Design of Tall Buildings: Trends and Achievements for Structural Performance

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Bangkok-Thailand
The Tussle

Can design be based on “Engineering Judgment” and “Intuition”

Or

It must be controlled by explicit computations and, restrictive limits and fully rational approaches
It is by logic we prove, but by intuition we discover.
What a Structural Engineer Says!

“As the size and complexity of projects increased, ... it became desirable and even necessary to ... set up a series of routine procedures for analysis and design. With these standardized formulas and specifications and methods it became possible to use a greater number of men and men with less training to produce engineering works. ... Standardization, as a check on fools and rascals or set up as an intellectual assembly line, has served well in the engineering world.”

Hardy Cross, 1885-1959
Structural Engineers are “trained” to follow the procedures and equations and rules and be conformists

Whereas Architects are encouraged to dream and be “defiant”
Determine the wall thickness and reinforcement (6x2x3m)

Most structural engineer should be able to do

Design the most cost effective water tank to hold 36 Cum of water

Most Structural Engineers would not know what to do (Will need a “Structural Designer”)
Design the most cost effective, beautiful, and amazing water tank to hold 36 Cum of water

Performance + Cost + Aesthetes  Will need “Structural Artist”
Structural Engineering and Art

- Structural Engineering in Art
  - Application of structural engineering in creating works of art in architecture and sculpture

- Art of Structural Engineering
  - Taking the structural design to the level of an Art

[Image of book cover]
The Rational Design Process

- Architectural Requirements
- Structural System Development
- Preliminary Sizing, Modeling and Analysis
- Response and Design Checks
- Detailed Modeling, Analysis and Design
- Performance Based Design

Can we speed up this part
Learning from Experience

To make design preliminary decisions *without* explicit calculations
Learn From Experience

Preliminary Design of Tall Buildings Using Artificial Neural Networks

Properly trained Artificial Neural Networks (ANN) based on data of existing buildings can provide a quick alternative for preliminary design and response estimation of new buildings, using basic architectural parameters.

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Thaung Htat Aung
Jose A. Sy

A Master Thesis in AIT, based on the Tall Buildings designed by Sy^2 and PBD carried out by AIT Solutions
Using Artificial Neural Networks
Learn From Experience
Methodology

- Data Collection
  - Extraction of data from drawings and Selection of input and output parameters
  - A Database Architectural & Structural Drawings and Analysis/Design Results of Case Study Buildings.

- Data Pre-Processing
  - Normalization of input and output variables using z-score normalization process

- Development of Neural Networks
  - Splitting dataset into two categories, Testing and Training
  - Appropriate number of hidden layers, hidden layers nodes
  - Select the appropriate activation function
  - Initialize the network weights and bias
  - Create Neural Network MLP
  - Network training based on BP algorithm

- Training, Testing and Sensitivity Analysis of Neural Networks
  - Selection of best networks after training and performance evaluation by comparison of test set results with actual outputs.
Using Trained Network for New Design or Quick Check

Inputs in the form of Architectural Parameters

Some Other Inputs:
- Ratio of total tower height to length of tower along both directions
- Aspect ratio of tower plan
- Ratio of tower height to length of core wall in both directions
- Ratio of length of core wall in x direction to length in y direction

Outputs for Performance-based Design:
- Area of Columns
- Area of Shear Walls
- Thickness of Shear Wall
- Shear Wall Reinforcement Ratio
- Column Reinforcement Ratio

Outputs for Code-based Design:
- Natural Time Periods
- Weight of Building Total Volume
- Weight of Building Cumulative Floor Area
- Maximum Base Shear Total Weight
- Maximum Roof Drift

Preliminary Design and Response Estimation
Figure 5: Comparison of actual and predicted values of natural period

Figure 6: Comparison of the ratio of total area of columns to floor area of tower
Figure 7: Comparison of ratio of total area of core wall to floor area with predicted values

Figure 8: Comparison of actual and predicted values of weight per unit floor area
A Swing Towards the AI

• Rich Pictures
• Analytical Hierarchy Process (AHP)

• Artificial Neural Networks (ANN)
• Genetic Algorithms (GA)
• Expert Systems (ES)

• Fuzzy Logic
• Deep Thinking
• Big Data and Data Mining
The Role of Computers and Software

• Initially, computers were used to program the procedure we had

• Now, we develop procedures that are suited for computing
Historical Prospective

• In nature, the structures of organisms differ according to their size. For example, the structure of a large animal such as an elephant is radically different from that of a dog or a mosquito.

• However, in spite of these obvious differences, until about the middle of the seventeenth century, scientists believed that it was possible to build larger structures simply by duplicating the form and proportion of a smaller one.

