

Comparative Study of Structural Systems for Tall Buildings

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Abstract: An investigation has been carried out to examine the most common structural systems that are used for reinforced concrete tall buildings under the action of gravity and wind loads. These systems include “Rigid Frame”, “Shear Wall/Central Core”, “Wall-Frame Interaction”, “Outrigger”, and “Tube in Tube”. The basic modeling technique and assumptions are made by “ETABS” Program, in 3-D modeling. Design considerations are made according to “ACI 318-05” Code and “ASCE 7-05” Standard. This comparative analysis has been aimed to select the optimal structural system for a certain building height. The structural efficiency is measured by the volume of concrete of main elements, structural period, and base shear values. The recommendations for each structural system are based upon limiting the wind drift of the structure, minimizing the cost of wind force resisting elements, and increasing the lateral stiffness.

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1. Introduction:

The achievement of structural system for tall buildings is not an easy task. Where, as building height increases the importance of lateral loads action rises in an accelerating rate. There are two types of lateral loads, wind and seismic loads. Wind load presents the most critical lateral loading for modern tall buildings, which have lightweight skeletons that cause uncomfortable horizontal movements for occupants. Also, wind is not constant either with height or with time and is not uniform over the sides of a building. So, windy weather creates a variety of problems in tall buildings, causing concern for buildings owner and engineers alike. Where, excessive vibration due to this load is a major obstacle in design and construction of a modern tall building. it should be limited to prevent both structural and nonstructural damage.

2. Main Objectives

Comparison between different types of tall buildings structural systems for certain building heights was introduced by “Fazlur Khan” (Wolfgang Schueller, 1977), and “The Council on Tall Buildings and Urban Habitat” (CTBUH, 1980), both was investigated according to optimum performance for a given height or number of stories only.

1. Recommending a structural system for a certain building height, with the intention of limiting the wind drift to acceptable limits without paying a high premium in the quantity of structural material.

2. Presenting a comparative analysis between the most common structural systems of tall buildings built around the world within the past decades according to volume of concrete, structural period and base shear values.
3. Conceiving and applying the structural systems to extremely tall buildings is a practical demonstration of the engineer's confidence in the predictive ability of the analysis by commercial software.

3. Case-Study

The case-study is a regular-shaped symmetrical plan with dimensions 30x30 m. In all structural modeling, slab spans are assumed to be 6 m, arranged in five bays in each direction, as shown in Fig. 1. The plan has a 6x6 m central core opening. The storey height is assumed to be 3.5 m. The analysis used is a three-dimensional analysis of detailed finite element models. The columns and beams were represented by frame- type element, while shear walls and core components were represented by shell-type element.

4. Common Structural Systems For Tall Buildings

Table 1(a) and 1(b) introduces the five major structural systems used in most of the famous buildings built around the world, they are also discussed in the study.

5. Main Assumptions for the Analysis

1. Material: Concrete is assumed to behave linearly elastic. The modulus of elasticity E_c will be taken as

4700 f'_c . Where, the specified compressive strength of concrete f'_c is assumed equal to 40 Mpa, as used in practical applications of tall buildings. The concrete cover will be taken as 4 cm (ACI 318-05, 2005).

2. Participating components: Only the primary structural components are assumed to participate in the overall behavior. The effects of secondary structural components and nonstructural components are assumed to be negligible; these include, staircases, partitions, cladding, and openings.

3. Floor slabs: are assumed to be rigid in plane, with thickness equal to 30 cm in all models. This assumption causes the vertical elements at any floor level undergo the same components of translational displacement and rotation in the horizontal plane.

4. Cracking: The effect of cracking in reinforced concrete members due to flexural tensile stresses is represented by reducing moment of inertia, as mentioned in (ACI 318-05, Section 10.11.1).

5. Constraints: Supporting bases of all structural models are fixed supports.

6. Loading:

§ Gravity Loads: Dead load is taken as 3 kN/m², The building weight and its content is considered in the dead load and calculated based on material densities by the program. While, live load is taken as 2 kN/m² (ASCE 7-05, 2005).

§ Wind loads: will be developed according to "ASCE 7-05" standard.

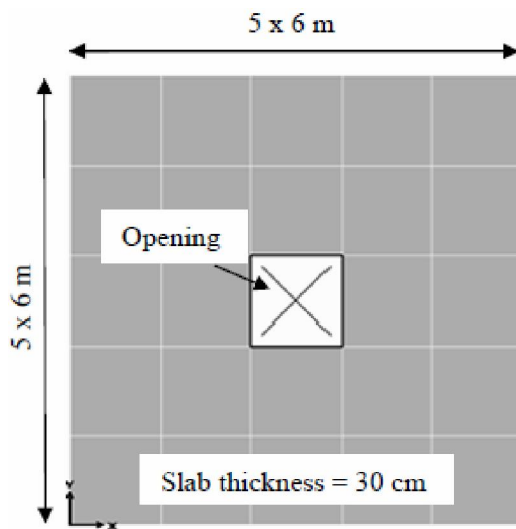


Fig.1 General layout for all structural models plans

6. Defining Wind Loads in "ETABS" Program

The design wind loads for buildings at height Z above ground level was determined according to the following Eq.(1), (ASCE 7-05, 2005).

$$P = q_z G_f C_p (\text{windward}) + q_h G_f C_p (\text{leeward}) \quad (1)$$

Where, G_f is the gust effect factor that accounts for the dynamic interaction between the flowing air and the structure. C_p is a pressure external coefficient, typically equal to 0.8 and 0.5 for the windward and leeward sides, respectively.

The velocity wind pressure q_z at height Z and the velocity suction q_h are given by Eq.(2) and Eq. (3), respectively.

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I_w \quad (2)$$

$$q_h = 0.00256 K_h K_{zt} K_d V^2 I_w \quad (3)$$

The previous equations contain some factors used in defining wind loads in "ETABS" program. These factors will be introduced, as follows:

- Velocity Pressure Exposure Coefficients K_z and K_h are used for weighting the probability of critical wind orientation for sites with significant directional wind amplitude variation within a hurricane hazard region. "ETABS" calculate them by one from the following Eq.(4) or Eq.(5).

$$K_z = 2.01 (z / z_g)^{2/\alpha} \quad \text{for } 15 \text{ ft} < z < z_g \quad (4)$$

$$K_z = 2.01 (15 / z_g)^{2/\alpha} \quad \text{for } z < 15 \text{ ft} \quad (5)$$

Where, α is 3-S gust-speed power law exponent, (See ASCE 7-05, Table 6.2) z_g is the nominal height of the atmospheric boundary layer.

