effective for 10-, 20-, and 30-story structures in this target area. This comparison is based on the total quantity of concrete and reinforcement needed for each system's structural sections; these quantities are determined by the compressive strength of concrete, minimum reinforcement ratio, and the section size of each of the columns, beams, slabs, and shear walls.

By using the software ETABS 2016, section dimensions will be determined and, on that basis, amounts of concrete and reinforcement required for each of the sections will be estimated and eventually the most economical system for each of the 10, 20, and 30 floors can be determined.

# 3 RESEARCH AND METHODS

## 3.1 Building Configuration

Three tower buildings of different heights with the same column distribution on grids (eight grids on the x-axis and six grids on the y-axis) have been chosen for all three systems to do a comparison. The tower is 25 m wide and 32 m long, and the height is 3.3 m from floor to floor. The first tower is 10 floors with a total height of 33 m from the ground floor, the second one is 20 floors with a total height of 66 m from the ground floor and the third one is 30 floors with a total height of 99 m from the ground floor as shown in below Figure 1, Figure 2, and Figure 3 for rigid frame system, dual system, and shear wall system respectively. In this research, the three different structural systems were studied for comparison (i.e., rigid frame, dual, and shear wall system) for each building. In other words, three systems of structure will be applied to each tower. After various trials on tower building elements with different structural systems to get minimum cross-section as well as minimum ratio of reinforcement to achieve the effective cost. Therefore, the results of all towers of different systems were for a rigid frame system, the size of columns, beams, shear walls, and slabs is shown in Table 1.

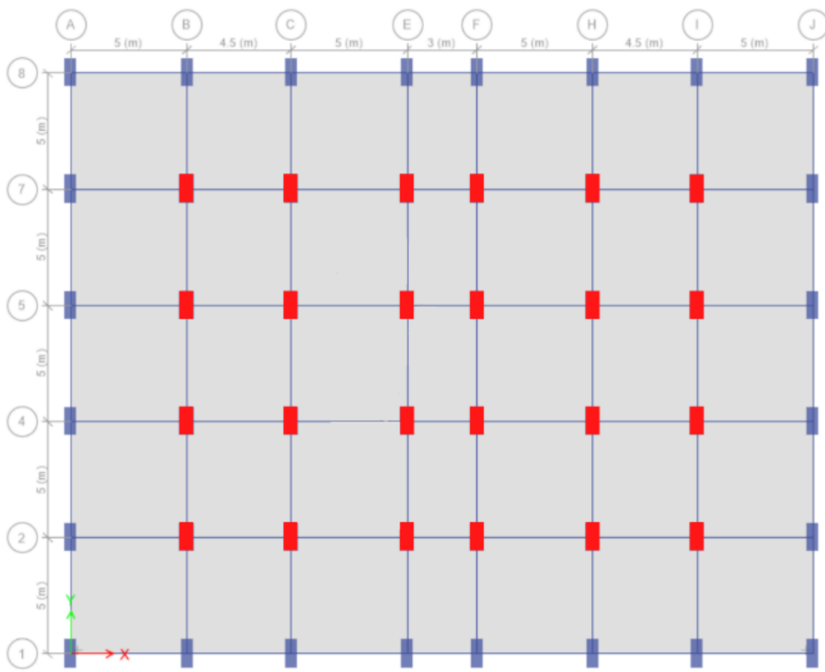


**Figure 1**: Plan of the rigid system (10,20,30)

**Table 1:** Building element dimensions with rigid frame system.

| Tower | Floors | Column (mm) | Middle columns (mm) | Beam (mm) | Slab (mm) |
|---|---|---|---|---|---|
| 10 Floors | 1-5 | 400 × 400 | 500 × 500 | 300 × 500 | 175 |
| | 6-10 | 400 × 300 | 400 × 300 | 300 × 500 | 175 |
| 20 Floors | 1-5 | 400 × 900 | 500 × 900 | 300 × 600 | 175 |
| | 6-10 | 400 × 700 | 500 × 700 | 300 × 600 | 175 |
| | 11-15 | 400 × 500 | 500 × 500 | 300 × 600 | 175 |
| | 16-20 | 400 × 400 | 400 × 400 | 300 × 600 | 175 |
| 30 Floors | 1-5 | 500 × 1200 | 600 × 1200 | 300 × 600 | 175 |
| | 6-10 | 500 × 1000 | 600 × 1000 | 300 × 600 | 175 |

| Tower | Floors | Column (mm) | Middle columns (mm) | Beam (mm) | Slab (mm) |
|---|---|---|---|---|---|
| | 11-15 | 500 × 800 | 600 × 800 | 300 × 600 | 175 |
| | 16-20 | 500 × 600 | 600 × 600 | 300 × 600 | 175 |
| | 21-25 | 500 × 500 | 500 × 500 | 300 × 600 | 175 |
| | 26-30 | 500 × 400 | 500 × 400 | 300 × 600 | 175 |

