Original Research Paper

Decision Making and Predicting the Cost for the Optimal Structural System of Multi-Story Buildings

[1]Hosam Elhegazy, [1]Ahmed Ebid,
[1]Ibrahim M. Mahdi, [2]S.Y. Aboul Haggag and [2]Ibrahim Abdel Rashid

[1]Department of Structural Engineering and Construction Management,
Faculty of Engineering and Technology, Future University in Egypt, Egypt
[2]Department of Structural Engineering, Faculty of Engineering, Ain Shams University, Egypt

Abstract: There are numerous structural lateral systems used in multi-story buildings design such as the shear wall, frame system, framed with core, dual systems and superframes, etc. Additionally, the system of slabs such as (Solid Slab, Flat Slab, Flat plates, Hollow blocks, ... and Waffle Slabs). Generally, the structural systems of multi-story buildings are considered to be different types. Multi-story buildings are commonly used in residential, commercial and administrative projects; therefore, determining the structural system with minimum cost is the top priority of the structural designer. This research aims to introduce recommendations for the optimum structural system for a multi-story Reinforced Concrete (R.C.) building from a perspective of direct cost to help decision-makers in the preliminary design for choosing the optimum structural system. This paper outlines the development of charts to predict optimal structural system costing, using the status of early conceptual design as the charts input. In order to achieve that goal, a parametric study was carried out using 27 RC buildings with several stories ranging between 5 to 50 floors and grid spacing ranged between 6.0 to 12.0 m. Three floor systems were considered which are solid, ribbed and flat slabs.

Keywords: Structural Optimization, Structural System, Multi-Story Buildings, RC Buildings, Lateral Loads Resisting System, Decision Making, Cost Optimization

Introduction

Multi-story buildings are "A building whose height creates different conditions in the design, construction and use than those that exist in common buildings of a certain region and period." A clear classification of multi-story buildings with respect to their structural system is difficult and a rough classification can be made with respect to effectiveness in resisting lateral loads. There are many types of structural systems for multi-story buildings to resist the forces of earthquakes. Construction of the multi-story building is rapidly increasing throughout the world. Advances in construction technology, materials, structural systems, analysis and design software facilitated the growth of these buildings. Multi-Story buildings (Low/medium/High) are emerging as structurally efficient as well as architecturally significant assemblies for multi-story buildings. The structural systems, which previously referred, considered more systems used in the design of were structures. In the design of multi-story buildings, we can adopt a particular structural system and generalized use of the structural system in the design of multi-story buildings regardless of the number of stories, structural types and whether this system achieves the economic cost of the building. In the conceptual design phase, the widest possible design space is explored and ultimately the most preferred designs between all alternative, based on their evaluation

against technical and economic criteria, are selected for further analysis. A set of objectives usually comprised of elements, from several operational, technical, economic, safety and other relevant factors are taken into account to derive the evaluation criteria used in the evaluation stage of the proposed solution. The economic cost is the most essential factor for the structural design after the safety factors and design requirements using the international codes for the structures. The structural analysis of the structural systems is done using Finite Element Methods (FEM). The design of these systems is done according to the international codes. We want to find out what happens if one of these systems achieve an economic cost of the multi-story building, whether those buildings are similar to or different from each other in the number of stories, structural types and the type of materials. To answer these questions and study the problem at hand the following models of multi-story buildings are imposed.

Literature Review

During the past decades, various structural systems have applied to build several multi-story building. Since a large segment of the public and private sectors' expenditure and the time is spent on the construction industry especially the construction of the multi-story building, it is essential to think how to properly direct this time and a huge amount of money spent on this crucial industry. Selecting the optimum of the structural system for multi-story buildings leads to saving a lot of time and costs in these projects. The scientific literature on the selecting of the optimal structural system for multi-story buildings was reviewed to identify the documented best practices and areas for further exploration. Various engineering databases, conference proceedings and journals including ASCE Civil Engineering Database (for ASCE journals and conference proceedings), Civil Engineering Abstracts, ProQuest Dissertation and Theses, SciFinder Scholar, google scholar were searched. Table 1 shows some publications in the last periods and it is classification according to the relation to this research study and frequency of this publishing research.

