Design of Slender Tall Buildings for Wind & Earthquake

Presented by
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Director (Group Design Division)
Meinhardt Singapore Pte Ltd
ABOUT MEINHARDT
ABOUT MEINHARDT

Largest Global Engineering & PM Company Owned and Headquartered in Singapore

Established in 1955 (in Australia) 1974 (in Singapore)

42 Offices worldwide

60+ Years of track record

4000+ Professional staff

Start-to-end services across entire project delivery cycle

Group undertakes projects worth US$20 billion annually

ENR 2014 Largest Independent Engineering Consulting Firm in Asia
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USA
40+
Staff Strength

EUROPE
100+
Staff Strength

MENA
400+
Staff Strength

ASIA
3200+
Staff Strength

AUSTRALIA
350+
Staff Strength
We Have The Credentials And Ability To Deliver Projects Of All Types And Complexities

Buildings
- Arts and Culture
- Commercial Offices
- Convention Centres
- Hotels and Leisure
- Mixed-use Developments
- Parking Structures
- Residential
- Retail / Shopping Malls
- Sports Facilities / Stadia

Industrial and Manufacturing
- Distribution Centres
- Industrial
- Pharmaceutical
- Petrochemical

Information Technology, Research and Communications
- Data Centres
- Life Sciences and Biotech
- Power Systems
- Telecommunications

Civic
- Defense
- Educational
- Healthcare/Hospitals
- Public

Urban Land Development
- Built Environment
- Conservation and Restoration
- Urban Regeneration
- Urban Infrastructure

Infrastructure
- Environmental Management
- Energy Generation and Distribution
- Waste Management
- Water, Wastewater and Environment

Sustainability
- Energy Audits and Conservation
- Green Buildings and Architecture

Transportation
- Aviation/Airports
- Bridges
- Highways
- Ports
- Railways/Metros
- Tunnels
High Rise Buildings

610 m
Mixed-Use Tower, South East Asia
C&S Engineering for International Contractor

385 m
Capital Market Authority, KSA
Specialist structural consultant & technical advisor to SBG

385 m
World Development Mumbai, India
85 & 52 Storey Mixed Use (Office & Residential)
MEP Engineering & Façade

360 m
Thamrin Nine Jakarta, Indonesia
68 & 58-Storey Mixed Use (Office/Residential)
Structural, MEP, Façade Engineering & Traffic

358 m
Signature Towers Dubai, UAE
81 /65/52 Storey Mixed Use (Office & Residential)
Lead, Structural, MEP & Façade Engineering
### HIGH RISE BUILDINGS

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Building Name</th>
<th>Location</th>
<th>Storeys/Use</th>
<th>Engineering Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>342</td>
<td>Four Seasons Place</td>
<td>Kuala Lumpur, Malaysia</td>
<td>76 Storey Mixed Use (Hotel &amp; Residential)</td>
<td>Structural Engineering</td>
</tr>
<tr>
<td>342</td>
<td>IFC Project</td>
<td>Wu Xi, China</td>
<td>65 Storey Mixed Use (Hotel &amp; Residential)</td>
<td>MEP Engineering, Façade</td>
</tr>
<tr>
<td>330</td>
<td>Shanghai Putuo CBD</td>
<td>Shanghai, China</td>
<td>57-storey Office Tower</td>
<td>MEP Engineering</td>
</tr>
<tr>
<td>320</td>
<td>Heartland 66</td>
<td>Wuhan, China</td>
<td>64-storey Office Tower</td>
<td>Structural Engineering</td>
</tr>
<tr>
<td>308</td>
<td>Ocean Heights</td>
<td>Dubai, UAE</td>
<td>82 Storey Residential Tower</td>
<td>Structural Engineering</td>
</tr>
<tr>
<td>300</td>
<td>ZhuJiang New Town B2-10</td>
<td>Guangzhou, China</td>
<td>68-storey Office Tower</td>
<td>MEP Engineering, Structural Checking</td>
</tr>
</tbody>
</table>
HIGH RISE BUILDINGS

300m
Dubai Pearl
70-storey
Mixed Use (Office, Hotel, Residential, Retail)
Structural and M&E Engineering

