Structural Analysis and Design of Concrete Tall Buildings: Efficiency and Effectiveness

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The history of concrete high-rise belongs to the twentieth century and was used in the Ingalls Building in Cincinnati, Ohio, the first 15-story concrete "skyscraper" built in 1903 by A. O. Elzner (64 m tall).

Concrete was proving itself to be an excellent fire-resistant material through its use in factories and providing sustenance during fires in those facilities.

The development in concrete technology covering materials, structural systems, analysis and construction made it possible to build concrete tall buildings up to 1001 m high.
• The tall buildings designed by dar al handasah during the last 20 years are mostly for mixed-use or office buildings.
• The height above ground ranges from 80 m to 1001 m.
• Generally tall buildings consists of five mases:
  o Foundation
  o Basement
  o Podium
  o Tower
  o Tower top
Total number of towers = 45
**Introduction & Problem Description**

- The structural system includes a flat slab (reinforced/post tensioned) supported on central core and interior boundary columns.
- In many cases, transfer of upper columns/walls to lower columns/walls was required.
- Transfer floor increases redundancy of the structural system and hence prevents progressive collapse.
Introduction & Problem Description
San Stefano Twin Towers, Alex., Egypt
Introduction & Problem Description

Marina Tower, Beirut, Lebanon
Introduction & Problem Description

Clock Tower, Makkah, KSA
Structural Steel is used in a variety of ways to improve the performance of tall concrete buildings.

- Composite with concrete such as composite mega columns and composite floor decking,
- Outriggers to stiffen the structure,
- Complete steel construction for the upper most floors of the tower where concrete cannot be easily delivered and to reduce weight.
A relationship was established between own weight of the concrete super-structure in terms of equivalent thickness of concrete per unit of built-up area in cm/m² and the building height was established.

Both horizontal and vertical elements contribute to the stiffening of the structure but with different rates.
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.
1- Approximate volume of reinforced concrete in a tall building

\[ V = (37.2 + 0.62N) \frac{A}{100} \] (1)

Where \( V \) is the required concrete volume in m\(^3\),
\( N \) 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\(^2\).

2- The standard error of the estimate = 7.88, thus:

\[ V_{\text{max}} = (60.8 + 0.62N) \frac{A}{100} \] (2)
\[ V_{\text{min}} = (13.6 + 0.62N) \frac{A}{100} \] (3)

3- The horizontal elements make \( 58\% \) of the total volume
Verification of DAR’s Formula
Long-term differential shortening between columns and core walls should be considered in the design of tall buildings. Long-term differential shortening may result in distortion of Hz. Elements and cracking of non-structural elements.

• Creep, shrinkage and constructional analysis shall be considered.
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 different elements.

Vibration is studied with respect to:

- Drift of the buildings
- Period of vibration
- Acceleration of vibration of the building
Drift should be limited to 1/500 of the building height to control cracking and distortion of non-structural elements of the building.

- Drift can be controlled by increasing the stiffness of the vertical/horizontal elements, by adopting stiffer elements such as walls/cores or by adding outrigger floor/belt trusses.

- Wind tunnel testing techniques is highly preferred due to its accurateness in estimating drift.
Wind Induced Vibrations
Wind Induced Vibrations
Fundamental Period of Vibration

Buildings designed by DAR

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Acceleration of Building Vibration

- Structures Designed by DAR
- Structures Designed by Others

<table>
<thead>
<tr>
<th>Perception of acceleration</th>
<th>Degree of Discomfort</th>
<th>Acceleration level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intolerable</td>
<td>&gt; 150 mg</td>
<td></td>
</tr>
<tr>
<td>Very Annoying</td>
<td>&lt; 50 mg – 150 mg</td>
<td></td>
</tr>
<tr>
<td>Annoying</td>
<td>&lt; 15 mg – 50 mg</td>
<td></td>
</tr>
<tr>
<td>Perceptible</td>
<td>&lt; 5 mg – 15 mg</td>
<td></td>
</tr>
<tr>
<td>Imperceptible</td>
<td>&lt; 5 mg</td>
<td></td>
</tr>
</tbody>
</table>
Effect of Outriggers on Tall Buildings Acceleration, Clock Tower, Makkah, KSA.
Kingdom Tower, Jeddah, KSA (1001 m)
Kingdom Tower, Jeddah, KSA (1001 m)