Ermolaeva *et al*. (2012) suggested the material selection in combination with structural optimization procedure the optimal material choice according to the constructed system based on the best potential of each material-candidate in mechanical behavior under given load and boundary conditions. Procedures and guidelines were proposed for the selection of optimum structural systems and materials in 2 stages. They used the STAAD Pro 2005 software to analyze these systems according to allowable stress requirements for an objective function to minimize drift, at minimal cost for a wind speed of 90 mph. In their study, they recommended that the shear wall is the optimum structural system and concrete the optimum material to minimize lateral drift at minimum material and labor costs (Al Shamrani and Schierle, 2007). The sizing optimization of structural systems of tall buildings in preliminary design was studied in the serviceability limit state. They considered that sizing optimization is an essential part of the initial design to achieve a structure with minimal costs and carbon footprint (Merza and Zangana, 2014).

Table 1: Summary of earlier researches in multi-story optimization

Research name	Researcher, year	Description and gaps
Innovative application of dispersed shear wall to a kilometer-high concrete skyscraper	Alam (2016)	Examined a new structural lateral system for RC Skyscraper using STAAD/PRO models
High-rise residential reinforced concrete building optimization	Xiong and Calvo (2015)	Suggested an optimization procedure for the RC slab floor system based on a set of CSI, SAFE 2014 models
Value engineering in residential house construction	Tom and Gowrisankar (2015)	A case study on VE of a residential RC building project
Value engineering for low-cost housing construction in Egyptian expansion urban	Agrama *et al*. (2014)	Case Studies of VE using the weighted evaluation technique to evaluate the selection of the optimal construction system for RC building
Analysis and design of dia-grid structural system for high rise steel buildings	Jani and Patel (2013)	Presented a procedure to analyze and design diagrid steel buildings using CSI ETABS software and compared the results of 36, 50, 60, 70 and 80 story steel buildings
Value engineering analysis for the educational buildings in Egypt	Youssef *et al*. (2012)	Questionnaire & case study to determine the optimum alternative to maximize the utilization of the available construction and maintenance budget of educational buildings in Egypt
Diagrid structures for complex-shaped tall buildings	Moon (2011)	Studied the structural performance and constructability of Tall buildings
An analysis of value management in practice: The case of Northern Ireland's construction industry	Perera *et al*. (2011)	Questionnaire and case studies to summarize the experience of construction professionals in Northern Ireland

Cho *et al*. (2007) studied the structural system optimization of high-rise building based on optimal topology. The compatibility condition neglected and used the force method formulation, cross-section area, redundant forces and values of the objective function can be obtained such that the objective function which may be the total volume or weight of the truss structure shall be minimized. The sum of lower bound allowable forces and redundant forces shall be limited to the range of lower and upper bound of permissible stresses utilizing computerized linear programming. Tests conducted such that lower bound cross-sectional area was assumed zero. In 2012, Azzam and Rana studied the optimization for selecting the reinforced concrete design of structural systems for high-rise buildings in resisting seismic forces through the study and design of three models of RC high-rise structure buildings consisting of (10-15-20) stories. The couple structural system achieved the best results, hence the optimization in designing the reinforced concrete high-rise buildings (Katkhoda, 2012).

Steps of the Research (Methodology)

The Research Adopts the Following Steps

1. Adoption of several models of multi-story buildings (Reinforced Concrete) consisting of (5-15-25) story for the span 6 m, (8-23-38) for the span 9 m and (10-30-50) for the span 12m as shown in the Table 2. These models for the three types of structural systems (Frame-Shear Walls - Dual) for supper structure system as shown in Fig. 3 that shows the steps in the analysis and design model the system and apply the Model during the design stage. The classification of the rise buildings done according to (Taranath, 1998) (Steel, concrete and composite design of the tall building - second Edition). The below table shows the classification of the rising building (Low rise,

medium-rise and high rise buildings) according to the height and the span. Table 3 shows the details for the height and the span for classification the buildings

The thickness for walls and dimensions of reinforced concrete elements and steel structures elements identified and inferred based on Finite Element Methods (FEM)