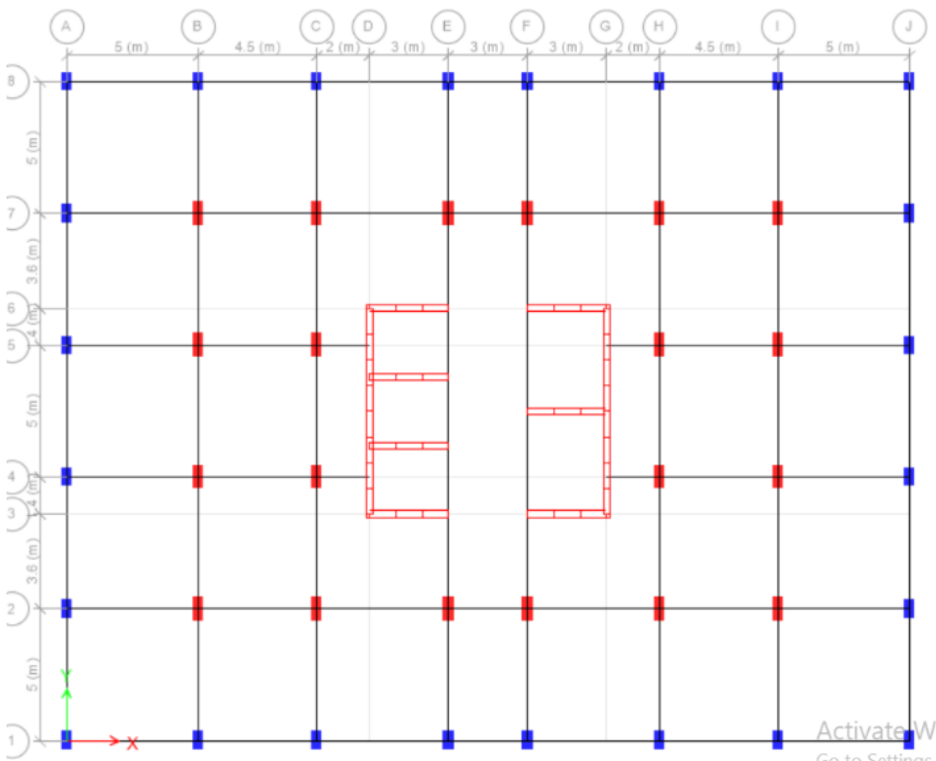


**Figure 2:** Plan of the dual system (10,20,30)

Table 2, Table 3, and Table 4 show the parameters of columns, beams, shear walls, and slabs for the dual system.

**Table 2:** Data of 10-story building Dual system.

| Story | Column (mm) | Beam (mm) | Slab (mm) | Shear wall (mm) |
|---|---|---|---|---|
| **1-5** | 300 × 500 | 300 × 500 | 140 | 250 |
| **6-10** | 300 × 400 | 300 × 500 | 140 | 250 |

**Table 3:** Data of 20-story building Dual system.

| Story | Outer column (mm) | Middle columns (mm) | Beam (mm) | Slab (mm) | Shear wall (mm) |
|---|---|---|---|---|---|
| **1-5** | 400 × 700 | 400 × 900 | 300 × 500 | 175 | 250 |
| **6-10** | 400 × 500 | 400 × 700 | 300 × 500 | 175 | 250 |
| **11-15** | 400 × 400 | 400 × 600 | 300 × 500 | 175 | 250 |
| **16-20** | 400 × 300 | 400 × 500 | 300 × 500 | 175 | 250 |

**Table 4:** Data of 30-story building Dual system.

| Story | Outer column (mm) | Middle columns (mm) | Beam (mm) | Slab (mm) | Shear wall (mm) |
|---|---|---|---|---|---|
| **1-5** | 500 × 900 | 600 × 1100 | 300 × 500 | 180 | 250 |
| **6-10** | 500 × 700 | 500 × 900 | 300 × 500 | 180 | 250 |
| **11-15** | 500 × 600 | 500 × 800 | 300 × 500 | 180 | 250 |
| **16-20** | 500 × 500 | 500 × 700 | 300 × 500 | 180 | 250 |
| **21-25** | 400 × 400 | 400 × 600 | 300 × 500 | 180 | 250 |
| **26-30** | 400 × 400 | 400 × 600 | 300 × 500 | 180 | 250 |