**Dar’s Role**

- Carry out an independent verification of the analysis/design by developing an independent 3D FEM.
- Review of the design criteria.
- Check the suitability of the chosen structural systems in respect of the efficiency, economy, constructability and safety.
- Confirm that the design complies with best known practice, all relevant codes.
- Carry out a detailed review of the wind tunnel analysis undertaken by the Designer.
- Confirm that the proposed foundation system is based on appropriate compatibility with the Geotechnical analysis.
- Review of load paths, materials, member sizes and codes to be used.
- Check of analysis and design for the computer modeling for gravity and dynamic behaviors of the structure.
Kingdom Tower, Jeddah, KSA (1001 m)
Kingdom Tower, Jeddah, KSA (1001 m)

- Over 1,000m when completed, 180 m higher than the current tallest building in the world (Burj Khalifa)
- 167 habitable floors (252 including spire void)
- Deepest piles in the Middle East at 110 m – over 13 km of piles placed in 12 months
- Structure - reinforced concrete - 465,000 m³
- Total tonnage of reinforcement - 94,000 t
- World’s highest Observation Deck (640m)
- The Spire is 321m in height
Kingdom Tower, Jeddah, KSA (1001 m)

Progress of Construction
Kingdom Tower, Jeddah, KSA (1001 m)

Key Structural Design Items

- Soil Structure Interaction
- Strut-and-Tie Models for Coupling Beam Design
- Steel Plate Coupling Beam Design
- Tower Stiffness Modifiers (Cracking Analysis)
- Vertical Shortening Analysis
- Damping Strategy
Parameters for Settlement Predictions
- Pile Springs for Structural Model – Matching Settlement Predictions
- Springs used for Structural Pile Design

Post-Settled Parameters for Transient Loading Events
- Higher Stiffness Springs for 1, 10 and 50yr Wind Events
- Used to Determine Dynamic Behavior under Transient Loading
Kingdom Tower, Jeddah, KSA (1001 m)

Soil-Structure Interaction

• More than 9 iterations were carried out in close collaboration with the GT team to reach compatibility of deformations between both the structural and geotechnical models at every single pile.

• The average stiffnesses at the central zone and at the edge were found to be around 80 MN/m and 300 MN/m, respectively.
Kingdom Tower, Jeddah, KSA (1001 m)

Soil-Structure Interaction

Pile Loads (MN) using Dar Values for Pile Stiffness

Pile Loads (MN)
Kingdom Tower, Jeddah, KSA (1001 m)  
Soil-Structure Interaction  

Raft Settlement Profile
Kingdom Tower, Jeddah, KSA (1001 m)

Strut and Tie for Coupling Beam Design

RC Shear Stress Design Limits

- 0.00 to 0.83 $\sqrt{(f'c)}$ – Conventional ACI 318 Approach
- 0.83 to 1.08 $\sqrt{(f'c)}$ – ACI 318 Strut-and-Tie (STM)
- 1.08 $\sqrt{(f'c)}$ and up – Embedded Steel Plate
Kingdom Tower, Jeddah, KSA (1001 m)
Strut and Tie for Coupling Beam Design
Kingdom Tower, Jeddah, KSA (1001 m)

Strut and Tie for Coupling Beam Design

- The two-panel Strut and Tie Method (STM) can be chosen for coupling beams with longer clear spans and span-to-depth ratios.

- With the STM, the structural engineer has the choice of formulating the model in any way that meets the provisions of Appendix A in ACI 318. The design model represents a lower-bound and therefore conservative.

