Regency Steel Asia Symposium on Latest Design & Construction Technologies for Steel and Composite Steel-Concrete Structures
09 July 2015

Design of Slender Tall Buildings for Wind & Earthquake

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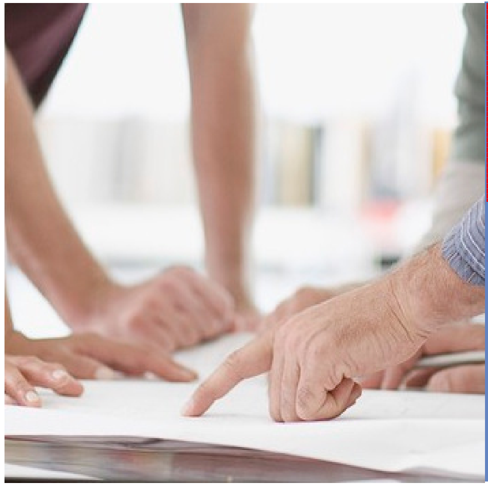

01

Structural Design Challenges for Tall Buildings

Structural Design Challenges for Tall Buildings

- Balancing structural needs vs. project demands are always a challenge …..specially for tall buildings.

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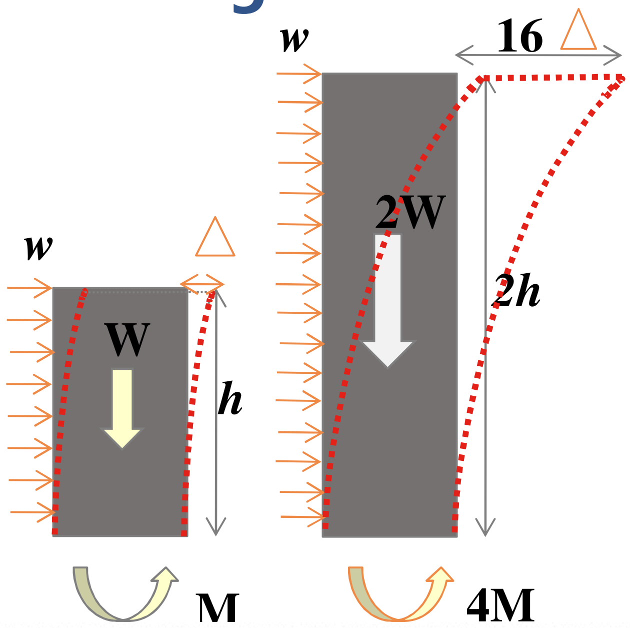
Structural Design Challenges for Tall Buildings

Premium for Height



Short Buildings:

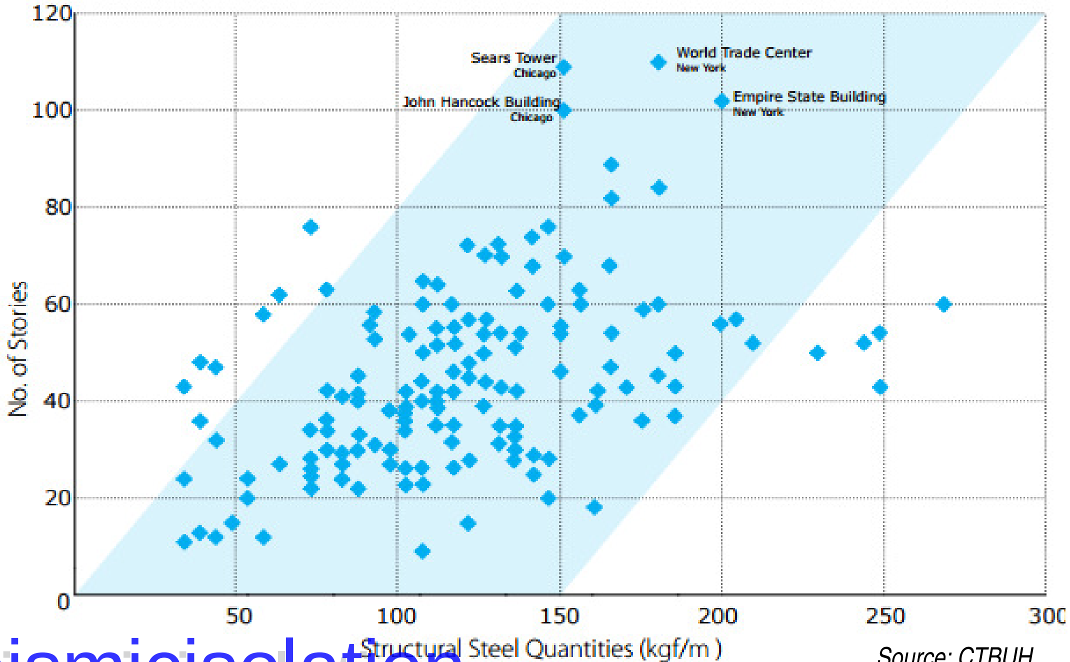
- Generally strength governs design
- Gravity loads predominant

Intermediate Buildings:

- Strength / drift governs design
- Gravity / lateral loads predominant

Tall Buildings:

- Generally drift / building motion governs design
- Lateral loads predominant

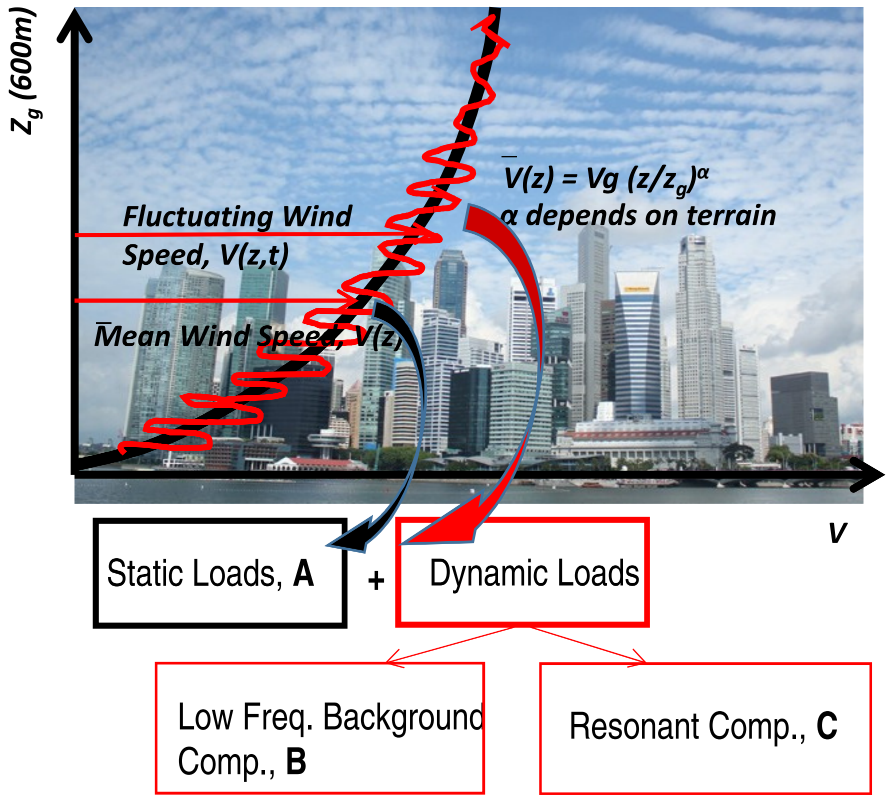


Source: CTBUH

Structural Design Challenges for Tall Buildings

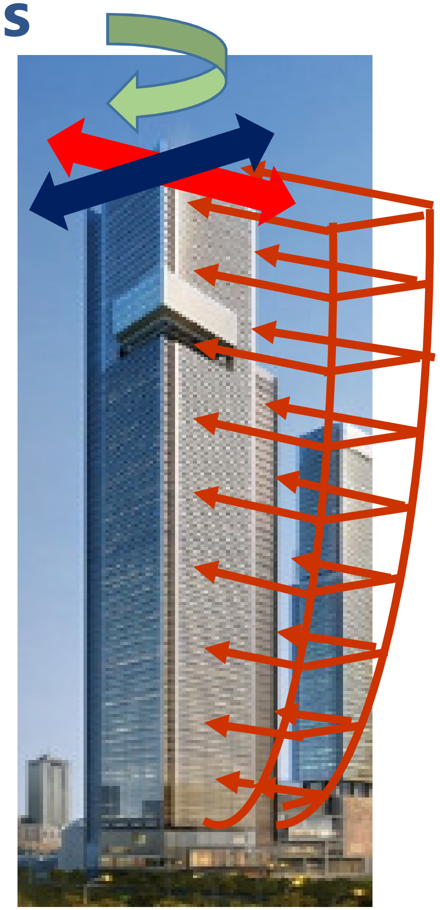
Wind

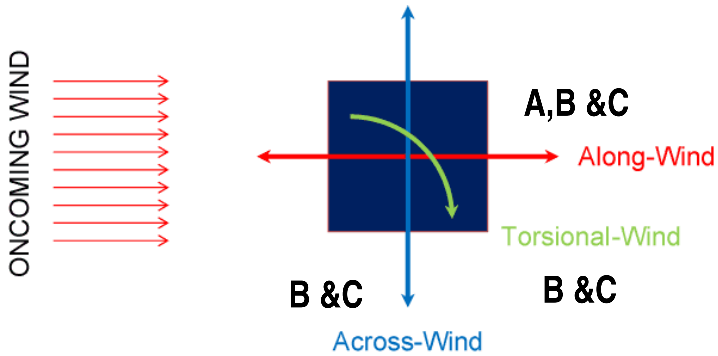
- As buildings get taller, wind-induced dynamic response starts to dictates the design.