2. Adoption of structural analysis program ETABS.v17.0.1 in analysis and structural design models after the process of analysis and design for imposed designing models according to the international codes

3. Then, study the conclusion models again after modification to the dimensions of cross-sections of some or all structural elements (beams-columns-shear walls). Then, the final models that all its structural elements achieve design code conditions as well as to make lower cost

4. Extraction the results of the design for the three types of structural systems (Frame - Shear Walls - Dual) for supper structure system (Reinforced Concrete) and calculation amounts of concrete and steel for whole structure building and then calculate the total cost of construction and then making a comparison between the models

5. Study the cost-effective for concrete and steel on the total cost of multi-story structure buildings for three cases of prices change and for the three types of structural systems (Frame - Shear Walls - Dual)

6. Drawing relations between the total cost and for the different types of structural systems (Frame - Shear Walls - Dual)

7. Determination the optimum and the appropriate of structural systems for the different multi-story buildings in the number of stories, type of structures and the different spans

8. The framework for this study show in the below Fig. 1 that show the steps for the study and the overall framework for it as a flow chart

Table 2: Show the classification of the structural system according to height and span

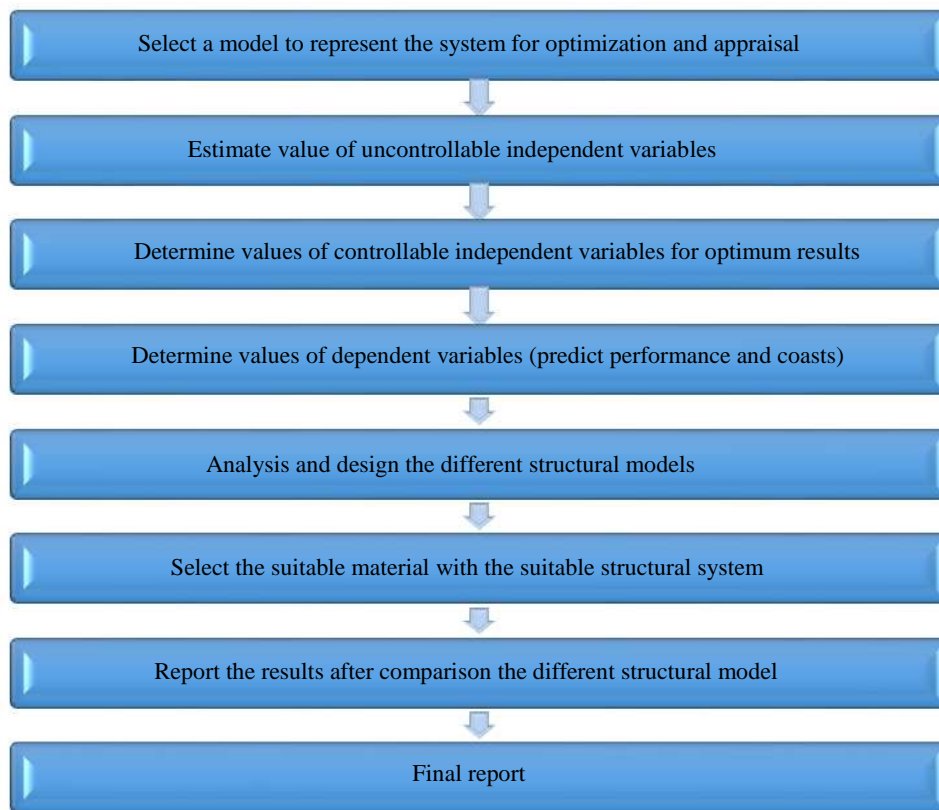| Height type	Height limitation	Span	No. of floor
Low rise	$\sum H < \sum L$	6 m	5
		9 m	8
		12 m	10
Medium rise	$\sum H = (1-5)\sum L$	6 m	15
		9 m	23
		12 m	30
High rise	$\sum H > 5\sum L$	6 m	25
		9 m	38
		12 m	50

Fig. 1: Flow chart for model the system and apply the model

Geometric Characteristic of the Problem (Assumptions)

