RECENT SUPERTALL CONCRETE TOWERS IN THE MIDDLE EAST

John Peronto and Robert Sinn

11th International Workshop on Structural Concrete

October 19, 2019
Uptown Dubai – Site of Supertalls
Uptown Dubai – Site of Supertalls

- 711m Supertall Tower and Structural System

- Concrete Material
  a. Strength (f’c)
  b. Modulus (MOE)
  c. Local Challenges

- Wind Tunnel Testing

- Site Challenges and Wake Buffeting

- Performance
Structural System

- Concrete Core
- Concrete Mega-Columns
- Steel Outriggers
  (3 – Stories Deep)
- Concrete Belt Wall
  (2 – Stories Deep)
- Concrete Secondary Columns
- Concrete Floor Framing
## High-Strength Concrete Data

<table>
<thead>
<tr>
<th>Mix Grade (Cylinder)</th>
<th>NORMAL: 520-OPC+45%GGBS+8%MS</th>
<th>Limestone</th>
<th>NORMAL: 520-OPC+45%GGBS+8%MS</th>
<th>Limestone</th>
<th>High pumping: 520-OPC+45%GGBS+8%MS</th>
<th>GABRO</th>
<th>High pumping: 520-OPC+45%GGBS+8%MS</th>
<th>GABRO</th>
<th>High pumping/NORMAL: 520-OPC+45%GGBS+8%MS</th>
<th>Limestone</th>
<th>High pumping/NORMAL: 520-OPC+45%GGBS+8%MS</th>
<th>Limestone</th>
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<td>@ 7 Days</td>
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<td>43900</td>
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<td>65.0</td>
<td>56.0</td>
<td>57.0</td>
<td>67.5</td>
<td>64.0</td>
<td>64.5</td>
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<td>58.2</td>
<td>65.0</td>
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<td>72.5</td>
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<td>76.0</td>
<td>70.0</td>
<td>72.5</td>
<td>80.0</td>
<td>84.0</td>
<td>82.5</td>
<td>83.0</td>
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<td>85.0</td>
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<td>81.0</td>
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<td>@ 56 Days</td>
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<td>81.0</td>
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</table>
Floor Framing – Concrete vs Steel

Typical Reinforced Concrete Floor Framing

Spandrel Beam RC Option Section

RC BEAM SPAN > 12m = 500 x 600
SPAN = 12m = 900 x 750

Typical Composite Steel Beam Floor Framing (Alternate)

Spandrel Beam Steel Option Section

GIRDERS
W310 (SPAN ≤ 1.5M)
W300 (SPAN > 1.5M)

NYC COMPOSITE ON METAL DECK

VARIES
Floor Framing – Flat Slab Analysis
# Mega-Column Design

## MEGA COLUMNS

<table>
<thead>
<tr>
<th>Levels</th>
<th>Mega Column Size (m) x (m)</th>
<th>fc' (MPa)</th>
<th>fy (MPa)</th>
<th>P_u_max (MN)</th>
<th>P_u_min (MN)</th>
<th>p (%)</th>
<th>DCR</th>
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<tbody>
<tr>
<td>BASE-L5</td>
<td>4.25x4.25</td>
<td>100</td>
<td>520</td>
<td>-892</td>
<td>230</td>
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<td>0.975</td>
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<tr>
<td>BASE-L5</td>
<td>4.00x4.00</td>
<td>100</td>
<td>520</td>
<td>-892</td>
<td>230</td>
<td>5.3</td>
<td>0.993</td>
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<tr>
<td>L5-L38</td>
<td>3.75x3.75</td>
<td>100</td>
<td>520</td>
<td>-773</td>
<td>230</td>
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<td>BASE-L38</td>
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<td>100</td>
<td>520</td>
<td>-892</td>
<td>230</td>
<td>8.7</td>
<td>0.993</td>
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<td>520</td>
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<td>520</td>
<td>-230</td>
<td>99</td>
<td>3.5</td>
<td>0.966</td>
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<td>0.735</td>
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</table>

![Graph showing service axial force vs. elevation for different levels](image-url)
Structural System
Concrete Core with Mega-Column and Outrigger Schemes

Concrete Wall with Concrete Outriggers

Two Story Belt Wall with Steel Outriggers

Three Story Steel Truss

Two Story Steel Truss
Outriggers and Seismic Overstrength
Outrigger MEP Coordination

Section per ASGG sketch
Footprint Comparison

Uptown Dubai T1 – Floor Plan

Jeddah Tower – Floor Plan
Footprint Comparison

Uptown Dubai T1 and Jeddah Tower – Floor Plan Overlay
Wind Tunnel Testing - RWDI

Test Configuration 2
Initial HFFB Wind Tunnel Test Response

![Graph showing wind tunnel test response with data points for different damping levels and time periods.]