298m
One Island East
Hong Kong
70 Storey Office
MEP Engineering

290m
Tanjong Pagar
Mixed Use Development
Singapore
64 Storey Mixed Use (Retail, Office, Hotel, Residential)
MEP Engineering

290m
Nanjing International Commerce Centre
Nanjing, China
59-storey Hotel & Office Tower
MEP Engineering

280m
One Raffles Place
Singapore
63 Storey Office Tower
Structural & MEP Engineering

267m
Petronas Tower 3,
Kuala Lumpur, Malaysia
60 Storey Office Tower
Structural Engineering
HIGH RISE BUILDINGS

261 m
The Masterpiece, Hyatt Regency Hotel, K11 Shopping Mall, Hong Kong
64 Storey Mixed Use (Hotel, Retail, Service Apartment)
MEP Engineering

254 m
Prima Pearl Tower
Melbourne, Australia
69 Storey Residential Tower
Structural Engineering

251 m
Rialto Towers
Melbourne, Australia
65 Storey Office Tower
Structural Engineering

258 m
The River
Bangkok, Thailand
74 Storey Residential Towers
Structural Engineering, Specialist Lighting

245 m
Marina Bay Financial Centre, Singapore
67/56/51/50/33 Storey Mixed Use (Office, Residential & Retail)
Structural & MEP Engineering

245 m
One Raffles Quay, Singapore
50/33 Storey Office Towers
Structural & MEP Engineering
DEFINITION & TRENDS OF TALL BUILDINGS
According to **CTBUH**, there is no absolute definition.

It is a building that exhibits some element of “tallness” in one or more of the following categories:

a) **Height Relative to Context**

   It is not just about height, but about the context in which it exists.
b) Proportion

Again, a tall building is not just about height but also about proportion.
c) Technologies

If a building contains technologies which may be attributed as being a product of “tall”, then this building can be classed as a tall building.
TALL BUILDINGS DEFINITION

- A structure that, because of its height, is affected by lateral forces due to wind or earthquake to the extent that the forces constitute an important element in structural design.

- In general
  - 200m: Tall
  - 300m: Super Tall
  - 600m: Mega Tall

Diagram of the World’s 20 Tallest in 2020 (estimated as of Dec 2011) © CTBUH
Historically tall buildings have been predominantly in North America.

At the end of 2012, 74% of the 100 tallest buildings were located in Asia.
Historically tall buildings have been predominantly office buildings.

At the end of 2012, 53% of the 100 tallest buildings were either mixed use or residential.
At the end of 2012, 82% of the 100 tallest buildings were either concrete or composite.

Historically, tall buildings have been predominantly in structural steel. The structural systems of the world's tallest buildings have historically been predominantly composed of steel. By the end of 2012, 82% of the world's 100 tallest buildings will be constructed of either concrete or composite construction.
KEY CONSIDERATIONS IN THE DESIGN OF TALL BUILDINGS
Balancing structural needs vs. project demands is always a challenge ......... specially for tall buildings.
Tall buildings present special challenges to design & construction.

Important considerations include:

- Efficient structural framing systems
- Drift control
- Dynamic behavior & perceived building sway
- Differential shortening between vertical elements
- Foundation settlements
- Wind Engineering
- Parametric Modeling & Optimization (Geometry > Analysis > Design & Optimization)
Short Buildings:
- Generally strength governs design
- Gravity loads predominant

Intermediate Buildings:
- Strength / drift governs design
- Gravity / lateral loads predominant

Tall Buildings:
- Generally drift / building motion governs design
- Lateral loads predominant
ARCHITECTURAL DESIRES NETT:GROSS

- In a really efficient tall building, nearly 65% ~ 75% of the building’s volume is useable, whereas as in a well designed low-rise building more than 80% of the space can be sold.

- The structure should respect the architecture and be designed to minimise any loss of nett : gross.
As buildings get taller, wind-induced dynamic response starts to dictate the design.

For many tall & slender buildings, cross wind response starts to govern loading & acceleration.

Building dynamic properties (natural frequencies, mode shapes & damping) greatly affect wind loads & accelerations.

\[ V(z) = V_g \left( \frac{z}{z_g} \right)^\alpha \]

\( \alpha \) depends on terrain.

