Design, Construction and Management of Tall Buildings
Challenges and Trends

Naveed Anwar
Tall Buildings – The Need
Percentage of Urbanized World

Rate of Urban Population Growth
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?

A Street of 10 small houses  
(Accommodating 10 Families)

Versus

A 40 story Tall Building on almost same area  
(Accommodating 200 Families)
The Case of London
The Shard in London
Mercury City Tower in Moscow

Tallest building of Europe

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>338.8 m</td>
</tr>
<tr>
<td>Floor count</td>
<td>75 (5 below ground)</td>
</tr>
</tbody>
</table>
Sky City (Changsha, China)

- **Height**: 838 m
- **Floor count**: 220 total
- **Construction to be done in 7 months**
Social and Affordable Housing
Systems and Components
Conventional Systems
The Diagrid System
BRB Based Systems
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
# Development of Basic 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>
</tr>
<tr>
<td>4</td>
<td>Coupled shear walls and beams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rigid frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Widely spaced perimeter tube</td>
<td></td>
<td></td>
</tr>
<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>
</tr>
<tr>
<td>10</td>
<td>Shear wall—Haunch girder frame</td>
<td></td>
<td></td>
</tr>
<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>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Structural Systems Categories
Main Floor Slab System Types - Various Schemes and Options

• Reinforced Concrete Systems
  – One-Way Slabs on Beams or Walls
  – One-Way Pan Joists and Beams
  – One-Way Slabs on Beams and Girders
  – Two-Way Flat Plates
  – Two-Way Flat Slabs
  – Two-Way Waffle Flat Slabs
  – Two-Way Slabs and Beams

• Steel Systems
  – One-Way Beam System
  – Two-Way Beam System
  – Three-Way Beam System
  – Metal Deck System

• Precast and Composite Systems
  – Precast Concrete Slab System
  – Precast Framed Systems
  – Composite Slab Systems
Lateral Load Resisting Systems - Various Schemes and Options

• Frame Systems
  – Rigid Frame
  – Rigid Frame with Haunch Girders
  – Flat Slab-Frame System

• Wall Systems
  – Coupled Shear Walls
  – Core-supported Structures
  – Spinal Wall Systems
  – Outrigger and Belt Wall System
  – Flat Slab-frame with Shear Walls

• Tubular Systems
  – Tube System with Widely Spaced Columns
  – Frame Tube System
  – Irregular Tube
  – Exterior Diagonal Tube
  – Bundled Tube

• Miscellaneous Systems
Innovative Systems

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 Systems

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

- Genetic Algorithms (GA)
- Artificial Neural Networks (ANN)
- Fuzzy Logic
- Expert Systems (ES)
- Linear/Nonlinear Programming
- Value Engineering
- Analytic Hierarchy Process (AHP)
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 is the “Consumption of Resources”
## Construction Cost of a Building Project

<table>
<thead>
<tr>
<th>Planning and Design Cost</th>
<th>2-4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Architectural Design</td>
<td>70%</td>
</tr>
<tr>
<td>• Structural Design</td>
<td>20%</td>
</tr>
<tr>
<td>• Building services Design</td>
<td>10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direct Construction Cost</th>
<th>90-95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Site Development</td>
<td>5-10%</td>
</tr>
<tr>
<td>• Structural Shell</td>
<td>25-40%</td>
</tr>
<tr>
<td>• Architectural Finishes</td>
<td>40-60%</td>
</tr>
<tr>
<td>• Building Services</td>
<td>5-15%</td>
</tr>
</tbody>
</table>

| Supervision and Management Cost | 1-3% |
Cost of Concrete Building Structural Shell

Foundations 25-40%
  - Excavation and Preparation 10-20%
  - Structural components 90-80%
    - Concrete 50-60%
    - Steel 40-50%

Super Structure 60-75%
  - Columns, Shear Walls etc 15-25%
    - Concrete 30-40%
    - Steel 40-50%
    - Formwork 20-30%
  - Floor Slab System 75-85%
    - Concrete 30-40%
    - Steel 30-40%
    - Formwork 25-35%

Excavation and Preparation 10-20%
Structural components 90-80%
Concrete 50-60%
Steel 40-50%