- Three exposure categories (B, C, and D) are defined according to (ASCE 7-05, Section 6.5.6.1). In summary, exposure B corresponds to surface roughness such as urban and suburban areas, exposure C to flat open country, while exposure D represents flat unobstructed area and water surfaces. In this study, exposure C will be applied to all cases.
- The wind importance factor I_w is used to adjust the return period for a structure based on its relative level of importance. This study is assumed that all buildings are classified category II, so I_w will be taken equal to 1.0
- The topographic factor K_{zt} reflected the speed-up effect over hills and escarpments. This study is assumed that all buildings does not subject to these sudden topography changes. So, this factor will be taken equal to 1.0

Table 1(a) Major structural systems for tall buildings

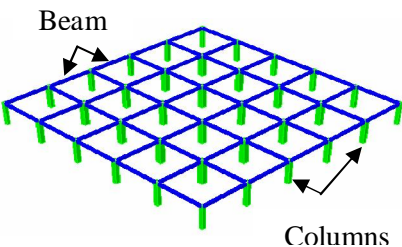
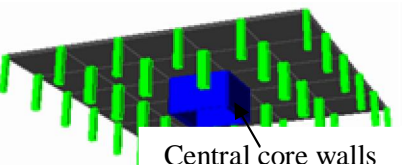
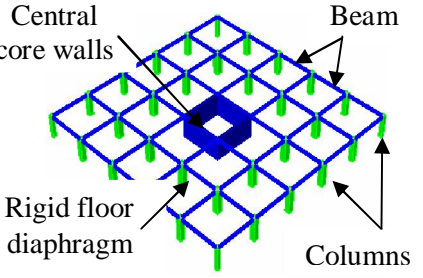
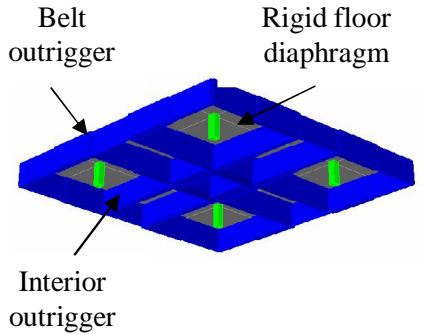
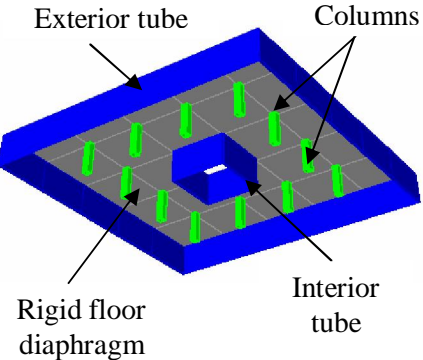
System & Configuration	Structural Elements	Usage	Behavior
<p>1. Rigid Frame</p> 	Columns and girders connected by rigid joints. Joints must have sufficient rigidity to resist lateral and gravity loads (Bryan Stafford Smith and Alex Coull, 1991).	Suited for reinforced concrete buildings, because the inherent joints rigidity, and used also in steel buildings, but connections tend to be costly.	Under gravity loads, The frame continuity reduce the positive moments in the center span of the girder. Under lateral loads, The lateral stiffness is provided by the bending stiffness of the columns, girders, and connections. In tall frame, it is governed by the axial rigidity of the columns (Wolfgang Schueller, 1977).
<p>2. Shear Wall/Central Core</p> 	It is a vertical continuous stiffening elements, that deform in bending mode.	Used in reinforced concrete buildings and suited to residential buildings and hotels.	Shear walls act as vertical cantilevers when responding to lateral loads, its response depends on the interaction between the horizontal floor and the vertical wall.
<p>3. Wall-Frame Interacting</p> 	A combination of shear walls and rigid frames.	Suited for reinforced concrete buildings, and used also in steel buildings,	Shear-mode profile of frames combined with parabolic mode of walls. The two systems are forced to deflect in the same way by rigid floor diaphragm. The upper part of wall is restrained by the frame, whereas at the lower part, the shear wall or truss restrains the frame.

Table 1(b) Major structural systems for tall buildings (Cont.)

System & Configuration	Structural Elements	Usage	Behavior
2. Outrigger Systems  <p>The diagram illustrates two types of outrigger systems. The top part shows a 'Belt outrigger' system where a rigid floor diaphragm is connected to exterior columns. The bottom part shows an 'Interior outrigger' system where the rigid floor diaphragm is connected to interior columns.</p>	<p>(a) Interior outrigger: Outriggers are connected directly to the core and to exterior columns</p>	Used in reinforced concrete and steel buildings.	Outriggers restrain the rotation of the core and convert part of the moment in the core into a vertical couple at the columns (columns restrained outriggers)
	<p>(b) Belt outrigger: Outriggers are at the exterior edges (not connected directly to core)</p>	Used in reinforced concrete and steel buildings.	Floor diaphragms transfer the moment from the core to outriggers in the form of a horizontal couple. The outriggers convert the horizontal couples into vertical couples in exterior columns (Bungale S. Taranath, 1998)
5. Tubular Systems  <p>The diagram shows a tubular system with an exterior tube and an interior tube. Columns are shown connecting the two tubes, and a rigid floor diaphragm is shown connecting them.</p>	Closely spaced columns and deep spandrels to tie the columns around the perimeter of the building. The floor diaphragm connecting the exterior and interior tubes .	Suited for steel buildings.	Floor slabs acts as a rigid diaphragm, distribute the lateral loads to the exterior and interior tubes according to their stiffness. Frames parallel to the lateral loads act as webs (resist shear), while the frames normal to the loads act as the flanges (resist bending).

- Wind directionality factor K_d varies depends upon the type of the structure. This factor shall only be applied when used in conjunction with load combinations specified in “ASCE 7-05” standard, Sections 2.3 and 2.4, as in this study. The K_d factor equal to 0.85 for most types of structures. This wind directionality factor accounts for two effects:
 1. The reduced probability of maximum winds flowing from any given direction.
 2. The reduced probability of maximum pressure coefficient occurring for any given direction.
- The basic wind speed V will be taken equal to 100 mph (ASCE 7-05, 2005).
- When “ETABS” calculate the design wind loads, it creates all cases specified in “ASCE 7-05” standard. There are four cases shown in Fig. 2.