- The two-panel strut-and-tie model produces a design with far more vertical stirrups than a one-panel model which relies heavily on the horizontal bars.
Kingdom Tower, Jeddah, KSA (1001 m)

**Strut and Tie for Coupling Beam Design**

- To further examine the STM, one beam has a clear length of 2500 mm and cross-sectional dimensions of 1000 mm wide by 1600 mm deep was modeled using ATENA.

- The analysis accounted for every single reinforcing bar in the concrete beam. The principal compressive strain distribution at failure exceeded 0.002.

- Failure was due to crushing of the concrete of the strut as the compressive strains exceed 0.002.
Kingdom Tower, Jeddah, KSA (1001 m)

Strut and Tie for Coupling Beam Design

Typical coupling beam modeled using ATENA
The results of nonlinear finite element analyses indicate that reinforced concrete link beams have significantly larger shear capacities than the nominal strengths calculated by the strut-and-tie model of ACI 318-08.

Such a phenomenon clearly matched the same observation concluded by Kuchma et al., 2006.
Kingdom Tower, Jeddah, KSA (1001 m)

Steel Plate Coupling Beam Design

- Plate Stability
- Anchorage (Depth and Bearing Above and Below)
- Mattock and Gaafar (1982) ACI
Cracking and ACI 318
Section 10.10.4.1 reduction modifiers are inappropriate for Tall Concrete High-rise Towers
• Inappropriate for Core Walls
• Columns in High-rise Towers are Predominantly Axial Load Members
• Most FEMs of Concrete Towers Neglect the Stiffness Increase – Rebar

Suggested Cracked Section Properties
• Cracked Wall – F11, F22, F12 = 0.7; M11, M22 = 0.7; M12 = 0.25
• Frame: Ix, Iy = 0.5; Vx, Vy = 0.5; J = 0.25
• Shell: F11, F22, F12 = 0.5; M11, M22 = 0.5; M12 = 0.25
• These are based on research and Ieff calculations.
Kingdom Tower, Jeddah, KSA (1001 m)

Vertical Shortening Analysis

- The analysis, prediction and recommended compensation for creep and shrinkage effects in a building such as Kingdom Tower is extremely complicated and requires very sophisticated and powerful computer-based tools and analysis techniques.
Concrete material properties are not the only variable of significance when conducting a vertical shorting analysis for a tower of this magnitude. Construction schedule and construction sequence is equally if not more important to accurately predict the movements of the tower over time.

Compensation/camber values are specified based on analysis for central core.
Kingdom Tower, Jeddah, KSA (1001 m)

Damping Strategy

- A supplemental tuned mass damper is normally required for tall buildings to improve the structural serviceability performance.
- Two TMDs are installed in the KT project.
Central Business District, Cairo, EGYPT

Iconic Tower
400 m

Residential Tower
200 m

© Council on Tall Buildings and Urban Habitat
Iconic Tower

Data

Total Height = 385 m,
T = 9.4 seconds
BUA of Tower = 146,000 m²
Total BUA = 241,000 m²
H/B = 7.7
Structural System = Central core + peripheral composite steel columns
Outrigger floors = 4
Foundation = Raft (5 m thick)
Wind Drift = h/416
Seismic Drift = 0.0097 < 0.01 (as per BS EN 1998-1:2004)
Across wind Acc. = 14.8 mg
Total Concrete Volume = 207,000 m³ (Including Foundation)
Equivalent Thickness = 85 cm
Reinf. tonnage = 32,000 ton
Structural steel = 23,500 ton
Central Core Configuration

Wall Thickness
- 800 mm
- 600 mm

Beam Depth
- 1000 mm
- 1400 mm
- 1600 mm

Zone 1 & 2

© Council on Tall Buildings and Urban Habitat
Central Core Configuration

Wall Thickness
- 800 mm
- 600 mm

Beam Depth
- 1000 mm
- 1400 mm
- 1600 mm

Zone 3 & 4

Top of the Tower
+243.00
Hotel
+133.80
Zone 3-4
Zone 1-2
-10.800
Central Core Configuration

Wall Thickness
- 800 mm
- 600 mm

Beam Depth
- 1000 mm
- 1400 mm
- 1600 mm

Hotel
Framing Plans
The lateral and vertical resistance of the tower is provided by the central core. The primary lateral resistance is provided by the core, outrigger, and frames.
Lateral Load Behavior

![Graph of lateral load behavior showing drift vs. building height in X and Y directions.]

