Super Tall Building Design Approach

Presented by:
Hi Sun Choi, P.E.
Principal, Vice President
March 6, 2009

Thornton Tomasetti

Thornton Tomasetti Inc. is a Registered Provider with The American Institute of Architects Continuing Education Systems. Credit earned on completion of this program will be reported to CES Records for AIA members. Certificates of Completion for non-AIA members are available on request.

This program is registered with the AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using, distributing, or dealing in any material or product. Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Copyright Materials

Thornton Tomasetti

Objectives

- Provide Guidelines for Super Tall Building Design Criteria
- Compare Structural Systems
- Compare Structural Shape Efficiencies
- Compare Aerodynamic Shape Efficiencies
- Wind Design + Bldg Motion
- Seismic Design
- Foundation Design
- Discuss Other Structural Considerations

History of Structures

- Stonehenge
  - 2500 BC ?
  - 76 feet (23m) tall
- Egyptian Pyramids
  - 2500 BC ?
  - 480 feet (146m) tall

Thornton Tomasetti

Lessons

- Truly 'monolithic'
  - mono = one
  - lith = stone
- All depends on the erector!

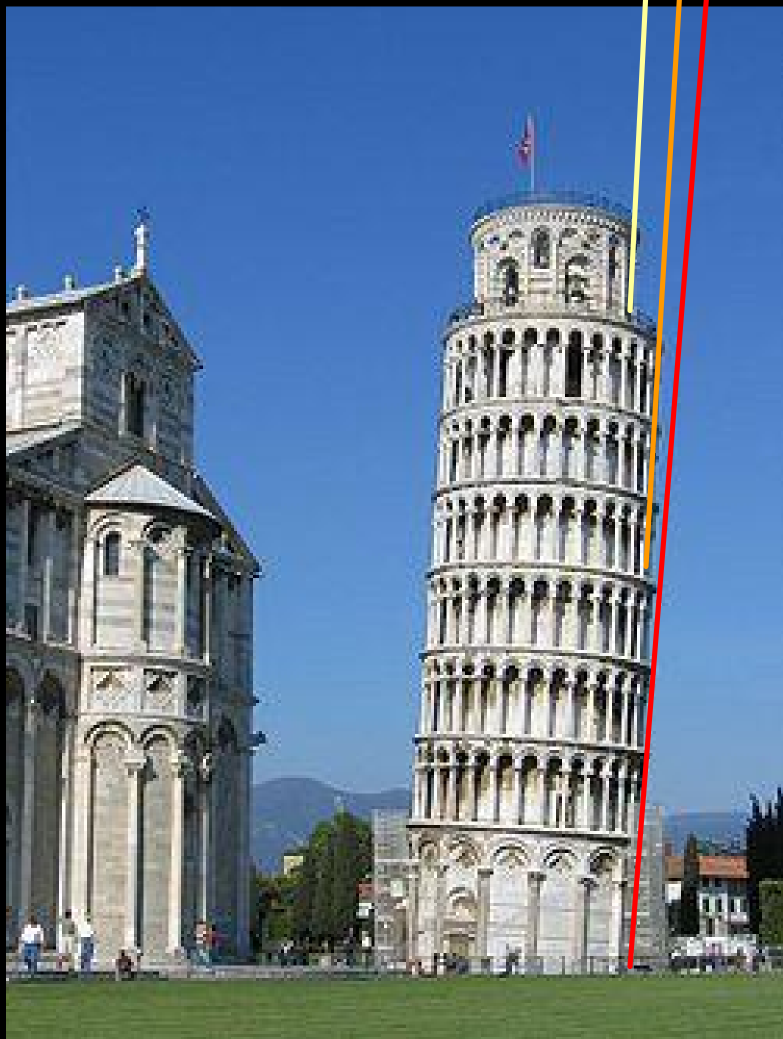
- Limited to stone
- Not slender
- Slope stability limit?
- Organization is key

History of Structures

- Tower of Pisa
  - 1350 AD
  - 183 feet (56m) tall

Thornton Tomasetti

Lessons



- Foundation settlement
  - Respect the geotech
- High aspect ratio = sensitive to small base movement
- Verticality during and after construction
- Correction attempted as they built

History of Structures

- Empire State Building
  - 1931
  - 102 stories
    1453 feet (443m) tall

Lessons

- Steel frame
- Full-width moment frames
- Window strips, masonry strips, trim
- Fast construction
  - Super-organized

Thornton Tomasetti

History of Structures

- Burj Dubai
  - 2008
  - 162 stories (850M ?)

Thornton Tomasetti

Tallest 20 in 2020 by TT

Shanghai Center Doha Convention Center Pentominium

Thornton Tomasetti

How Tall? Or How Many Floors?

- Floor-to-Floor Height Estimates

  - Typical Office:

    11’ ~ 14’ (8’ ~ 9.5’clear)

    3.35m ~ 4.25m (2.5m ~2.9m clear)

  - Typical Residential:

    8’ ~ 11’ (7.5’ ~ 9’ clear)

    2.45m ~ 3.35m (2.3m ~ 2.75m clear)

What is "Aspect Ratio"?

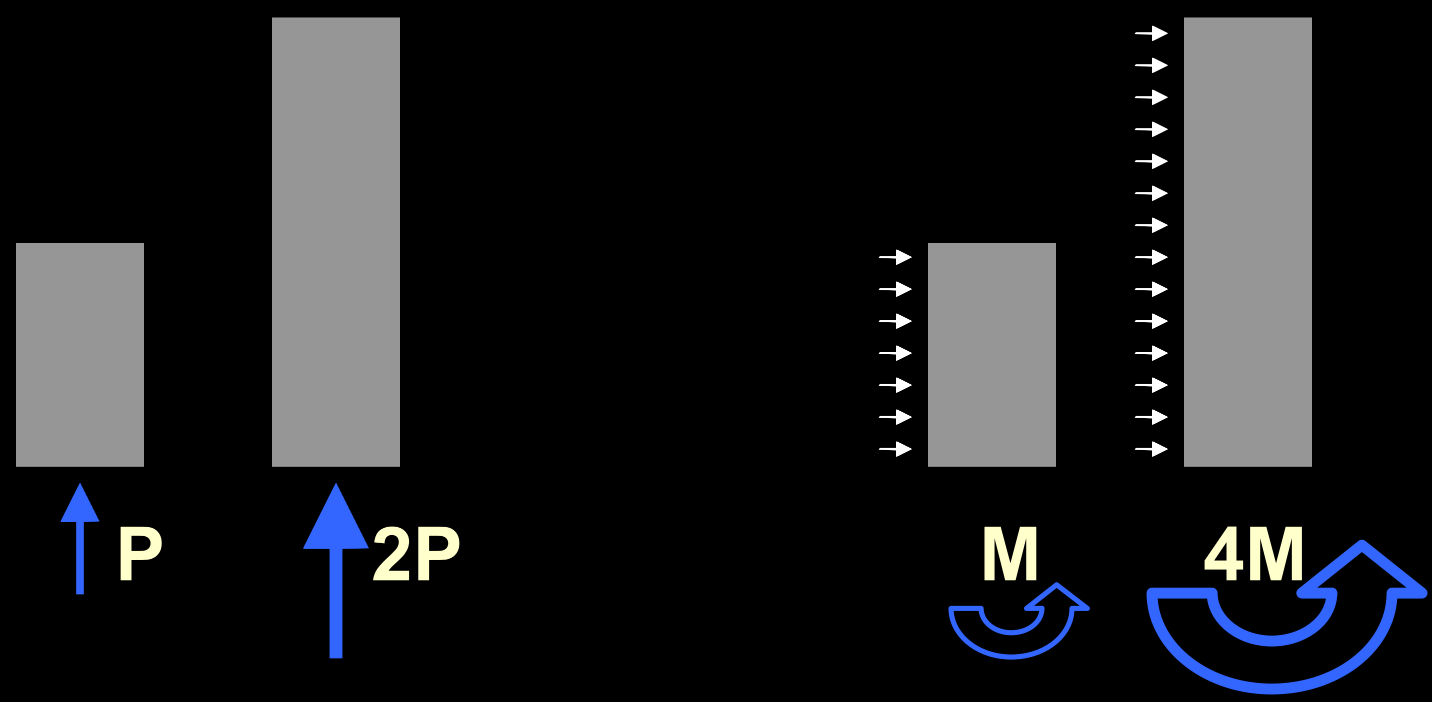
- Building height vs. footprint
- Aspect ratio (height/structural lateral system footprint width or depth)