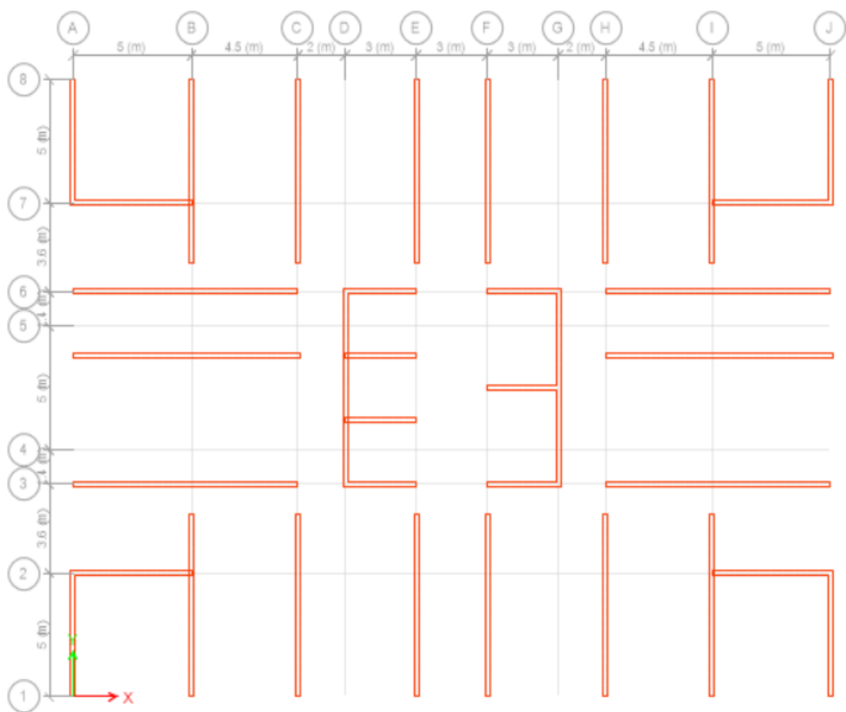


**Figure 3:** A plan of shear wall system (10,20,30)

Table 5 shows the dimensions of shear walls and slabs for dual systems.

**Table 5:** Data of 30-story building shear wall system.

| Story | Shear wall thickness (mm) | Slab thickness (mm) |
|---|---|---|
| **10** | 200 | 160 |
| **20** | 225 | 165 |
| **30** | 250 | 165 |

## 3.2 Loads on Towers Configuration

To analysis and design the towers and determine the comparison, first, it must define the forces acting on the building. There are mainly two types of loads; gravity loads such as live loads and dead loads and lateral loads for instance; seismic loads and wind loads. The dead loads are self-weight loads that are taken from the weight of the structure. In addition to this load, 2 kN/m$^2$ was applied as a super-dead load such as the weight of tiles, sand, mortar, plastering, and false ceiling. The wall load in this study was also taken and considered super-dead. The live load was taken from the American Society of Civil Engineering (ASCE 7-16) code [15] but it was considered the same for all floors with the value of 3kN/m$^2$. According to Iraqi code 303 [16], the s1 and ss are 0.2 and 0.6 respectively for the Duhok city zone. The soil site class is D. The seismic design category was D. Meanwhile, 85 mph was wind speed, exposure type of wind was type C. The importance factor is taken 1 with the windward and leeward coefficients of 0.8 and 0.5 respectively. All loads applied to the structures are summarized in Table 6.

**Table 6:** Summary of loads on the structure

| Pattern of loads | Weight |
|---|---|
| **Vertical loads** | |
| **Dead load** | Weight per unit volume= 24 kN/m$^3$ |
| **Super-Dead load** | Wearing (finishing) load = 2.0 kN/m$^2$ |
| **Live load** | Every floor = 3.0 kN/m$^2$ |
| **Lateral loads** | |
| **Wind speed** | 38 m/sec |
| **Exposure type** | C |
| **Windward Coefficient** | 0.8 |
| **Leeward Coefficient** | 0.5 |

## 3.3 Analysis and Design software.

The software ETABS 2016 is used for the analysis and design of towers in this article. The materials defined are concrete with variable compressive strength of each element as shown in Table 7 and reinforced steel with the constant value for all research of yield strength of 420 MPa and 200000 MPa as its modulus of elasticity. According to ACI 318-19 code [17], the stiffness modifier was taken as shown in the for each element. As well as the load combinations were followed by ASCE 7-16 [15]. The parameters such as Response modification R, System over strength Ω, Deflection amplification cd, and Occupancy importance I were taken based on ASCE 7-16 [15] as seismic parameters for each system as shown in Table 8.