A & B : Dependent on building geometry & turbulence environment

C : Dependent on building geometry. turbulence environment & structural dynamic properties (mass, stiffness, damping)





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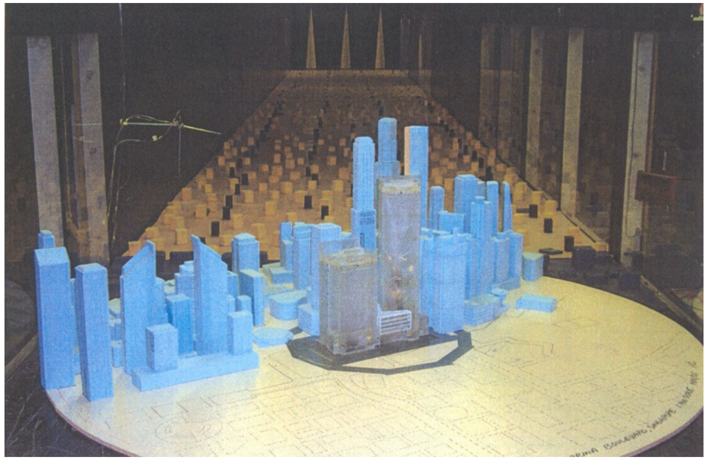
Structural Design Challenges for Tall Buildings

Wind

- For many tall & slender buildings *cross wind* response can govern loading & acceleration.

- *Wind codes generally cover along-wind response* based on the Gust Factor Approach – but little guidance on cross-wind & torsional responses.

- EN 1991-1-4 states that for slender buildings (h/d > 4), *Wind Tunnel Studies* are necessary if
  - ✓ *distance between buildings is < 25 x d*
  - ✓ *natural frequency < 1 Hz.*
- *BCA guidelines: H > 200m or f < 0.2Hz*



- Prediction of building dynamic properties: *natural frequencies, mode shapes & damping* have a great effect on the predicted wind loads & accelerations.

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Structural Design Challenges for Tall Buildings

Wind

- As an engineer, there are a number of approaches to minimize cross-wind response
  - ✓ *orientation*
  - ✓ *setbacks, varying cross-section*
  - ✓ *softened corners*
  - ✓ *twisting, tapering*
  - ✓ *introducing porosity*

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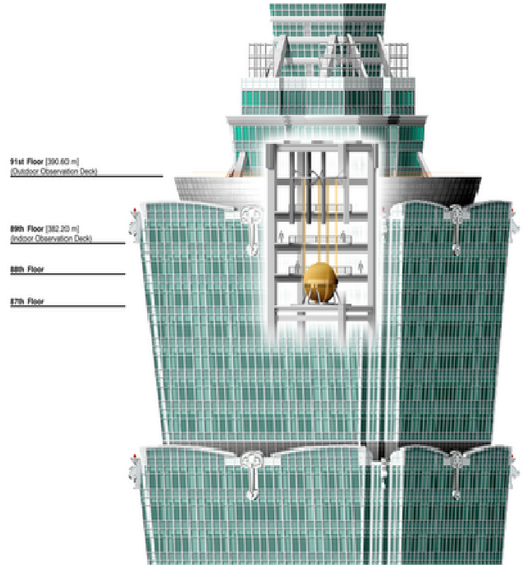
Structural Design Challenges for Tall Buildings

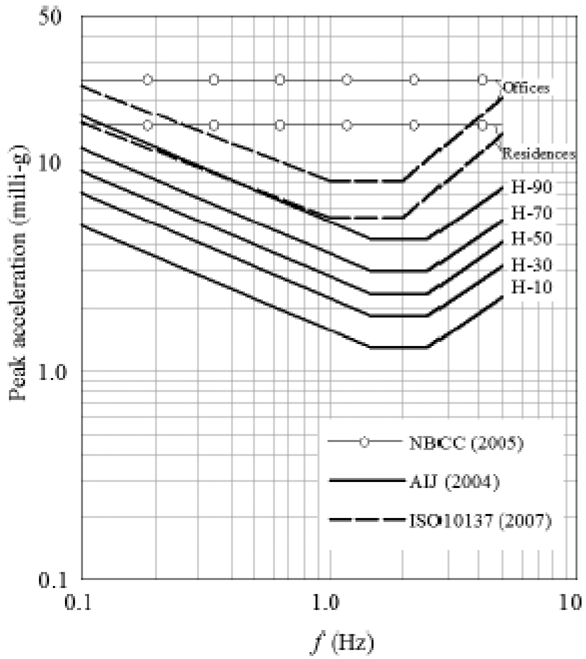
Occupant Comfort

- Tall buildings design often driven by occupant comfort criteria, i.e., limits to *lateral acceleration*

- *Two conditions* are generally important
  - ✓ *alarm* caused by large motions under *occasional strong winds*
  - ✓ *annoyance* caused by perceptible motions on a *regular basis* - *more important*

- Solutions include *stiffening* the building, *increasing mass* or use of *supplemental damping*.





Structural Design Challenges for Tall Buildings

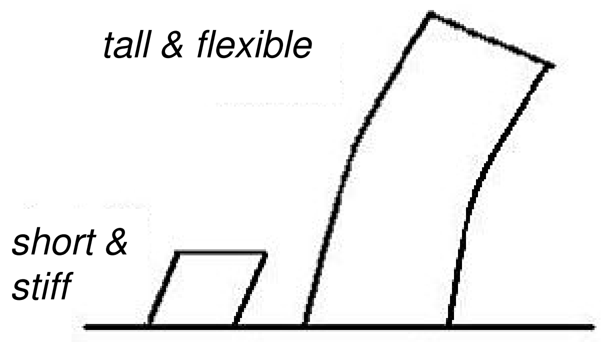
Drift

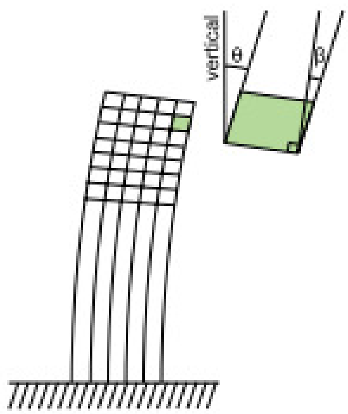
- Many codes specify (& some provide guidelines) for a deflection limit of *h/400 ~ h/600*.

- Drifts can be based on winds of *appropriate return period* - generally between 10 to 25 year return period winds.

- Story drifts have *two components*:
  - *Rigid body displacement*
    - ✓ Due to rotation of the building as a whole
    - ✓ No damage
  - *Racking (shear) deformation*
    - ✓ Angular in-plane deformation
    - ✓ Creates damage in walls and cladding

- *Limit can be reviewed* if damage to non-structural elements can be prevented, especially the façade, & lift performance is not affected.





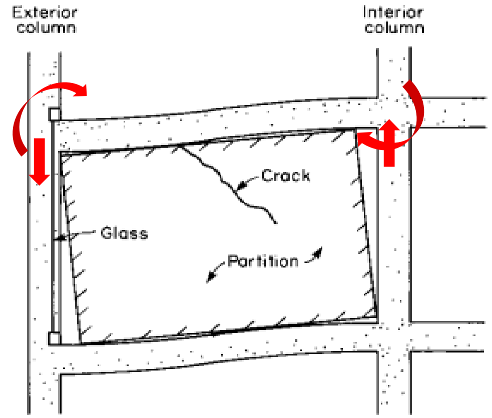
Structural Design Challenges for Tall Buildings

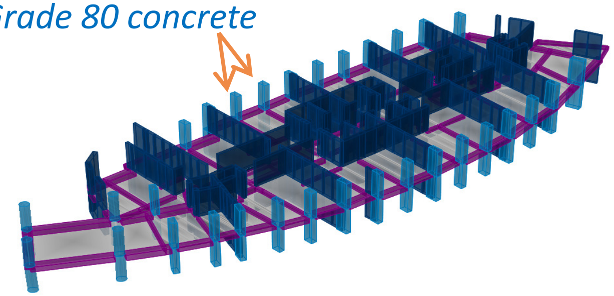
Differential Shortening

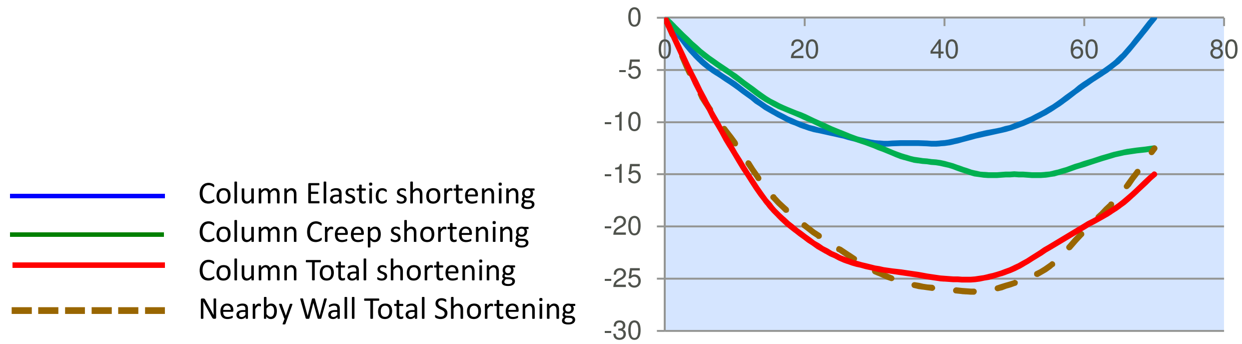
- Differential shortening of vertical elements *need special consideration*.

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

- Mitigation options include appropriate *stiffness proportioning*, choice of *material*, vertical *cambering*, etc..







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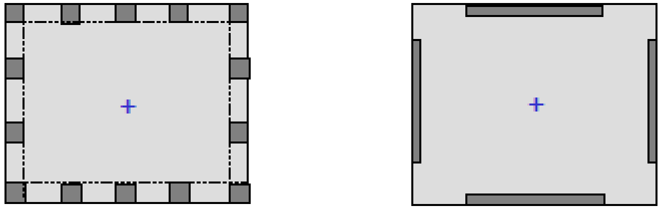
Structural Design Challenges for Tall Buildings

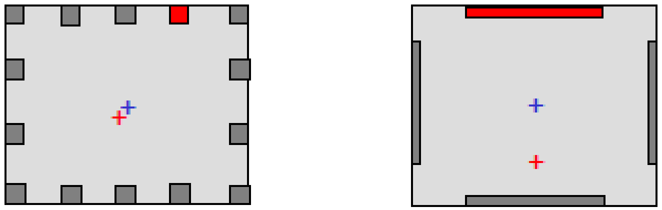
Robustness

Same strength & deformation capacity



System A System B

Which system is better?