- Structure regular multi-story building (Reinforced Concrete) structures are supposed (the architectural plan is symmetrical for axes x and y)
- The height of story is 3.6 m
- The structural systems are: Frame - Shear Walls - Dual
- The building uses (assumed): Hotel, Office and Residential
- Seismic zone "C" and therefore the seismic zone factor is Z = 0.15
- The essential factor of construction is I = 1
- Fixed Columns (Raft or piles)
- Without dumping system
- Equivalent static loads
- Fire Rot (4 hours) (Steel - County)
- Dead load (Walls and Floor Cover) on all slabs equal 0.5 ton/m^2
- Live Load on all slabs equal to 0.3 ton/m^2

As shown in Table 3 that identify the various variables:

- The area of the structure
- The thickness of the floor slab
- The yield strength of steel for longitudinal reinforcement
- The yield strength of steel for cross-sectional reinforcement for shear walls and stirrups in beams and columns
- The characteristic compressive strength of concrete
- To simplify the problem, it assumed that all columns have a square cross-section

The types of slabs defined according to the study for (Abohashish and Ebid, 2015) that studied estimating the economic quantities of different concrete slab types and summarized the data for the different concrete slab types as shown in Table 3 that shows the identification of slabs in RC structural according to international Codes and calculations for quantity surveying and shows the final results for optimum the slabs.

These models apply to the building that has a live load and floor cover does not exceed 0.5 ton/m^2 such as commercial buildings, government buildings, educational buildings and residential buildings as shown in Fig. 2 that shown three different cases that are studied in this study.

Table 3: Show the Identification of RC Slabs

	Variables	SS	WS	HB	FS	Results from calculations	International codes
6×6 m	Thickness	16.000	16.000	16.000	20.000	Waffle Slab	Solid Slabs
	Steel bars (Kg/Bay)	0.660	0.520	0.520	0.720		
	Concrete (ton/Bay)	7.522	6.186	6.186	7.522		
	No of Blocks /Bay (20×40×11)	0.000	0.000	288.000	0.000		
	Cost	17825.670	14386.030	16834.030	18672.760		
9×9 m	Thickness	24.000	24.000	24.000	30.000	Waffle Slab	Waffle Slab
	Steel bars (Kg/Bay)	1.820	1.700	1.700	3.370		
	Concrete (ton/Bay)	23.400	13.497	13.497	23.400		
	No of Blocks /Bay (20×40×16)	0.000	0.000	648.000	0.000		
	Cost	52536.880	38787.340	44295.340	72744.660		
12×12 m	Thickness	30.000	30.000	30.000	40.000	Waffle Slab	Waffle Slab
	Steel bars (Kg/Bay)	3.790	3.780	3.780	9.680		
	Concrete (ton/Bay)	50.400	22.502	22.502	50.400		
	No of Blocks /Bay (20×40×20)	0.000	0.000	1152.000	0.000		
	Cost	120579.720	81068.980	90860.980	197361.860		

(a)   (b)   (c)
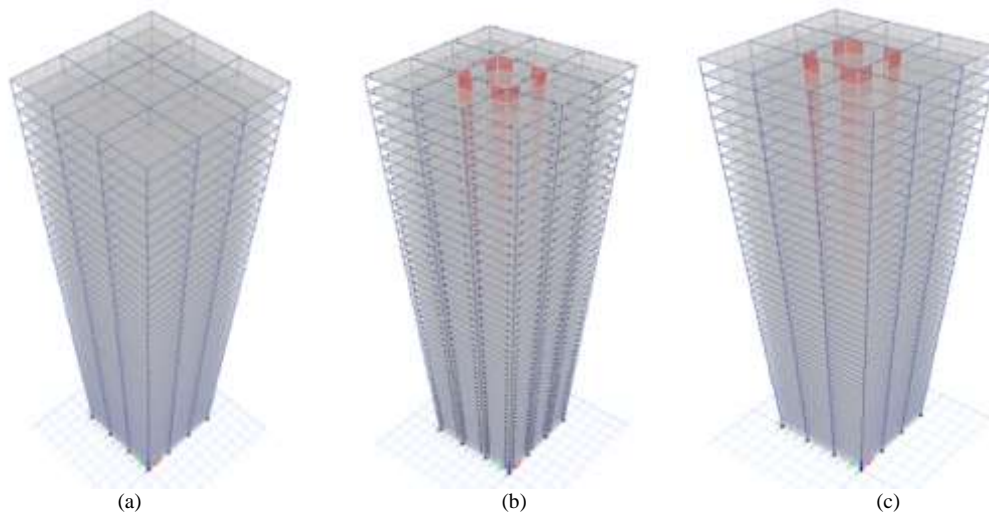
Fig. 2: Shown that the supposed structural models for Reinforced concrete structural systems (a) Frame System (b): Shear Wall System (c): Dual System

