Designing and Constructing Tall Buildings for Higher Cost Effectiveness and Performance

Dr. Naveed Anwar
Tall Buildings – The Need
Percentage of Urbanized World

Rate of Urban Population Growth

URBAN GROWTH,
2000-2005
Average Annual Rate of
Change of the Urban
Population

- Extreme: 5% or more
- High: 4% to less than 5%
- Medium: 1% to less than 4%
- Low: less than 1%

www.globalchange.umich.edu
World’s Population Urban-to-Rural Ratio

(www.un.org)
Urbanization - Future Trends

Source: www.globalchange.umich.edu
Urbanization → Growing Needs for built-up space
Why Tall Buildings?

Single Family Dwelling
(Accommodating 10 Families)

Versus

A 40 story Tall Building on
almost same area
(Accommodating up to 200 Families)
The Case of London
Sky City (Changsha, China)

- **Height**: 838 m
- **Floor count**: 220 total

*Construction to be done in 7 months*
Systems and Components
Building Systems

• Building is an assemblage of various Systems
  – Basic Functional Systems and Architecture
  – Structural Systems
  – Vertical Transport Systems - Elevators
  – HVAC Systems
  – Plumbing and Drainage Systems
  – Electrical, Electronic and Communication Systems
  – Foundations Systems
  – Fire Safety Systems
  – Cladding Systems
  – Security Systems
  – Other specialized systems
The Professionals Involved

- Architects – Team Leader
- Structural Engineers
- Geotechnical Engineers
- Electrical and Electronic Engineers
- Mechanical Engineers
- Plumbing Engineers
- Construction Engineers
- Communication Engineers
- Landscape Architects
- Fire Safety Engineers
- Security Consultants
Conventional Systems

Evolution of Structural Systems
### Range of Structural Systems

#### Structural systems for concrete buildings

<table>
<thead>
<tr>
<th>No.</th>
<th>System</th>
<th>Number of stories</th>
<th>Ultra-tall buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat slab and columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Flat slab and shear walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Flat slab, shear walls and columns</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td>Coupled shear walls and beams</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>Rigid frame</td>
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<td></td>
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<tr>
<td>6</td>
<td>Widely spaced perimeter tube</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>Rigid frame with haunch girders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Core supported structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Shear wall—frame</td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>Shear wall—Haunch girder frame</td>
<td></td>
<td></td>
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<tr>
<td>11</td>
<td>Closely spaced perimeter tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Perimeter tube and interior core walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Exterior diagonal tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Modular tubes, and spine wall systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>with outrigger and belt walls</td>
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</tbody>
</table>
The Diagrid System
BRB Based Systems
BRB Based Building - Manila

- Located in Makati City, Philippines
- 50-story + 3½ - story below grade parking
- Total height of 166.8 m above ground level
Innovative Building

Doha Tower, Qatar
CTBUH Best Tall Building Award 2012

KfW Westarkade, Frankfurt
CTBUH Best Tall Building Award 2011

Burj Khalifa, Dubai
CTBUH best Tall Building Award 2010
Innovative Buildings

Linked Hybrid, Beijing
CTBUH best Tall Building Award 2009

Shanghai World Financial Center, China
CTBUH best Tall Building Award 2008

The Beetham Hilton Tower, Manchester, UK
CTBUH best Tall Building Award 2007
Structural System Selection

- Multi and Interdisciplinary process
- Fuzzy Logic
- Expert Systems (ES)
- Value Engineering
- Blackboard Approach
- Rich Pictures
- Analytic Hierarchy Process (AHP)
• The Analytical Hierarchy Process (AHP)
  – A weighted importance and suitability value analysis to determine the comparative value of a system or option

Value of an Option

\[
V_l = \sum_{i=1}^{m} A_i S_i \left( \sum_{j=1}^{n} B_{ij} S_{ij} \sum_{k=1}^{p} C_{ijkl} S_{ijk} \right)
\]
Cost and Performance
The Cost Issues

What is Project Cost?

How are Project Cost and Design Related?

What Factors effect the Cost?

How to Reduce the Cost?

How Performance and Cost are inter-related?
What is the Cost of a Project?

- Cost may include:
  - Financial Cost (loan, interest, etc)
  - Planning and Design Cost
  - Direct Construction Cost
  - Maintenance Cost
  - Incidental Cost
  - Liquidated Cost (lost profit etc)
  - Opportunistic Cost
  - Environmental Cost
  - Emotional Cost
  - Non-determinist Resources

Cost may be:
“Consumption of Particular Resources, at Particular Time”

Sustainability may be:
<Consumption of all resources, and their impacts through throughout the life cycle>
Sustainable buildings need sustainable design, sustainable certification and sustainable regulation.