System A System B

What is the impact of *premature loss* of one element?

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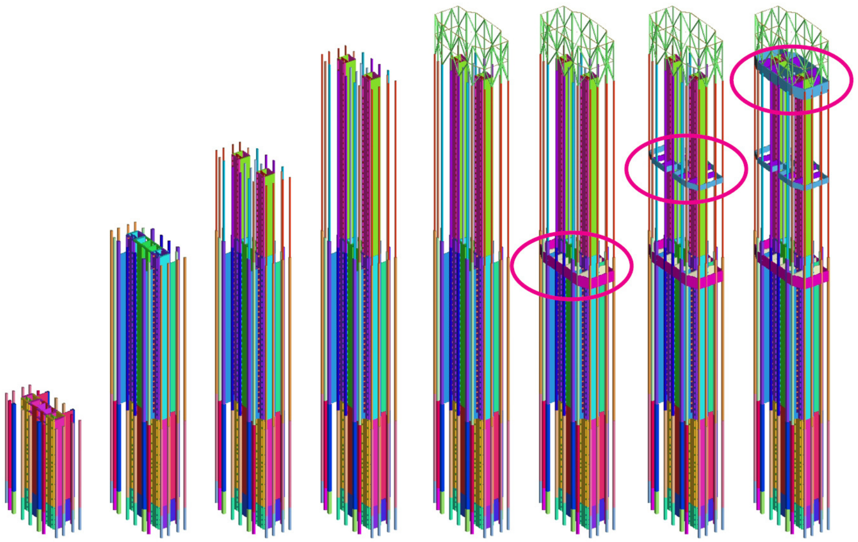
Structural Design Challenges for Tall Buildings

Sequential Analysis

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

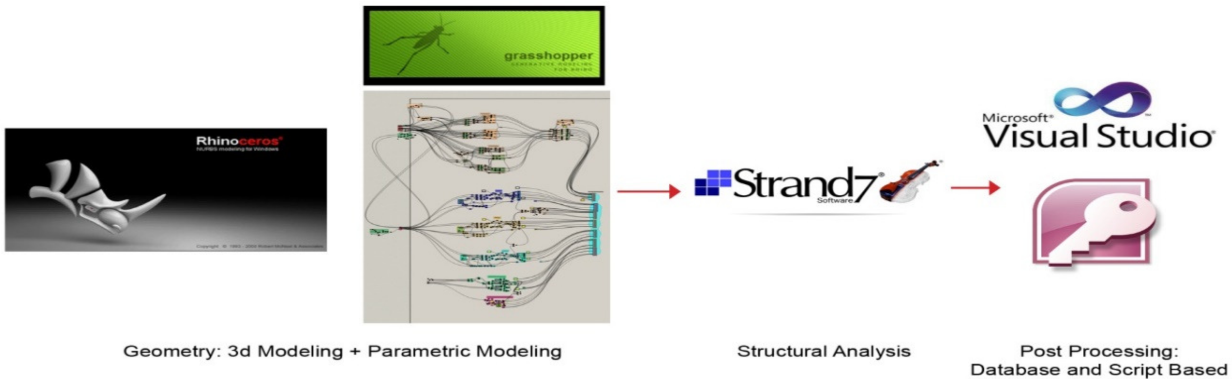
- Becomes more *complex on non-symmetric structures* where the axial shortening can cause floors to twist and tilt under self weight.

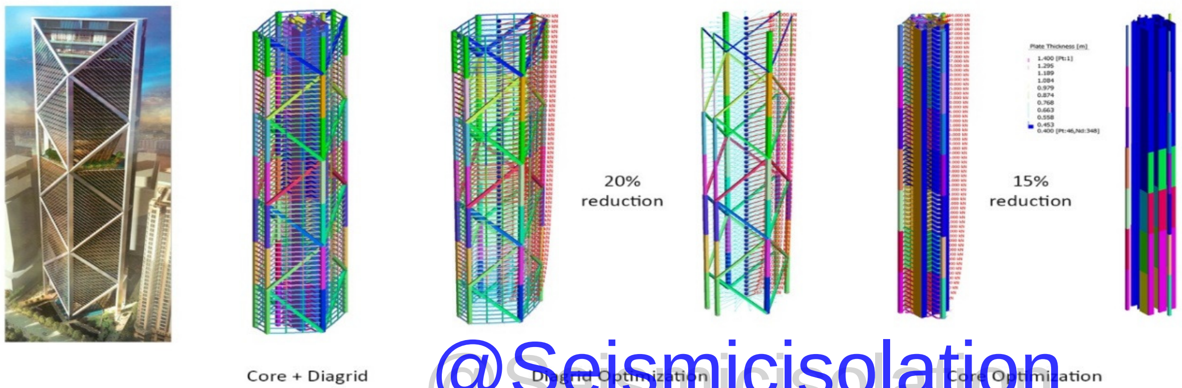


Structural Design Challenges for Tall Buildings

Structural Optimization

- Tall buildings are *big budget projects* – small savings per sq. m can become large amounts of money.
- Efficiency & economy are *not defined by codes*.
- *Custom programs & scripts required* to interface directly with commercial structural analysis packages to rapidly and efficiently establish optimum element sizes.





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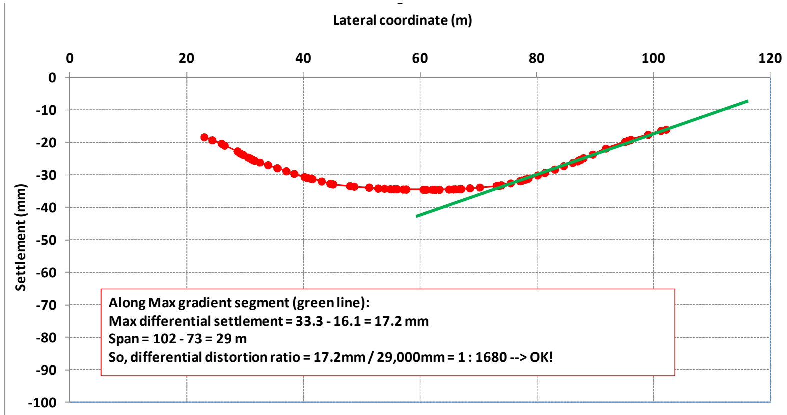
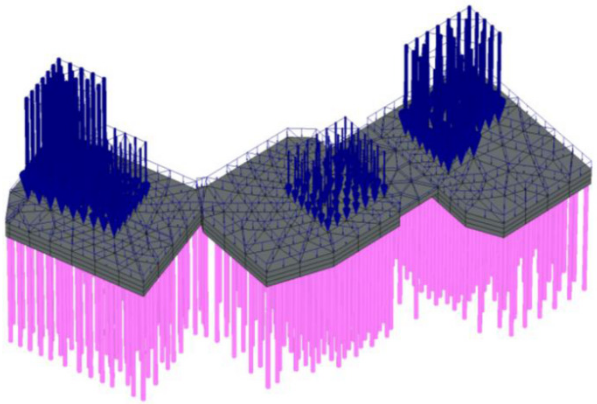
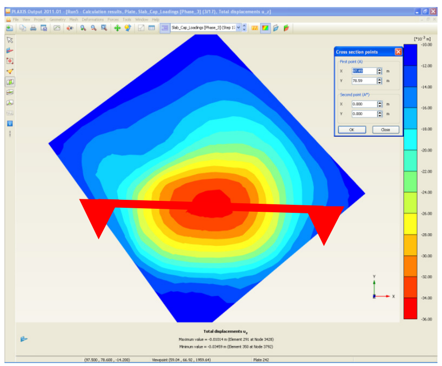
Structural Design Challenges for Tall Buildings

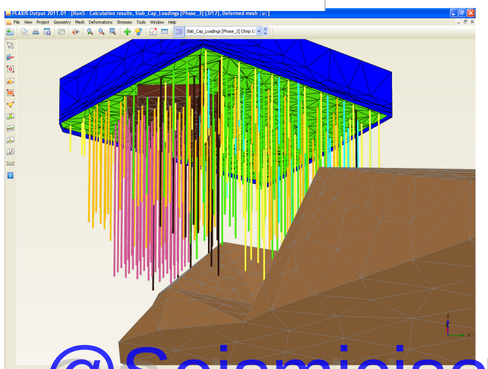
Foundation Settlements

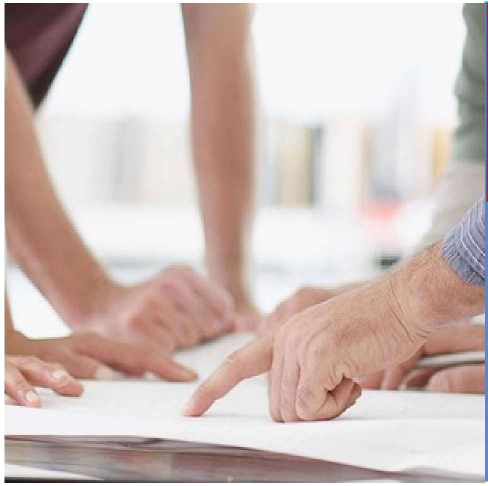
- Settlement control critical for tall buildings to *prevent tilt*.
- *Soil – structure interaction analysis* may be required for accurate determination of foundation flexibility.
- *Thick pile rafts* minimize differential settlements.











