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# Structural Design of Reinforced Concrete Tall Buildings



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## Ali Sherif S. Rizk

Dr. Rizk is the director of the Structural Department at Dar Al-Handasah Consultants (Shair & Partners), a position he has held since 1998. He joined Dar in 1982 as a senior structural engineer and became the head of the department in 1990. Prior to joining Dar his academic career started in 1964 as an instructor and a lecturer at Ain Shams University, Egypt. Then he joined the University of Southampton, England as a post-doctoral and a senior research fellow. Then he returned to Egypt for the post of a professor at the University of Tanta. He has published about 30 papers in the fields of reinforced and prestressed concrete, fracture mechanics and fatigue of reinforcing bars.

"The development in concrete technology over the twentieth century covering materials, structural systems, analysis and construction techniques, made it possible to build concrete tall buildings such as Petronas towers (452m), Jin Mao (421m) and Burj Dubai (800m+)."

During the last 12 years the Structural Engineering Department at Dar Al-Handasah has designed 45 mixed-use tall buildings in different Arab countries. The designed towers are primarily made of reinforced concrete and vary in height from 80m (22 floors) to 590m (85 floors). This paper summarizes the tall buildings structural design experience gained by the structural design team. The tall buildings projects designed by the department are outlined and the static and the dynamic characteristics of these buildings are compared with those of some of the tallest buildings in the world. The relationship between the needed volume of reinforced concrete and tower height is established and a method for estimating the approximate total construction cost is proposed. The lateral load resisting systems, drift, vibration under wind loads, human comfort, and long-term shortening in vertical elements are among the subjects discussed. Monitoring results of heat of hydration and strains in some critical elements of the tallest designed building are also reviewed. The lessons learned and recommendations for future designs are given.

## ...restrictions

“While the proposed design of the building is exemplary, the applicant has not made a convincing argument that the building’s top 200 feet be worthy of the zone in which it would rise.”

*Amanda Burden, New York City Planning Commission Chairwoman explaining the decision to require a 200 ft height reduction to Jean Nouvel's Midtown Tower. From 'Lopped Off,' The Architects Newspaper, September 23, 2009, p 9*

## Introduction

The first reinforced concrete tall building was built in 1903 by A.O. Elzm [1] using E.I. Ransome's system of casting square twisted steel bars with concrete as a frame with slabs and concrete exterior wall. This is a 15-story building and known as Ingalls building in Cincinnati, Ohio, USA. Since the construction of this building engineers have realized the advantages of building with reinforced concrete as compared to building with steel. Among the early realized advantages are cheaper construction cost and better fire resistance. Concrete tall buildings have larger mass and damping ratio than steel tall buildings, which helps in minimizing motion perception, and providing better stability against wind and seismic loads.

The development in concrete technology over the twentieth century covering materials, structural systems, analysis and construction

techniques, made it possible to build concrete tall buildings such as Petronas towers (452 m high and 85 floors), Jin Mao (421 m high and 88 floors) and Burj Dubai (800m+ high and 160 floors). For these buildings of height exceeding 400 m, steel is used in a variety of ways to improve the performance of the building. Steel is usually used as:

- Composite with concrete such as composite mega columns and composite floor decking
- Outriggers to stiffen the structure
- Complete steel construction for the upper floors of the tower to reduce weight and where concrete cannot be delivered

Concrete construction is preferred in our area of the world because of the availability of concrete materials in the local markets and the traditionally more experienced concrete construction industry. It is therefore expected