**Table 7:** Concrete properties of structural members.

| Section | $fc'$ | Modulus of elasticity=4700 × $\sqrt{fc'}$ |
|---|---|---|
| **Column** | 35 MPa | 27805 MPa |
| **Beam** | 30 MPa | 25742 MPa |
| **Shear wall** | 35 MPa | 27805 MPa |
| **Slab** | 25 MPa | 23500 MPa |

**Table 8:** Seismic parameters.

| Parameters | Rigid-Frame-System | Dual-System | Shear-Wall-System |
|---|---|---|---|
| **Response modification R** | 8 | 7 | 5 |
| **System over strength Ω** | 3 | 2.5 | 2.5 |
| **Deflection amplification cd** | 5.5 | 5.5 | 5 |
| **Occupancy importance I** | 1 | 1 | 1 |

## 3.4 Analysis checking configuration

Each building was meshed for accurate results and the mass source was defined with a live reduction factor for each floor, then the target building was run in the ETABS 2016 software. The deflection of slabs with static and dynamic were checked for each tower. As shown in Table 9 for checking deflection to determine the thickness of the slab for each floor. The deflection was based on long-term deflection. The static checks include P-delta, Eccentricity, horizontal such as torsion as in Table 10, vertical such as story drift as in Table 11, soft story irregularity in Table 12, and heavy story irregularity in Table 13 were considered. In addition, the dynamic check was studied for checking the building. Therefore, the Response Spectrum function is defined in software to withstand studying dynamic checks.

**Table 9:** Deflection checking for Shear wall system.

| Number of stories | The thickness of the slab (mm) | Deflection check |
|---|---|---|
| **10** | 160 | okay |
| **20** | 165 | okay |
| **30** | 165 | okay |

**Table 10:** Torsion checking.

| Number of stories | Rigid-Frame | Dual | Shear-Wall |
|---|---|---|---|
| **10** | Okay | Okay | Need to be considered |
| **20** | Okay | Okay | Need to be considered |
| **30** | Okay | Need to be considered | Need to be considered |

**Table 11:** Story drift checking.

| No. of stories | Rigid-Frame | Dual | Shear-Wall |
|---|---|---|---|
| **10** | Okay | Okay | Okay |
| **20** | Okay | Okay | Okay |
| **30** | Okay | Okay | Okay |

**Table 12:** Soft story irregularity checking.

| No. of stories | Rigid-Frame | Dual | Shear-Wall |
|---|---|---|---|
| **10** | Okay | Okay | Okay |
| **20** | Okay | Okay | Okay |
| **30** | Okay | Okay | Okay |

**Table 13:** Heavy story irregularity checking.

| No. of stories | Rigid-Frame | Dual | Shear-Wall |
|---|---|---|---|
| **10** | Okay | Okay | Okay |
| **20** | Okay | Okay | Okay |
| **30** | Okay | Okay | Okay |

# 4 RESULTS AND DISCUSSION

## 4.1 Comparison based on concrete

As shown in Figure (4-6), the amount of concrete for each structure was calculated by calculating the volume of each section of the structure. The volumes of beams, columns, slabs, and shear walls were calculated and then the summation of all those volumes was calculated, based on that volume the amount of concrete required was determined.

According to the amount of concrete required by each system for 10, 20, and 30 floors, the most economical system would be a rigid frame system, however, this is not the result because comparison based on reinforcement is also required, hence comparison based on concrete is not adequate for the result.