Fluctuating Wind Speed, \( V(z,t) \)

Mean Wind Speed, \( V(z) \)

Static Loads, A + Dynamic Loads
WIND ENGINEERING INFLUENCING FORM

- There are a number of approaches to minimize cross-wind response
  - orientation
  - setbacks, varying cross-section
  - softened corners
  - twisting, tapering
  - introducing porosity

- Burj Khalifa: initial force balance predictions indicated 37 milli-g accelerations at the 10 year return period, reduced to 18 milli-g through shape and orientation changes

- Taipei 101: 25% reduction in base moment due to change in geometry of building corners
■ Shortcomings of Code Analytical Methods
  ✓ Limited range of shapes
  ✓ No aerodynamic interactions between buildings (wake buffeting, channelling)
  ✓ No directional effects & crosswind response
  ✓ Approximate treatment of torsional loads
  ✓ Topographic effects may not be well described
  ✓ Building accelerations are not addressed
  ✓ Can give a false sense of precision
Wind tunnel testing is used to optimise & interrogate:
- Building geometry, orientation and form
- Structural loads
- Building acceleration sensitivity studies
- Cladding wind pressures
- Pedestrian level wind environment
- Balconies & Terrace environments

Signature Tower, Dubai

One Raffles Quay
Design of tall buildings is often controlled by building lateral deflection or acceleration (occupant comfort)

Lateral deflection (drift) control necessary to prevent damage to non-structural elements

Lateral acceleration control necessary to prevent annoyance to occupants from perceptible building motions

Careful considerations required for building stiffness and dynamic properties

Supplemental damping devices may be required to control accelerations
MOVEMENTS HUMAN COMFORT CRITERIA

- The building lateral acceleration is used to establish the human comfort criteria.

- There are different codes in the world that recommend different criteria for these limits for different types of accommodation.

- Humans notice lateral accelerations more when they are stationary, hence residential buildings are the most sensitive.

- Typical limits are:
  - Residential 10 – 15 milli-g
  - Hotel 15 – 20 milli-g
  - Office 20 – 25 milli-g
  - Retail 25+ milli-g
MOVEMENTS DIFFERENTIAL SHORTENING

- Differential shortening of vertical elements take on added significance and need special consideration for tall buildings.

- Initial position of slabs are affected with time consequently affecting partitions, mechanical equipment, cladding, finishes, etc.

- Careful considerations **required** to mitigate effects of such shortening. These include appropriate proportioning of stiffness, and vertical cambering if necessary.
MOVEMENTS SEQUENTIAL (CONSTRUCTION) ANALYSIS

- Important to consider construction sequence in analysis to capture effects of:
  - compressive shortening,
  - creep & shrinkage, &
  - any locked in stresses from transfer beams, outrigger systems, stiffer elements

- Becomes more complex on non-symmetric structures where the axial shortening can cause floors to twist and tilt under self weight
DAMPING

Why is it significant to tall buildings?

- Wind loading is a DYNAMIC force, causing oscillation of buildings
- Tall buildings with long natural periods are especially susceptible
- Sometimes the wind loading is significantly higher because of dynamic amplification
- Damping reduces build up of resonant response
- Adding supplementary damping is reliable, safe and more economic
DAMPING

- Supplementary damping can be in many forms, e.g.,
  - Tuned mass dampers
  - Slosh dampers
  - Viscous dampers
  - Active systems
SECURITY FIRE ENGINEERING

- Inherent capacity for fire resistance in concrete with appropriate detailing
- Fire protection required for steel structures
- A fire engineered approach can significantly reduce the cost of fire protection
Which system is better?

What is the impact of premature loss of one element?
Depending on detailed threat assessment, structural design may require to adapt to blast resistance / secondary load paths providing robustness against disproportionate collapse.
Ultra-high strength concrete and steels are becoming common for tall buildings because of the need to reduce member size and structural self-weight.

Steel strengths up to 780MPa & concrete strengths up to 180MPa are now available.

Care must be taken since limited testing information is available.

\[ F_y = 590\text{MPa}, \quad F_{ck} = 150\text{MPa} \]
CONSTRUCTION DESIGNING FOR BUILDABILITY

- Slip-forming on the Stability Core
- Limited or No back-propping
- Precast Construction
- Strut Free Excavation

- Precast Façade
- Precast Beam
- Precast Bathroom Unit (PBU)
- Precast Plank
- Precast Staircase, Household Shelter
- Precast Insitu Wall
- Tall buildings are big budget projects: small savings / m² = large $$
- Efficiency & economy are not defined by codes.
- Custom programs & scripts required to optimize design.
STRUCTURAL SYSTEMS FOR TALL BUILDINGS
- The cost premium for height varies depending on lateral load considerations & choice of structural systems.