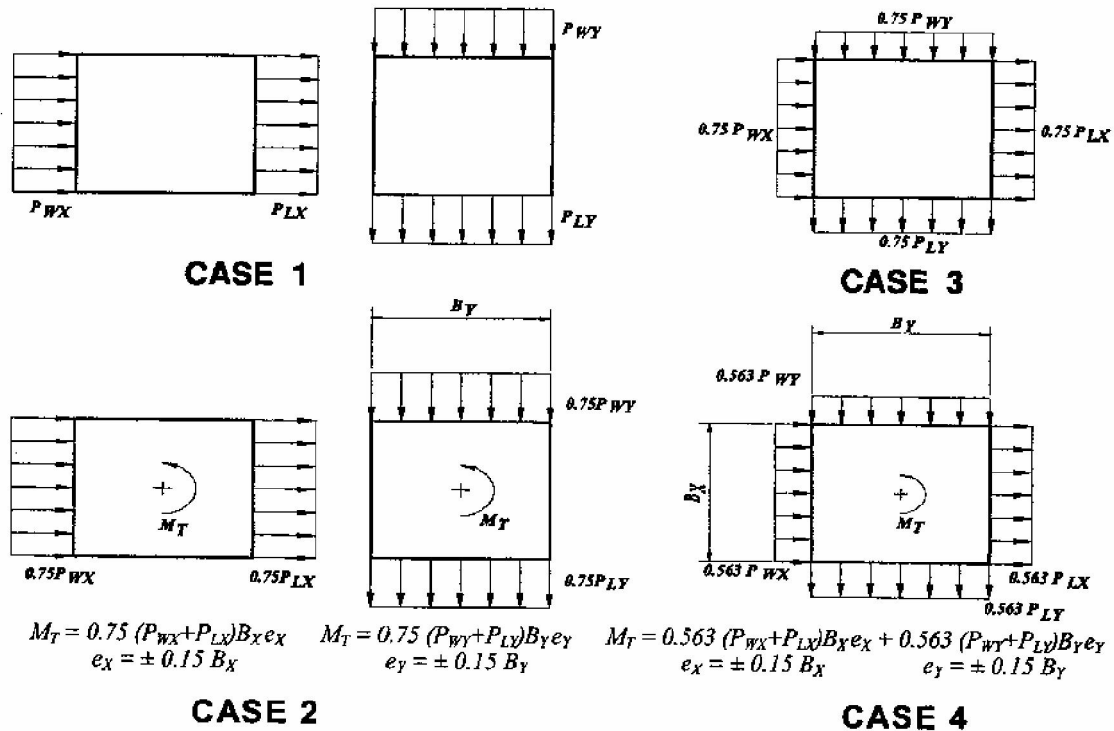


Fig. 2 Design wind load cases (ASCE 7-05, 2005)

“ETABS” program wind loading calculations was validated with manual calculations before analyzing the structural models (El-leithy, 2010).

7. Preliminary And Final Analysis

Structural systems have been applied to the considered case-study using two models.

§ Preliminary model: is constructed based upon designing the wind force resisting elements according to “ACI 318-05” Code.

§ Final model: If the lateral wind drift within any storey in the preliminary model exceeds the allowable limits, an inspection of the components of drift will indicate which members should be increased in size to most effectively limit the drift.

8. Allowable Lateral Wind Drift

§ Total building drift: must be limited to ensure the comfort of the occupants and the protection of mechanical and architectural systems. “ASCE 7-05” standard has recommended that the maximum sway shall be less than 0.002 times the building height for normal wind pressure.

Storey drift: is defined as the difference between the lateral displacements of one level relative to the level below (ASCE, 1988), must be limited to minimize damage of cladding and nonstructural walls and partitions, “ASCE 7-05” standard has recommended that it shall be less than 0.0025 to 0.002 of the storey height

9. Results and Discussions

9.1 Rigid frame results

Only 10 stories structure (35 m high) has allowable wind drift. While, 20 stories structure (70 m high) and more have a drift more than the allowable limits, as shown in Fig. (4a). So, the sizes of wind force resisting elements needed to be increased (Fig. 4b). Thus, its stiffness is increased, as shown in Fig. (4c). For more heights, wind drift values reached double of the allowable limits. This required an increased volume of concrete that would exceed other structural costs. Also, it is argued that as the height increases beyond 10 stories, the wind drift starts controlling the design. Considering the base shear, the sizes of columns and beams increases largely toward the base with the increase of shear storey. Figure 4d shows the values of base shear.

9.2 Shear wall/central core results

In general, this system has several additional advantages with respect to rigid frame system in limiting the wind drift. However, the wind drift is still more than the allowable limits in 20 stories structure, as shown in Fig. 5a. Thus it needs an increase in the volume of concrete, as shown in Fig. (5b). If we used this system for much taller building, the cost of the building will highly increase and a large area will be lost in the lower stories due to huge cross sections area in order to limit the wind drift. Considering the structural period (Fig. 5c), there are a big step in the values of 20 stories and taller height which reflects the inefficiency of this system. The values of base shear in shear wall/central core system are less than that in rigid frame system by a small difference, about 5%, in case of comparing the final models.

9.3 Wall-frame interaction results

10 and 20 stories structures have conservative values of wind drift with respect to the allowable limits, as shown in Fig. 6a. While, 30 stories structures need a small increase in the volume of concrete to limit the lateral drift (Fig. 6b). It is uneconomic to use this system for 50 stories structures. Considering the structural period, as shown in Fig. (6c), a change in stiffness with the total height occurs because the top flexibility of the central core walls is proportional to the cube of the height, whereas the flexibility of the frames is directly proportional to its height. The external shear will be distributed in proportion to shear walls and frames stiffness, shear walls capture a large portion of base

shear with respect to frames, approximately from 78 to 94%.