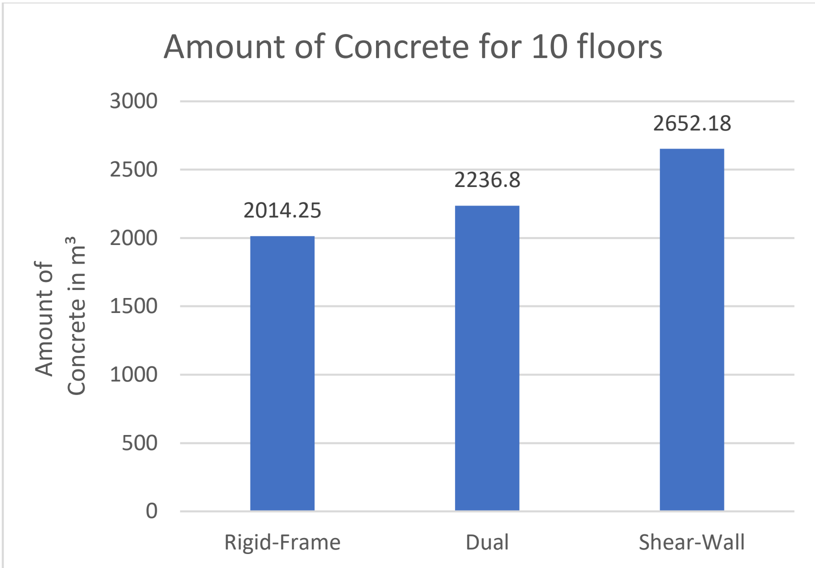


**Figure 4**: Amount of Concrete for 10 floors

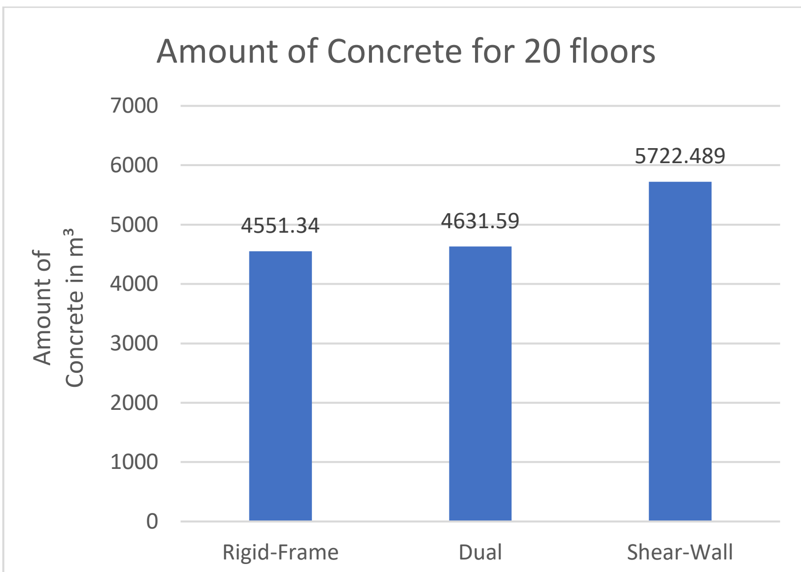


**Figure 5:** Amount of Concrete for 20 floors

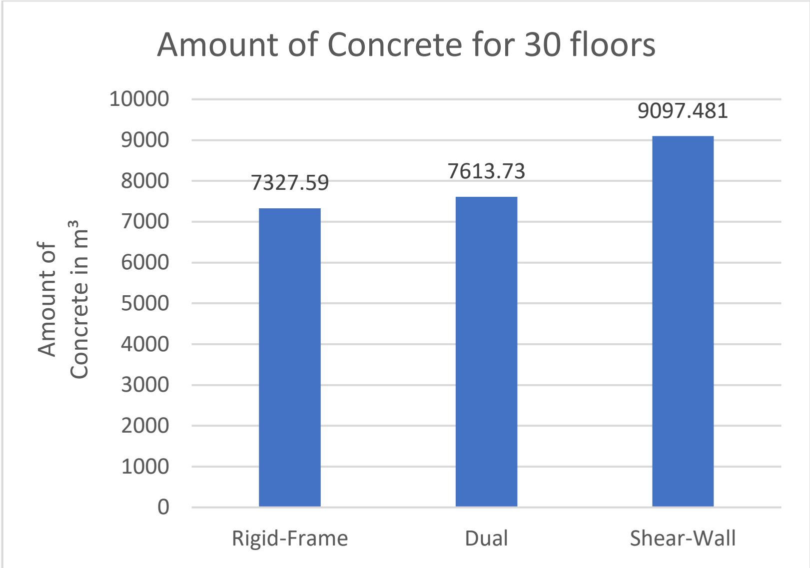


**Figure 6:** Amount of Concrete for 30 floors

## 4.2 Comparison based on reinforcement

As shown in Figure (7-9), the amount of reinforcement required for each section of the structure was calculated. Reinforcement required for each of the columns, beams, slabs, and shear walls was calculated and then the total amount of reinforcement by summation was determined.

As a result, by comparing the three structural systems mentioned, for 10, 20, and 30 floors, the shear wall system is the most economical since it requires the smallest amount of reinforcement compared to the other systems. However, this is not the result, because concrete calculations must also be included.