Columns, Shear Walls etc 15-25%
Concrete 30-40%
Steel 40-50%
Formwork 20-30%

Floor Slab System 75-85%
Concrete 30-40%
Steel 30-40%
Formwork 25-35%

Construction in the 21st Century
Cost and Design

• How are Cost and Design Related
  – Economical Design
  – Least Cost Design
  – Low Cost Design
  – Optimum Design
  – Optimized Design
  – Cost Sensitive Design
  – Cost Effective Design
  – Cost Conscious Design
Cost vs. 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
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
Optimum Design

• Optimization
  – When objective function has least value
  – Single Variable, Multi-Objective
  – Multi Variable, Single Objective
  – Multi Variable, Multi Objective

• Least Cost Design
  – When objective function is the Cost and least cost is achieved
  – Cost needs to be defined
  – Variables and their constraints need to be defined
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
Cost and Performance

The general belief
Increased Performance $\rightarrow$ Increased Cost

Increased performance can be achieved for same cost

Reduced cost for same performance

Improved/efficient designs

Easy

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

Need not be true
A reinforced concrete wall section

(a) 

(b) 

(c) 

Cost and Performance
Built to Last - A challenge

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.

Green and Sustainable Buildings
Managing Existing Facilities

GIS-based Integrated Systems
Typical Review Objectives

• **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
Design Methodologies and Technologies
The Responsibility

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

Public/ Users/ Occupants

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

Construction in the 21st Century
**The First Code - Hammurabi's Code (1772 BC)**

**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.

Performance → Consequence
"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

... Ultimately..... Performance is what is desired...
Intuitive/Artistic Creations – Need no codes
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.

(ACI 318 – 11)

Do this ...

Your structure is safe
Shortcomings of the Traditional Codes

- 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
Unsuitability of Traditional Design Codes

• **Implicit Performance Objective**
  – Resist minor earthquake without damage, which is anticipated to occur several times during the life of a building, without damage to structural and non-structural components
  
  – Resist the design level of earthquake with damage without causing loss of life
  
  – Resist strongest earthquake with substantial damage but a very low probability of collapse.

• **Explicit verification not specified or required**
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
Consequence-based Engineering
A New Engineering Paradigm

CBE Paradigm

Systems Integration
- technologies, methods, techniques, maps, motions
- test beds:
  - hazard regions
  - perturbed networks

Enabling Technologies
- system needs
- field and lab tests, construction projects
- technology needs

Knowledge Base
- data, information, theories, models

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)
Insurance, Risks in Projects

Assessing and Managing Risk in Projects
Tall Building Performance Objectives

Base Shear

Damage Threshold

Collapse Onset

Deformation

ASCE 41 Performance Levels

First generation

Next generation

IO

LS

CP

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
Wind and Earthquake effects on Tall Buildings

How Safe are our Buildings for Earthquakes and Winds?
Construction Innovations
Pre Fabrication
Slip Forming
Top Down Construction

- Retaining Wall
- Roof Slab to be Constructed
- Strut
- Decking
- Roof Opening
- Roof Slab

CITC - VII
Construction in the 21st Century
Modular Construction – 30 story in 15 days - China
Concrete Printing — An Innovative Construction Process

Concrete Printing is an innovative construction process that utilizes 3D printing technology to create building structures. The process involves the use of concrete materials, which are printed layer by layer to form complex architectural designs. This method offers several advantages, including reduced construction time, increased precision, and the ability to create structures with unique geometries that are difficult or impossible to build using traditional methods. The process is particularly useful in construction projects where rapid prototyping or custom architectural features are desired. The integration of technology and material science in this process is driving advancements in the field of construction engineering, making it a promising area for future development.
Contour Crafting
Foundations/Basements

Innovative Solutions for Foundations and Deep Basements
ALT 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

Outcomes
Projects
New Problems
B
C
D

MS/PhD Degrees
Return to Professions
Advanced Tools for Tall Buildings

**CSiBRIDGE**
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

**PERFORM3D**
Nonlinear Analysis and Performance Assessment for 3D Structures

**CSiCOL**
Design of Simple and Complex Reinforced Concrete Columns
Construction in the 21st Century

- Park Terraces Tower 1 Podium, Philippines
- GSIS, Philippines
- LDCC, Nepal
- The Sequoia, Philippines
- La Residenza, Thailand
- Gramercy, Philippines
- Serendra, Philippines
Thank You

Dr. Naveed Anwar
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Affiliated Faculty, Structural Engineering
Director, ACECOMS