02

Structural Systems for Tall Buildings

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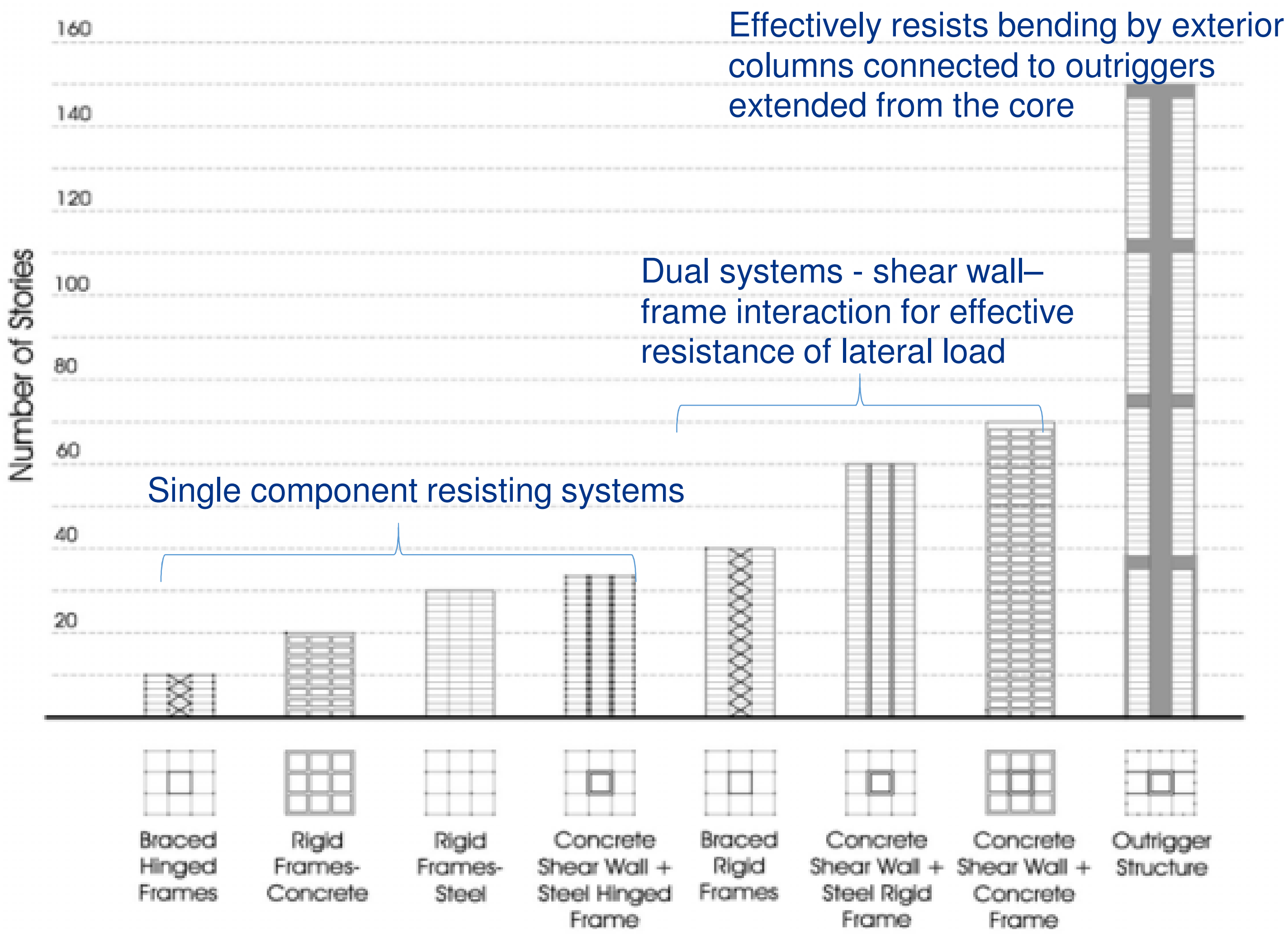
Structural Systems for Tall Buildings

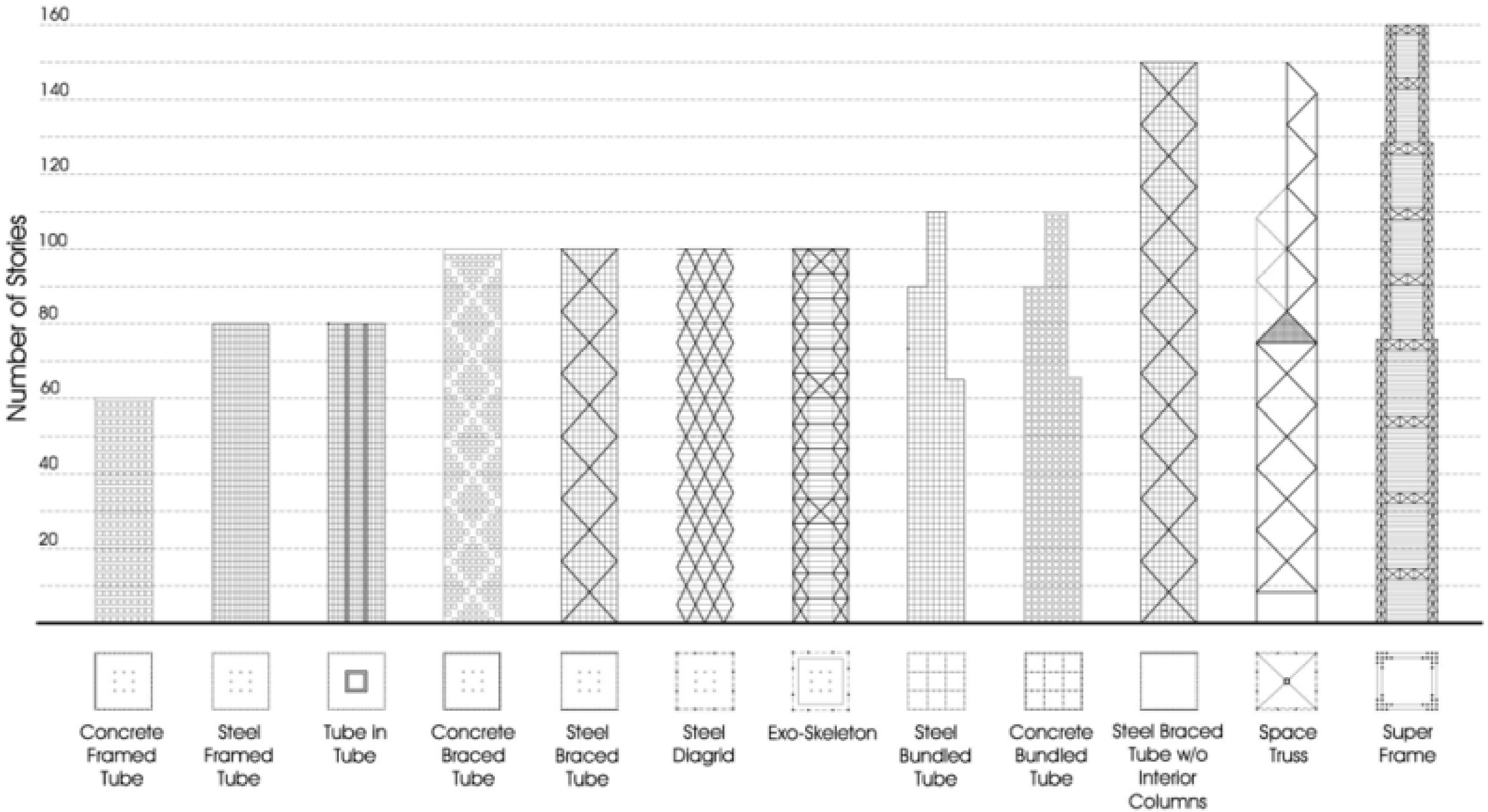
- Interior Structures: single / dual component planar assemblies in 2 principal directions.



Interior Structures *Courtesy : Architectural Science Review*

Structural Systems for Tall Buildings

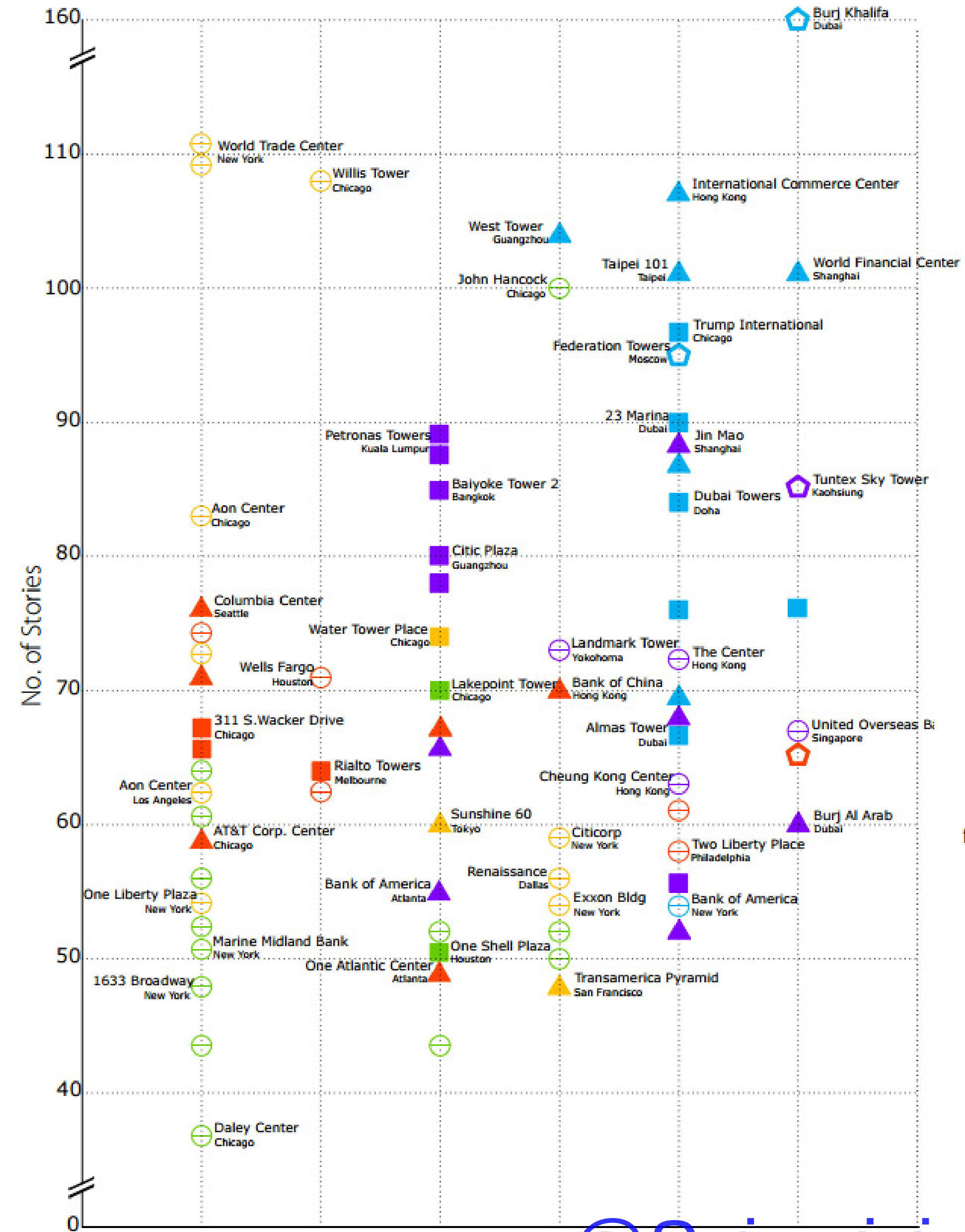
- Exterior Structures: effectively resist lateral loads by systems at building perimeter