9.4 Outrigger results

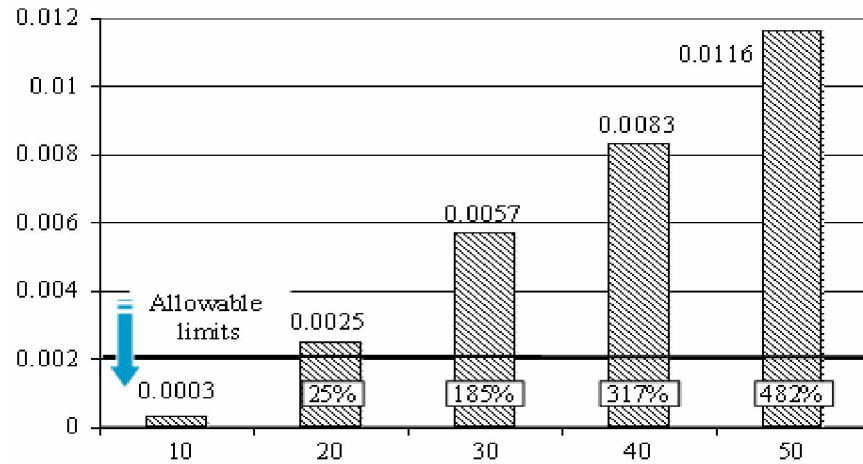
Outrigger system offers lot of benefits in resisting wind loads in tall buildings. Where, a significant reduction in the wind drift can be achieved, in case of using it in stiffening central core structures, as shown in Fig. (7a). The location of the outrigger is the main factor in limiting the wind drift. After many iterations, the final model for 20 stories central core structure the outrigger will be placed at the top of the structure, for 30 stories at the mid-height. for 40 stories, two of both interior and belt outriggers will be used, at the one third and two thirds of height. 50 stories was stiffened by three outriggers at one quarter, half quarter, and three quarters with belt outrigger placed at the middle, while 60 stories stiffening by four of both interior and belt outriggers. This concept is clear when comparing the volumes of concrete of central core with and without outriggers, as shown in Fig. (7b). Outrigger system is effective in increasing the structure's flexural stiffness, as shown in Fig. (7c), but it does not increase its resistance to shear, which has to be carried mainly by the core. The values of base shear of the two systems are shown in Fig. (7d).

9.5 Tube in tube results

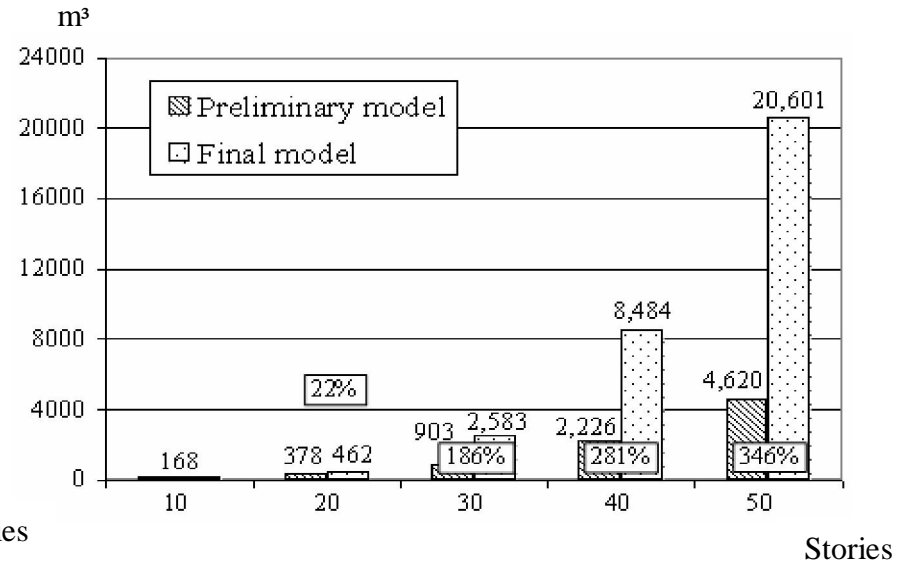
Tube in tube system has been used for increasing the effective depth of central core structures. The maximum wind drift values of tube in tube system and central core system are shown in Fig. (8a). Figure 8b. shows the volumes of concrete of both tube in tube and central core systems. The structural period values of both systems are shown in Fig. (8c). The effect of shear lag on the tube action occurs in 60 stories structure (210 m high), results in nonlinear pressure distribution along the columns envelop, the columns at the corner of the building are forced to take a higher share of the load than the columns in between. Figure (8d) shows the results of base shear with respect to number of stories.

10. Comparison between the Five Structural Systems

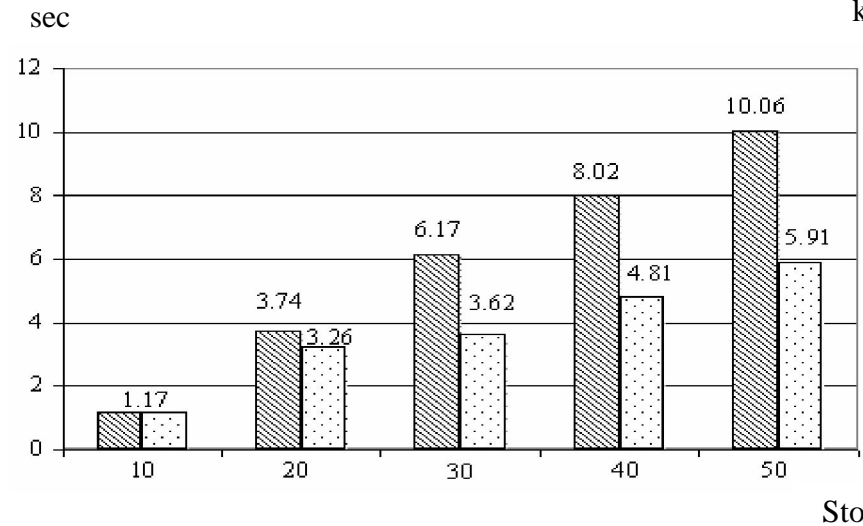
In this study, figure 9a, 9b and 9c represent a comparison between the most commonly used structural systems, due to the volume of concrete, structural period, and base shear values for different number of stories.