Lateral Drift Comparison

The lateral drift measured after defining member size for strength to assure the actual lateral drift is less than the maximum allowable as shown in the Table 4 for all systems:

$$\left(\frac{\Delta H}{H} \to \frac{1}{100 \sim 200}\right) Take \, \Delta H$$

$$= \left(\frac{H \left(Height \, of \, floor\right)}{150}\right) = \Delta e \times 0.7 \times 5$$

$$\Delta e = \left(\frac{H}{150 \times 0.7 \times 5}\right) = \frac{H}{525} \simeq \frac{H}{500} = 0.002H$$

$$\left(\frac{\Delta e}{H}\right) \simeq 0.002 \, That \, is \, the \, max. \, drift$$

Cost Comparison

Labor and material cost for each system based on current costs According to international (global) prices and according to the standard construction rule. The costs of concrete and steel according to the workable local prices in Egypt. Table 5 shows the results of quantity surveying for all systems and Fig. 3 shows the comparison between these systems according to the cost of materials.

Reinforced Concrete Structural per m³ of Building

To select the structural systems for multi-story buildings in the preliminary stage, we are comparing lateral drift and the cost for various structural systems at different heights. Structural models for R.C. multi-story structure buildings consisting of (5-15-25) story for the

span 6 m, (8-23-38) story for the span 9 m and (10-30-50) story for the span 12 m, structural systems in this study consist of:

- Frames system
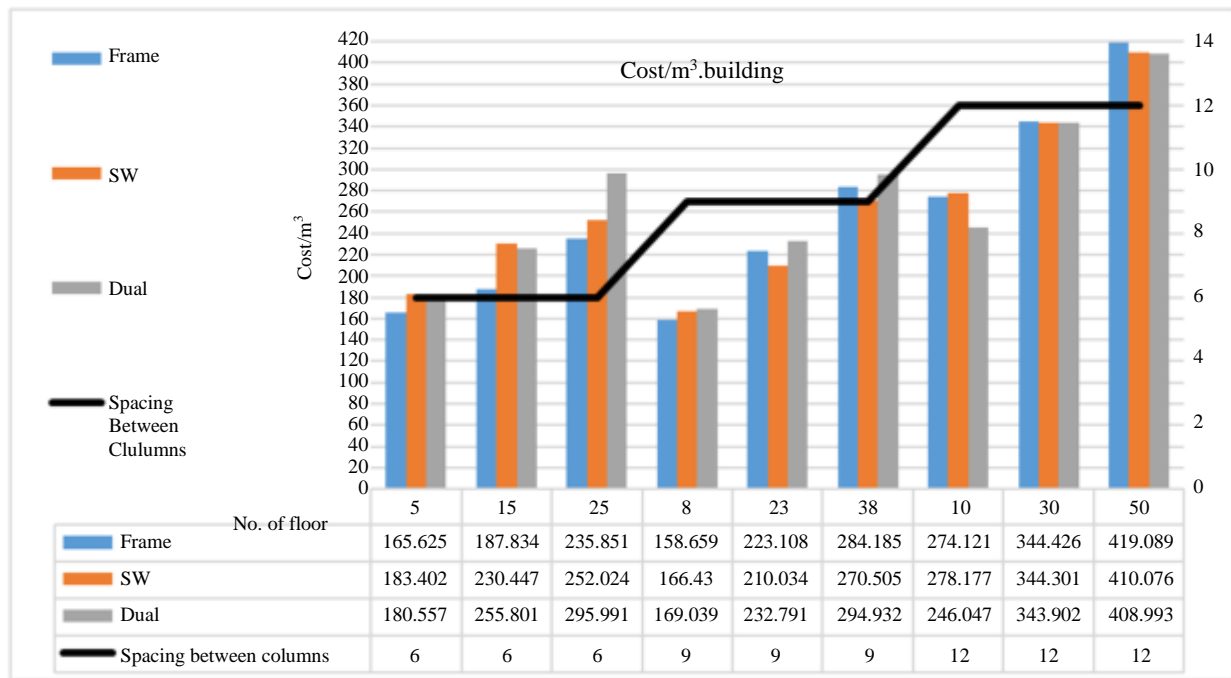- Shear Walls system
- Dual system