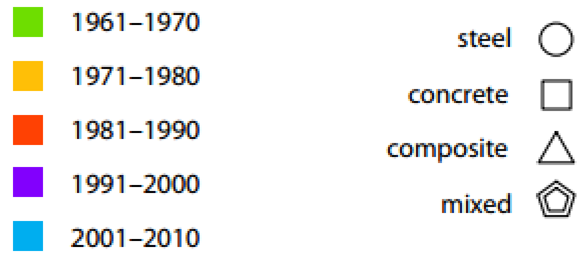


Exterior Structures

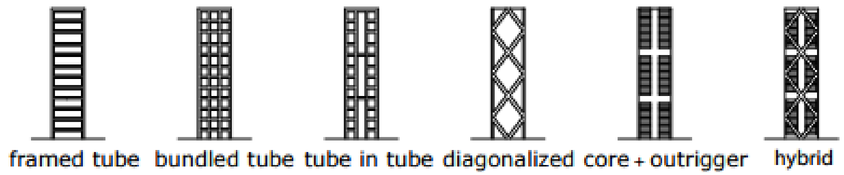
Courtesy : Architectural Science Review

Structural Systems for Tall Buildings





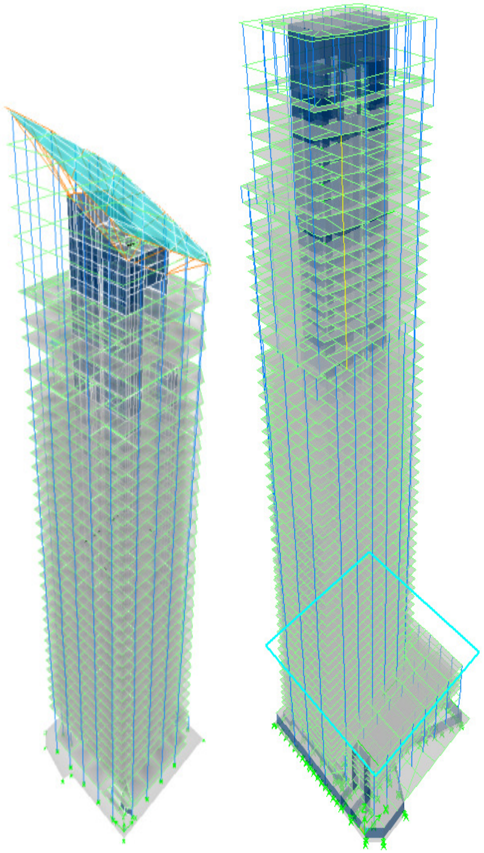
Structural Systems	No. of Buildings
framed tube	20
bundled tube	4
tube in tube	15
diagonalized	10
core + outrigger	19
hybrid	7
Total	**75**

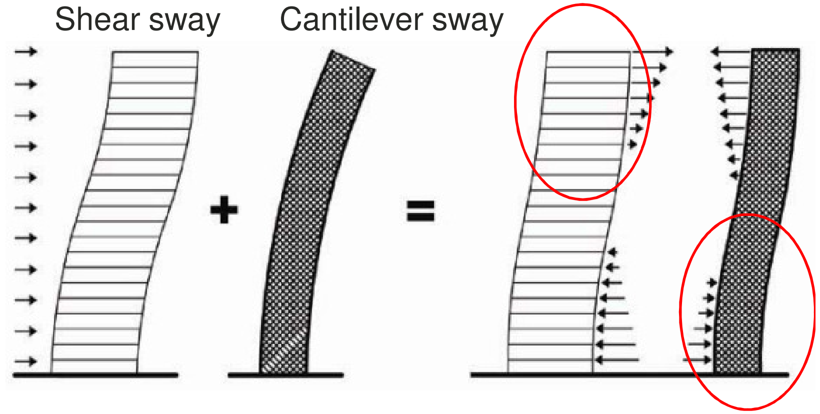


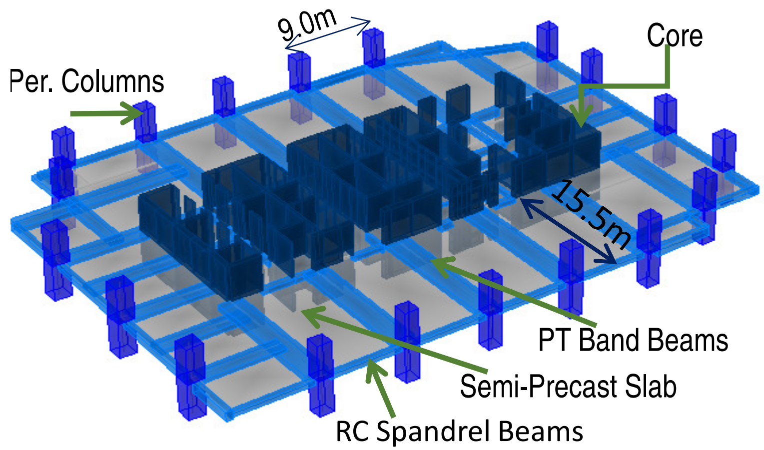
Structural Systems for Tall Buildings

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.







Marina Bay Financial Centre, Singapore

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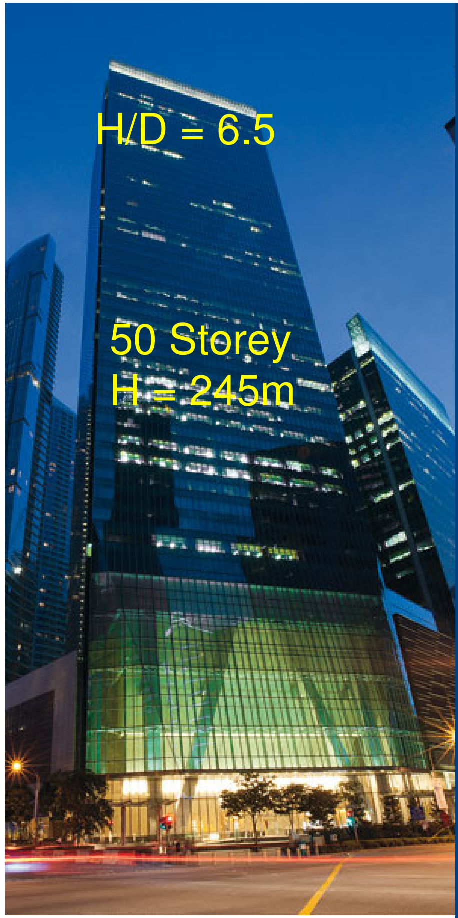
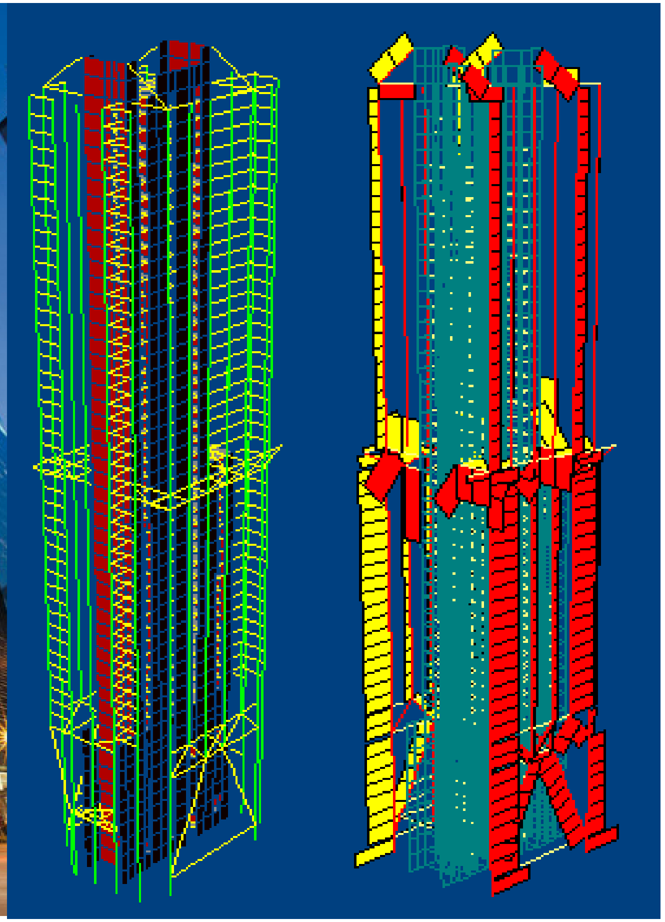
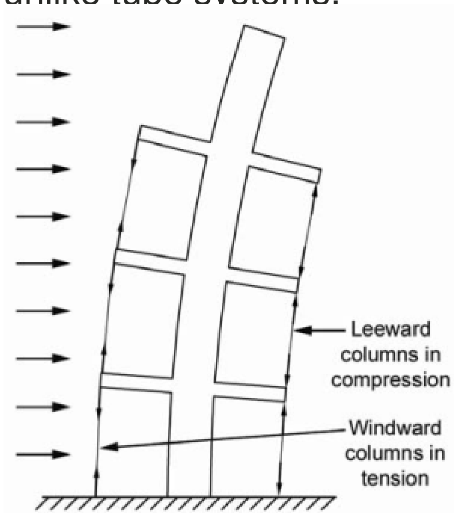
Structural Systems for Tall Buildings

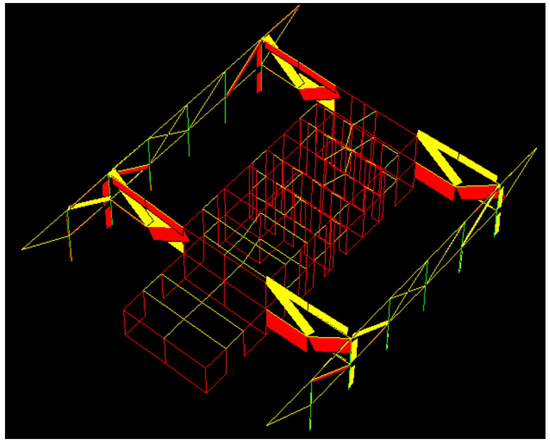
Core + Outrigger + Belt Truss

- Extremely efficient system: outriggers engage perimeter columns & reduce core overturning moment.
- Architecturally unobtrusive since outriggers are located at mechanical floor & roof.
- Exterior column spacing meets aesthetic & functional requirements, unlike tube systems.