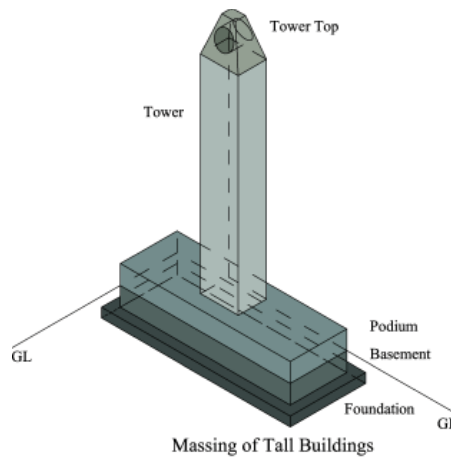


Figure 1. Massing of tall buildings

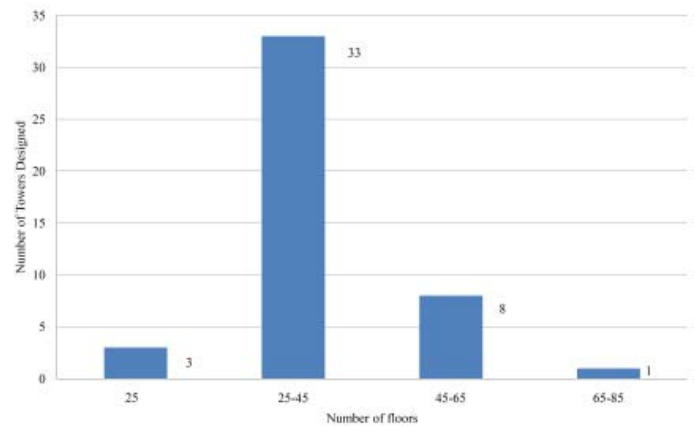


Figure 2. Distribution of height for designed towers

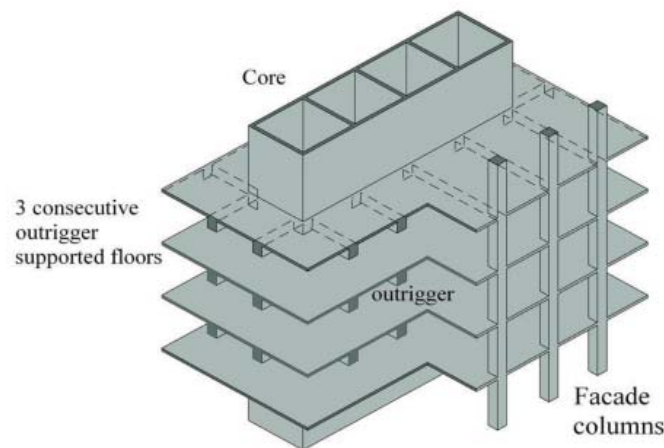


Figure 3. Outriggers

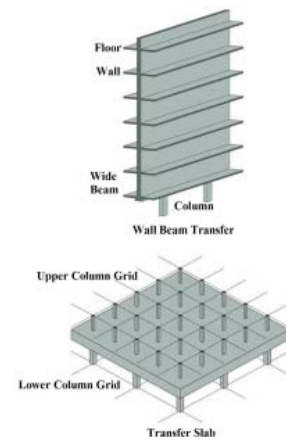


Figure 4. Transfer systems

to see more tall concrete and composite buildings constructed in the major cities of the Arab countries.

In this paper an overview of the experience gained by the structural team of Dar Al-Handasah Consultants in the design of concrete tall buildings is given. A useful approximate relationship between the required concrete volume and the number of floors (Dar's Formula) is established.

### Main Features of Designed Towers

The tall buildings designed by Dar Al-Handasah during the last 12 years are mostly for mixed-use and some are dedicated for single-use as office or hotel. The height above ground level of these buildings ranges from 80m (22 floors) to 590m (85 floors). Generally a tall building consists of five main masses namely, foundation, basement, podium, tower

and tower top as seen in Figure 1. The podium and the tower masses are primarily constructed of reinforced concrete. The upper floors of the highest designed building, i.e. above 400m is made of steel. All tower tops are also made of steel construction.

Figure 2 shows the distribution of the height of the designed towers indicating that most designed buildings are of height ranges between 90m (25 floors) and 200m (45 floors). The concrete grades used vary from 30-50MPa for floors and 50-70MPa for columns, walls and cores.

The structural system used includes flat slab construction (reinforced or post-tensioned) with drop beams, if needed, for floors. Central cores, inner and boundary columns and walls framing with the floor system complete the skeleton of the tower. Reinforced concrete outriggers framing boundary columns or walls and central core, see Figure 3, were introduced

at one or two locations along the height of some towers to control total and inter-storey drifts. The adopted total and inter-storey drifts limit due to the design wind speed is 1/500 of the height.

In many cases, transfer of upper column and wall loads to lower columns and walls was required. Figure 4 shows two of the systems used, i.e. the wall to column transfer and the transfer floor system in the form of a thick, solid slab. The transfer floor increases redundancy of the structure and thus helps in containing local failures and combating progressive collapse. If a ground floor column is missing for any reason the upper part of the column works as a tie carrying the load of the missed column to the transfer slab, which in turns distributes it to the adjacent columns and walls. This overloads the adjacent column and walls as discussed by Risk et al [2].

## ...TAIPEI 101

“TAIPEI 101’s management team not only wishes to make profits (we are trying to reach the break-even point and hence bring returns to our shareholders) but is also expecting to make TAIPEI 101 an icon of green building industry in Taiwan and worldwide.”