Fig. 3: Shows the overall cost comparison for

Table 4: Show the summarize for results of lateral drift for RC structural

No. of #floors	Span	Frame system RC	Shear walls system RC	Dual system RC	Final results	According to the materials cost
5	6	0.001832	0.000791	0.000323	0.000323	Dual System Shear Walls System Frame System
15	6	0.001471	0.000452	0.000225	0.000225	Dual System Shear Walls System Frame System
25	6	0.001057	0.000464	0.000191	0.000191	Dual System Shear Walls System Frame System
8	9	0.001621	0.000171	0.000163	0.000163	Dual System Shear Walls System Frame System
23	9	0.000544	0.000245	0.000109	0.000109	Dual System Shear Walls System Frame System
38	9	0.000368	0.000407	0.000093	0.000093	Dual System Frame System Shear Walls System
10	12	0.002043	0.002602	0.000769	0.000769	Dual System Frame System Shear Walls System
30	12	0.002032	0.001494	0.000498	0.000498	Dual System Shear Walls System Frame System
50	12	0.001558	0.001291	0.000468	0.000468	Dual System Shear Walls System Frame System

Table 5: Show the results of the total quantities of materials for design R.C. Structural

Case No.	Q. S. Concrete (m³)	Q. S. steel bars (Quantity Slabs) (Ton)	Q. S. steel bars (Quantity Columns) (Ton)
1	436.80	31.7	7.213
2	1,328.00	82.1	63.000
3	2,352.00	123.8	181.000
4	1,396.80	104.0	39.000
5	4,718.40	288.4	299.000
6	8,580.80	427.4	817.000
7	4,446.40	435.1	126.000
8	14,011.1	1008.9	1171.000
9	26,356.8	1413.2	3230.000
10	484.80	35.0	8.000
11	1,609.60	100.6	79.000
12	2,441.60	121.1	212.000
13	1,475.20	110.2	39.000
14	4,347.20	254.9	307.000
15	7,945.60	367.5	841.000
16	4,443.20	426.9	149.000
17	13,753.2	941.5	1265.000
18	24,621.8	1022.6	3647.000
19	475.20	34.5	8.000
20	1,608.00	102.5	71.000
21	3,067.20	175.4	197.000
22	1,501.31	112.3	39.000
23	4,910.40	300.1	314.000
24	8,904.00	442.6	849.000
25	3,974.40	387.2	118.000
26	13,884.8	978.0	1210.000
27	26,166.4	1512.3	2971.000

Table 6: Show the summarize results of the cost of materials for design reinforced concrete structural according to the materials cost index

No. of #floors	Span	Frame system RC	Shear walls system RC	Dual system RC	Final results According to the materials cost index
5	6	0.97	1.07	1.05	Frame System Dual System Shear Walls System
15	6	3.29	4.03	3.95	Frame System Dual System Shear Walls System
25	6	6.87	7.35	8.63	Frame System Shear Walls System Dual System
8	9	3.33	3.49	3.55	Frame System Shear Walls System Dual System
23	9	13.47	12.68	14.05	Shear Walls System Frame System Dual System
38	9	28.34	26.98	29.41	Shear Walls System Frame System Dual System
10	12	12.79	12.98	11.48	Dual System Frame System Shear Walls System
30	12	48.21	48.19	48.14	Dual System Shear Walls System Frame System
50	12	97.77	95.66	95.41	Dual System Shear Walls System Frame System

The results according to analysis and design for the proposed structural systems using FEM for the total quantity of materials and materials cost index in Egypt shown in Table 6 that can summarize the results for the materials cost. The designers and estimators can use this data for decision making in the preliminary design phase that can predict the cost.