One Raffles Quay, Singapore

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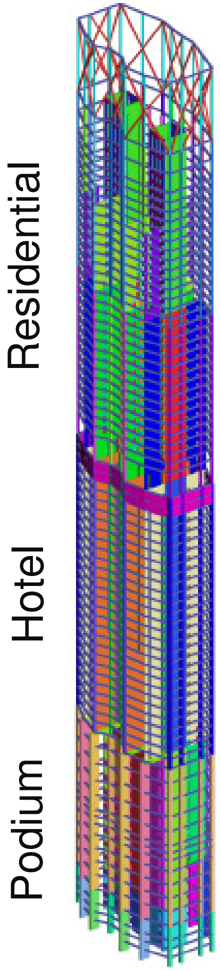
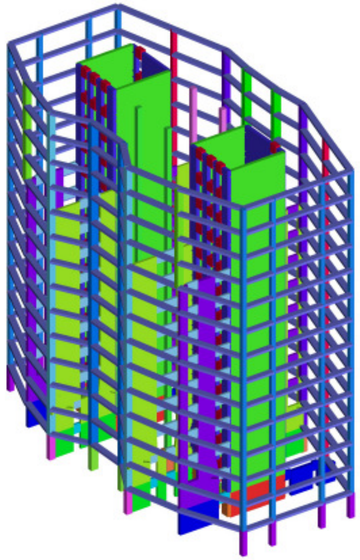
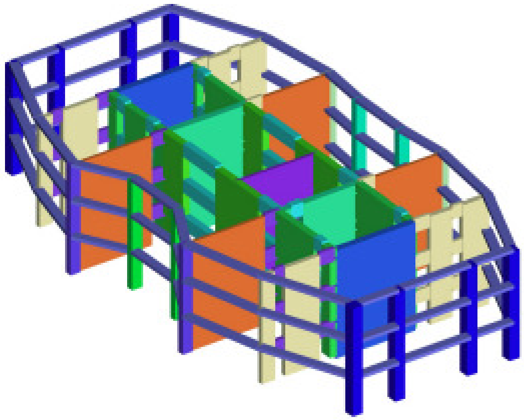
Structural Systems for Tall Buildings

Coupled Outrigger Shear Walls

- Innovative system to address extreme slenderness.
- Coupled walls extend over entire depth of floor plate to resist overturning moment & shear at every floor.







Four Seasons Place, KL, Malaysia

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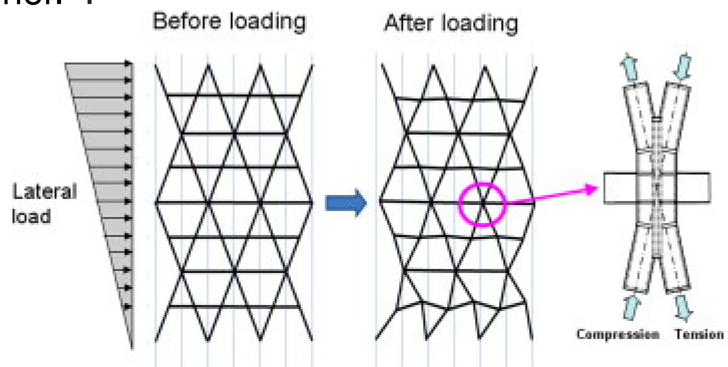
Structural Systems for Tall Buildings

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. .

Tornado Tower, Doha, Qatar

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



Joints are complicated

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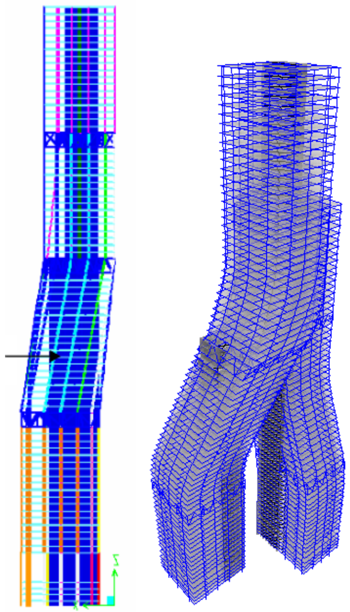
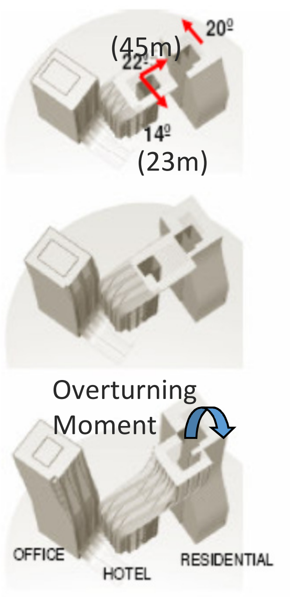
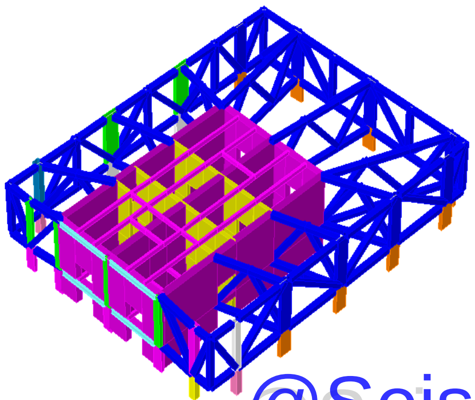
Structural Systems for Tall Buildings

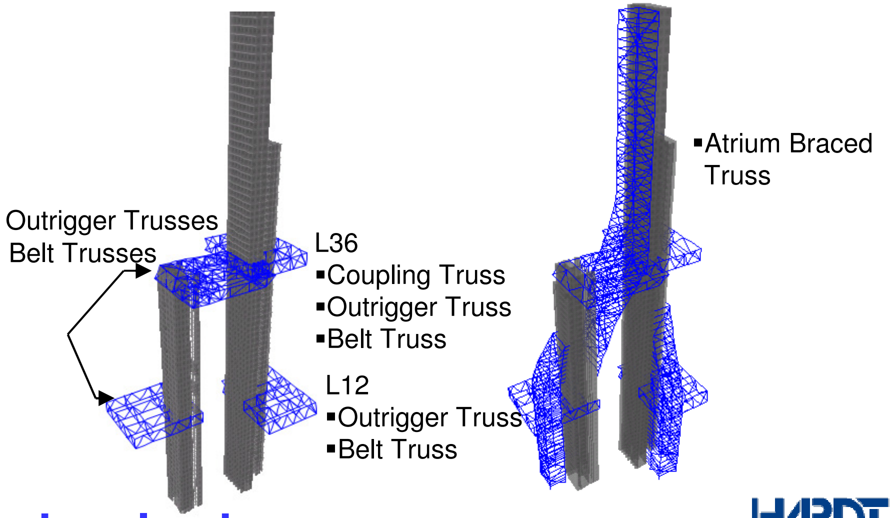
Hybrid

- Towers with large mass eccentricity - weight sensitive & large movements.
- Long-term serviceability challenges.
- Structural System: Shear Wall + Rigid Frame + Outriggers + Belt Truss + Core Coupling Truss + Internal Braced Truss