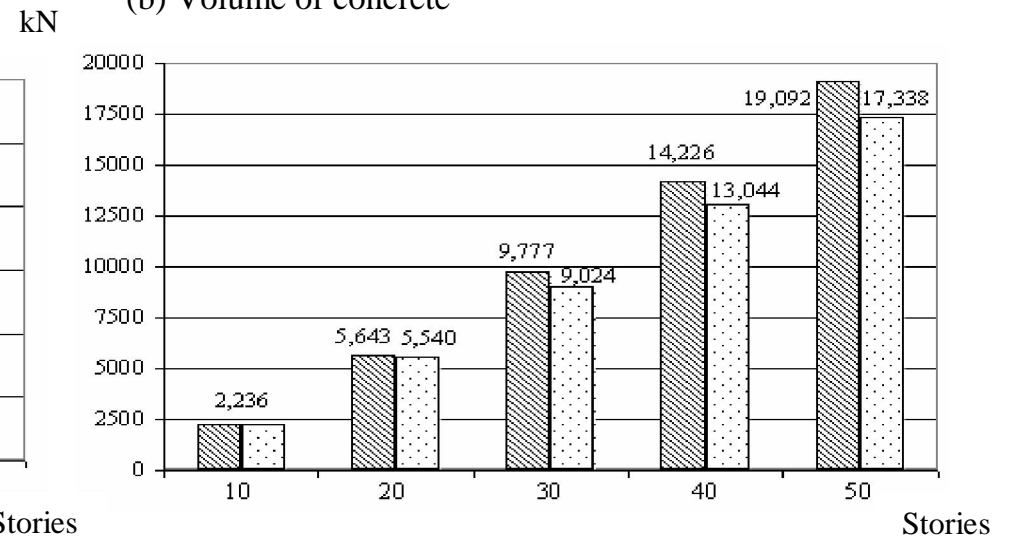
(a) Maximum wind drift



(b) Volume of concrete



(c) Structural period



(d) Base shear

Fig. 5 Shear wall/central core results for different number of stories

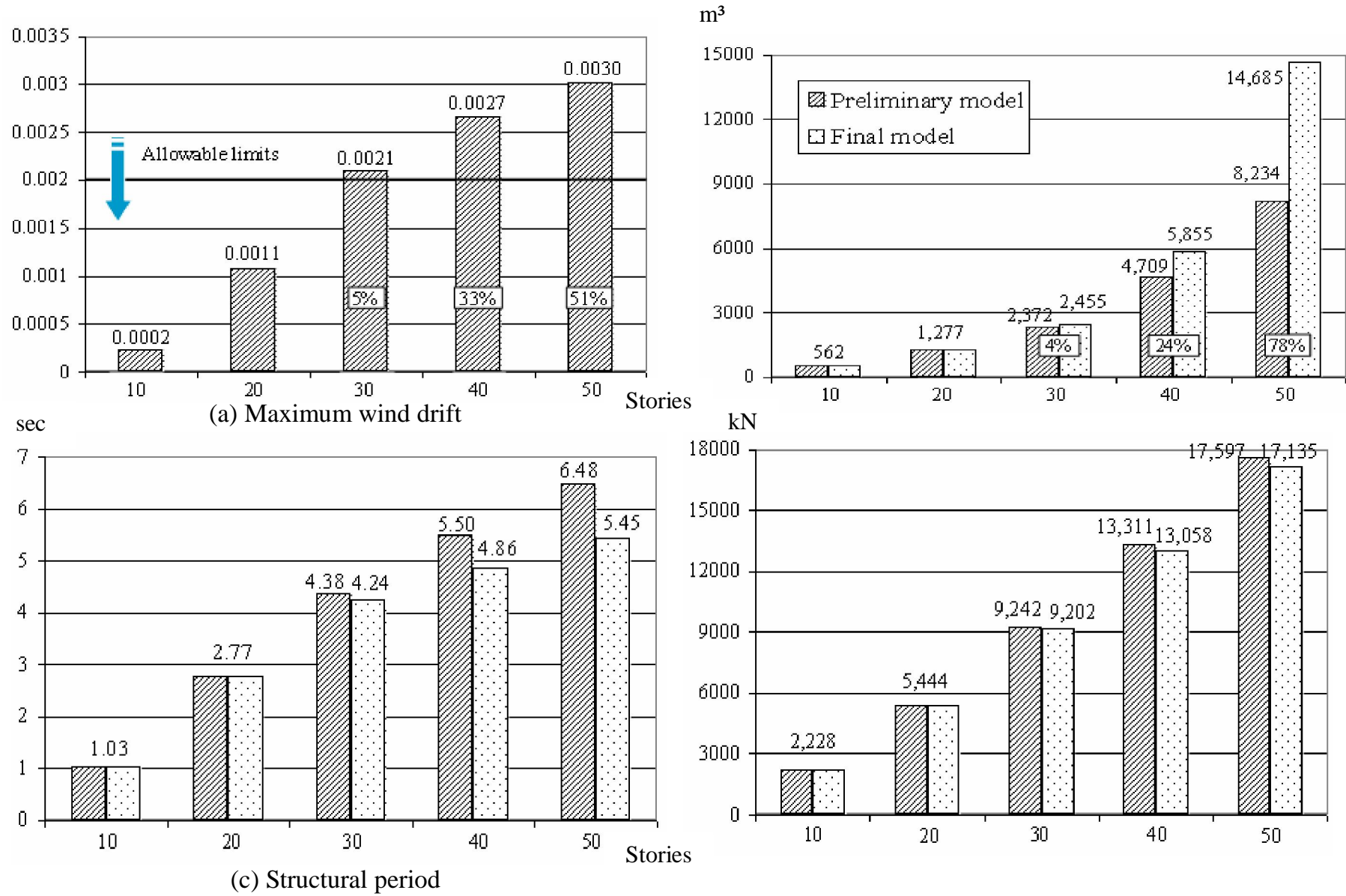
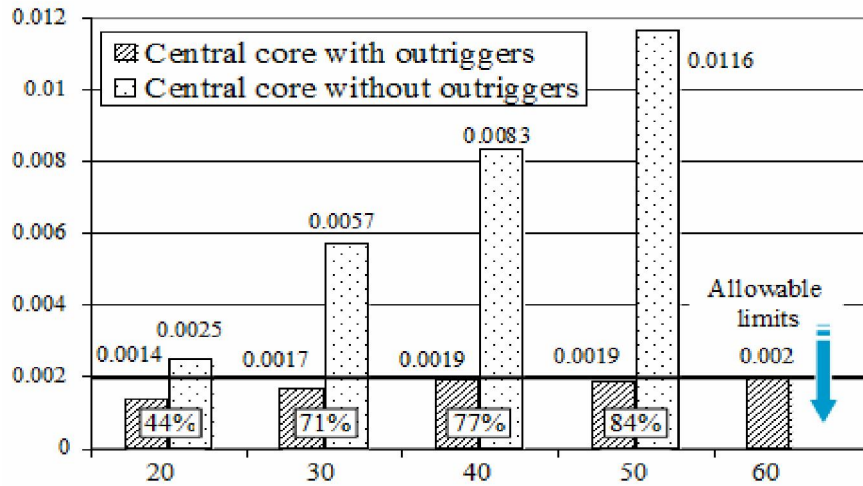
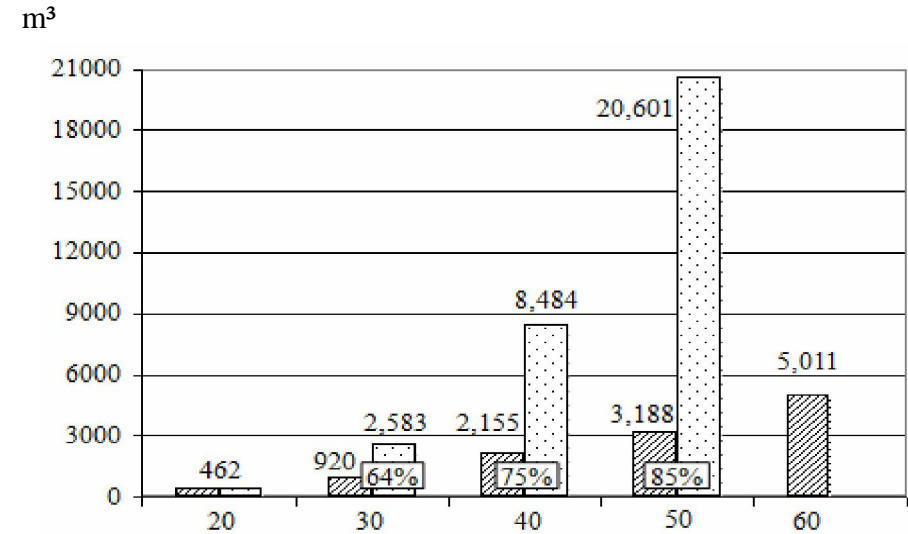