Discuss the Results

This paper presents the economic cost of reinforced concrete multi-story buildings consist of various storeyes by studying three structural systems (Frame system – Shear wall system - Dual System) with the same price of materials and determining the best structural system that achieves saving in the use of concrete and steel materials. The results show in the Table 6. The dual system is the optimum structural system, because of adding shear walls with frame system in the concrete building is essential to reduce lateral drift and decrease the materials cost especially in the high rise building category. Adding shear wall to R.C. moment frame minimizes the lateral drift, the cost and the building mass. Drift governs the design when the height exceeds 50 stories for the concrete moment Dual system.

Conclusion

This study is expected to design a model and charts that can be used to decision making and give the recommendation for selecting the optimal structural system for multi-story buildings. A flexible model structure and final charts that will facilitate selecting an optimal structural system for multi-story buildings will be designed as shown in Fig. 4 that can use it in the preliminary design that the decision-makers can use it with the value engineering process to selecting the optimal structural system for multi-story buildings according to the span and height the buildings and the Fig. 5 that show the summarize for lateral drift from FEM.

The data from FEM helps us to design charts and models for decision making that help designers and decision-makers in the preliminary design for choosing the optimum structural system. Engineering field professionals are trying to build multi-story buildings taller than the existing tallest ones and according to the spans between columns. Generally, these multi-story buildings require additional lateral systems to control the drift and the total of materials quantities that effect on the costing of buildings during the construction.
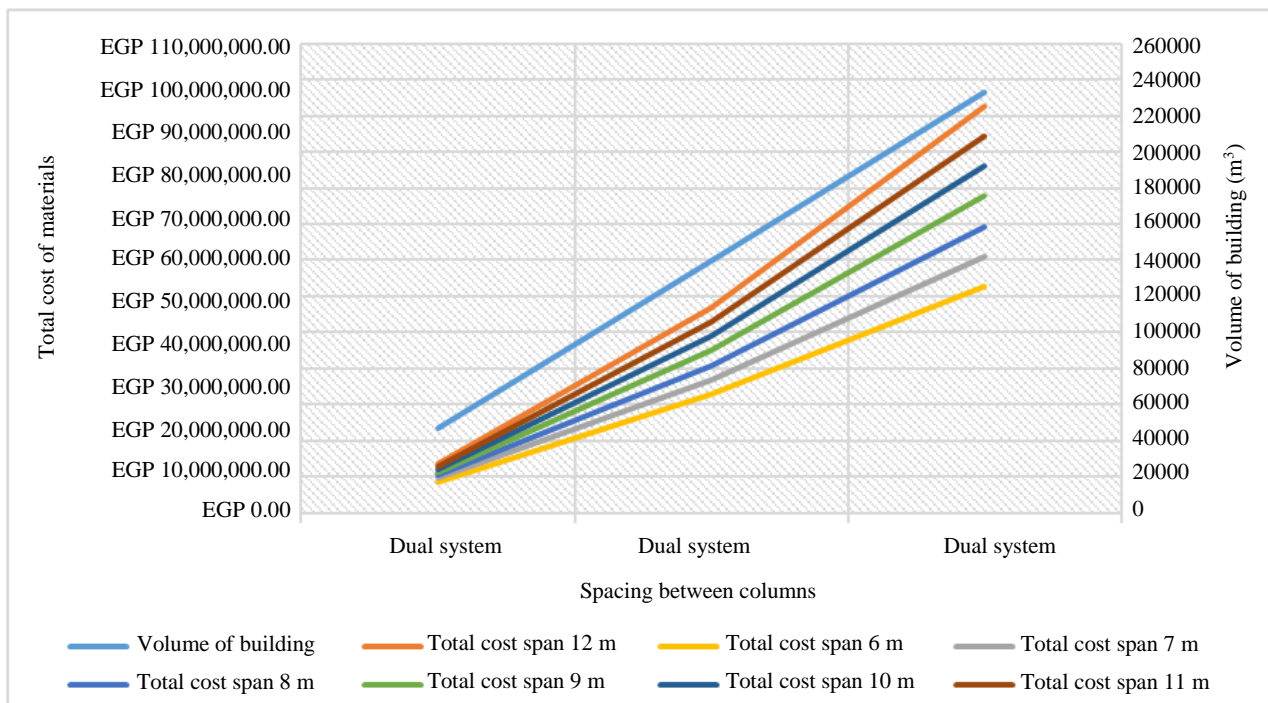
Fig. 4: Shows the overall cost comparison for dual reinforced concrete structural according to different spacing between columns
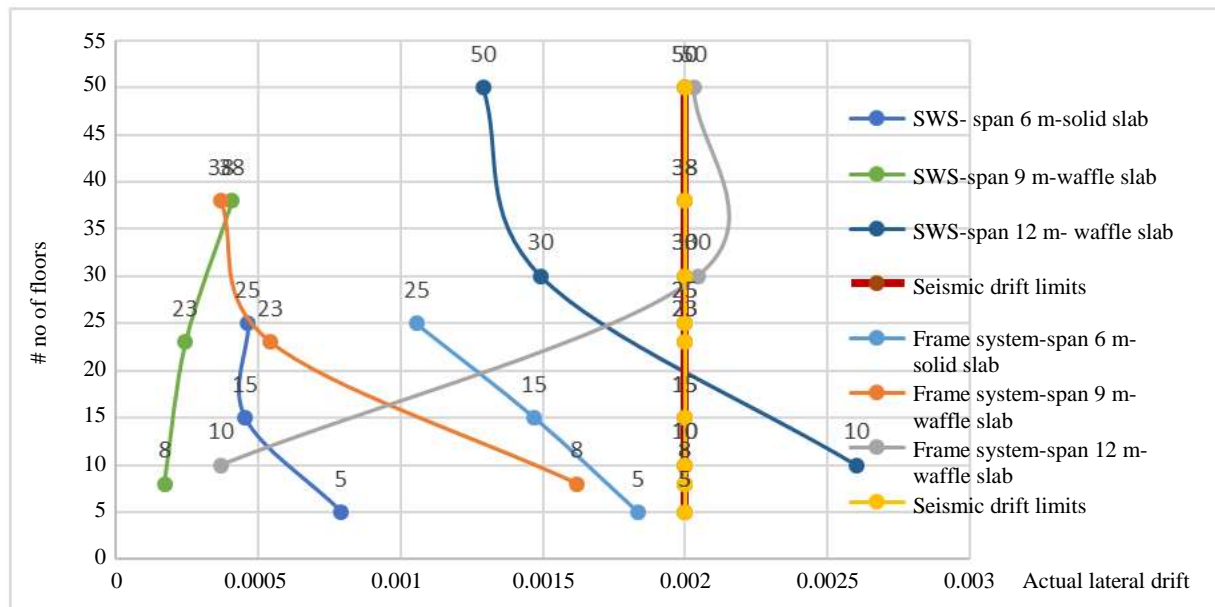
Fig. 5: Shows the overall lateral drift comparison for Reinforced Concrete Structural

The Implications of this Research Study

The construction industry and engineering can use the findings from this research as a basis for selecting the optimal structural system for multi-story buildings. The ability of the estimating team to accurately to decision making and give a recommendation for selecting an optimal structural system for multi-story buildings for different activities will have a significant impact on the crew cost component, schedule of the project and improve projects' performance. The use of the models is expected to result in savings in cost and timing of construction projects and savings in the cost of the overall project. The details and further analysis of the structural models are kept for further reference, can be discussed as needed.

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Author's Contributions

All authors contributed to design the study, write and revise the manuscript.

Ethics

The present study and ethical aspect were approved by the Future University in Egypt and Ain Shams University. The present study was approved by the Future University in Egypt and Ain Shams University.

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