- Appropriate choice of the lateral load resisting system is paramount for structural efficiency and constructability.
Interior Structures: single / dual component planar assemblies in 2 principal directions.

- Effectively resists bending by exterior columns connected to outriggers extended from the core.
- Dual systems - shear wall–frame interaction for effective resistance of lateral load.
- Single component resisting systems.

**Interior Structures**

Courtesy: Architectural Science Review
Exterior Structures: effectively resist lateral loads by systems at building perimeter.
STRUCTURAL SYSTEMS: TRENDS

No. of Stories

Columbia Center
Seattle

Water Tower Place
Chicago

Wells Fargo
Houston

AT&T Corp. Center
Chicago

World Trade Center
New York

Willis Tower
Chicago

West Tower
Oxenhoj

West Tower
Oxenhoj

Federation Towers
Chicago

Federation Towers
Chicago

International Commerce Center
Hong Kong

San Francisco

Global Crossing
London

Citicorp
New York

Etox Island
New York

Bank of America
New York

Pennsylvania Station
New York

Lehman Building
New York

One Shell Plaza
Manhattan

Transamerica Pyramid
San Francisco

311 S. Wacker Drive
Chicago

One Liberty Plaza
New York

Meridian Midland Bank
New York

One Atlantic Center
Manhattan

Dealey Center
Chicago

Aon Center
Los Angeles

Flats Tower
Singapore

PETRONAS TOWER
Kuala Lumpur

Suntec City
Singapore

Jin Mao
Shanghai

Unosky Tower
Hangzhou

Sunshine 63
Taipei

Cheung Kong Center
Hong Kong

The Center
Shanghai

Landmark Tower
Shenzhen

China World Towers
Beijing

The Great Wall
Beijing

Dalian International Hotel
Dalian

Taikoo Trust Tower
Shenzhen

Guangzhou International Convention & Exhibition Center
Guangzhou

International Convention Center
Hong Kong

World Trade Center
New York

John Hancock Center
Chicago

Trump International Hotel
Chicago

22 Marshall
Shanghai

300 North Michigan
Chicago

211 North Michigan
Chicago

150 North Michigan
Chicago

De La Salle Institute
Chicago

Robert A. Strakosch Plaza
Chicago

KPMG Building
Chicago

US Bank Tower
Los Angeles

The Center
London

LEED Gold Certified
Los Angeles

Diagonalized
Hong Kong

Core + outrigger
Hong Kong

Hybrid
Hong Kong

Total
75

Structural Systems

<table>
<thead>
<tr>
<th>No. of Buildings</th>
</tr>
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<tbody>
<tr>
<td>framed tube</td>
</tr>
<tr>
<td>bundled tube</td>
</tr>
<tr>
<td>tube in tube</td>
</tr>
<tr>
<td>diagonalized</td>
</tr>
<tr>
<td>core + outrigger</td>
</tr>
<tr>
<td>hybrid</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Types of Structural Systems:
- Framed tube
- Bundled tube
- Tube in tube
- Diagonalized
- Hybrid
- Core + outrigger
STRUCTURAL SYSTEM CENTRAL CORE

8 CANADA SQUARE (HSBC TOWER), LONDON

200m. 45 storeys.
STRUCTURAL SYSTEM MEGA FRAME

HONG KONG & SHANGHAI BANK

179m. 43 storeys. Steel Mega-Frame.
HERON TOWER, LONDON

230m. 48 storeys. Open C-section tube, cantilevered core
WORLD TRADE CENTRE, NEW YORK

417m. 110 storeys. Steel Tube. Columns @ 1m. Aspect Ratio 6.6
STRUCTURAL SYSTEM BRACED TUBE SYSTEM

JOHN HANCOCK TOWER, BOSTON
344m. 100 storeys. Braced Steel Tube. Columns @ 12m.
STRUCTURAL SYSTEM BUNDLED TUBE SYSTEM