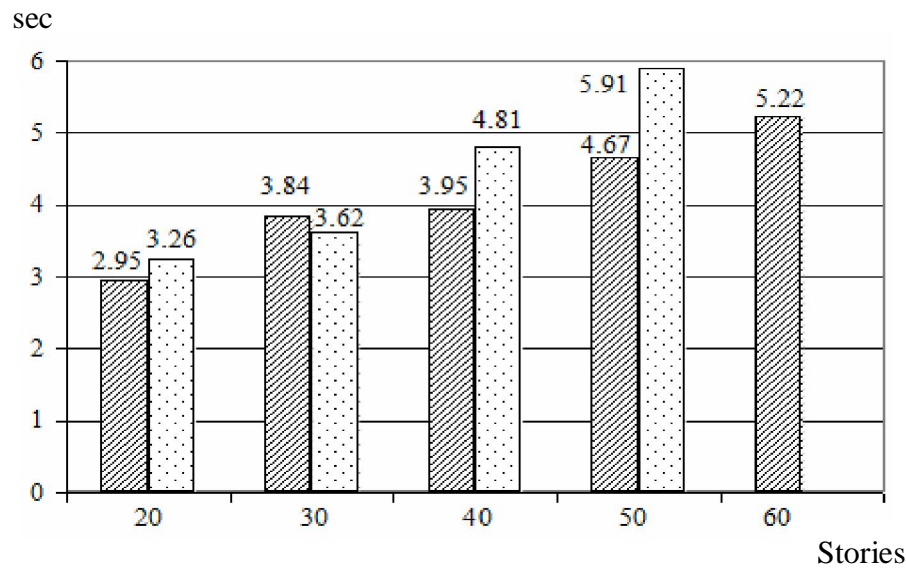
Fig. 6 Shear wall-frame interaction results for different number of stories



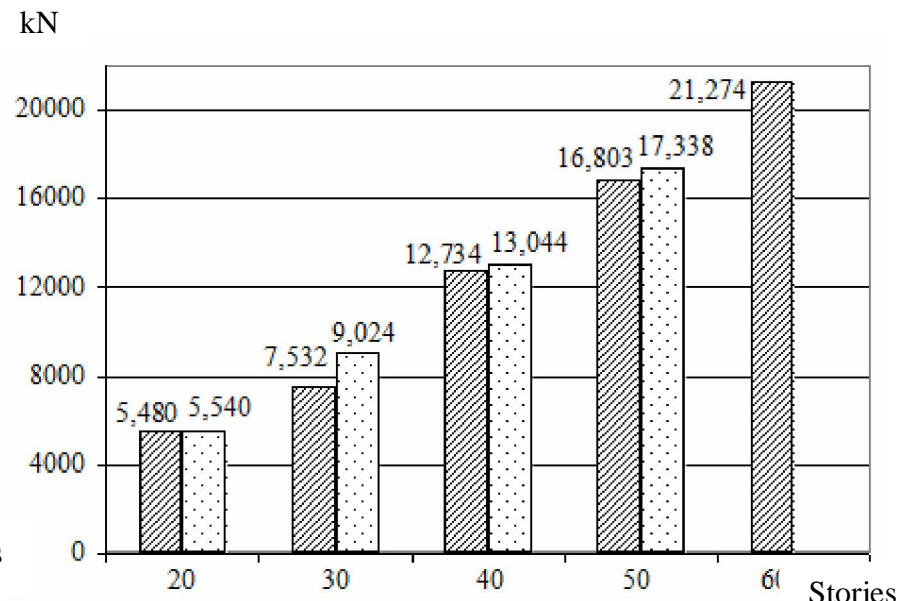
(a) Maximum wind drift Stories



(b) Volume of concrete Stories



(c) Structural period Stories



(d) Base shear Stories

Fig. 7: Results of central core with and without outriggers for different number of stories