*Harace Lin, Chairman of TAIPEI 101 announced that TAIPEI 101 is aiming to become the first skyscraper obtaining the LEED Gold certification for existing buildings. From 'Fighting Against Global Warming; Loving The Earth!'; Press release by TAIPEI 101, November 2, 2009*

Figure 5, 6 and 7 show site photographs of some of the designed towers under construction or in the finished stage. These figures also show the typical floor plan and the global finite element model of each of these towers. Figure 7 shows the floor plans below and above the transfer floor. The transfer floor in this case is a solid 4m thick slab cast in two stages. The tallest designed building is rated in reference [3] as one of the twentieth tallest towers to be completed between 2008 and 2020.

### Own Weight vs. Height

The relationship between own weight of the concrete super structure in terms of equivalent thickness of concrete per unit of built up area in  $\text{cm/m}^2$  units and the building height in terms of number of built floors is shown in Figure 8. It should be mentioned that for reinforced concrete  $1 \text{ cm/m}^2$  equals  $25 \text{ kg/m}^2$ . The plotted data shows, in general, an increase of the own weight of the structure with the increase in the number of floors.

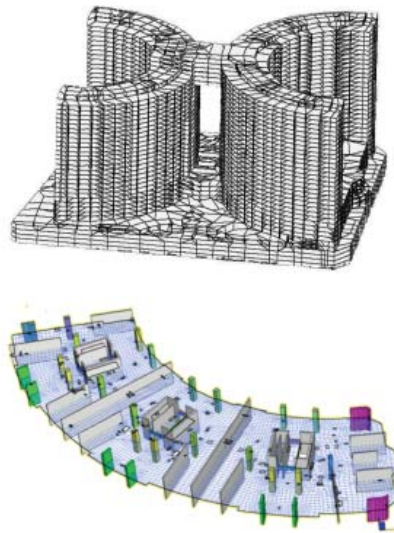


Figure 5. San Stefano Twin Tower, Alexandria

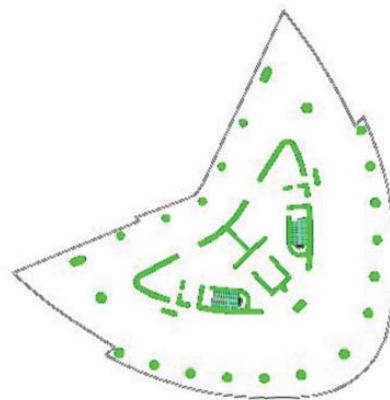


Figure 6. Marina Tower Beirut

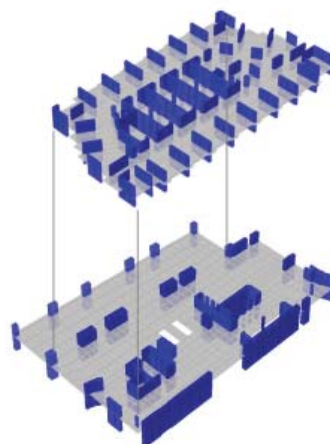


Figure 7. Hotel Tower, Mecca, KSA



Figure 8 also shows that both the horizontal elements of the building structure (i.e. slabs, beams, outriggers, ... etc.) and the vertical elements of the structure (i.e. columns, walls and cores, ... etc.) increase in weight with the increase in the number of floors in the building. This observed behavior indicates that for the designed towers both the horizontal and vertical members contribute, at different rates, to the required stiffening of the structure with the increase of its height. The percentage of the own weight of the horizontal members to that of the full structure weight is about 58%.

### Dar's Formula

Within the range of number of floors between 22 and 85, a simple straight line relationship is proposed by Dar Al Handasah as DAR'S formula for predicting the approximate volume of reinforced concrete in a tall building as follows:

$$V = (37.2 + 0.62N) A/100 \quad (1)$$

Where

V is the required concrete volume in m<sup>3</sup>,

N is the number of concrete floors in the building and

A is the total built up area of the concrete superstructure of the building in m<sup>2</sup>.

The observed scatter of the data points around the trend line is mainly due to the difference between the designed projects regarding the following:

- Adopted design criteria for the project i.e. gravity and lateral loads,
- Adopted percentage of reinforcement especially in vertical members.
- Concrete grade especially in vertical members.
- Podium size and stiffness
- Intensity of load transfers in the building

The standard error of the estimate i.e. (sest) for the proposed Dar's formula is 7.88. It was found that the percentages of data points

