Aquablue at the Golden Mile

Hato Rey, Puerto Rico

General Building Information
Proposal and Project Goals
Proposed Shear Wall Design
Lateral Design Loads
ETABS Model
Drift Analysis
Coupling Beam Feasibility Test
Final Shear Wall Design
Impact on Existing Foundation
Architectural Breadth Study
Conclusions
### General Building Information

<table>
<thead>
<tr>
<th>Building Facts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 7-story parking structure + luxury apartments</td>
</tr>
<tr>
<td>• 900,000 ft²</td>
</tr>
<tr>
<td>• 31 stories above grade</td>
</tr>
<tr>
<td>• total height = 276’</td>
</tr>
<tr>
<td>• approximate plan dimensions = 120’ x 490’</td>
</tr>
<tr>
<td>• Construction dates: February 2007 – August 2009</td>
</tr>
<tr>
<td>• Structural Engineer: DeSimone Consulting Engineers</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Existing Structural System:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• foundation – drilled piles beneath 10” concrete slab</td>
</tr>
<tr>
<td>• gravity system – two-way, post-tensioned slabs</td>
</tr>
<tr>
<td>• lateral system – 18” concrete shear walls</td>
</tr>
<tr>
<td>• 5” seismic joint</td>
</tr>
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**Building Facts:**
- 7-story parking structure + luxury apartments
- 900,000 ft²
- 31 stories above grade
- total height = 276’
- approximate plan dimensions = 120’ x 490’
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**Existent Structural System:**
- foundation – drilled piles beneath 10” concrete slab
- gravity system – two-way, post-tensioned slabs
- lateral system – 18” concrete shear walls
- 5” seismic joint
Aquablue at the Golden Mile

Parking Garage Level
- 51,900 ft²
- plan dimensions = 120' x 490'

Apartment Towers
- 11,600 ft² and 14,500 ft²
- plan dimensions = 90' x 160' and 90' x 200'

Typical Floor Plans
### Existing Shear Wall Design

#### Features of Shear Walls:
- $f'_c = 8000$ psi up to level 13
- $f'_c = 6000$ psi above level 13
- Detailed integration of shear wall segments
- Intricate construction process

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**Aquablue at the Golden Mile**

- **Hato Rey, Puerto Rico**
Codes and References used for this design project:

- ACI 318-08 (American Concrete Institute)
- ASCE 7-05 (American Society of Civil Engineering)
- IBC 2006 (International Building Code)
- ETABS Nonlinear v9.2.0 (Computers and Structures, Inc.)
- pcaColumn v3.64 (Portland Cement Association)
Overview of Project Proposal:

- Lateral force analysis
- Shear wall and coupling beam re-design
- Reinforcement design
- ETABS and pcaColumn analysis
- Architectural breadth study
- Construction Management breadth study

Project Goals:

- Detailed analysis of lateral loads
- Concrete shear wall design (ACI 318-08 building code)
- Computer modeling as a means of structural analysis
- Architectural impact of structural design
Proposed Shear Wall Design

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Ideas for Shear Wall Re-design:
- Two I-shaped shear walls with connecting coupling beams
- More regular and efficient shape
- Minor architectural impact
- Hand calculations + computer modeling for analysis
- Reinforcement design
- Focus on the core of one tower

Preliminary Sketch (N.T.S.)
Aquablue at the Golden Mile

Wind Analysis:
- ASCE 7-05 (Chapter 6)
- Analytical Procedure (Method 2)
- Basic Wind Speed, $V = 145$ mph
- Importance Factor, $I = 1.0$
- Exposure Category = B
- Special Wind Cases

Seismic Analysis:
- ASCE 7-05 (Chapters 11 and 12)
- Equivalent Lateral Force Procedure
- Importance Factor, $I = 1.0$
- Seismic Design Category = D
- Response Modification Coefficient, $R = 6$
- Fundamental Period, $T = 2.031$
- Seismic Response Coefficient, $C_s = 0.0165$
Lateral Design Loads

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Factored Story Shears for NS Direction
Factored Story Shears for EW Direction