  - Preferably <6
  - Could be >10 if special features to improve wind comfort are included

Evolution of Building Design Approach

- **Short Building : Strength Design**

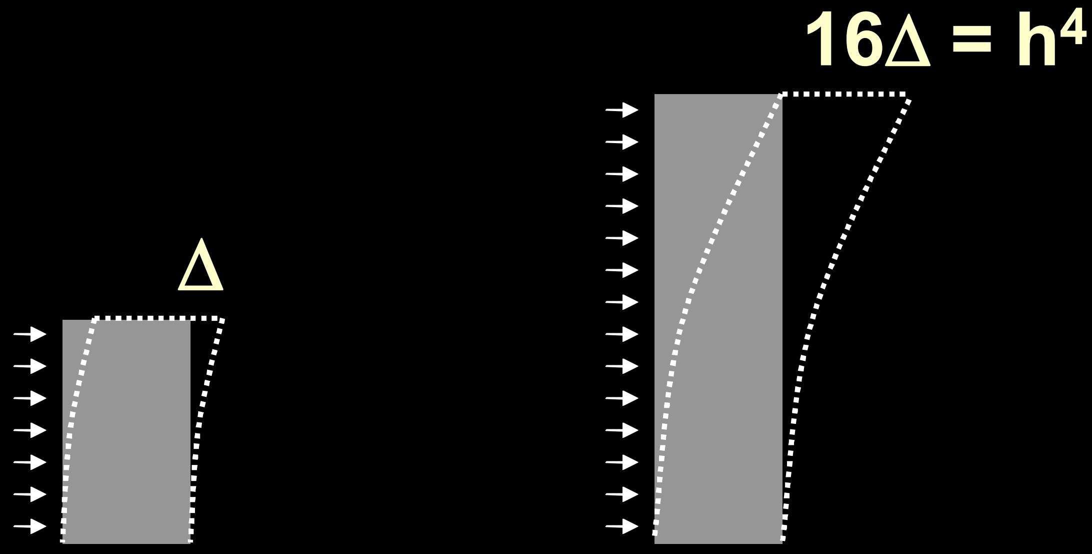
  Gravity Control (~h) – Strength Design (~h^2)



Thornton Tomasetti

Evolution of Building Design Approach

- **Intermediate Size Building: Deflection Lateral Load Control – Stiffness Design (~h^3)**

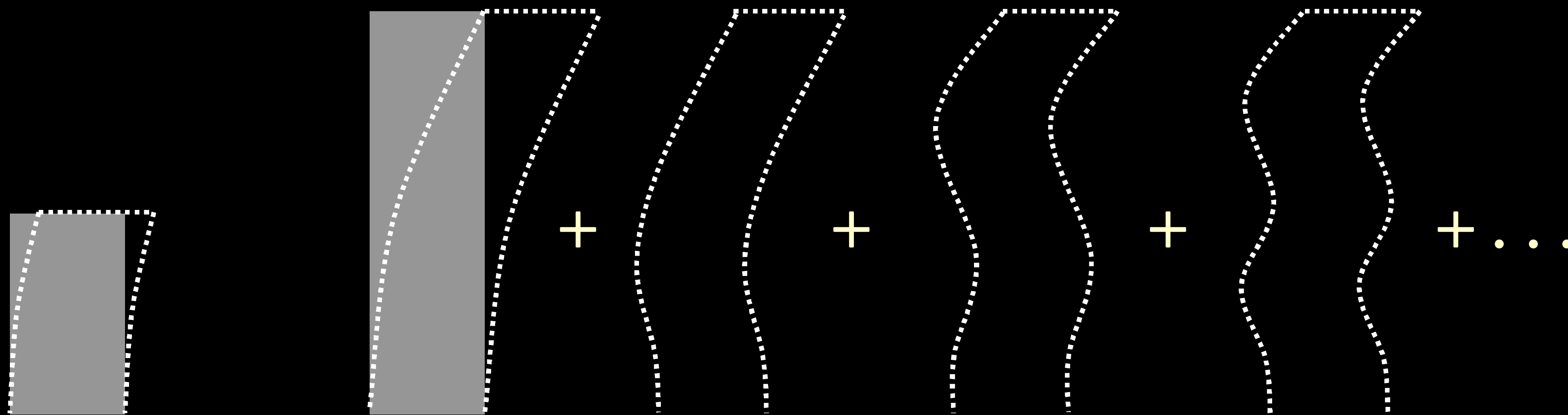


- **Drift limit based on h; $h^4 / h \sim h^3$**

Evolution of Building Design Approach

- **Tall Building:**

  Wind Induced Bldg Motion (acceleration) Control – Dynamic Stiffness Design (~h^3)



Evolution of Building Design Approach

- Force Based Design

    ➔

    - Displacement Based Design

        ➔

        - Performance Based Design

Building Drift or Lateral Deflection

- **Overall Building : no P-Delta**

US/Dubai	(10-20 year wind)	H / 400 – H / 500
Korea	(50-100 year wind)	H / 500

- **Inter-story Wind Drift: no P-Delta**

US/Dubai	(10-20 year)	h / 350
Korea	(50-100 year)	h / 350
China	(100 year)	h / 500 – h / 800 depends on H