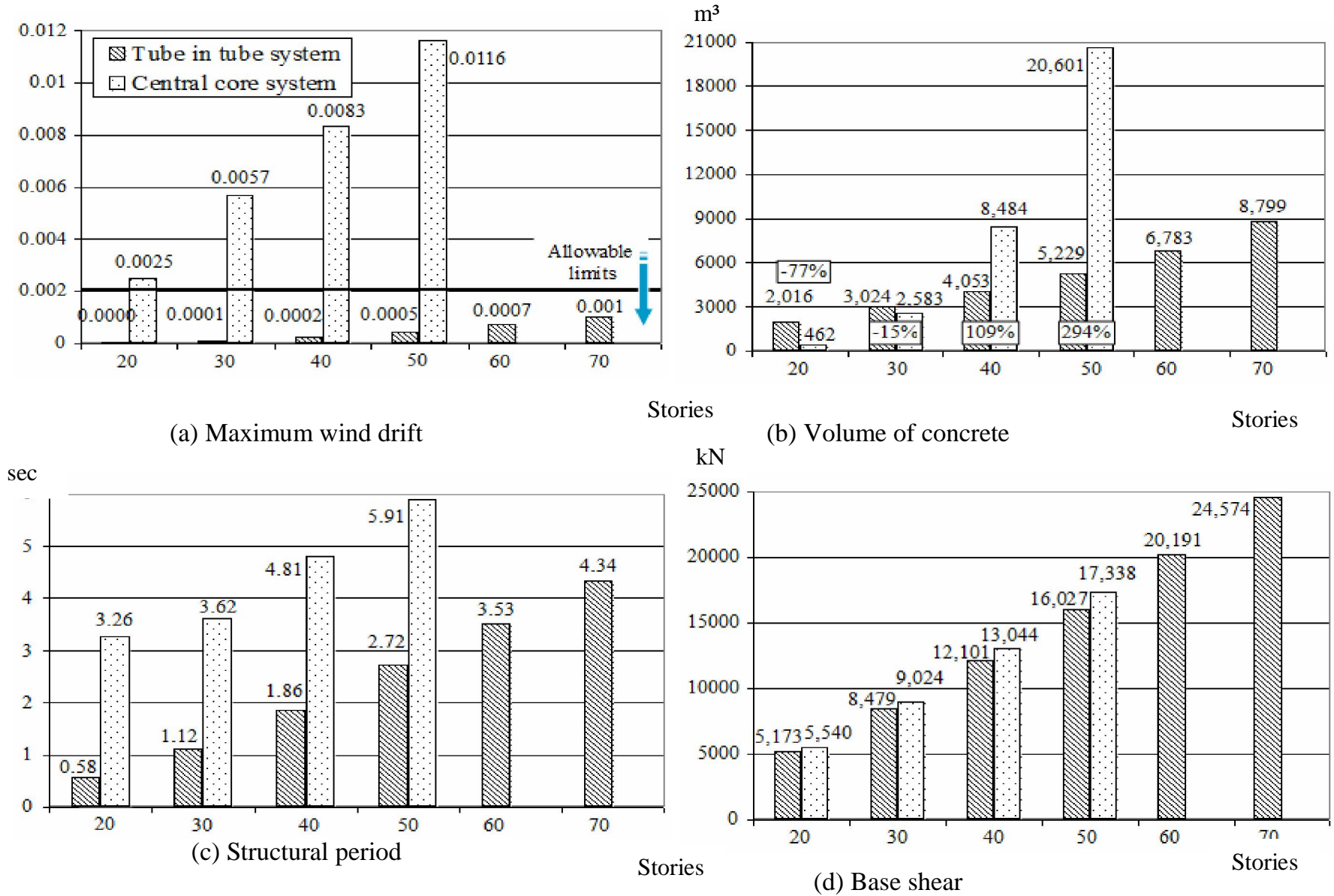


Fig. 8: Results of tube in tube and central core systems for different number of stories