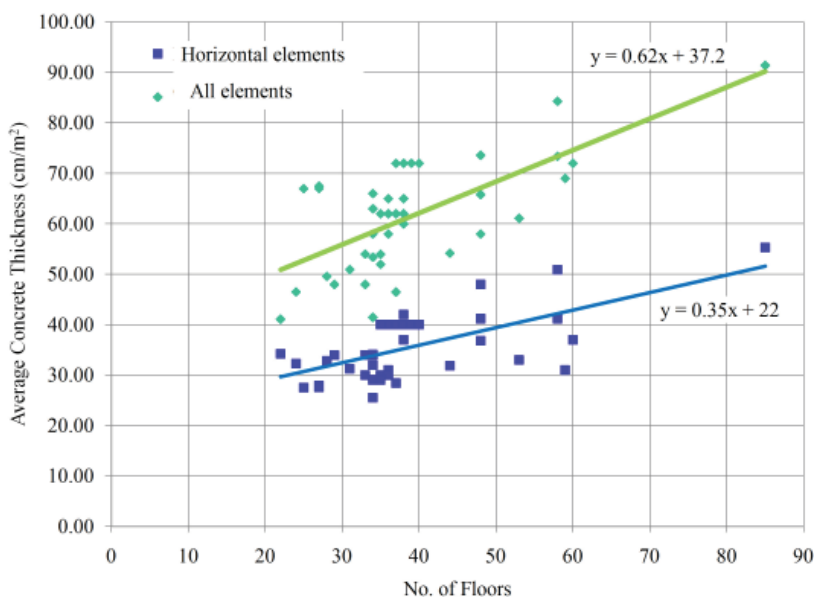


Figure 8. Average concrete thickness vs. number of floors for concrete framed tall buildings

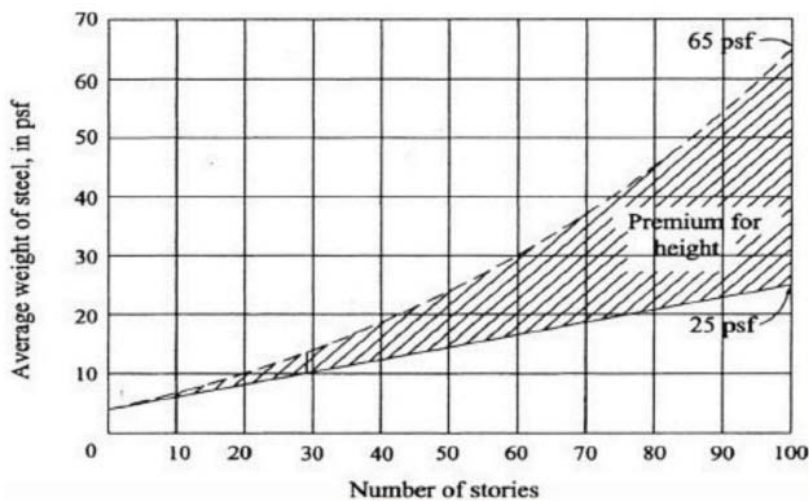


Figure 9. Average concrete thickness vs. number of floors for concrete framed tall buildings

inside the ranges  $\pm 1$  sest,  $\pm 2$  sest and  $\pm 3$  sest are 66.7%, 97.8%, and 100% respectively. Therefore, the maximum and minimum of the volume of concrete as predicted by Dar's formula can be calculated by the following equations:

$$V_{max} = (60.8 + 0.62 N) A/100 \quad (2)$$

$$V_{min} = (13.6 + 0.62 N) A/100 \quad (3)$$

The Dar's formula can also be used to assess the total construction cost of a tall building knowing that the concrete structure cost constitutes from 20 to 30% of the total cost,

reference [4]. This approximate method should only be used in the pre-concept design stage and the predicted total construction cost should be modified as design progresses.

### Comparison with Steel Tall Building

Figure 9 shows the weight of steel framed structures in the form of steel weight per unit of built up area (i.e. psf) and the number of floors in the building. It should be noted that 1 psf equals 4.882 kg/m<sup>2</sup>. This relationship generally takes the form of a hyperbola [5]. ↗

A fourfold increase in the number of floors i.e. between 20 to 80 floors, in steel buildings necessitates 370% increase in the needed weight of the steel. Similar increase in the number of floors, for concrete structures necessitates only 70% increase in the needed weight of the reinforced concrete. One can, therefore, come to the conclusion that reinforced concrete tall buildings are very much less sensitive to height than steel tall buildings.

### Long-Term Shortening

Long-term differential shortening between columns and core walls should be considered in the design of tall buildings. In very tall concrete buildings, long-term differential shortening may result in distortion of horizontal elements of the concrete structure and cracking in non-structural elements. Not only elastic shortening but also that due to creep and shrinkage should be accounted for. Construction techniques such as floor-by-floor construction and construction schedules have tremendous effect on the amount of differential shortening. Figure 10 shows the difference between the elastic column shortening calculated considering and not considering the floor-by-floor construction schedule in one of the designed towers at the end of construction. Figure 11 shows the contribution of each of elastic, creep and shrinkage shortening in a column after 30 years from the end of construction.