- **Inter-story Seismic Drift : with P-Delta**

  Inelastic Drift < 0.01h – 0.02h (h / 100 – h / 50)

Thornton Tomasetti

Human Comfort Criteria under Wind-Induced Building Motions

- **US Practice:**

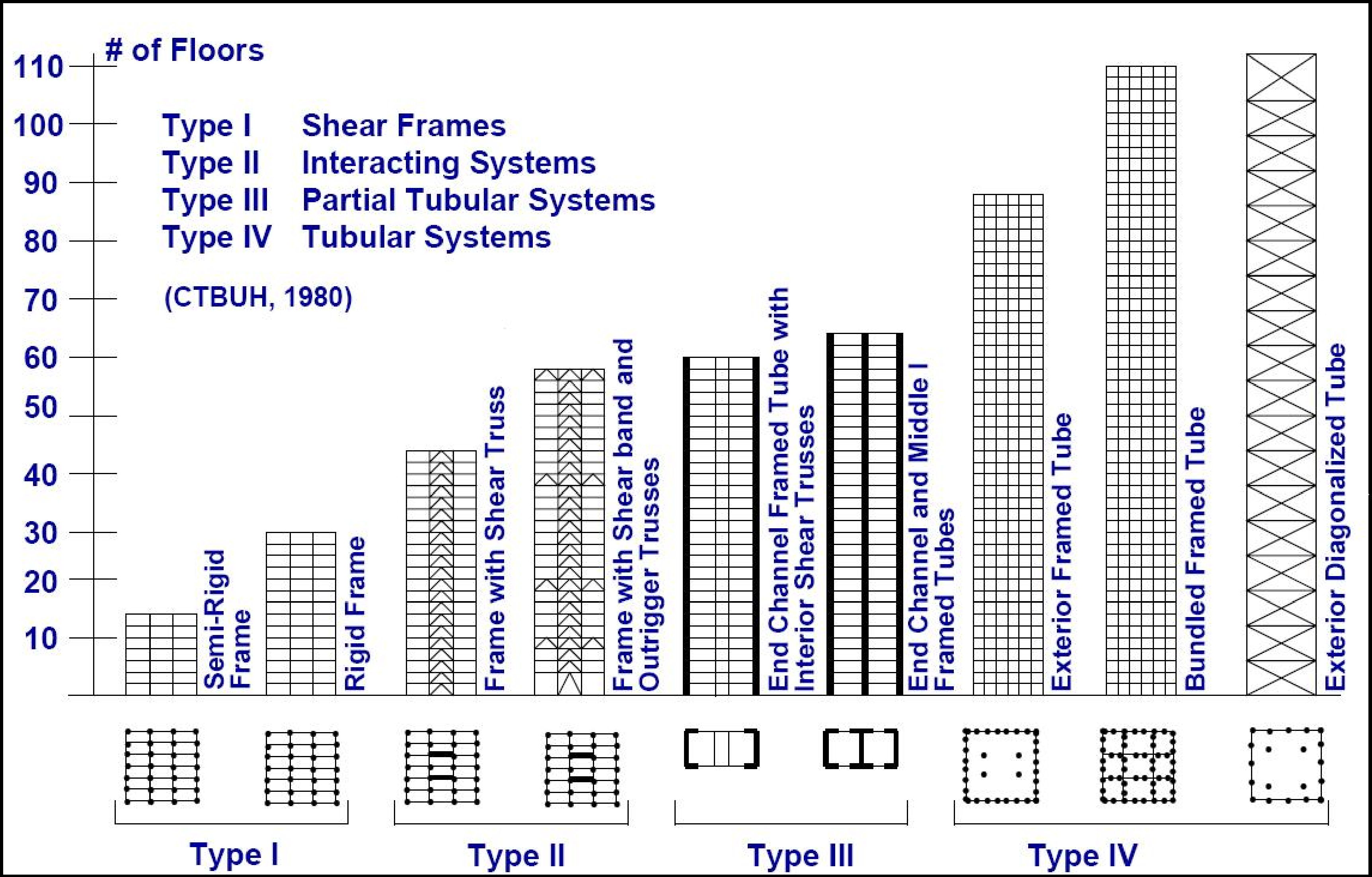
  Building Acceleration Limit (10 year wind)

Residential	= 10 – 15 milli-g
Hotel	= 15 - 20 milli-g
Office	= 20 - 25 milli-g
Retail	= 25 + milli-g

- **ISO based on 1 year**

- **Japanese Code (AIJ) based on 1 year seasonal**

Lateral Load Resisting Systems



Thornton Tomasetti

Ideal Structural Systems for Super Tall Buildings

- Flared
- Bundled
- Mega-Frame
- Linked
- Tripod

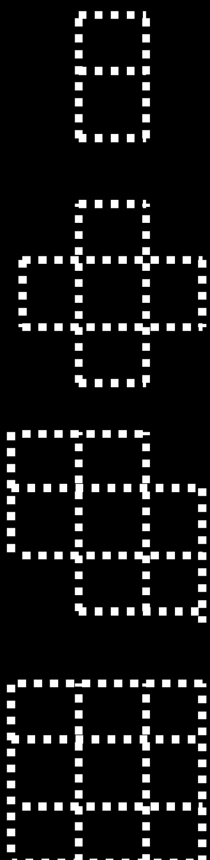
Structural System #1 ▪ Flared

Eiffel Tower

Burj Dubai

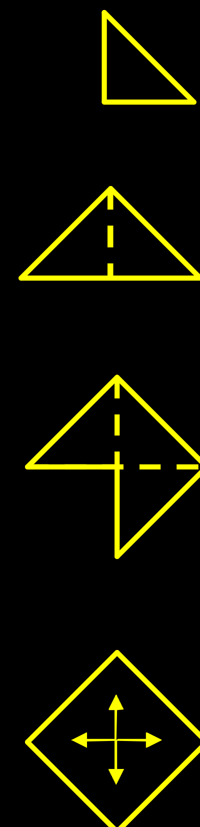
Thornton Tomasetti

Structural System #2 ▪ Bundled



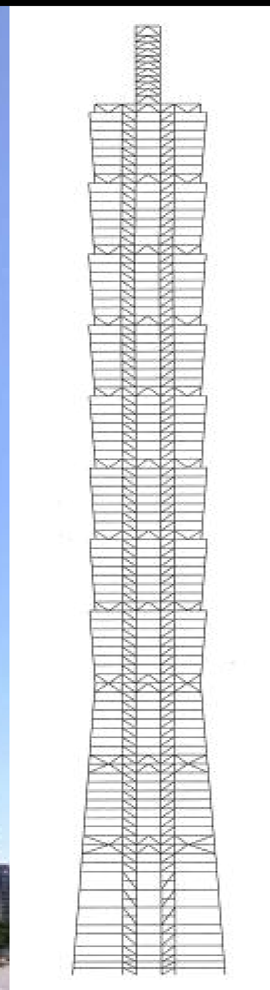
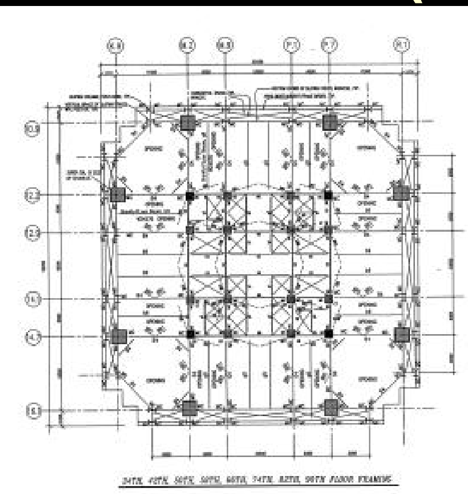
Sears Tower