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Drift Behavior

Seismic Drift - X Direction

CB: Coupling Beam

Effect of Combined Outriggers+Belt Trusses
Effect of Outriggers
Effect of Belt Trusses

Building Height (m)

Drift

NOB-NCB-MAX.
3OR-CB-MAX.
NOB-CB-MAX
3BT-CB-MAX.
3BT+3OR-CB-MAX.
### Load Transfer Mechanism

**Gravity Loads Transfer Path**

<table>
<thead>
<tr>
<th>Structure Component</th>
<th>Gravity Loads (%)</th>
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<tbody>
<tr>
<td>Central Core</td>
<td>73</td>
</tr>
<tr>
<td>Peripheral Columns</td>
<td>27</td>
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</tbody>
</table>

**Lateral Loads Transfer Path**

<table>
<thead>
<tr>
<th>Structure Component</th>
<th>Shear Force (%)</th>
<th>Overturning moment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Core</td>
<td>91</td>
<td>60</td>
</tr>
<tr>
<td>Peripheral Columns</td>
<td>9</td>
<td>40</td>
</tr>
</tbody>
</table>
Residential Towers (145 - 200 m)
Residential Tower D01

Data

Total Height = 192 m,
T = 6.50 seconds
Total BUA = 106,000 m²
H/B = 10 (conservative estimate for the top plans)
Structural System = Concrete coupled shear walls + cores
Outrigger floors = 2
Foundation = Raft on piles (3.0 m thick & 2.5 & 2.0 m diameter piles)
Wind Drift = h/550
Seismic Drift = 0.0086 < 0.01 (as per BS EN 1998-1:2004)
Across Wind Acc = 9.7 mg
Total Concrete Volume = 91,000 m³ (Including Foundation)
Equivalent Thickness = 86 cm
Reinf. tonnage = 13,100 ton
Prestressing steel = 350 ton
Drift Behavior
Podium Effect on Behavior

D01 Tower Drift With Podium

D02 Tower Drift With Podium

D05 Tower Drift With Podium

A01 Tower Drift Without Podium

D01 Tower Drift Without Podium

D02 Tower Drift Without Podium

D05 Drift Without Podium
Conclusions

- The structural systems used in the design of tall buildings by Dar Al-Handasah during the past 20 years are reviewed.
- The static and dynamic characteristics are outlined.
- A relationship between the volume of concrete structure and its height is established.
- The main key issues related to the tallest concrete building in the world are discussed.
- Design of coupling beams using S&T is reviewed compared to FEM.
Conclusions

• Within the range of heights designed by Dar, the volume of concrete needed for a tall building is linearly related to the number of floors in the building.
• Dar’s formula is established to predict the volume of concrete needed to build a tall R.C building.
• Initial verification of Dar’s formula shows that the extent of elevation setbacks and concrete grade also affect the volume of concrete.
• If the tall building height is outside the limits of wind load calculations in either the UBC or ASCE, wind tunnel testing is essential to produce efficient design.
Conclusions

• CFD may be used to evaluate wind loads on tall buildings if wind climate can be properly represented in the analysis.

• Structural steel construction shall be used for the upper part of concrete tall buildings higher than 400 m to control the size of vertical elements in the lower floors and reduce the own weight of the structure.

• Heat of hydration study is required for tall buildings with element width or thickness greater than 1.0 m.

• For complex concrete tall buildings field strain measurements in critical elements are needed to verify design assumptions.
Thank You