**Return Period [Years]**
- 1
- 5
- 10

**Peak Accelerations**
- Total [X, Y and torsional components]
- 1.5% Damping
- 2.0% Damping
- 5.0% Damping

<table>
<thead>
<tr>
<th>Return Period [Years]</th>
<th>Peak Accelerations((^{(j)}) (milli-g)</th>
<th>Peak Torsional Velocities (milli-rads/sec)</th>
<th>CTBUH(^{(i)}) Criteria</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Total - [X, Y and torsional components]</td>
<td>1.5% Damping</td>
<td>2.0% Damping</td>
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<tr>
<td>1</td>
<td>22 - [20, 20, 0.6]</td>
<td>0.3</td>
<td>0.2</td>
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<tr>
<td>5</td>
<td>47 - [45, 26, 0.8]</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>48 - [47, 26, 1.0]</td>
<td>0.4</td>
<td>0.4</td>
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Images per RWDI report (Figure 6a)
Aeroelastic Wind Tunnel Test Refined Response

![Graph showing the relationship between total peak acceleration (milli-g) and typical time between occurrences for 1.5% and 2.0% damping.]

<table>
<thead>
<tr>
<th>Return Period (Years)</th>
<th>Peak Accelerations (milli-g)</th>
<th>Peak Torsional Velocities (milli-rads/sec)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Total - [X, Y and torsional components]</td>
<td>1.5% Damping</td>
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<tr>
<td></td>
<td>1.5% Damping</td>
<td>2.0% Damping</td>
</tr>
<tr>
<td>1</td>
<td>19 - [19, 13, 0.54]</td>
<td>17 - [16, 11, 0.47]</td>
</tr>
<tr>
<td>5</td>
<td>26 - [25, 16, 0.80]</td>
<td>22 - [21, 14, 0.69]</td>
</tr>
<tr>
<td>10</td>
<td>27 - [26, 19, 0.95]</td>
<td>23 - [22, 16, 0.82]</td>
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</table>

Images per RWDI report (Figure 6a)
Tower 2 (340m) – WAKE BUFFETING !!

Tower T2

1) Site Orientation
2) Inter-Tower Spacing
3) T1 Relative Height
4) T1 Wake in Resonance with T2
5) T2 Structural Properties
6) T2 Geometry
Tower 2 (340m) – WAKE BUFFETING !!

Results
Phase 1 - Construction Progress (Raft)
Phase 1 - Construction Progress (Tower Rising)
Jeddah Tower – 1st 1km Tall Structure
<table>
<thead>
<tr>
<th>Name</th>
<th>City</th>
<th>Country</th>
<th>Height</th>
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<td>Jeddah Tower</td>
<td>Jeddah</td>
<td>Saudi Arabia</td>
<td>1000m</td>
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<tr>
<td>Burj Khalifa</td>
<td>Dubai</td>
<td>United Arab Emirates</td>
<td>828m</td>
</tr>
<tr>
<td>Shanghai Tower</td>
<td>Shanghai SH</td>
<td>China</td>
<td>632m</td>
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<tr>
<td>Taipei 101</td>
<td>Taipei</td>
<td>Taiwan</td>
<td>508m</td>
</tr>
<tr>
<td>Petronas Towers</td>
<td>Kuala Lumpur</td>
<td>Malaysia</td>
<td>452m</td>
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Team/Code Recap

- Structural Engineer: Thornton Tomasetti (TT)
- Architect: Adrian Smith + Gordon Gill Architecture (AS+GG)
- Developer: Jeddah Economic Company (JEC)

- Competition Start: June 2009
- Complete Design Docs: August 2013
- Reinforced Concrete: Design to ACI 318
- General Contractor: Saudi BinLaden Group (SBG)
- Employers Engineer: Dar Al-Handasah
Structural System