Bank of China, HK



Structural System #3

- **Mega-Frame (Outriggers)**

Taipei 101

Jin Mao

Structural System #4

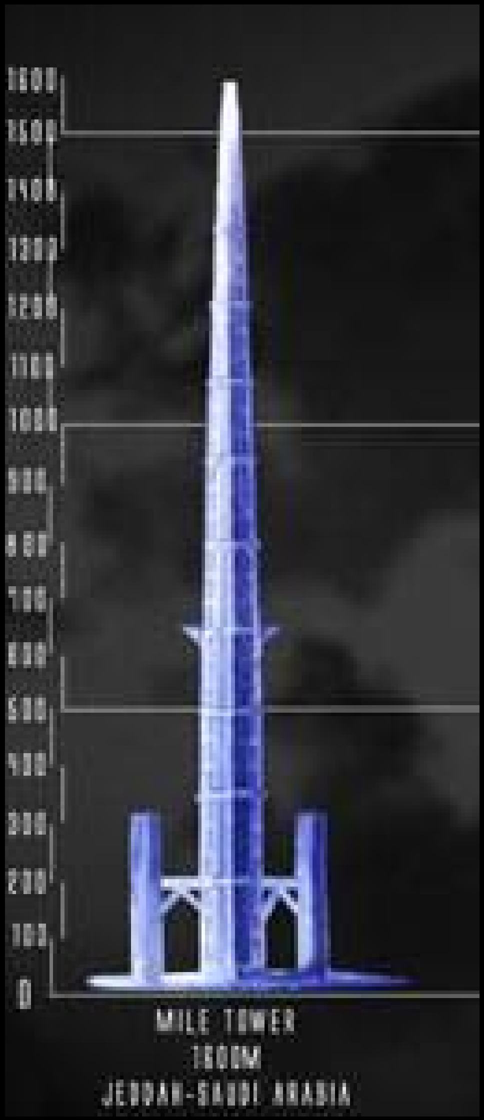
- Linked

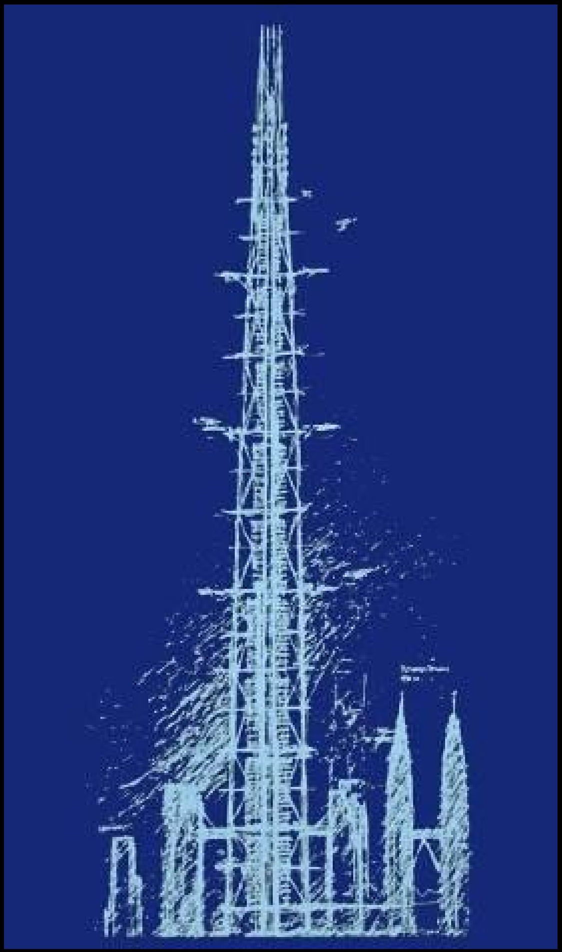
151 Incheon Tower

Nakheel Tower

Thornton Tomasetti

Structural System #5 ▪ Tripod Solution





Mile High Tower

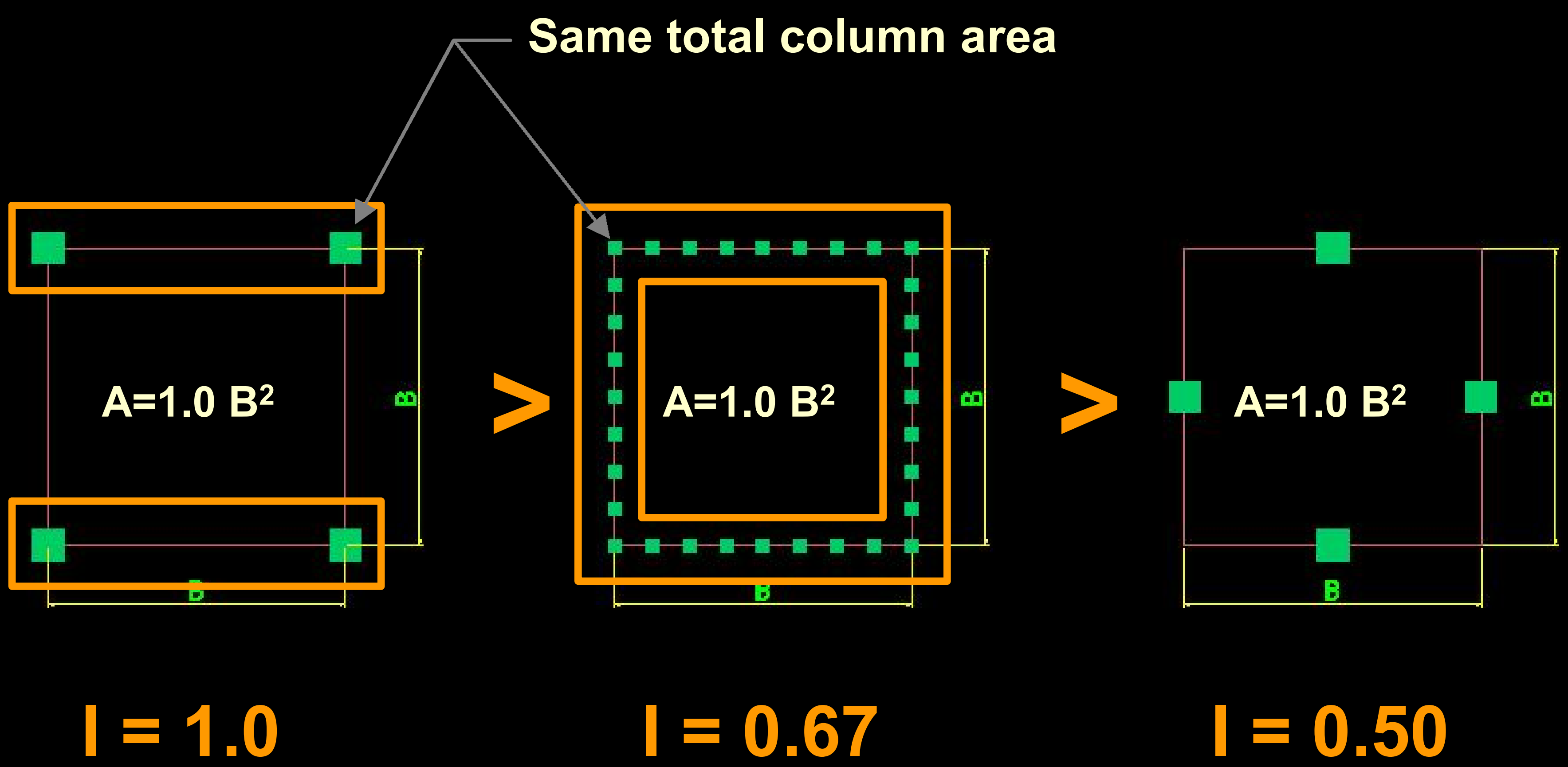
Thornton Tomasetti

Ideal Structural Shape Efficiencies