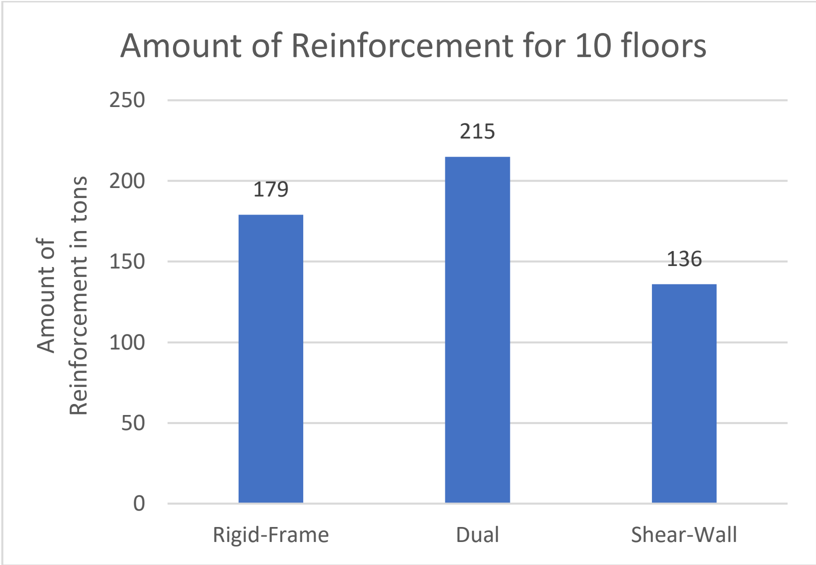


**Figure 7:** Amount of Reinforcement for 10 floors

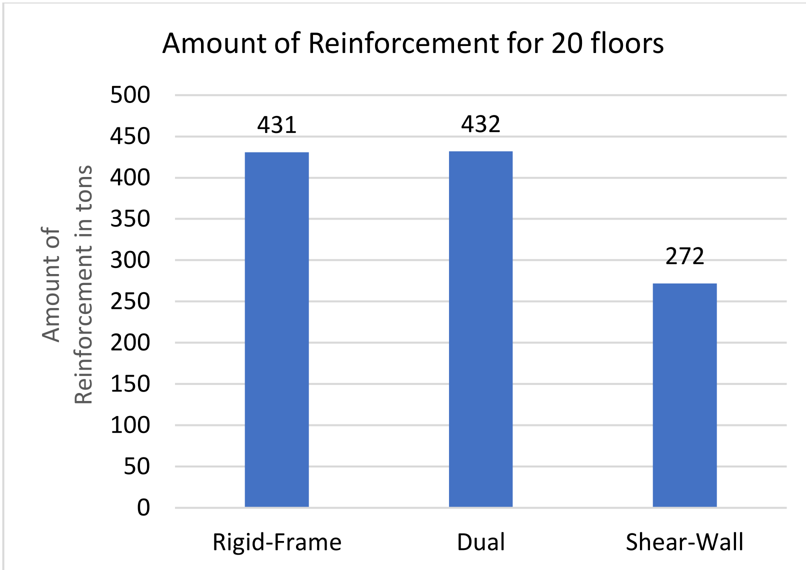


**Figure 8:** Amount of Reinforcement for 20 floors

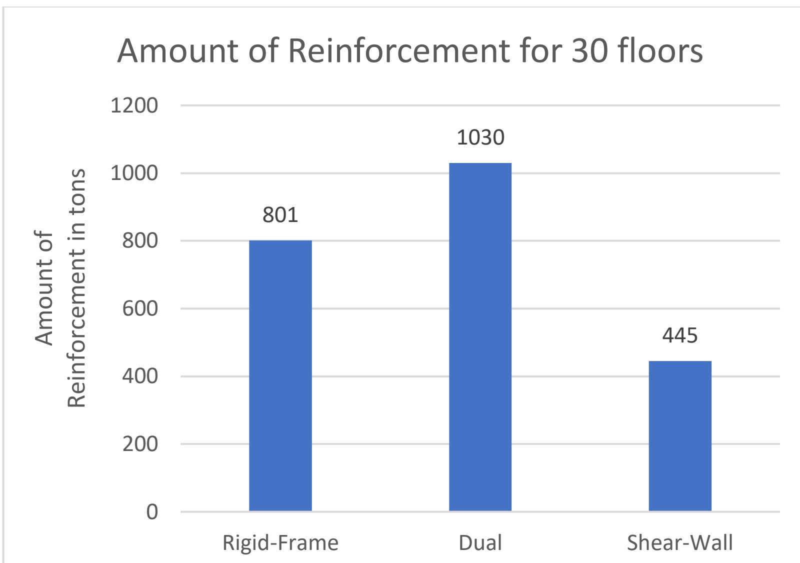


**Figure 9:** Amount of Reinforcement for 30 floors

### 4.3 Comparison Based on Other Factors Including (Time, Architecture, And Seismic Effects)

In terms of time, the shear wall system requires less amount of time for construction than the other two systems, and the dual system requires more time compared to the rigid frame system for construction, hence, to save more time in construction, the shear wall system is the best choice.