SEARS TOWER, CHICAGO

442m. 110 storeys. Bundled Steel Tube. Columns @ 4.6m.
STRUCTURAL SYSTEM SPACE TRUSS

BANK OF CHINA, HONG KONG

369m. 70 storeys. Composite Space Truss.
STRUCTURAL SYSTEM OUTRIGGERS

IFC2, HONG KONG

407m. 88 storeys. Outrigger with composite columns.
PARC1, KOREA

334m. 72 storeys. Chevron braced tube with outriggers & composite columns. Aspect Ratio 8.
A key consideration in mega tall buildings is the overall floor structure weight. Minimisation of the building weight will benefit the foundations & reduce seismic loads.

Acoustic / vibration criteria also needs to be satisfied, along with the integration of MEP services.

Floor construction cycles are heavily dictated by the chosen solution, and can vary the overall tower construction programme.
Settlement control critical to prevent tilt.

Soil – structure interaction analysis may be required for accurate determination of foundation flexibility.

Thick pile rafts minimize differential settlements. To limit overall settlement, majority of working load should be resisted by friction only for deep foundations (piles).

TAM ‘tube à manchette’ base grouting to mitigate ‘soft toe’
- **Top-down construction** whilst being a more expensive from a capital cost can actually save time in the overall construction duration.
KEY CONSIDERATIONS FOR SEISMIC DESIGN
SEISMIC DESIGN Key Considerations

- Seismic design philosophy focuses on safety rather than comfort.

- For Design Level Earthquakes, structures should be able to resist:
  - ✓ Minor shaking with no damage
  - ✓ Moderate shaking with no severe structural damage
  - ✓ Maximum design level shaking with structural damage but without collapse

- Tall or small? Which is safer?

Source: FEMA Mexico City Earthquake, 1985
SEISMIC DESIGN Key Considerations

<table>
<thead>
<tr>
<th>Plan Conditions</th>
<th>Resulting Failure Patterns</th>
</tr>
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<tbody>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<td><img src="image3" alt="Diagram" /></td>
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<td><img src="image5" alt="Diagram" /></td>
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<td><img src="image7" alt="Diagram" /></td>
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<td><img src="image12" alt="Diagram" /></td>
</tr>
<tr>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
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</tbody>
</table>

- Torsional Irregularity: Unbalanced Resistance
- Re-Entrant Corners
- Diaphragm Eccentricity
- Non-parallel LFRS
- Out-of-Plane Offsets

Source: FEMA
### SEISMIC DESIGN Key Considerations

<table>
<thead>
<tr>
<th>Vertical Conditions</th>
<th>Resulting Failure Patterns</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td>▪ Stiffness Irregularity: Soft Story</td>
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<tr>
<td><img src="image2.png" alt="Image" /></td>
<td>▪ Mass Irregularity</td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td>▪ Geometric Irregularity</td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td>▪ In-Plane Irregularity in LFRS</td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td>▪ Capacity Discontinuity: Weak Story</td>
</tr>
</tbody>
</table>

Source: FEMA
CASE STUDIES One Raffles Quay, Singapore

Core + Outrigger + Belt Truss

- Extremely efficient system: outriggers engage perimeter columns & reduce core overturning moment.
- Exterior column spacing meets aesthetic & functional requirements, unlike tube systems.
- 50 storey tower directly above existing subway tunnels
- Unique transfer systems

![Diagram of core + outrigger + belt truss system](image)

50 storey, 245m
CASE STUDIES One Raffles Quay, Singapore

Core + Outrigger + Belt Truss
CASE STUDIES The Sail @ Marina Bay, Singapore

Core + Coupled Outrigger Shear Walls

- Towers have extreme slenderness ≈ 13
- Seismic design, super high strength concrete & unique strut-free retention system.
CASE STUDIES The Sail @ Marina Bay, Singapore

- Seismic design adopted for enhanced safety & robustness

Select Structure System & Materials

Modal Analysis

Building Dynamic Properties

Lateral Loads (wind, seismic), WTT

Dynamic Analysis (Response Spectrum Analysis)

Building Performance/Strength (Seismic Design to UBC 97)