Sustainable buildings are quality buildings with low energy requirements.

Sustainable buildings are healthy buildings, avoiding toxic materials and offering control to their occupants.

Sustainable buildings are built to last - with the next generation in mind.

SESSION 3: What Makes Buildings Green and Sustainable? Dr. Brahmanand Mohanty
The general belief: Increased Performance → Increased Cost

- Increased performance can be achieved for the same cost
- Need not be true

- Reduced cost for the same performance
- Improved/efficient designs

- Needs Knowledge, innovation, better tools, better technology, critical thinking, out-of-the-box solutions

- Easy
Cost and Performance

• **Enhancement of Performance**
  - Dynamic response parameters
  - Lateral load response
  - Vertical load response
  - Demand and capacity ratios
  - Response irregularity, discontinuity
  - Explicit Performance Evaluation at Service, DBE and MCE

• **Cost Effectiveness**
  - Capacity utilization ratio
  - Reinforcement ratios
  - Reinforcement volume ratios
  - Concrete strength and quantity
  - Rebar quantity
  - Constructability, time and accommodation of other constraints
Optimization

- Need to define What to optimize? And what are the parameters that can be changes?
- Optimizing one or two items may “un-optimize” others
- Optimizing everything is a “Holy Grail”
  - … and “Holy Grail” doesn't exist
- Tools
  - Genetic Algorithms (GA)
  - Artificial Neural Networks (ANN)
  - Linear and Nonlinear programing
Levels of Optimization

- **Micro-Micro Level**: One part of a component, “Steel”
- **Micro Level**: One Component, “Column”
- **Local**: One part or aspect
- **Global**: Entire Problem, Project
- **Universal**: Entire System
Local Vs Global Optimization

- Simple Example of a Column Stack – What and how can we optimize?
  - Concrete Strength
  - Steel Strength
  - Column Size
  - Rebar Amount
  - Composite Section

- Material Cost, Labor Cost, Formwork Cost, Management and operations Cost, Time ??
Cost Effectiveness > Utilization Ratio

- **Utilization Ratio**
  - Compare, What is Needed against What is Required

- **One measure**
  - The Demand/ Capacity Ratio (D/C)

<table>
<thead>
<tr>
<th>Demand/ Capacity</th>
<th>Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
</tr>
<tr>
<td>D/C&lt;0.5</td>
<td>178</td>
</tr>
<tr>
<td>0.5&lt;D/C&lt;0.7</td>
<td>534</td>
</tr>
<tr>
<td>0.7&lt;D/C&lt;1</td>
<td>346</td>
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<tr>
<td>1&lt;D/C&lt;1.5</td>
<td>30</td>
</tr>
<tr>
<td>1.5&lt;D/C&lt;2.5</td>
<td>12</td>
</tr>
<tr>
<td>D/C&gt;2.5</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>1100</td>
</tr>
</tbody>
</table>
Cost and Performance

- **Base Cost and Performance**
- **Increased Performance, Same Cost**
- **Reduced Cost for Same Performance**

![Graph showing cost and performance relationships]

(A folded structure on the left with a grid pattern. On the right, a graph with axes labeled P and M, depicting different cost and performance scenarios. The graph includes annotations for increased performance, same cost, and reduced cost for same performance.)
Cost and Time

• Time, Cost and Performance need to be balanced
• Time can be “Cost”

• How to reduce construction time
  – Automation
  – Reducing no. of components
  – Prefabrication
  – Innovative structural systems
  – Innovative construction process and management
Technology

- Technology is a broad term and may include
  - Data, Information and Knowledge
  - Understanding of Knowledge
  - Application of Knowledge
  - Techniques for application of knowledge
  - Tools for applications
  - Ability to use the right tools for the right application
  - Finding Innovative, out of the box solutions
Technology

• **Knowledge**
  – Academic knowledge
  – Research outcome
  – Design Codes and Guidelines

• **Techniques and Tools**
  – System Development, Selection
  – Modeling, Analysis, Design
  – Lab Tests, Simulations, Software
The Responsibility

- Client/Owner
- Architect
- Structural Designer
- Geotech Consultants
- Peer Reviewer
- Builder/Contractor

- General Building Codes
- Structural Design Codes
- Law Makers
- Building Officials
- Legal and Justice System

Public/ Users/ Occupants
**Clause 229:** If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death.
“In case you build a new house, you must also make a parapet for your roof, that you may not place bloodguilt upon your house because someone falling might fall from it”.