Story Shear Forces
**Preliminary Shear Wall Thicknesses**

<table>
<thead>
<tr>
<th>Location</th>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
<th>SW4</th>
<th>SW5</th>
<th>SW6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>25'9&quot;</td>
<td>25'9&quot;</td>
<td>16'0&quot;</td>
<td>16'0&quot;</td>
<td>31'9&quot;</td>
<td>31'9&quot;</td>
</tr>
<tr>
<td>Coupling Beam</td>
<td>CB1</td>
<td>CB2</td>
<td>CB1</td>
<td>CB2</td>
<td>CB1</td>
<td>CB2</td>
</tr>
</tbody>
</table>

Equation variables:
- \( t \) = wall thickness (in)
- \( \rho \) = fraction of story shear force
- \( V_x \) = total factored shear force
- \( \phi = 0.75 \) for wind, \( \phi = 0.60 \) for seismic
- \( f'_c \) = approximate shear stress of the wall
- \( l_w \) = length of the wall (in)
ETABS Model

Design Assumptions:

- Same concrete strength as original building
- ‘User-defined’ loads
- Rigid floor diaphragms with assigned masses
- Meshed walls with 0.7 multiplier for moment of inertia
- 18” wide x 19.5” deep coupling beams with reduced moment of inertia

Impact on Existing Foundation

Seismic Joint

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Hato Rey, Puerto Rico
Final Shear Wall Thicknesses:

- 18” – 30” thickness
- (2) 18” thick walls added through parking levels

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Check for horizontal structural irregularity:
- Extreme torsional irregularity
- Torsional amplification factor, $A_x = 1.46$
- Accidental eccentricity ratio = 0.073

Drift limitations:
- \( \frac{L}{400} \) for wind loads (0.70W permitted by section CC.1.2 of ASCE 7-05)
- 0.020\( h \) for seismic loads
- Deflection amplification factor, $C_d = 5$ (seismic drifts)
- Drifts within the required limits
- Maximum drift at level 7 = 1.06" (assumed that seismic joint is adequate)
Drift Analysis

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Drift Analysis for Wind

Drift Analysis for Earthquake

Drift at Each Level

Impact on Existing Foundation

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Drift Analysis for Wind

Drift at Each Level

Impact on Existing Foundation

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Drift Analysis for Earthquake

Drift at Each Level

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Drift Analysis for Wind

Drift at Each Level

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Drift Analysis for Earthquake

Drift at Each Level

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Drift Analysis for Wind

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Drift Analysis for Earthquake

Drift at Each Level

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Drift Analysis for Wind

Drift at Each Level

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Drift Analysis for Earthquake

Drift at Each Level

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Drift Analysis for Wind

Drift at Each Level

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Drift Analysis for Earthquake

Drift at Each Level

Impact on Existing Foundation

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Drift Analysis for Wind

Drift at Each Level

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Drift Analysis for Earthquake

Drift at Each Level

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Drift Analysis

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Coupling Beam Feasibility Test

Equation variables:
- \( V_u \): factored shear force in the beam
- \( 1.2D + 0.5L + 1.6W \)
- \( 0.9D + 1.6W \)
- \( 1.32D + 0.5L + 1.0E \)
- \( 0.78D + 1.0E \)
- \( \lambda = 1 \) (normal weight concrete)
- \( A_{cw} \): cross-sectional area of the beam

Results:
- Diagonal reinforcement is not required
- Beam depths are feasible
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CB1 Shear Stresses (Wind)

CB1 Shear Stresses (Seismic)
Aquablu at the Golden Mile

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CB2 Shear Stresses (Wind)

CB2 Shear Stresses (Seismic)
Aquablue at the Golden Mile

Hato Rey,
Puerto Rico

Design process:
- Preliminary design according to seismic provisions of ACI 318-08, chapter 21
- Reinforcement checked for wind loads using ACI 318-08, chapter 11
- (2) curtains for both transverse and longitudinal reinforcement

Transverse (horizontal) Longitudinal (vertical)