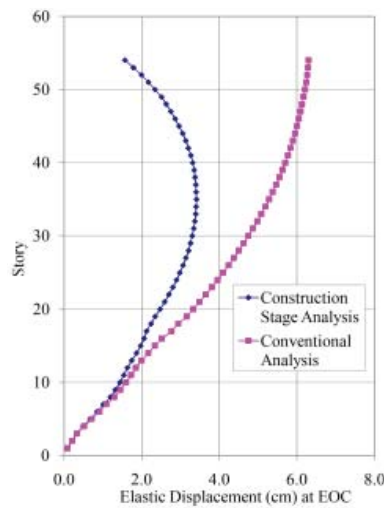


Figure 10. Column shortening at end of construction

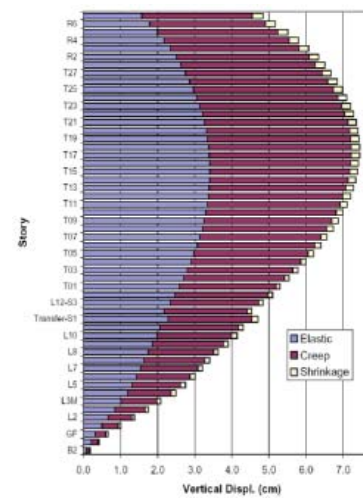


Figure 11. Column shortening after 30 years

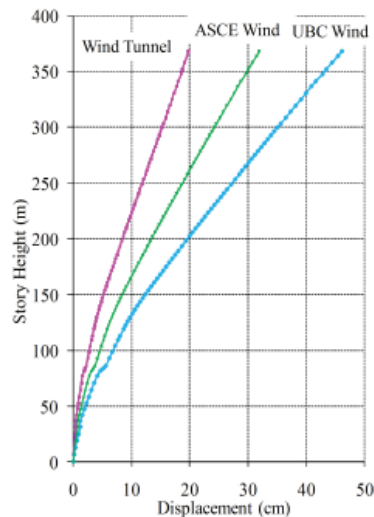


Figure 12. Drift calculated using different methods

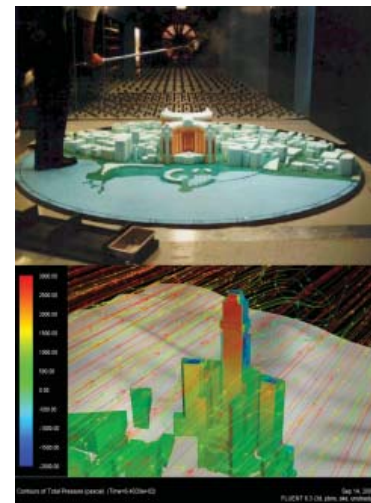


Figure 13. Wind tunnel test and CFD model

### Wind Induced Vibrations

Wind on a tall building is one of the main loads which govern its design. It induces vibration of the building and applies bending, shear and torsion on the different structural components of the buildings. The vibration of a tall building when exposed to wind is studied in this section with respect to the following three issues:

- drift of the building under wind load;
- period of vibration of the building; and
- acceleration of vibration of the building.

### Building Drift due to Wind Loading

Tall buildings drift under the effect of wind loads. The drift should be limited to 1/500 of the building height to control cracking and distortion of the non-structural elements of the building [7]. Drift can be controlled by either increasing the stiffness of the vertical and horizontal elements or by adopting stiffer elements such as walls or core walls.

An accurate assessment of wind-induced load on the building is essential to attain a practical and economical design. Figure 12 shows the drift of one of the designed buildings under

wind loads as calculated by either an extended UBC method or the ASCE method [6, 7]. It also shows the drift due to wind loads obtained from wind tunnel test, such as that shown in Figure 12. It is clear that for economical reasons wind tunnel testing techniques should be used. Recently, computational fluid dynamics (CFD) techniques, Figure 13, can also be used to verify wind loading from wind tunnel testing and to check the effect of architectural/structural changes made to minimize the wind load on the structure and thus improve the performance of the building under wind loads.

