Structural optimization of high-rise commercial buildings using high performance Q690 to Q960 steel materials

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Outline of Presentation

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   1.2 Challenges and Research Motivations
   1.3 Scope and Objectives of Current Study
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   2.3 Lateral Load Resisting System
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Background
Global Trend of Tall Building Construction

Countries
➢ China and U.S.A. are the two countries with the largest numbers of tall buildings.
➢ Before 1990s, U.S.A. led the number of tall buildings built.
➢ Since 2000s, China surpassed the U.S. and became the country with the most tall buildings.

Cities
➢ Hong Kong, New York City and Dubai are the top three cities in term of the number of tall buildings.
➢ The number of tall buildings in these developed cities are only steadily increased.
➢ Meanwhile, the total number of tall buildings increased in developing cities, particularly in China and Asia, due to urbanization.
Background
Challenges and Research Motivation

CHALLENGES
➢ Increasing height and number

➢ BUT additional COST of increasing height is not linear.

Current Practice (HK/China/Asia)
Concrete construction
➢ Local practice
➢ Material availability
➢ Good cost-strength ratio

Composite and Steel Construction?
➢ Utilize material choice (concrete vs steel)
➢ Faster Erection
➢ Lighter
➢ Prefabricated
➢ Small member members
➢ Tensile Slim and Lighter

Is the approach effective in both COST and TIME?

Cost Effective?
Time Saving?
Practical Construction?
Aesthetic?
Scope and Objective of Current Study

Objective of current study

• To maximize the benefits of composite and steel construction
• To investigate the potential applications of high strength steel material

Scope of current study

• Effective structural forms and layouts
  • Compare popular structural forms (lateral load resisting systems)
  • Investigate structural layouts
• Element sizing structural cost optimisation
  • Predefined Structural Systems
  • Design variables: element sizes and type
• Cost effectiveness comparisons
  • Material choices
  • Element design
  • Construction
# Representative Projects

## Engineering and Optimisation Projects

- Samsung Tower Palace III (79 storey building) in South Korea
  - One of representative buildings listed in *Outrigger Design Technical Guide (2017)*

## Notable Projects

<table>
<thead>
<tr>
<th>Notable Projects</th>
<th>Building Height</th>
<th>Construction Material</th>
<th>Structural Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kowloon Mega Tower</td>
<td>474 m</td>
<td>Composite Steel and Concrete</td>
<td>Outrigger Braced System</td>
</tr>
<tr>
<td>Two International Finance Center</td>
<td>420 m</td>
<td>Composite Steel and Concrete</td>
<td>Outrigger Braced System</td>
</tr>
<tr>
<td>URA Project K11, Tsimshatsui</td>
<td>274 m</td>
<td>Composite Steel and Concrete</td>
<td>Outrigger Braced System</td>
</tr>
<tr>
<td>Sorrento Tower 1</td>
<td>255 m</td>
<td>Concrete</td>
<td>Coupled Shear Wall and Frame</td>
</tr>
<tr>
<td>The Harbourside Development</td>
<td>242 m</td>
<td>Concrete</td>
<td>Coupled Shear Wall and Frame</td>
</tr>
<tr>
<td>(3 towers)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Victory Arch Development</td>
<td>230 m</td>
<td>Concrete</td>
<td>Coupled Shear Wall and Frame</td>
</tr>
<tr>
<td>(2 towers)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park Central Development</td>
<td>173 m</td>
<td>Concrete</td>
<td>Coupled Shear Wall and Frame</td>
</tr>
<tr>
<td>(10 towers)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge House Development</td>
<td>161 m</td>
<td>Composite Steel and Concrete</td>
<td>Outrigger Braced System</td>
</tr>
<tr>
<td>Housing Authority Standard Housing Blocks (Harmony, Concord and New Cruciform Blocks)</td>
<td>125 m</td>
<td>Concrete</td>
<td>Coupled Shear Wall</td>
</tr>
</tbody>
</table>

Source: Keynote paper “Advances in Structural Optimization of tall Buildings in Hong Kong” at Third China-Japan-Korea Joint Symposium
# Implementation Plans