T1 = 6.4s  T2 = 5.5s  T3 = 4.9s
**Seismic Design to UBC 97**

- Seismic Base Shear (V) depends on
  - Zone (Z), Soil Profile (S), Structural Framing (R), Importance (I), Time Period (T) & Weight (W)
  - \((0.11C_a I) W \leq V = \left(C_v I / R T\right) W \leq (2.5 C_a I / R) W\), where
    - \(Z\) represents expected ground acceleration at bedrock
    - \(C_a\) & \(C_v\) are coefficients depending on Soil Profile and Zone

<table>
<thead>
<tr>
<th>Seismic Zone</th>
<th>Zone Factor, Z</th>
<th>Base Shear, V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 2A</td>
<td>0.15g</td>
<td>2.4% W *</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(with special detailing)</td>
</tr>
</tbody>
</table>

*Governed by minimum load required by code*
CASE STUDIES The Sail @ Marina Bay, Singapore

- ≈ 60% higher loads
- Special detailing

### Structural Performance Indicators

<table>
<thead>
<tr>
<th>Structural Performance Indicators</th>
<th>Tower 1 (245m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Period</td>
<td>6.4 secs</td>
</tr>
<tr>
<td>Building Acceleration</td>
<td>14.1 milli-g</td>
</tr>
<tr>
<td>Inter-storey Drift under Wind</td>
<td>h / 550</td>
</tr>
<tr>
<td>Inter-storey Drift under Seismic</td>
<td>h / 280 (elastic), h / 70 (inelastic)</td>
</tr>
</tbody>
</table>

**Coupled Walls**

**Uncoupled Walls**

- ≈ 60% higher loads
- Special detailing
The 75-storey, 342m tower will be 2nd tallest building in Malaysia when completed in 2017.

Challenging project due to 12.5 slenderness ratio.

WT studies revealed significant wake vortices and strong cross wind effects.
An innovative lateral load resisting system was devised incorporating:

- suitably located fin walls
- two levels of concrete outrigger and perimeter belt walls,
- all coupled with the central core-walls.

CASE STUDIES Four Seasons Place, KL, Malaysia

Core + Outrigger Wall + Belt Wall + Fin Walls

Ty = 10.1s  
Tx = 6.4s  
Tr = 6.0s
CASE STUDIES  Thamrin Nine, Jakarta, Indonesia

- The 360,000m$^2$ mixed use development comprising 4 tall Towers is located in the central business district on Jalan Thamrin, Jakarta.

- The 71-storey, 325m tower will be the tallest building in Jakarta when completed in 2018.
CASE STUDIES Thamrin Nine, Jakarta, Indonesia

Core + Outrigger + Belt Trusses + Moment Frames

Ty = 7.2s  
Tx = 6.8s  
Tr = 3.2s

Outriggers & Belt Trusses

RC Walls/Columns/Beams/Slabs
# Seismic Design Parameters

**SNI-02-1726-2012/ ASCE 7 (2010)**

<table>
<thead>
<tr>
<th>Seismic Parameters</th>
<th>Values</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Classification</td>
<td>D</td>
<td>Medium hard soil.</td>
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<tr>
<td>$S_{ds}, S_{d1}$</td>
<td>0.57g, 0.36g</td>
<td>Spectral response acceleration parameters at short and 1 second periods</td>
</tr>
<tr>
<td>Importance Factor</td>
<td>I = 1.25</td>
<td>For general buildings &amp; structures</td>
</tr>
<tr>
<td>Response Modification Coefficient</td>
<td>R = 7</td>
<td>Ductile RC shear walls with special moment resisting frames</td>
</tr>
<tr>
<td>Risk Category</td>
<td>III</td>
<td></td>
</tr>
</tbody>
</table>

**Seismic Building Drift**

**CASE STUDIES** Thamrin Nine, Jakarta, Indonesia
CASE STUDIES  Thamrin Nine, Jakarta, Indonesia

**Structural Performance**

- **Elevation (m)**
- **Lateral Load (kN)**
- **Story Shear (kN)**
- **Story Moment (kN-m)**
- **Story Drift**

Elevation (m) vs. Lateral Load (kN), Story Shear (kN), Story Moment (kN-m), and Story Drift for both Wind and Seismic conditions.