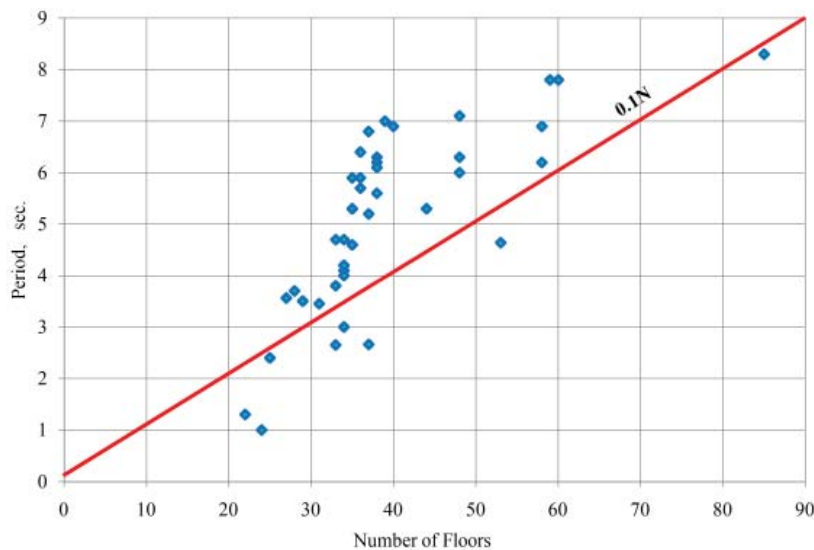


Figure 14. Relationship between period of vibration and number of floors

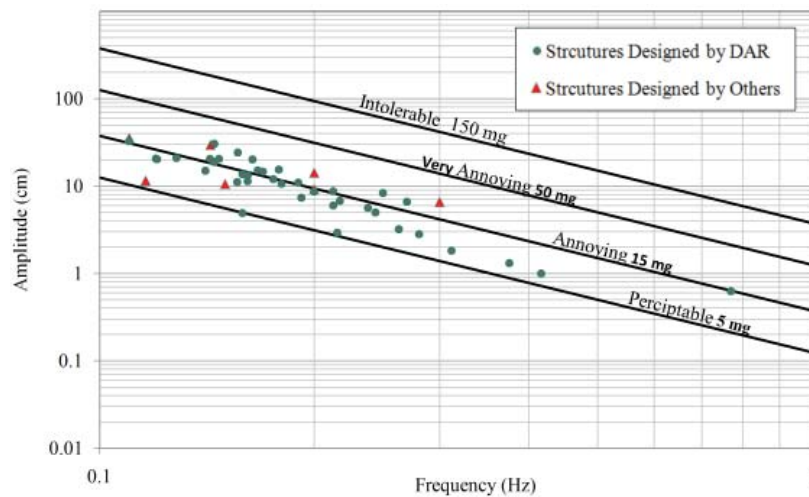


Figure 15. Tall building acceleration

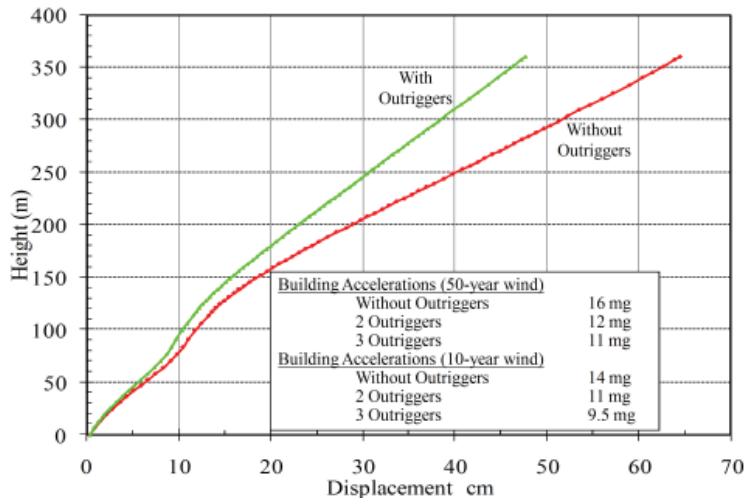


Figure 16. Effect of outriggers on tall building acceleration

### Fundamental Period of Building Vibration

Figure 14 shows the increase of the fundamental period of vibration of the designed buildings with their height. The data does not support the well known relationship, which approximates value of the fundamental period as one tenth of the number of floors in the building. Most data values are higher than the values calculated by this approximate relationship and thus this relationship should only be used for evaluation of concept designs. For preliminary and final designs a detailed dynamic 3D analysis of the building frame should be made.