- All walls connected with link beams
- No columns
- No outriggers
- No column transfers
- Flat plate floors
- No spandrel beams
High Strength Concrete and Reinforcing Bar Materials

**Vertical Rebar**
- 420 MPa / 60 ksi

**Concrete (f’c) Cylinder**
- 65 MPa / 9,500 psi
- 75 MPa / 11,000 psi
- 85 MPa / 12,500 psi
- 60 MPa / 9,000 psi
85 MPa Concrete Spec

- $f'_c = 85 \text{ MPa} (12,300 \text{ psi})$ at 90d
- MOE = 43.3 GPa (6300 ksi) at 90d
- Mix: Near SCC

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<tr>
<th>Ingredient</th>
<th>lb</th>
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<td>OPC</td>
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<tr>
<td>SF</td>
<td>76</td>
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<tr>
<td>PFA</td>
<td>170</td>
</tr>
<tr>
<td>3/8” CA</td>
<td>1580</td>
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<tr>
<td>Fine Agg</td>
<td>1245</td>
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<tr>
<td>Water/Ice</td>
<td>235</td>
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<td>HRWR</td>
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<tr>
<td>VMA</td>
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<tr>
<td>Polycarboxylate</td>
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Water/Cementitious Ratio = 0.25

Density = 156 pcf
High Strength Concrete – Site Testing for f’c

Jeddah Tower C85 Concrete Compressive Strength: Aggregate Comparison
High Strength Concrete – Site Testing for MOE
Bayesian Statistical Analysis

Creep Calibration

\[ J(t, t_0), 10^{-6} \text{in/in/psi} \]

- Test Data Used In Regression
- Prediction w/ Strength Test Only
- Max 95% Confidence w/ Str Test Only
- Min 95% Confidence w/ Str Test Only
- Classical Prediction
- Bayesian Prediction
- Bayesian Max 95% Confidence
- Bayesian Min 95% Confidence

\[ t - t_0, \text{days} \]
Construction Guidelines & Monitoring

Kingdom Tower

*PreConstruction Testing Program

*Full Construction Concrete Testing Program
  - Modulus
  - Strength
  - Creep

*Surveying/Monitoring Requirements

*Reporting

*Compensation Instructions
  - Vertical
  - Horizontal

*Assumed Sequence of Construction
Kingdom Tower-Staging Assumptions

- CORE CONSTRUCTED FIRST
- WINGS ONE STAGE BEHIND
- SLABS TWO STAGES BEHIND

Representative Stages - Construction Sequence
Results – Kingdom Tower

Wall Stress vs. Time

Wall Stress vs Time
Wing A End Wall - Midas Element #78692 - Level CON

- Red: Dead Load
- Green: Live Load
- Purple: Creep
- Blue: Shrinkage
- Blue: Total

Effect of Creep & Shrinkage may redistribute load over time
Results – Kingdom Tower

Horizontal Displacement

**At End of Construction**

- Static (ETABS)
- Staged (Midas)

**At 10 Years**

- Total
- Dead Load
- Creep
- Shrinkage
- Static
Construction – January 2014
Construction – February 2014
Mat Concrete

- \( f'c = 60 \text{ MPa} \) (8,700 psi) at 56d
- MOE = No requirement
- Mix: Self-Consolidating Concrete

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<th>Material</th>
<th>Quantity</th>
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<td>SF</td>
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<td>PFA</td>
<td>305 lb</td>
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<td>1/2,3/8” CA</td>
<td>1440 lb</td>
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<tr>
<td>Fine Agg</td>
<td>1390 lb</td>
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<td>Water/Ice</td>
<td>250 lb</td>
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<td>HRWR</td>
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<td>VMA</td>
<td>Polycarboxylate</td>
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Mat Foundation – Steel Fixing

Foundation of *Wing B*: Steel reinforcement works

19-03-2014
Tower Mat Formwork
Tower Mat Concrete Pour
Mat Foundation – Insulation / Curing
Construction Progress
Sequence of Construction
Wing/Corridor Wall Formwork
October 2019
Progress:

- Height 265m
- Exterior Wall Installation Commenced
- First Column Setback Reached
- ~40% Concrete placed