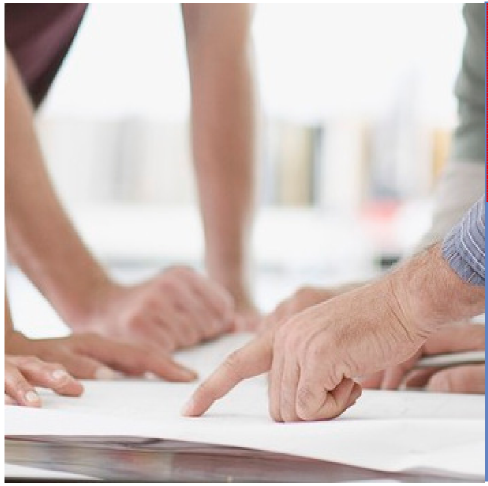








HARDT



03

Key Considerations for Seismic Design

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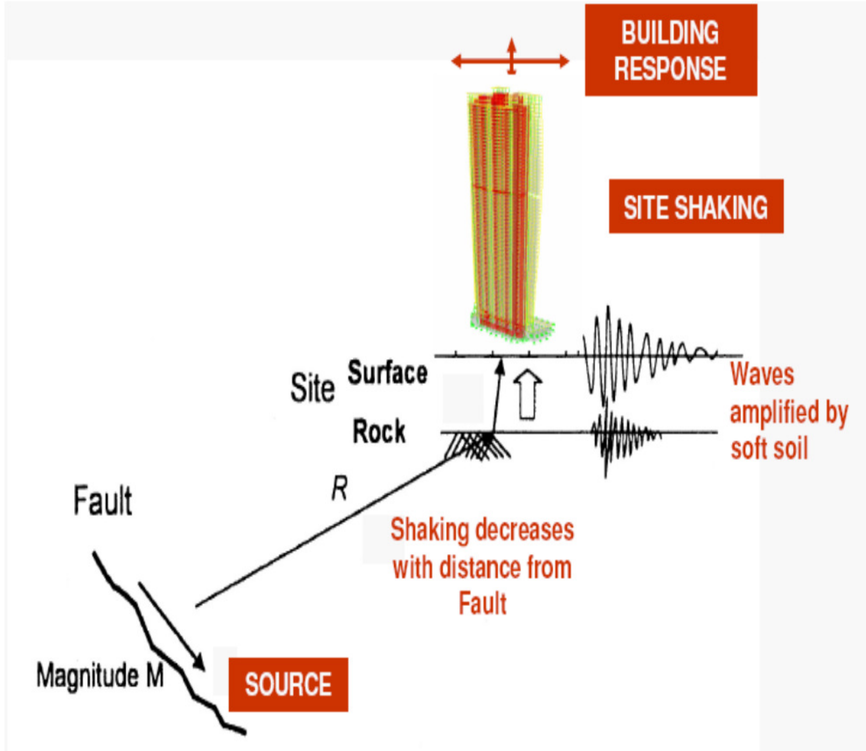
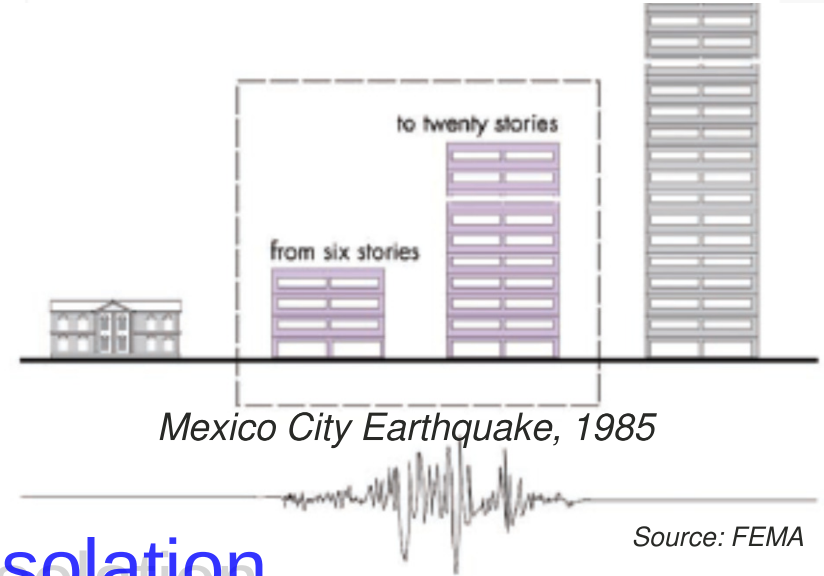
Seismic Design Considerations

- Seismic design philosophy focuses on safety rather then 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?



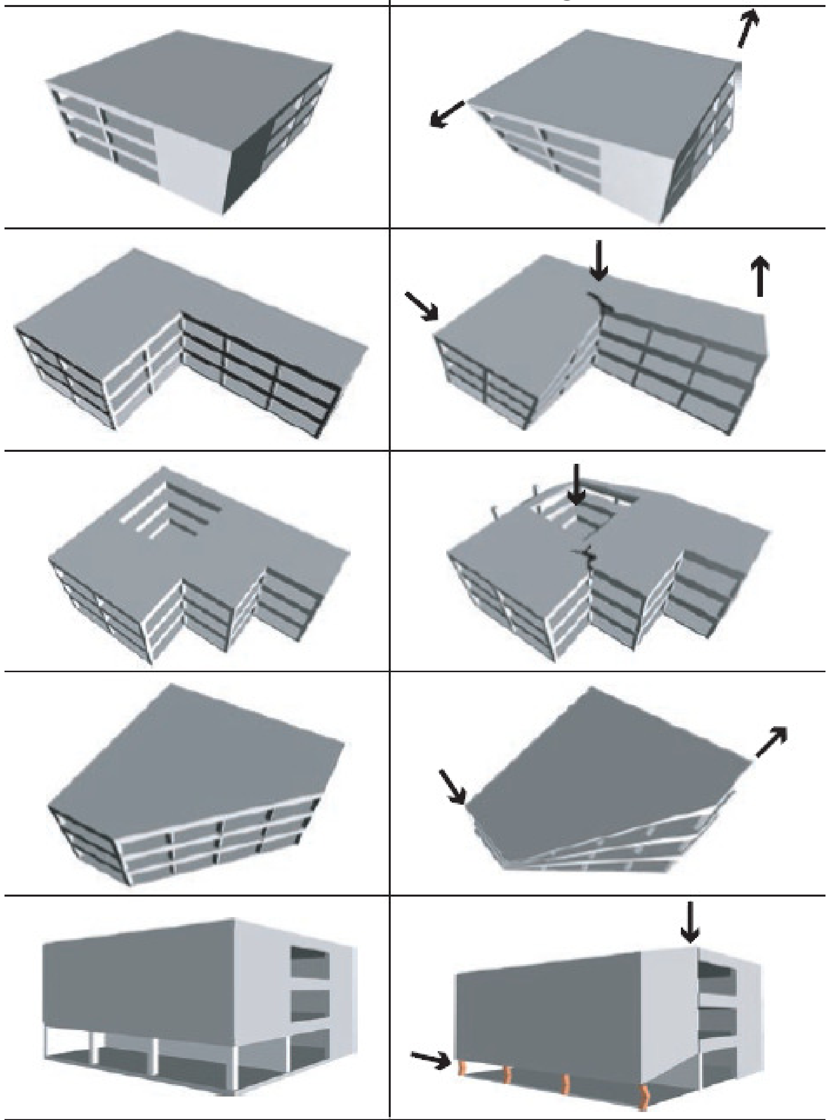


Mexico City Earthquake, 1985

Source: FEMA

Seismic Design Considerations

Plan Conditions | Resulting Failure Patterns

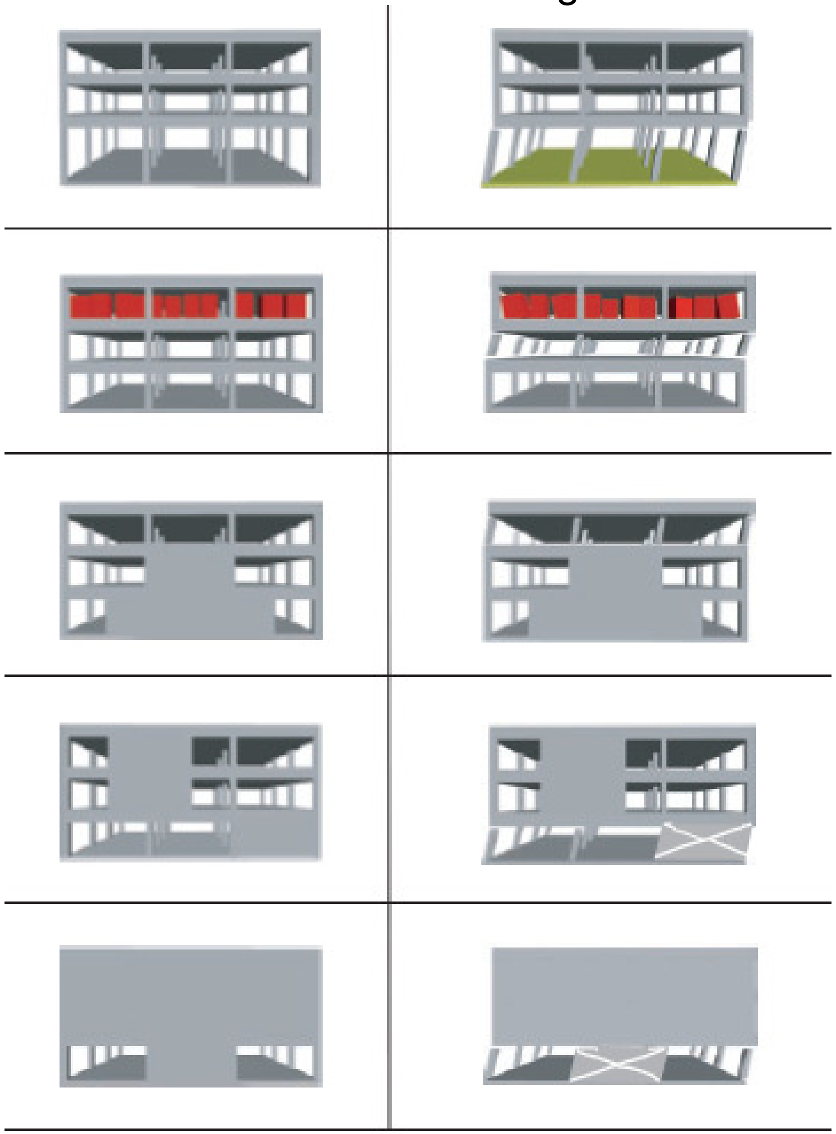


Source: FEMA

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

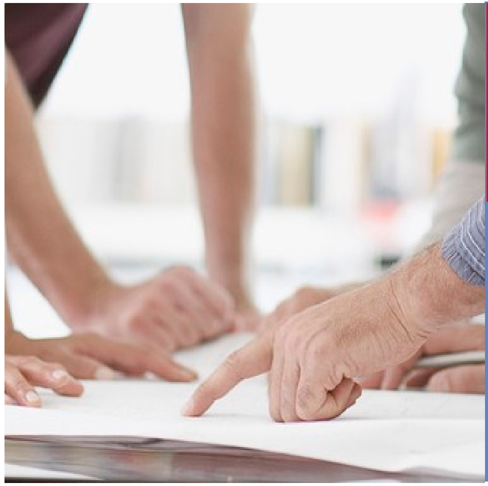
Seismic Design Considerations

Vertical Conditions | Resulting Failure Patterns



- Stiffness Irregularity: Soft Story
- Mass Irregularity
- Geometric Irregularity
- In-Plane Irregularity in LFRS
- Capacity Discontinuity: Weak Story