In terms of architectural plan, a rigid frame system is a very flexible system which means when the structural system of the building is a rigid frame system it can be used for many purposes, all in the same building, for instance, the same building can include a parking garage, shopping mall, and residential apartments, all of them together in the same building. Meanwhile, a dual system is less flexible since a dual system consists of a core in the center, however, a shear wall system can be used for only one function, and it can be used for residential or commercial purposes only.

In terms of seismic performance, shear walls exceed the other two systems because shear walls in high seismic zones need detailing. In previous earthquakes, however, even structures with a significant number of walls that were not particularly detailed for seismic performance (but had adequate well-distributed reinforcement) were protected from collapse. Shear wall structures are a popular option in many earthquake-prone regions, including Chile, New Zealand, and the United States. Shear walls are simple to build since wall reinforcement detailing is uncomplicated and hence readily installed on the job site. Shear walls are useful in limiting earthquake damage in structural and non-structural components (such as glass windows and building contents), both in terms of construction cost and efficacy.

## 4.4 Comparison Based on The Total Amount Of Concrete And Reinforcement

As in Figures 10-12, a comparison among the three structural systems based on the total amount of concrete and reinforcement results is: (i) the Rigid frame system is the most economical system for a 10-story building, (ii) Shear wall system is the most economical system for a 20-story building, and (iii) Shear wall system is the most economical system for a 30-story building.