## 1) Research Studies

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
</table>
| Phase A | **Analyze the potential applications** of composite construction and high strength steel to define the main scope of works.**  
InVESTIGATE the cost efficiency of high strength steel applications for tall buildings in Hong Kong. | Complete       |
| Phase B | **Quantify and validate the cost efficiency** of steel and composite structural system | In-Progress    |
| Phase C | **Develop an optimization platform** to quantify and utilize the application of high strength steel material and composite construction | In-Progress    |

## 2) Publications

<p>| | |</p>
<table>
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<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td><strong>Publish a technical guide “Structural Optimization on Design of Tall Buildings”</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Summarize the results and recommendations in a technical conference paper.</strong></td>
</tr>
</tbody>
</table>
Case Studies (IFC2)
Structural Systems using Composite or Steel Construction

Lateral Load Resisting System
- Tall buildings are slender structures, whose design are governed by wind loads and effects.
- Wind deflection is stiffness-control.
- High strength steel (e.g. S690, S960) has no advantage over normal strength steel due to the same Modulus of Elasticity (E).

Gravity Load System
- Members are designed based on gravity loads only.
- Members may be strength-control if the serviceability requirements (e.g. beam deflection) are met.

Example
Outrigger System for wind load resistance

Composite Floor System

Second Tallest Building in Hong Kong
Height = 420m
No of stories = 88
Structural System = Outrigger systems
Choosing Structural Systems
- Effective Lateral Load Resisting Systems
- Stiffness-control members vs Strength-control members

Lateral Load Resisting System

Gravity Load System

Approaches
- Perform optimization to determine the choices of Lateral Load Resisting Systems
- Utilize the advantages of smaller steel or composite sections
- Design for lighter structures

Approaches
- Utilize the strength advantages of High Strength Steel material.
- Provide composite elements (e.g. columns) to replace concrete elements.
## Summary

### Cost Assumption

**Assumptions**

- **Construction Cost**

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit Value (HK$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete (including reinforcement and formwork)</td>
<td></td>
</tr>
<tr>
<td>Grade C45</td>
<td>HK$ 3,000/m³</td>
</tr>
<tr>
<td>Grade C60</td>
<td>HK$ 3,500/m³</td>
</tr>
<tr>
<td>Structural Steel</td>
<td></td>
</tr>
<tr>
<td>Grade S355</td>
<td>HK$ 11,000 / tonne</td>
</tr>
<tr>
<td>Grace S690</td>
<td>HK$ 12,500 / tonne</td>
</tr>
<tr>
<td>Grade S960</td>
<td>HK$ 14,000 / tonne</td>
</tr>
</tbody>
</table>

- **Floor Area Saving #**

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit Value (HK$)</th>
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</thead>
<tbody>
<tr>
<td>Office Floor Rental</td>
<td>HK$ 4,700 / ft²</td>
</tr>
<tr>
<td></td>
<td>(HK$ 50,600 / m²)</td>
</tr>
</tbody>
</table>
Floor System

Structural Optimisation

- After the study of different buildings, the cost savings of floor system potentially leads to 10-15% savings by using high strength steel material.
Floor System

Upper Zone (65/F – 89/F)