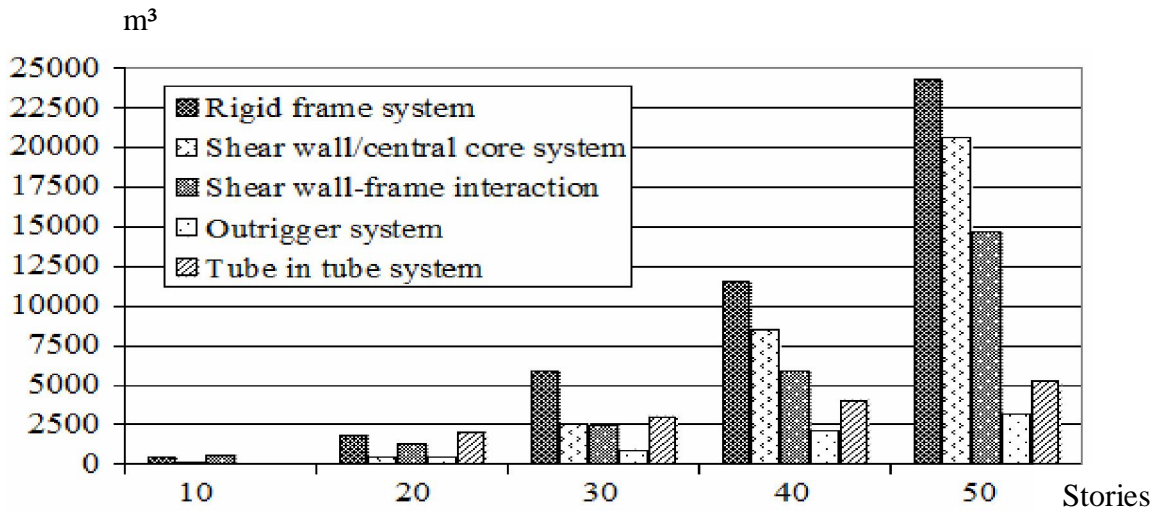


Fig. 9a: Comparison between the five systems due to volume of concrete

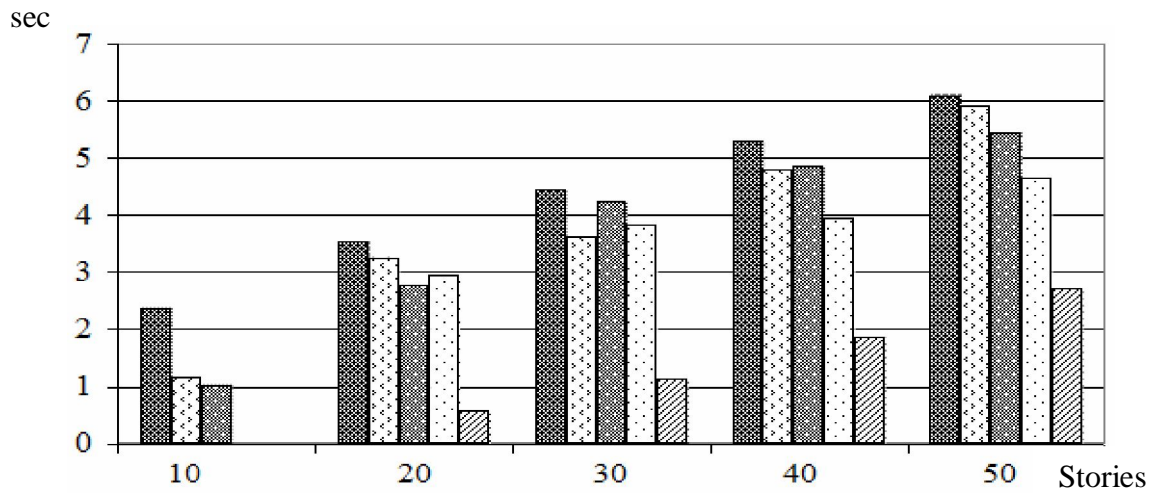


Fig. 9b: Comparison between the five systems due to structural period

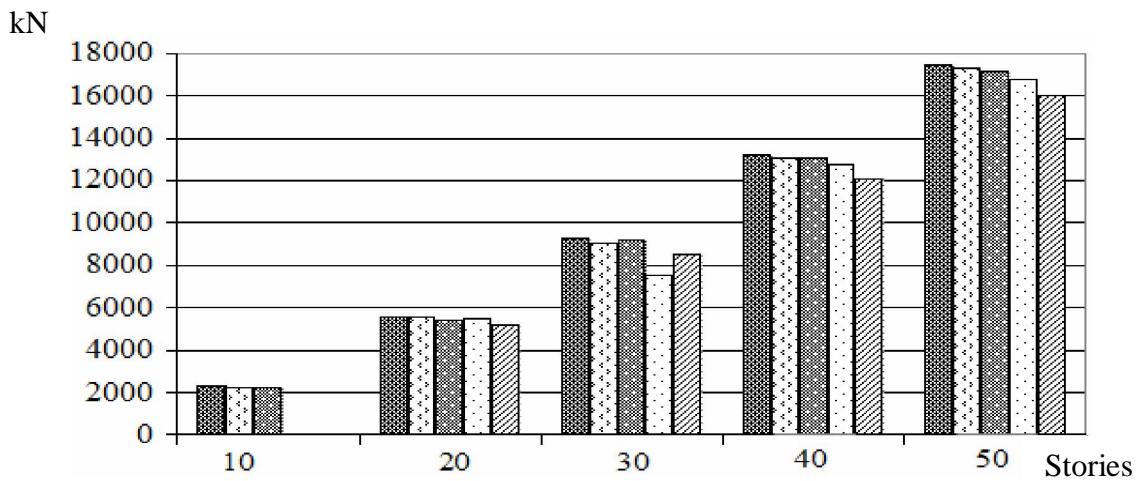


Fig. 9c: Comparison between the five systems due to base shear

11. Conclusions

The following conclusions are based on the results obtained in this study:

11.1 General conclusions

1. Under the effect of wind loads, as the height of the structure increases, the lateral deflection and the overturning moment at the base increase.
2. The volume of concrete increases almost linearly with the height of the structure with respect to gravity loads. While, for resisting wind loads the volume of concrete increases at a drastically accelerating rate.
3. Tall buildings almost always require additional structural material, in order to limit the lateral deflection and resist the overturning moment, over and above that required for gravity loads only.
4. The key idea in limiting the wind drift in a tall building is by changing the structural form of the building into something more rigid and stable to confine the deformation and increase stability.
5. The stiffness (rigidity) and stability requirements become more important as the height of the structure increases, and they are often the dominant factors in the design.
6. Computer programs have given the structural engineer the tools to respond to the changing in architecture with daring structural solutions.

11.2 Structural systems conclusions

The main conclusions of this comparative study, concerning the efficiency of the presented five structural systems and the ability of each system in limiting the wind drift for a certain building height, can be summarized in the following:

11.2.1 Rigid frame system

- § Recommended up to 20 stories (70 m high).
- § The relatively high lateral flexibility calls for uneconomically large members.
- § It is not possible to accommodate the required depth of beams within the normal ceiling space in tall rigid frame.
- § Not stiff as other four systems and considered more ductile and more susceptible to wind failures.

11.2.2 Shear wall/central core system

- § Recommended up to 20 stories (70 m high).
- § More economic than rigid frame.
- § A great increase in flexural stiffness with respect to rigid frame.

11.2.3 Shear wall-frame interactive system

- § More conservative for heights up to 20 stories (70 m high).
- § Recommended in the range of 30 to 40 stories (105 to 140 m high).
- § The benefits of this system depend on the horizontal interaction, which is governed by the relative stiffness of walls and frames and the height of the structure.
- § As the structure height and the stiffness of the frames increase, the interaction between walls and frames increases.
- § The major factor in determining the influence of the frames on the lateral stiffness of this system is the height.
- § As the structure height increases, the sharing of walls from the base shear decreases with respect to frames and more interaction induced between both of them.
- § Stiffness of this system came in between rigid frame and shear wall/central core systems in recommended heights (30 to 40 stories).

11.2.4 Outrigger system

- § Recommended in the range of 20 to 60 stories (70 to 210 m high).
- § The most economic system.
- § Created a wider effective system for reducing the overturning moment in the core structures.
- § The beneficial action is a function of two factors:
 1. The stiffness of the outrigger
(Varies inversely with the outrigger distance from the base)
 2. Its location in the building.
- § An effective system in case of finding out at what level the outriggers should be placed in order to have a maximum impact on the wind drift.
- § Very effective in increasing the structure's flexural stiffness, but it does not increase its resistance to shear, which has to be carried mainly by the core.

11.2.5 Tube in tube system

- § Recommended in the range of 30 to 70 stories (105 to 245 m high) & more.
- § The most stiff system.
- § Much more conservative values for wind drift.

12. Suggested Systems For Different Heights

Table 2 demonstrates the recommended structural systems for different heights. This table is organized according to the structural efficiency in limiting the wind drift as well as the cost and stiffness of the structure. These suggestions provide a direction to structural engineers for optimum system selection.

Table 2 Suggested systems for different heights

Height	Suggested System
10 stories (35 m)	Rigid frame, Shear wall/central core
20 stories (70 m)	Shear wall/central core, Outrigger
30 stories (105 m)	Wall-frame interaction, Outrigger
40 stories (140 m)	Wall-frame interaction, Outrigger, Tube in tube
50 stories (175 m)	Outrigger, Tube in tube
60 stories (210 m)	Outrigger, Tube in tube
70 stories (245 m)	Tube in tube

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Engineering, Cairo University, Giza, Egypt

References:

ACI 318-05, American Concrete Institute Code (2005), "Building Code Requirements For Structural Concrete And Commentary".

ASCE 7-05, American Society of Civil Engineers (2005), "Minimum Design Loads for Buildings and Other Structures", Washington DC.

ASCE Task Committee on Drift Control of Steel Building Structures (1988), "Wind drift design of steel-framed buildings": state of the art." J. St.; Div., ASCE, 114(9), 2085-2108.

Bryan Stafford Smith and Alex Coull (1991), "Tall Building Structures, Analysis and Design",

New York: John Wiley & Sons, Inc.

Bungale S. Taranath (1998), "Steel, Concrete, and Composite Design of Tall Buildings", Los Angeles, California: John A. Martin & Associates.

Bungale S. Taranath (2004), "Wind and Earthquake Resistance Buildings Structural Analysis and Design", Los Angeles, California: John A. Martin & Associates.

CTBUH (1980), Council on Tall Buildings and Urban Habitat, New York.

El-leithy, N.F. (2010), M.Sc, Thesis "Comparative Study of Structural Systems for Tall Buildings", Faculty of Engineering, Cairo University.

Wolfgang Schueller (1977), "High-Rise Building Structures", New York: John Wiley and Sons.

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