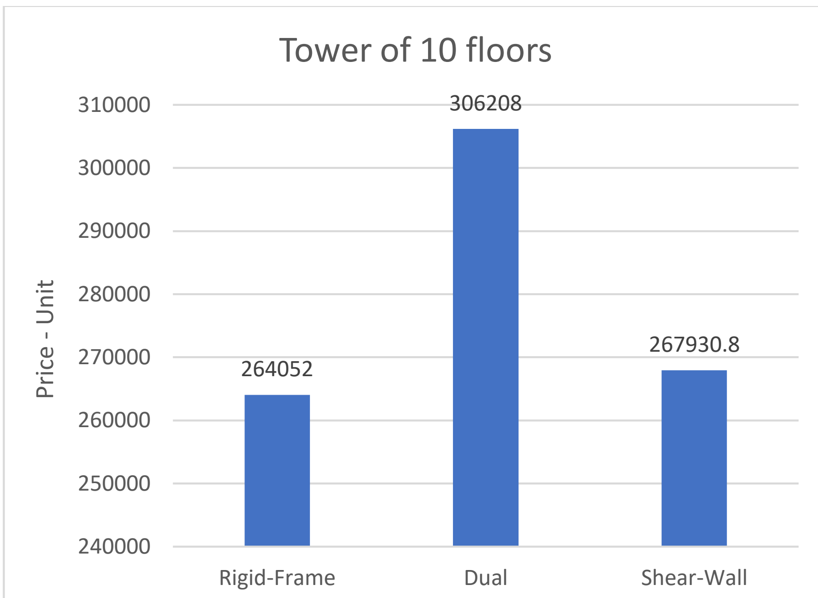


**Figure 10**: Tower of 10 floors

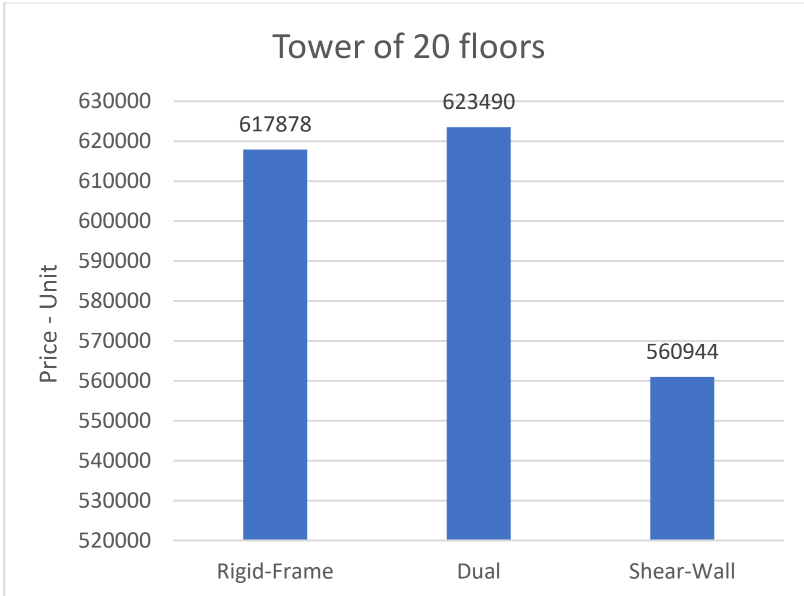


**Figure 11:** Tower of 20 floors

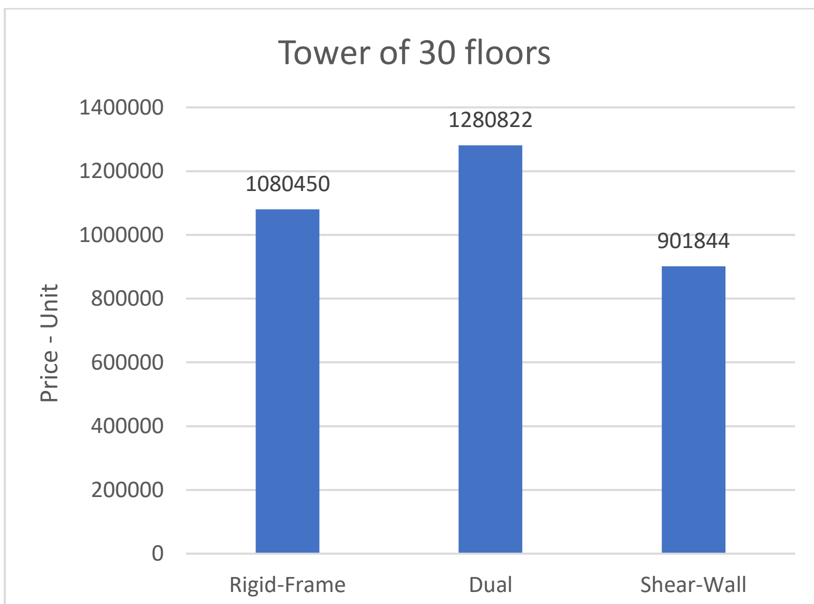


**Figure 12:** Tower of 30 floors

## 5 CONCLUSION

After calculating and estimating the amount of materials needed by each of the systems, the rigid frame system is the most economical system for 10 floors, although this was expected, since for rigid frame system material is only needed for frame sections and because it does not contain any shear walls, also lateral loads in 10 floors is not as critical as that of 30 floors, hence for gravity loads only rigid frame system is the best choice, while for 20 floors, the shear wall system is the most economical, even though it was expected that dual system would be more economical, however, the shear walls in the dual system required large sections, because almost all of the lateral load that the building is subjected to it is carried by those shear walls, and the other sections only carry gravity loads. For 30 floors, the shear wall system is the most economical system, and this was expected, because lateral loads are even more critical in 30 floors buildings and because they are always subjected to lateral loads, hence shear wall system would be the best choice for 30 floors, in terms of safety and economy as well.

## 6 FUTURE STUDIES

If there was more time, foundation calculations would have also been included, however, foundation calculations in this study were kept constant.

For further studies, basement and underground floors can also be included in the structures so their calculations would also be considered in the calculations, resulting in different results and calculations.

Also, Architectural plans would have been included and detailed in this paper if there was enough time, but because of lack of time, the architectural plans in this research were also kept constant, however for future studies, the topics mentioned above can be discussed and explained further.

The results obtained from this article will also encourage engineers to work with structural systems in high-rise buildings more economically and encourage them to get out of their comfort zone and try new, more economical systems depending on the number of floors of the structure.

This paper also suggests the idea of comparing these three structural systems however a larger number of floors, such as 40 and 50 floors, or the same number of floors can be used for comparison however by using different structural systems such as coupled wall system, tube structural system, and many others.

Also, in the future, comparisons among different structural systems can be based on some other factors such as architectural plans and details, time, and many more factors.

For future studies, more loads can be studied and affect the structure, such as wall line loads.

Finally, the work that has been achieved in this paper can be developed and improved more in the future and can lead to further studies and engineering discoveries and explorations in the field of engineering.

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