(Based on Building Stiffness for the Same Floor Area)

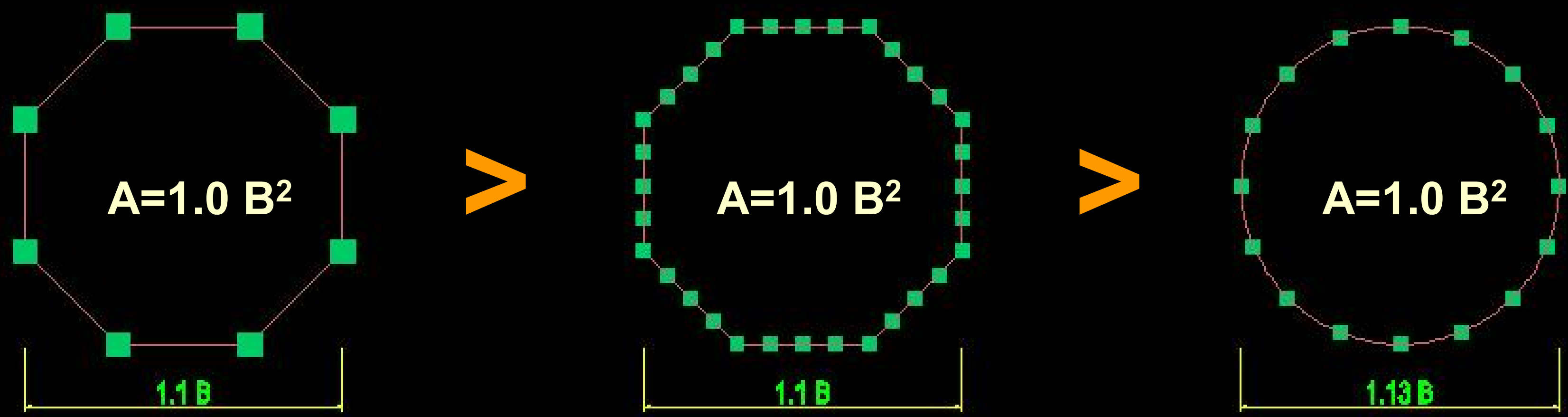
- Rectangular
- Circular (Polygon)
- Triangular

Rectangular Shape Efficiency



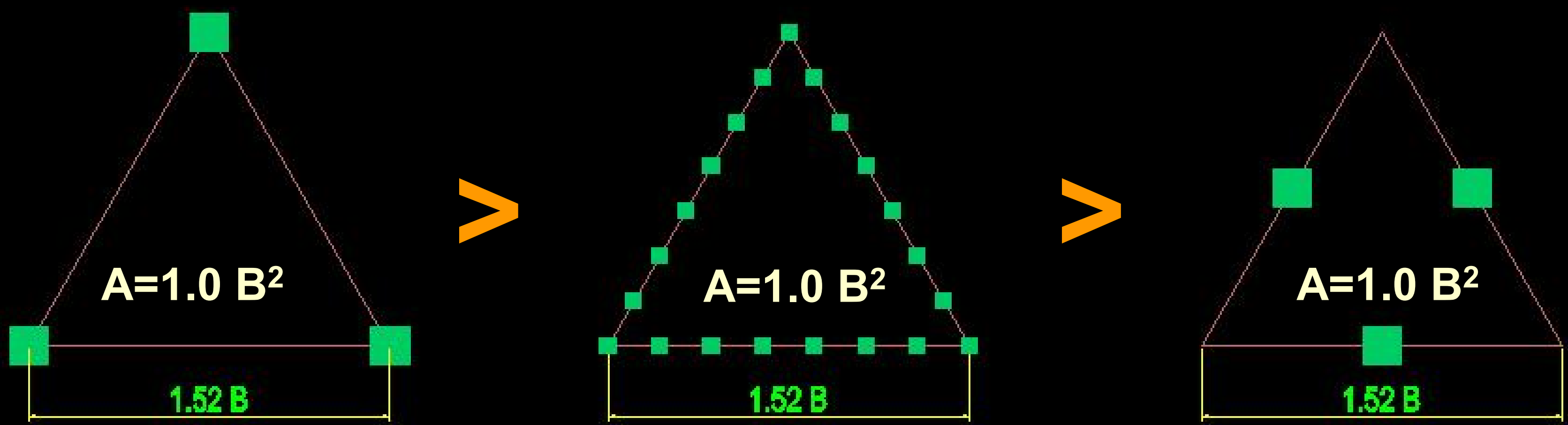
Thornton Tomasetti

Polygon/Circular Shape Efficiency



I = 0.71 I = 0.65 I = 0.64

Triangular Shape Efficiency



I = 1.54

I = 0.77

I = 0.38

Thornton Tomasetti

Ideal Structural Shape Efficiencies

(Based on Building Stiffness for the Same Floor Area)