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[Graphs and data related to structural performance metrics for Thamrin Nine, Jakarta, Indonesia.]
CASE STUDIES Thamrin Nine, Jakarta, Indonesia

Non-Linear Static Push-Over Analysis
CASE STUDIES Marina Bay Financial Centre, Singapore

Dual System: RC Core + Perimeter Frames

- Efficient system using
  - Central Services Core as the primary system
  - Coupled with the Perimeter Frame for additional stiffness

- Generally economical up to 50 ~ 60 stories.

50 storey
H = 245m

33 storey
H = 186m

Shear sway
Cantilever sway

Per. Columns
Core
PT Band Beams
Semi-Precast Slab
RC Spandrel Beams

Marina Bay Financial Centre, Singapore

CASE STUDIES Marina Bay Financial Centre, Singapore

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H = 186m

Shear sway
Cantilever sway

Per. Columns
Core
PT Band Beams
Semi-Precast Slab
RC Spandrel Beams

CASE STUDIES Marina Bay Financial Centre, Singapore

Dual System: RC Core + Perimeter Frames

- Efficient system using
  - Central Services Core as the primary system
  - Coupled with the Perimeter Frame for additional stiffness

- Generally economical up to 50 ~ 60 stories.

50 storey
H = 245m

33 storey
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CASE STUDIES  Tornado Tower, Doha, Qatar

Diagrid
- Conceived to integrate with architectural form.
- Extremely efficient “exterior structure” suitable for up to 100+ stories.
- Variant of tubular systems & exterior braced frames.
- Carries gravity & lateral forces in a distributive and uniform manner.

Effective because they carry shear by axial action of the diagonal members (less shear deformation).

52 storey, $H = 200m$

Joints are complicated
Curvilinear Form + Large Inclinations + Atrium Voids

Unique Engineering Challenge

- Lateral effect due to gravity loads
  - > 2 times design wind load
  - ≈ Zone 1 EQ
- All columns & internal walls curved
- Atrium voids throughout height
- Extremely weight sensitive
- Large building movements
- Lift operation & long-term serviceability challenges.

CASE STUDIES Signature Towers, Dubai, UAE
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Hybrid

- Structural System: **Core Wall + Rigid Frame + Outriggers + Belt Truss + Core Coupling Truss + Internal Braced Truss**

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- 65 storey, \( H = 305 \text{m} \)
- 79 storey, \( H = 351 \text{m} \)
- 52 storey, \( H = 251 \text{m} \)
CASE STUDIES  Signature Towers, Dubai, UAE

Un-deformed Shape

Self-WT Drift

Wind Load Drift

Earth-Quake Drift

H/840  360mm

H/1890  160mm

H/380  800mm
CASE STUDIES  Confidential Project, SEA

~120 storey, H = 610m, H/D ≈ 10

Core + Mega Columns + Outrigger + Belt Truss
- 400,000 m² of residential, hotel and commercial space.
- Civil & Structural Engineer for an international contractor.
• Structural Engineering is the science and art of designing & making, with economy and elegance, buildings, bridges, frameworks & other similar structures so that they can safely resist the forces which they may be subjected. ¹

• Structural Engineering is the art of moulding materials that we do not really understand .... into shapes that we cannot really analyze .... so as to withstand forces that we cannot really assess .... in such a way that the public does not really suspect. ¹

(¹: Stansfield, K. The Structural Engineer, 2006)
What is the general industry perception of a structural engineer?

1 + 1 = ?

The Mathematician

There exists a solution and it is unique.

The Physicist

Two point zero zero, plus or minus zero point zero two.

The Engineer

Oh, that's easy! It's two. No...better make it three, just to be safe.
STRUCTURAL ENGINEERS WHAT IS HIS VALUE

Generally, it is said that architects take the glory

& engineers take the blame......

Whatever the case may be, a good structural engineer has value way beyond his cost to his client !!

Hopefully this presentation has demonstrated how structural engineers can add value through innovative engineering solutions.
Balancing structural engineering needs with multiple other project requirements & constraints is always challenging.

This is specially true for tall buildings.

These varied challenges can however be addressed through innovative planning & unique design concepts.

Such engineering solutions benefit not only the projects themselves but also the construction industry as a whole.

In the future, more complex & taller buildings will regularly be conceived & constructed.

Structural engineers have the biggest contribution to make towards a better built environment.
MANY THANKS FOR YOUR ATTENTION