• The prevailing opinion was that if the ratios between structural elements in the larger structure were made identical to the ratios in the smaller structure, the two structures would behave in a similar manner.
4 Commandments of Tall Buildings Design

1. Resist overturning forces due to lateral loads by using vertical elements placed as far apart as possible from the geometric center of the building.

2. Channel gravity loads to those vertical elements resisting overturning forces.

3. Link these vertical elements together with shear-resisting structural elements that experience a minimum of shear lag effects such that the entire perimeter of the building resists the overturning moments.

4. Resist lateral forces with members axially loaded in compression rather than those loaded in tension due to overturning.
A Quick Look at Structural Systems
The Building Structural System - Conceptual

Gravity Load Resisting System (GLRS)

- The structural system (beams, slab, girders, columns, etc.) that act primarily to support the gravity or vertical loads

Lateral Load Resisting System (LLRS)

- The structural system (columns, shear walls, bracing, etc.) that primarily acts to resist the lateral loads

Floor Diaphragm (FD)

- The structural system that transfers lateral loads to the lateral load resisting system and provides in-plane floor stiffness
# Vertical Load Resisting Systems

| Slabs supported on long rigid supports | • Supported on stiff beams or walls  
• One-way and two-way slabs  
• Main consideration is flexural reinforcement |
|---------------------------------------|----------------------------------------------------------------------------------|
| Slab-system supported on small rigid supports | • Supported on columns directly  
• Flat slab floor systems  
• Main consideration is shear transfer, moment distribution in various parts and lateral load resistance |
| Slabs supported on soil | • Slabs on grade: light, uniformly distributed loads  
• Footings, mat, etc. Heavy concentrated loads |
Lateral Load Bearing Systems

PURPOSE

• “To transfer lateral loads applied at any location in the structure down to the foundation level”

SINGLE SYSTEM

1. Moment Resisting Frames
2. Braced Frames
3. Shear Walls
4. Tubular Systems

DUAL SYSTEMS and Multiple

1. Shear Walls-Frames
2. Tube + Frame + Shear Walls
Lateral Load Resisting Systems

- Moment Resisting Frame
- Shear Wall and Frame
- Shear Wall – Frame Coupled
Lateral Load Resisting Systems

Braced Frame

Tubular Structure

Braced Tube Systems

Dr. Naveed Anwar
Wall Systems

- Outrigger
- Interior shear wall
- Exterior columns
- Shear base
- Belt wall
- $x = 0.45H$
Coupled Shear Walls

• A system of interconnected shear walls exhibits a stiffness that far exceeds the summation of the individual wall stiffness.

• The system is economical for buildings in the 40-story range as Walls behave as if they are connected through a continuous shear-resisting medium.

• Placement of walls around elevators, stairs, and utility shafts is common because they do not interfere with interior architectural layout.

• Resistance to torsional loads must be considered in determining their location.
Coupled Shear Walls

Representation of coupled shear wall by continuum model:
(a) Wall with openings,  (b) Analytical model for close-form solution
Core-supported Structures

- Shear walls placed around building services such as elevators and stair cores can be considered as a spatial system capable of transmitting lateral loads in both directions.

- The shape of the core is typically dictated by the elevator and stair requirements and can vary from a single rectangular core to multiple cores.

- Floor framing around the core typically consists of systems such as cast-in-place mild steel reinforced or post tensioned concrete.
Core-supported Structures

(a) Precast double-tee system
- Precast columns
- Cast-in-place concrete shear walls
- Precast spandrel beams

(b) 110 ft
- Posttensioned slab

(c) 125 ft
- One way skip joists
Core-supported Structures

Full depth interior shear walls acting as giant K-brace. (a) Plan and (b) schematic section
Spinal Wall System

• Well Suited for ultra tall residential towers

• Shear walls are placed along both sides of corridor.

• Spine walls run through the floors to resist lateral loads

• Loads in perpendicular direction are resisted through cross wall placed in orthogonal direction
Outrigger and Belt Wall System

• External moment is resisted through the combination of core and exterior columns connected through outriggers.

• Effective depth of structure for resisting bending is increased when core flexes as vertical cantilever.
Optimum Location of a Single Outrigger Wall

Deflection index versus outrigger and belt wall location

Deflection index versus outrigger and belt wall location
Frame action from flat slab–beam and column interaction is generally insufficient to provide the required strength and stiffness for tall buildings.

A system of shear walls and flat slab-frames may provide an appropriate lateral bracing system.