- **Triangular > Rectangular > Circular (Polygon)**

  I = 0.77-1.54   I = 0.67-1.00   I = 0.64 – 0.71

  B = 1.52   B = 1.00   B = 1.1 -1.3

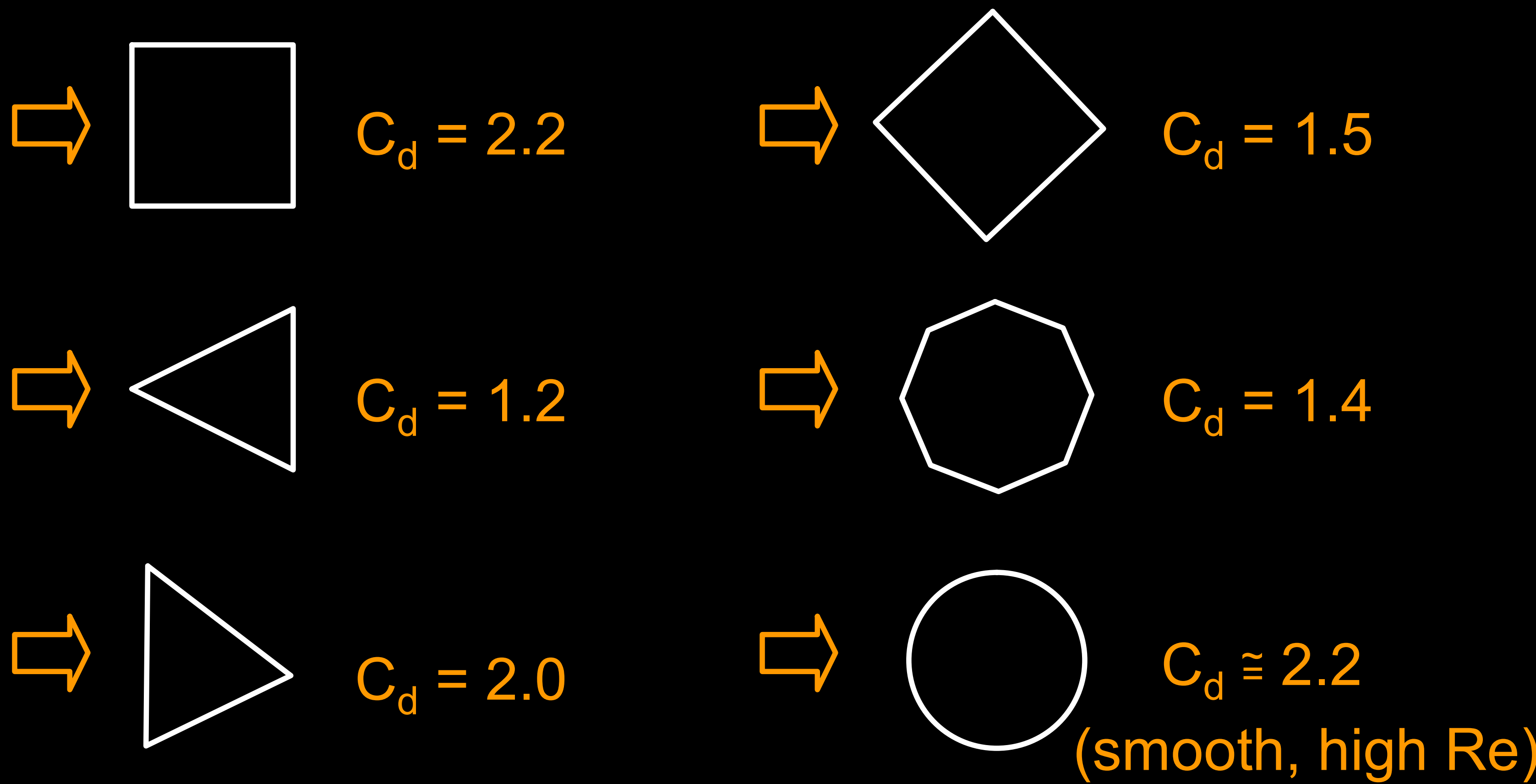
- **Lumped Corner Columns > Distributed Columns**