- The Bible, Book of Deuteronomy, Chapter 22, Verse 8

Life Safety

... Ultimately..... Performance is what is desired...
7.2.3 — Inside diameter of bend in welded wire reinforcement for stirrups and ties shall not be less than $4d_b$ for deformed wire larger than MD40 and $2d_b$ for all other wires. Bends with inside diameter of less than $8d_b$ shall not be less than $4d_b$ from nearest welded intersection.

Do this ...

Your structure is OK

(ACI 318 – 11)
Shortcomings of the Prescriptive Codes For Tall Buildings

• Traditional codes govern design of general, normal buildings
  – Over 95% buildings are covered, which are less than about 50 m

• Not specifically developed for tall buildings > 50 m tall
• Prescriptive in nature, no explicit check on outcome
• Permit a limited number of structural systems
• Do not include framing systems appropriate for high rise
• Based on elastic methods of analysis
• Enforce uniform detailing rules on all members
• Enforce unreasonable demand distribution rules
• Do not take advantage of recent computing tools
Performance-based Engineering

Design for the achievement of specified results rather than adherence to particular technologies or prescribed means.

- Peter May, 2004

... Now, instead of worrying about mix proportions of concrete, you can directly ask contractor for a 60 MPa concrete → Courtesy: Performance based approach
Performance-based Design Approach

Client

Designer

Independent Engineer

Guidelines: PEER, TBI, ATC, FEMA, CTBUH etc.

What to expect?

How to achieve?

Knowledge – Skills – Tools
Building Performance Objectives

First generation

Next generation

Base Shear

Damage Threshold

Collapse Onset

Deformation

ASCE 41 Performance Levels

0 25% 50% 100%

0.0 0.0001 0.001 0.01 0.25

0 1 7 30 180

Casualty rate

Downtime, days

Jack Moehle 2011, PEER, SEAOSC
Current Guidelines

Tall Buildings Initiative
Guidelines for Performance-Based Seismic Design of Tall Buildings
Version 1.0
November 2010

Council of Tall Buildings and Urban Habitat (CTBUH)
http://www.ctbuh.org/

National Earthquake Hazards Reduction Program
http://www.nehrp.gov/

http://peer.berkeley.edu/tbi/
Consequence-based Engineering
A New Engineering Paradigm

CBE Paradigm

Systems Integration
- technologies, methods, techniques, maps, motions
- hazard regions, perturbed networks
- system needs
- field and lab tests, construction projects

Enabling Technologies
- test beds: data, information, theories, models
- technology needs

Knowledge Base

Research
- CBE Framework
- Uncertainty Modeling
- Network Vulnerability
- Regional Damage Synthesis
- Loss Visualization
- Inventory Technologies
- Computational Methods
- Damage-Probability Models
- Design/Rehab. Techniques
- Synthetic Earthquake Hazards
- Economic Flows
- Decision Making
- Structural Response
- Component Vulnerability
- Source/Path/Site Characterization
- Ground Deformation

(Abrams D.P, 2002)
Core Research Thrust Areas

Stakeholder Thrust Areas

(Abrams D.P, 2002)
Construction Innovations
Construction Technology

• **Pre-Fabrications**
  – Single parts
  – Larger components and units
  – Fully assembled systems
  – Modular Construction

• **Rapid Construction**
  – Slip forming, flying forms, pre-assembled cages
  – Rapid hardening concretes, newer material,
  – Top-down and bottom up construction

• **Improved Management**

• **Technologies in development**
  – Printed Buildings
Pre Fabrication
Slip Forming
Top Down Construction
Modular Construction

30 story in 15 days - China
Concrete Printing
Contour Crafting
AIT and Tall Buildings
AIT Integrated Knowledge Development and Application

- Present AIT’s Model/role
  A. Existing Knowledge → Teaching/Academics
  B. New Problems/New Knowledge → Research
  C. Apply Knowledge → Consulting
  D. Develop Skills → Executive Education
Advanced Tools for Tall Buildings

**CSI BRIDGE**
Integrated 3D Bridge Design Software

**SAP2000**
Integrated Software for Structural Analysis and Design

**ETABS**
Integrated Analysis, Design and Drafting of Building Systems

**SAFE**
Integrated Design of Flat Slabs, Foundation Mats and Spread Footings

**PERFORM-3D**
Nonlinear Analysis and Performance Assessment for 3D Structures

**CSI COL**
Design of Simple and Complex Reinforced Concrete Columns