<table>
<thead>
<tr>
<th>Level</th>
<th>Transverse</th>
<th>Longitudinal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to sky lobby</td>
<td>(2) #5 @ 12&quot;</td>
<td>(2) #5 @ 10&quot;</td>
</tr>
<tr>
<td>4 to 13</td>
<td>(2) #5 @ 9&quot;</td>
<td>(2) #5 @ 8&quot;</td>
</tr>
<tr>
<td>2 to 3</td>
<td>(2) #7 @ 9&quot;</td>
<td>(2) #7 @ 8&quot;</td>
</tr>
<tr>
<td>SW3 and SW4</td>
<td>Transverse</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>2 to sky lobby</td>
<td>(2) #5 @ 12&quot;</td>
<td>(2) #5 @ 12&quot;</td>
</tr>
<tr>
<td>SW5 and SW6</td>
<td>Transverse</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>16 to 19</td>
<td>(2) #5 @ 8&quot;</td>
<td>(2) #5 @ 6&quot;</td>
</tr>
<tr>
<td>2 to 15</td>
<td>(2) #7 @ 8&quot;</td>
<td>(2) #7 @ 6&quot;</td>
</tr>
</tbody>
</table>
Check in pcaColumn:

- Shear wall design checked in pcaColumn for level 9
- #5 bars at either 8" or 12" spacing
- #9 bars for the boundary elements
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Biaxial moment interaction diagrams

P = 1983 kip

P = 3898 kip
Coupling Beam Reinforcement

Longitudinal reinforcement design:

- Minimum steel area from chapters 10 and 21 of ACI 318-08
- Area of steel for 6 ksi strength concrete:
  \[ A_p = \frac{M}{4.17f_{y}} \]
- Area of steel for 8 ksi strength concrete:
  \[ A_p = \frac{M}{4.25f_{y}} \]
- Generally, (6) – (10) #7 bars at both the top and bottom of the beams sufficed
- Reinforcement ratio below 0.025 (acceptable)

<table>
<thead>
<tr>
<th>Level</th>
<th>Required Reinforcement (top and bottom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 9</td>
<td>(10) #7</td>
</tr>
<tr>
<td>1 to 8</td>
<td>(8) #7</td>
</tr>
<tr>
<td>1 to 7</td>
<td>(6) #7</td>
</tr>
<tr>
<td>1 to 6</td>
<td>(4) #7</td>
</tr>
<tr>
<td>1 to 4</td>
<td>(2) #7</td>
</tr>
<tr>
<td>2</td>
<td>(2) #7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level</th>
<th>Required Reinforcement (top and bottom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 to roof level</td>
<td>(8) #7</td>
</tr>
<tr>
<td>6 to 10</td>
<td>(6) #7</td>
</tr>
<tr>
<td>3 to 5</td>
<td>(4) #7</td>
</tr>
<tr>
<td>2</td>
<td>(2) #7</td>
</tr>
</tbody>
</table>
Stirrup reinforcement design:

- Shear capacity of concrete neglected
- Required steel area determined by chapters 11 and 21 of ACI 318-08
- (3) – (4) legs of #3 stirrups in each beam
- 2" spacing at supports
- 4" spacing throughout beam
Impact on Existing Foundation

General Building Information
- Original foundation:
  - Drilled compression piles (147) and drilled tension piles (23)
  - Compression capacity = 200 tons (170 total piles)
  - Lateral capacity = 20 tons (170 total piles)
  - Tension capacity = 40 tons (23 tension piles)
  - Mat slab under group of columns and shear walls

Proposal and Project Goals
- Wind and seismic design loads
- ETABS model
- Drift analysis
- Coupling beam feasibility test
- Final shear wall design

Proposed Shear Wall Design
- Base shear analysis
  - Maximum factored base shear determined
  - Force converted to number of required piles
  - No change necessary for existing design

Lateral Design Loads
- Wind cases:
  - Case 1a: 0.8 k, 1961.8 ktons
  - Case 1b: 2951.6 ktons
  - Case 2a: 151.9 ktons, 1472.4 ktons
  - Case 2b: 2183.1 ktons
  - Case 3: 1510.9 ktons, 1454.1 ktons
  - Case 4: 1630.9 ktons, 1102.0 ktons
- Seismic loads:
  - NS: 9.7 ktons, 932.1 ktons
  - EW: 540.7 ktons, 75.9 ktons

Lateral Design Loads
- Total shear (tons):
  - Case 1a: 1475.8 ktons
  - Case 1b: 980.9 ktons

ETABS Model
- Drift analysis
- Coupling beam feasibility test
- Final shear wall design