Thornton Tomasetti

Wind Design:
Building Shapes and Aerodynamics

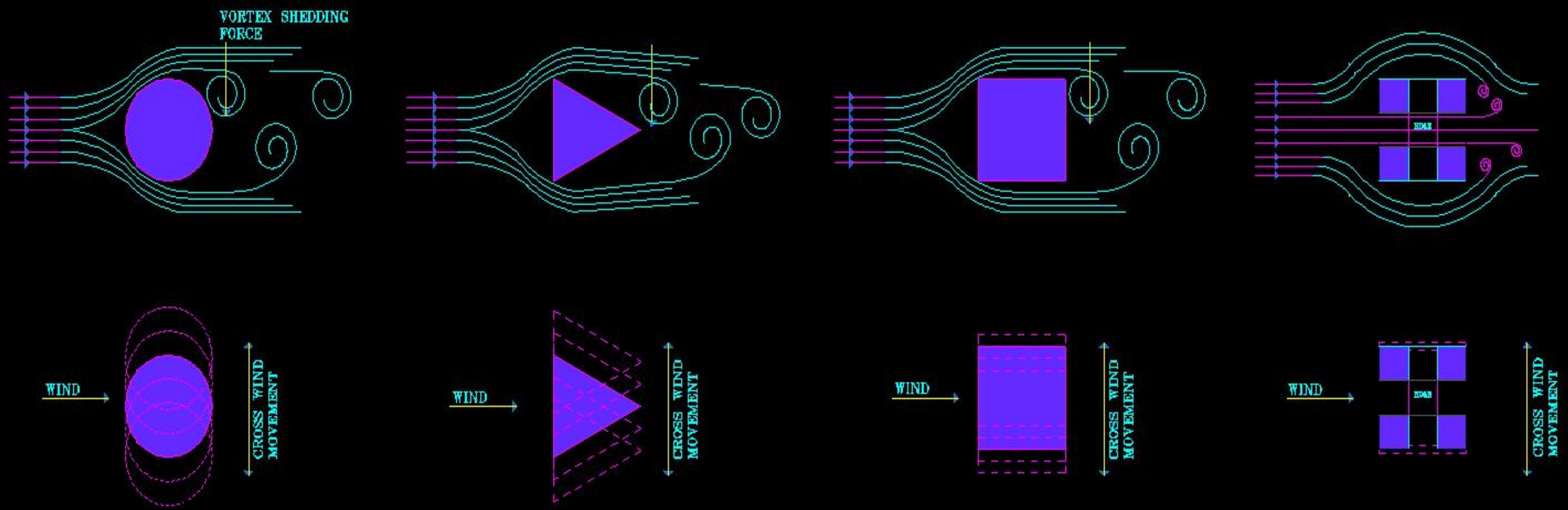
- Rectangular
- Circular
- Triangular

Drag Coefficient – along wind



Thornton Tomasetti

Vortex Shedding Effects - Crosswind

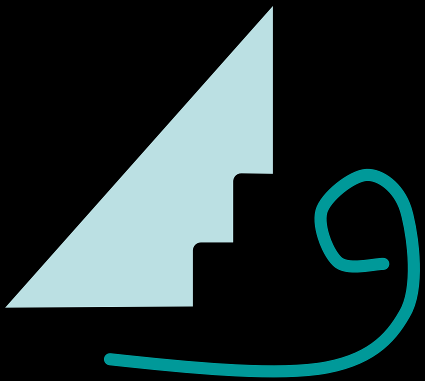


Modification to Building Shapes to reduce Wind Effect

- Stair Step Corner
- Through Building Openings
- Rotate ad Twist

‘Stair Step’ Corners

- **Rough corner can reduce Vortex Shedding effects.**



Taipei 101

Through-Building Openings

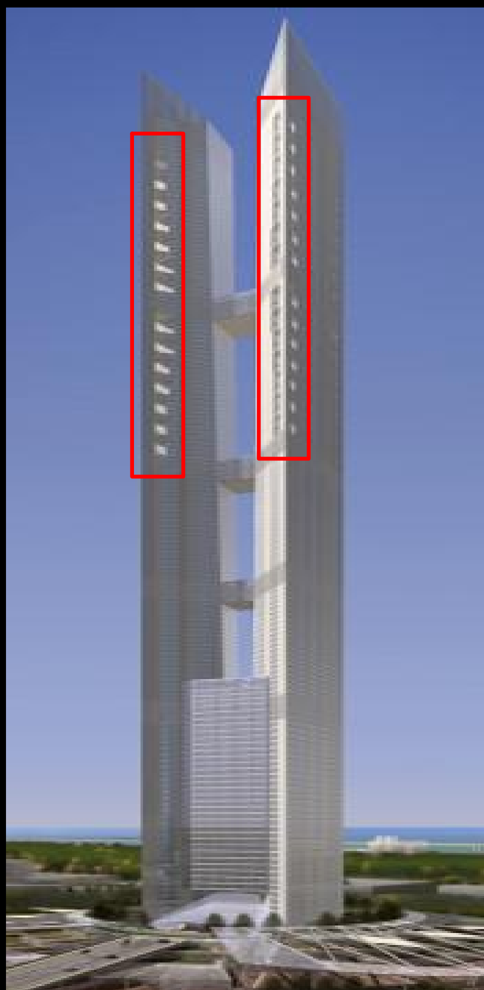
Shanghai Financial Center

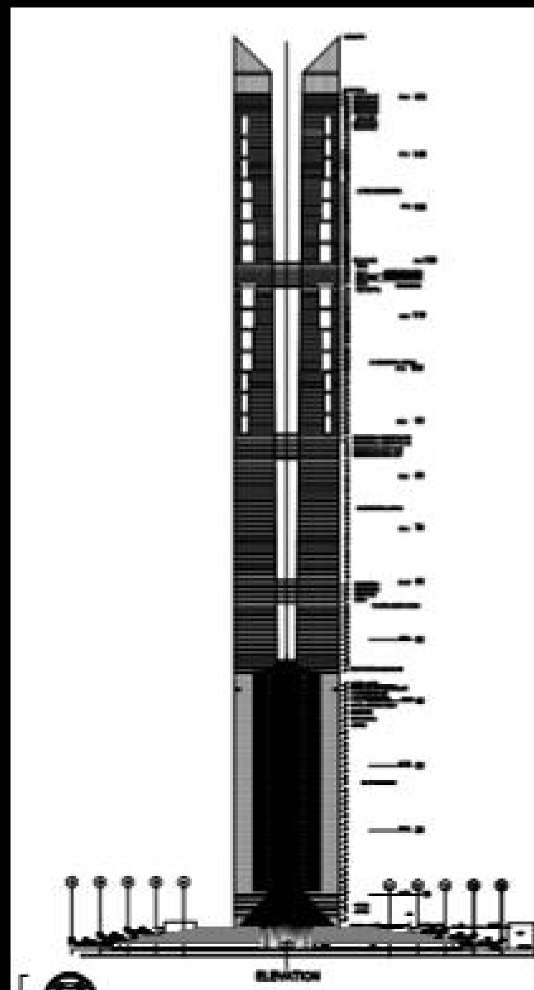
- **Openings reduce wind forces**

  (Reduced 'Sail Area')

Thornton Tomasetti

Through-Building Openings





151 Incheon Tower

- Slots reduce wind forces and sway from vortex shedding

Thornton Tomasetti

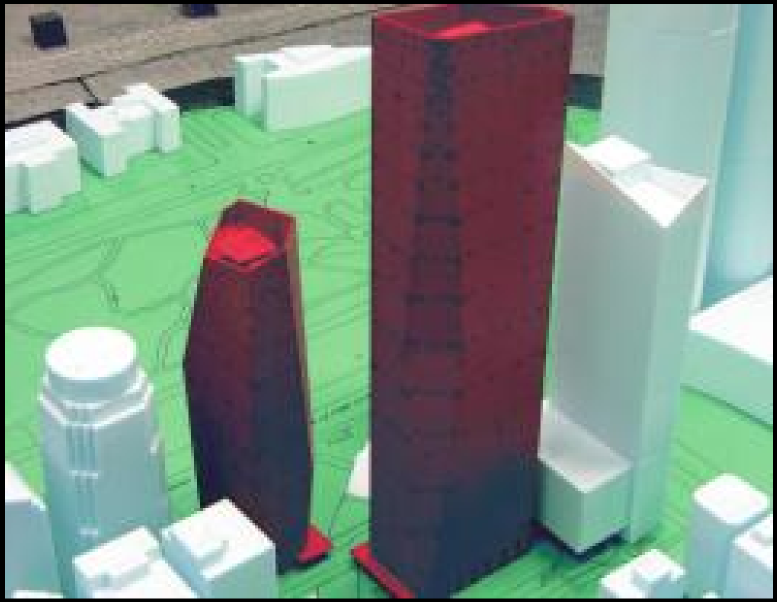
Rotate/Twist

Shanghai Center

- Rotate to minimize load from prevailing direction
- Twist avoids simultaneous vortex shedding along height

Wind Tunnel Test

- HFFB: High Frequency Force Balance Test
- Cladding 'Pressure Tap' Test
- HFPI: High Frequency Pressure Integration using rigid pressure tap model
- Aerodynamic Elastic Model Testing