Coupling of walls and columns solely by slabs is a relatively weak source of energy dissipation.
Tubular Systems
Tube System with Widely Spaced Columns

Tube System with Widely Spaced Columns for 28-story building constructed in New Orleans
Frame Tube System

Frame Tube Building. (a) Schematic plan and (b) isometric view
From Frame to Tube

Tube ➔ Frame
Shear Lag Effects in Frame Tube System

(a) cantilever tube subjected to lateral loads,
(b) shear stress distribution
(c) distortion of flange element caused by shear stresses.
Irregular Tubes

Secondary frame action in an irregular tube; schematic axial forces in perimeter columns
Exterior Diagonal Tube

- Adding diagonal bracing improves the efficiency of frame tube in tall buildings by eliminating shear lag in flange and web frames.

- Allows greater spacing between columns.

- By applying structural principles, it is possible to visualize a concrete system consisting of closely spaced exterior columns with blocked-out windows at each floor to create a diagonal pattern on the building facade.

- The diagonals carry lateral shear forces in axial compression and tension, thus eliminating bending in the columns and girders.
Bundled Tube

- Spandrel beams
- Interior gravity framing
- Exterior closely spaced columns

Cell 1  Cell 2  Cell 3
Selection of Structural Systems
Latest Techniques

- Genetic Algorithms (GA)
- Artificial Neural Networks (ANN)
- Fuzzy Logic
- Expert Systems (ES)
- Linear/Nonlinear Programming
- Value Engineering
- Analytic Hierarchy Process (AHP)
Rich Pictures
Try to consider as many factors as possible

Take “Bird’s Eye” View
Knowledge Model for System Selection

- Architecture
- Building Services
- Construction Engineering
- Value Engineering
- Aesthetics
- Ergonomics Engineering
- Structural Engineering
- Knowledge Engineering
- Economics
- Artificial Intelligence
- System Engineering
- Common Sense
Rich picture Diagram for System Selection

A Master Thesis at AIT:
Sudiksha Amatya
Naveed Anwar
Rich Pictures

Different professionals involved and their interrelationship with structural engineer during the selection of structural systems
Structural System Suitability using AHP

• The Analytical Hierarchy Process

• A weighted importance and suitability value analysis to determine the comparative value of a system or option

\[ V_l = \sum_{i=1}^{m} A_i S_i \left( \sum_{j=1}^{n} B_{ij} S_{ij} \sum_{k=1}^{p} C_{ijkl} S_{ijk} \right) \]
### Evaluating System Suitability

#### Using the Suitability Equation

<table>
<thead>
<tr>
<th>Slab Systems</th>
<th>Criteria Weights and Scores</th>
<th>System Value (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Main Criteria</strong> $A_i$</td>
<td>$A_m$</td>
</tr>
<tr>
<td></td>
<td><strong>Sub Criteria</strong> $B_{ij}$</td>
<td>$B_{mn}$</td>
</tr>
<tr>
<td>Item $k$</td>
<td>Item $p$</td>
<td>Item $p$</td>
</tr>
<tr>
<td><strong>Wt</strong></td>
<td><strong>Score</strong></td>
<td><strong>Wt</strong></td>
</tr>
<tr>
<td><strong>Score</strong></td>
<td><strong>Wt</strong></td>
<td><strong>Score</strong></td>
</tr>
</tbody>
</table>

- **System – 1**
- **System – q**

Using the Suitability Equation

$$C_{ijkl} \times S_{ijkl} + C_{ijnl} \times S_{ijpl} + C_{inkl} \times S_{inkl} + C_{inpl} \times S_{inpl} + S_{mnpl}$$
## Assigning Suitability Values

<table>
<thead>
<tr>
<th>Score or Weight</th>
<th>Representation of Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Most important, most suitable, most desirable, essential</td>
</tr>
<tr>
<td>8, 9</td>
<td>Very important, very suitable, very desirable</td>
</tr>
<tr>
<td>6, 7</td>
<td>Important, suitable or desirable</td>
</tr>
<tr>
<td>5</td>
<td>May be or could be important, suitable or desirable</td>
</tr>
<tr>
<td>3, 4</td>
<td>May not be important, suitable or desirable</td>
</tr>
<tr>
<td>1, 2</td>
<td>Not important, not suitable, not desirable</td>
</tr>
<tr>
<td>0</td>
<td>Definitely not required, definitely not suitable, ignore</td>
</tr>
</tbody>
</table>
To do a Good Conceptual Design

Develop the “Concept” at a higher level
Identify the challenges and find solutions
Compare value of alternatives
Use previous experience

Be innovative, be defiant, think outside the box
“The intuitive mind is a sacred gift and the rational mind is a faithful servant. We have created a society that honors the servant and has forgotten the gift.”

It is by logic we prove, but by intuition we discover.
Thank You