Lower Zone (9/F – 64/F)
## Lateral Load Resisting System

<table>
<thead>
<tr>
<th>Floor Zone</th>
<th>Type</th>
<th>Area (cm²)</th>
<th>for Strength</th>
<th>for Stiffness</th>
<th>for Stiffness</th>
<th>x times</th>
</tr>
</thead>
<tbody>
<tr>
<td>67-77</td>
<td>Q</td>
<td>Typical</td>
<td>1783</td>
<td>7166</td>
<td>5383</td>
<td>4.02</td>
</tr>
<tr>
<td>64-67</td>
<td>P</td>
<td>Outrigger</td>
<td>1831</td>
<td>6617</td>
<td>4786</td>
<td>3.61</td>
</tr>
<tr>
<td>57-64</td>
<td>N</td>
<td>Typical</td>
<td>2382</td>
<td>7060</td>
<td>4678</td>
<td>2.96</td>
</tr>
<tr>
<td>55-57</td>
<td>M</td>
<td></td>
<td>3264</td>
<td>11586</td>
<td>8322</td>
<td>3.55</td>
</tr>
<tr>
<td>52-R3</td>
<td>K</td>
<td></td>
<td>3465</td>
<td>9153</td>
<td>8088</td>
<td>3.00</td>
</tr>
<tr>
<td>47-52</td>
<td>J</td>
<td>Typical</td>
<td>3854</td>
<td>11530</td>
<td>7676</td>
<td>2.99</td>
</tr>
<tr>
<td>36-37</td>
<td>H</td>
<td>Typical</td>
<td>4789</td>
<td>13730</td>
<td>8584</td>
<td>3.09</td>
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<tr>
<td>33-35</td>
<td>F</td>
<td></td>
<td>5838</td>
<td>17876</td>
<td>12039</td>
<td>3.06</td>
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<td>R2-33</td>
<td>E</td>
<td>Outrigger</td>
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<td>11284</td>
<td>3.09</td>
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<tr>
<td>30-31</td>
<td>D</td>
<td>Typical</td>
<td>6638</td>
<td>17681</td>
<td>11042</td>
<td>2.66</td>
</tr>
<tr>
<td>09-21</td>
<td>B</td>
<td>Typical</td>
<td>6894</td>
<td>17910</td>
<td>11016</td>
<td>2.60</td>
</tr>
<tr>
<td>04-09</td>
<td>A</td>
<td></td>
<td>7594</td>
<td>19410</td>
<td>12676</td>
<td>3.00</td>
</tr>
</tbody>
</table>
## Concluding Remarks
### Cost Breakdown Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Normalized cost summary (IFC2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original (Normalized as 100%)</td>
</tr>
<tr>
<td>Structural System</td>
<td>Composite outrigger structure</td>
</tr>
<tr>
<td>Column Sizes</td>
<td>100%</td>
</tr>
<tr>
<td>Total “Cost” Benefits</td>
<td>100%</td>
</tr>
</tbody>
</table>
Prototype Study
Building Information and Setup

Floor Plan (Composite Floor System)

Outer Core:
- Typical Floor (60 m x 60 m)
  - Dead Load = 3.1 kPa
  - SDL = 1.6 kPa
  - Live Load = 3 kPa
- Mechanical Floor
  - Dead Load = 3.7 kPa
  - SDL = 1.6 kPa
  - Live Load = 7.5 kPa

Inner Core:
- All Floor (30 m x 30 m)
  - Dead Load = 3.1 kPa
  - SDL = 2.5 kPa
  - Live Load = 5 kPa

Elevation (Mega Braced System)
- Typical floor height = 4.167 m
- Mechanical floor
  - Occupy 3 stories
  - Located at every 32 floor

<table>
<thead>
<tr>
<th>Height</th>
<th>No. of Floors</th>
</tr>
</thead>
<tbody>
<tr>
<td>267m</td>
<td>64</td>
</tr>
<tr>
<td>333m</td>
<td>80</td>
</tr>
<tr>
<td>400m</td>
<td>96</td>
</tr>
<tr>
<td>467m</td>
<td>112</td>
</tr>
<tr>
<td>533m</td>
<td>128</td>
</tr>
</tbody>
</table>
Choice of Lateral Load Resisting System

Popular choices

- Shear Wall System
- Mega Braced Frame System
- Tubular System
- Outrigger System
  - Good Balance of Usage and Design

Current Study (for effective system)

- Mega Braced Frame System + Interior Gravity Systems
  - Known as one of the most effective systems to resist wind loads
    - Minimize the material cost for stiffness control members
    - Maximize the strength-control member applications
  - Composite or Steel Columns are used to minimize column sizes
  - Columns are heavily loaded as gravity columns to maximize the benefits of high strength steel.
Summary
Cost Breakdown (In Progress)

Mega Braced System

- Grouping by Member Types (with levels)
  - Designation example (C1_L0108 represents “C1” members from Level 01 to Level 08)
  - Columns (C1 typical, C2, etc.)
  - Beams (B1 typical, B2, etc.)
  - Bracing (X1 typical, X2, etc.)

- Cost Breakdown (minimum information)
  - No of members
  - Member size (weight)
  - Total weight (per group)
  - Total weight (per type)
    - Pie Chart (e.g. Column ~ 30% weight)
  - Bar chart