### Acceleration of Building Vibration

Human perception of building vibration is related to both amplitude (i.e. drift) and frequency of the building vibration. The tall building designers are therefore very interested in evaluating the acceleration of their designed towers especially at top floors to ensure the comfort of the human occupants and the reliable performance of equipment in these buildings. Five levels of human perception [8] are usually identified as follows:

Perception of acceleration	
Degree of Discomfort	Acceleration level
Imperceptible	< 5 mg
Perceptible	< 5 mg – 15 mg
Annoying	< 15 mg – 50 mg
Very Annoying	< 50 mg – 150 mg
Intolerable	> 150 mg

Figure 15 shows the different levels of human perception to vibration in terms of building acceleration. This figure also shows the accelerations of the designed building and those of some tall buildings designed by others. The acceptable acceleration values for the designed towers are 10 – 30 mg as specified in NBCC 1990. An effective way to control drift is by adding outriggers as shown in Figure 16. ☞

## Heat of Hydration

Generally, reinforced concrete columns, walls and cores in tall buildings are massive in size especially in lower floors. The smallest column dimension and thickness of walls are often larger than 1.0 m. Also concrete mixes used in tall buildings are of the highest possible grade and thus contain high dose of cement. Due to those two reasons it is expected that high quantities of heat of hydration are liberated during the early days after casting. The temperature of the reinforced concrete elements usually reaches above 70°C and the differential temperature between the center of the element and its surface usually exceeds the safe limit of 20°C.

Exposure of the concrete to high temperature at early age may result in delayed ettringite attack causing cracking and long term reduction in concrete strength. High temperature differentials cause cracking of concrete elements. It is therefore important to check if this high temperature and high temperature differential during the early age of the concrete have no detrimental effect on its long-term strength. Additional reinforcement might be necessary to limit the induced cracks as a result of temperature variation along the height of thick concrete rafts and due to cooling to the ambient temperature.

Figure 17 shows the temperature readings in the center, midway and the surface of a 1.5 m, thick core wall made with a grade C70 concrete. The peak concrete temperature reached 86°C and differential temperature of 30°C is reported. In this particular case compressive strength results on cores taken from this concrete show that the long-term concrete strength has not been affected by the shown temperature regime.

## Strains in Concrete Elements

Vibrating wire strain gauges were installed in a number of the critical reinforced concrete elements of the tallest designed tower to measure strains during the construction period and after completion, Figure 18. This is necessary to verify design assumptions and calculations of the working stresses. Figure 19 shows the 5th floor plan, one of the three

instrumented floors, with all the instrumented columns and walls marked. Figures 20, 21, and 22 show samples of the recorded strains in a column, a core wall and the transfer floor with time. It should be noted that shrinkage and creep strains are included in these readings.

The strain readings in the column show close agreement between the four gauges in the column whereas wider variation exists between the different gauge readings in the core wall. This is expected as core walls carry higher percentage of the applied bending moment due to both the inherent eccentricity of the building and wind loads. The readings in Figure 21 for gauges installed in the transfer floor, in the compression and in the tension sides, show large variation in the recorded values due the domination of the bending effect on this section of the transfer floor. For all cases the highest values of the measured strain (700-800 micro strain) indicate that stresses in all studied reinforced concrete elements are within the safe limits and the constructed structure performance is generally acceptable.

## Summary & Recommendations

The structural systems used in the design of tall buildings by Dar Al-Handasah Consultants during the past 12 years are reviewed. The static and dynamic characteristics of the designed towers are outlined and compared with those of some tall buildings designed by others.

A relationship between the volume of the concrete structure and its height is established. Dar's formula is recommended for evaluation of concrete volume of a tall building and its total construction cost during the early concept design stage.

Monitoring results of the heat of hydration and strains in critical elements are illustrated and discussed. It is recommended that monitoring of concrete temperature and its effect on long-term strength of the concrete should be carried out during the early construction stage. For complex concrete tall buildings, strain monitoring campaign should be made to verify design assumption and calculations of critical elements.

Although concrete can be lifted up to about 600m, it is believed that for tall buildings of height exceeding about 400 m, the use of composite concrete-steel construction seems to be inevitable to reduce gravity loads on columns and walls of the lower floors. This also facilitates construction of the upper floors where concrete is most difficult to be delivered.

## Acknowledgement

The author is indebted to the top management of Dar Al-Handasah (Shair and Partners) for their support and encouragement. Special thanks are given to all members of the structural team in both Dar Cairo and Dar Beirut for their dedication, hard work and contributions to the success of this work. ■

**Editor's Note:** To further discuss this topic with the author, please join our CTBUH Skyscraper Group at <http://LinkedIn.ctbuh.org>