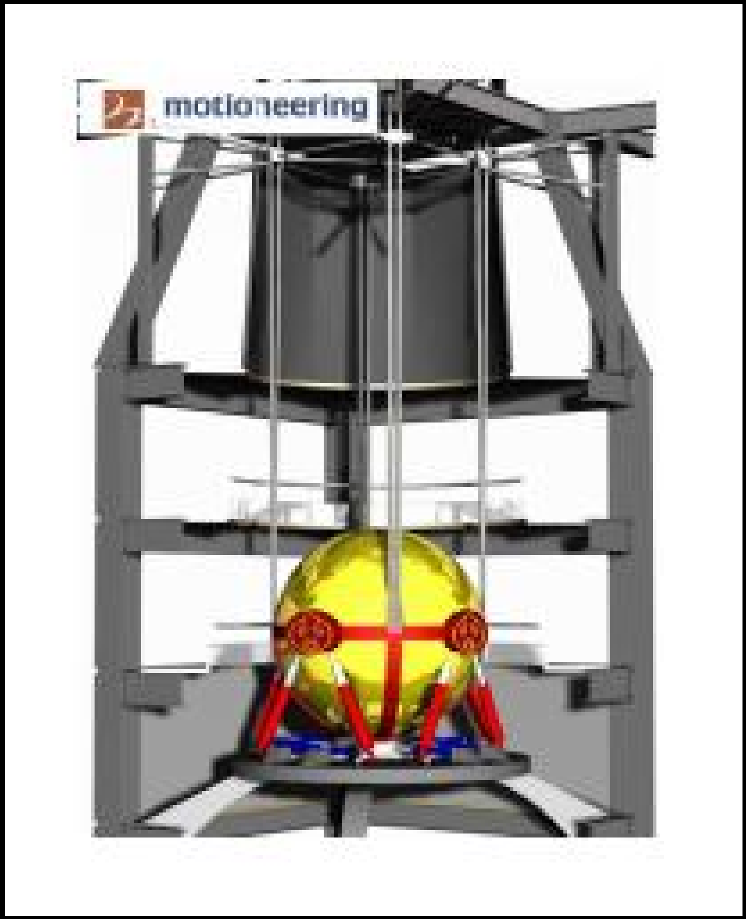


Damping and Dynamics

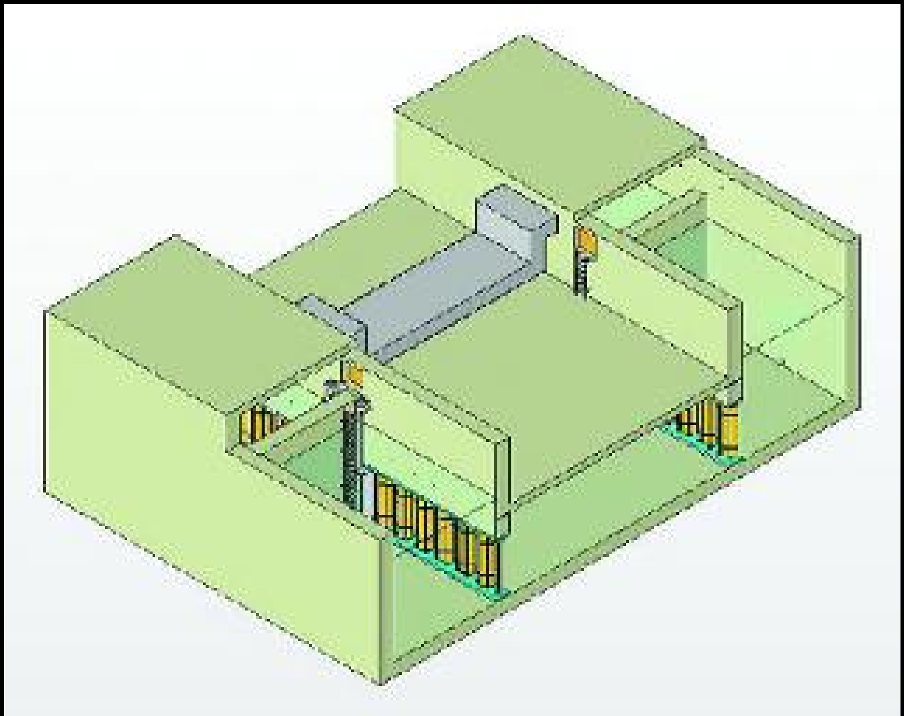
- Damping directly reduces bldg accelerations
- Some damping inherent in construction
  (Concrete framing > steel framing)
- When inherent damping is not sufficient, provide supplementary damping
- Dampers occupy space : Quantity and location based on modes to be treated
- Costs include purchase, installation, tuning, maintenance, inspection

Supplementary Damping Devices

Tuned Mass Damper



Tuned Liquid Column/Slush Damper



Seismic Design Issues

- Less critical than wind for tall building with long natural period

  - Minimum base shear may govern seismic

- Inter-story drift

  - max at upper floors

- Ductile detailing still important!
- Geometric compatibility
- Performance Based Design

Structural Material Selection (1)

- Availability of local material
- Reliability of material quality control
- Reliability of local labor and training
- Constructability (ability to erect large, heavy steel members)
- Relative cost
- Construction speed
- Architectural layout Impact
- Cultural attitudes

Structural Material Selection (2)

- Building weight
  - Foundation load
  - Net uplift
  - Seismic mass
- Dynamic behavior
  - Stiffness
    - Concrete E increases with strength
    - Steel E constant for all strengths
  - Period (~ mass / stiffness)
  - Damping

Foundation Design

- Intensive soil investigation and analysis
- Concentrated building weight affecting strength and settlement studies
- Construction sequences
- Model deep basement "anchor" against overturning vs. baseline at top of mat
- Pile depths – verticality
- Dewatering for deep basements

Building Height-related Issues (1)

- Differential column shortening and column cambering
  - Steel = elastic
  - Concrete = creep, shrinkage
  - Mixed (concrete core, steel perimeter) = severe differential

- Construction sequence for outriggers
  - Load redistribution
  - Delayed connections

Building Height-related Issues (2)

- Verticality during and after construction
- Effects on nonstructural components (cladding area, riser lengths, elevators, stairs, etc.)
- Experience in design and construction
- Capability to interpret codes
  - Apply international standards?

Building Height-related Issues (3)

- Concrete rate of strength gain
  - Slow loading of columns, foundations
  - Fast floor cycles
- Consistent specifications
  - Structure
  - Equipment (elevators)
  - Architecture (shaft sizes and tolerances)
- Appropriate Value Engineering

Thornton Tomasetti

Other Consideration
- Think Green

EDDIT Tower
Singapore

O14, Dubai

Thornton Tomasetti

Structural Sustainable Design

- Recycled materials
- Local manufacturers
  - Less travel distance = less pollution
- No waste of materials
- Fly ash or slag in concrete mixes

Design Team Requirement Highlights

- Collaborate with each other
- Respect professional opinions
- Try to meet all requirements
- Use all available resources
- Perform proper decision-making and value engineering
- Think green
- Work with experienced professionals!

Questions?

Thornton Tomasetti

This concludes The American Institute of Architects Continuing Education Systems Program

Thank you

Hi Sun Choi, P.E.
Thornton Tomasetti
51 Madison Avenue
New York, NY 10010
T 917.661.7800
F 917.661.7801