Drift Analysis
- Coupling beam feasibility test
- Final shear wall design

Conclusions
- No change necessary for existing design

Base Shear Analysis

Aquablue at the Golden Mile
- Hato Rey, Puerto Rico
Impact on Existing Foundation

Analysis of tension capacity:
- Maximum factored overturning moment determined
- Moment divided by wall length for tension force at extreme fiber
- Force converted to number of required piles
- Approximately 33 required piles unnecessary due to gravity load effects
- 56 piles still required (convert 33 compression piles to tension piles)

<table>
<thead>
<tr>
<th>Wind Case</th>
<th>Base Moment (k-ft)</th>
<th>Tension Force (k)</th>
<th>Tension Force (tons)</th>
<th>Number of Required Piles</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>183657.6</td>
<td>7922.7</td>
<td>3546.4</td>
<td>88.7</td>
</tr>
<tr>
<td>3b</td>
<td>33449.4</td>
<td>1295.1</td>
<td>647.6</td>
<td>16.2</td>
</tr>
<tr>
<td>3a</td>
<td>136919.1</td>
<td>5317.2</td>
<td>2658.6</td>
<td>66.5</td>
</tr>
<tr>
<td>3b</td>
<td>23847.2</td>
<td>926.1</td>
<td>463.1</td>
<td>11.6</td>
</tr>
<tr>
<td>3</td>
<td>183866.3</td>
<td>5273.4</td>
<td>2686.7</td>
<td>67.2</td>
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<tr>
<td>4</td>
<td>103412.1</td>
<td>4068.2</td>
<td>2034.1</td>
<td>50.2</td>
</tr>
<tr>
<td>Seismic - NS</td>
<td>35783.5</td>
<td>1788.3</td>
<td>847.3</td>
<td>47.0</td>
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<tr>
<td>Seismic - EW</td>
<td>8810.0</td>
<td>438.9</td>
<td>173.4</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Overturning Analysis

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Hato Rey, Puerto Rico
Impact of New Shear Wall Design on the Existing Architecture:

- Elimination of two columns of existing windows
- More narrow bedroom windows

**Aquablue at the Golden Mile**

Hato Rey, Puerto Rico

**New Shear Wall Design**

**Existing Shear Wall Design**

Windows to be removed
Impact of New Shear Wall Design on the Existing Architecture:

- Elimination of two columns of existing windows
Impact of New Shear Wall Design on the Existing Architecture:

- Additional Floor Space

<table>
<thead>
<tr>
<th>Level</th>
<th>Original Shear Wall Design</th>
<th>New Shear Wall Design</th>
<th>Floor Area Gained in New Design (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky Lobby</td>
<td>4.47</td>
<td>4.56</td>
<td>-4.0</td>
</tr>
<tr>
<td>17 - Roof</td>
<td>1.75</td>
<td>1.60</td>
<td>20.8</td>
</tr>
<tr>
<td>14 - 16</td>
<td>2.14</td>
<td>2.23</td>
<td>-10.0</td>
</tr>
<tr>
<td>8 – 13</td>
<td>2.14</td>
<td>2.45</td>
<td>-34.8</td>
</tr>
<tr>
<td>3 – 7</td>
<td>1.88</td>
<td>1.72</td>
<td>38.6</td>
</tr>
<tr>
<td>2</td>
<td>2.08</td>
<td>1.72</td>
<td>83.9</td>
</tr>
</tbody>
</table>

Aquablue at the Golden Mile

Impact on Existing Foundation:

- Additional Floor Space
The project was a success because the initial goals were met and valuable design experience was gained:

- Completion of lateral analysis
- Familiarity with the ACI 318-08 design code
- Use of ETABS for modeling purposes
- Study of architectural impact

Opportunity for further study – Dynamic analysis of the structure
The following people need to be recognized for their assistance in the completion of this senior thesis project. Collectively, they provided technical expertise, general engineering consulting, patience and support throughout the year.

- Dr. Andres Lepage (structural advisor)
- Professor Kevin Parfitt (general thesis advisor)
- Professor Robert Holland (general thesis advisor)
- Anh Trong Nguyen (project structural engineer)
- Architectural Engineering Peers
- Family and Friends