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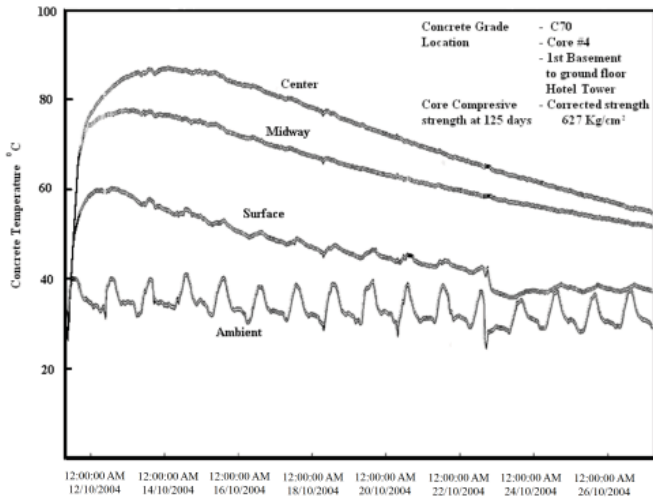


Figure 17. Concrete Temperature



Figure 18. Installation of vibrating wire strain gauges

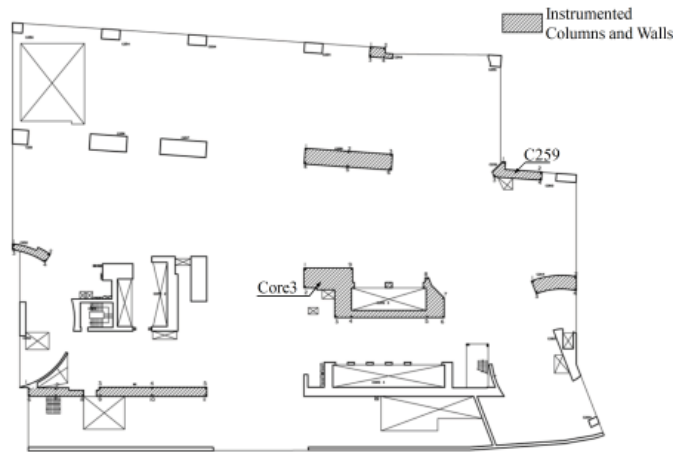


Figure 19. 5th Floor Plan showing Instrumented Columns and Walls

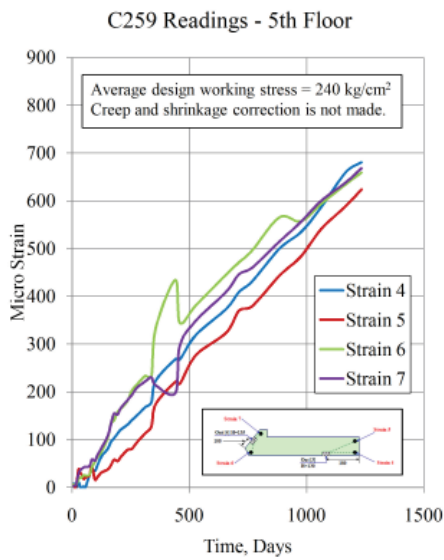


Figure 20. Record strains in a column

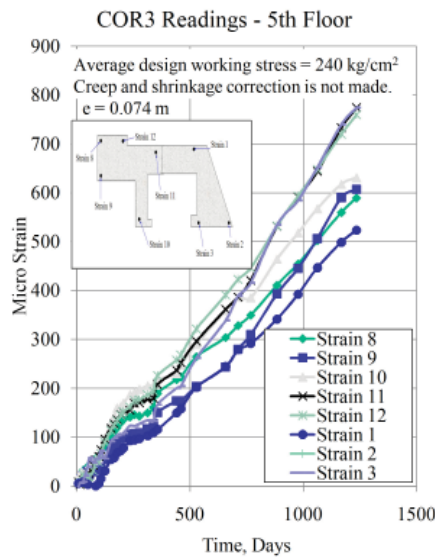


Figure 21. Recorded strain in a core wall

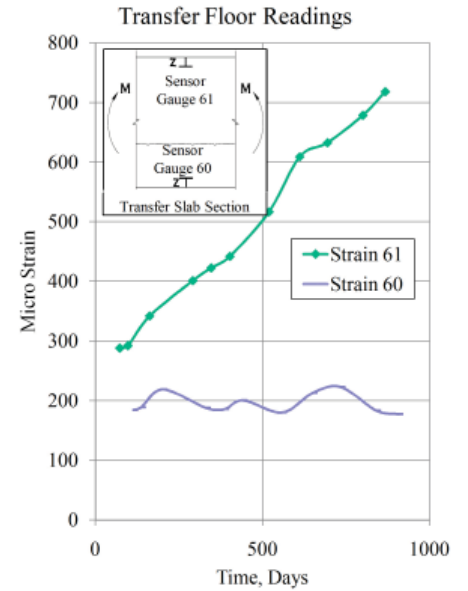


Figure 22. Recorded strain in transfer floor