Source: FEMA



04

Overview of BC3

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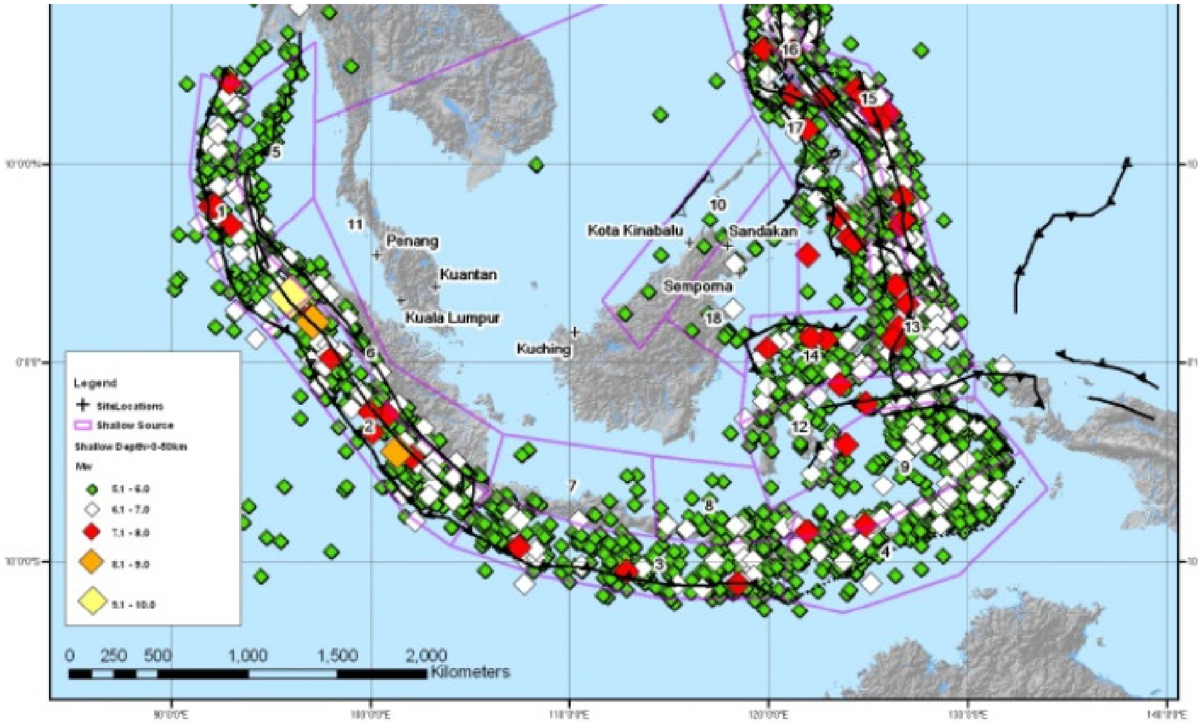
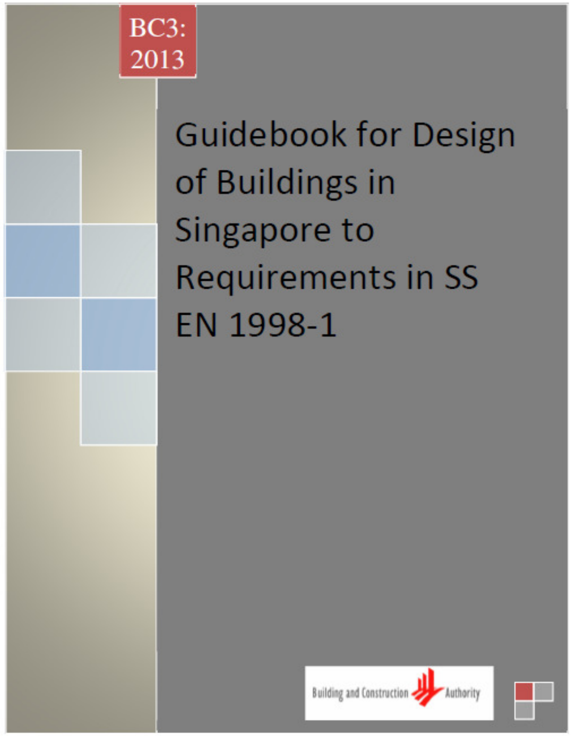
Overview of BC3

- Seismic requirement in Singapore from 1 Apr 2015





Source: Pappin et. al.

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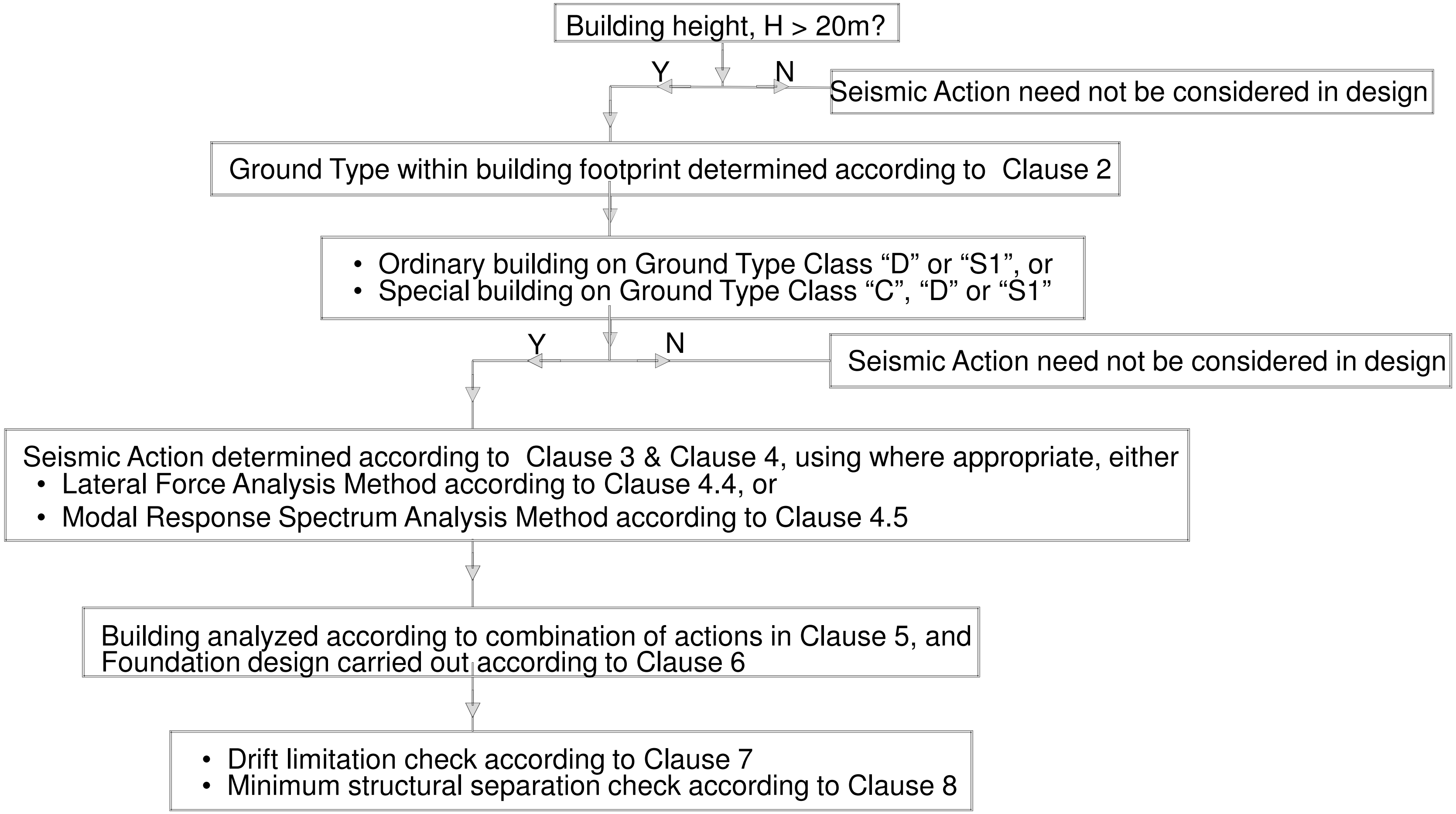
Overview of BC3

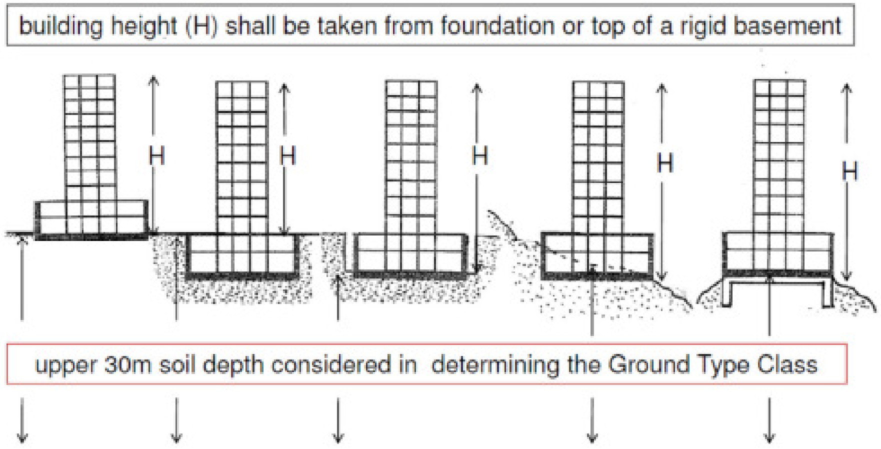
Design Flowchart

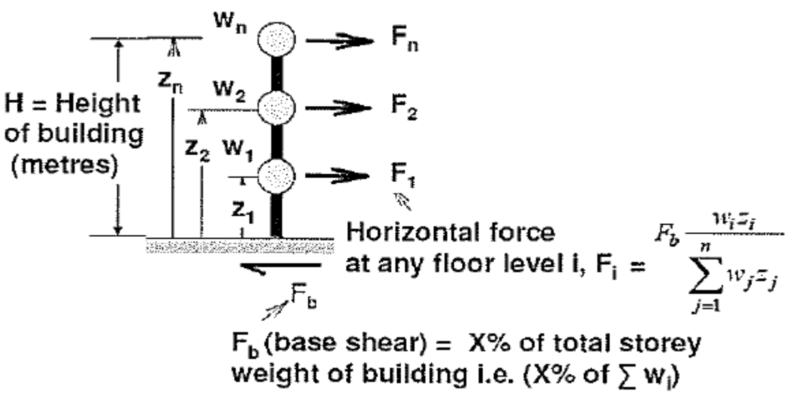


Overview of BC3

Definitions

Building classification	Importance Factor γ_I	Building H > 20m Ground Type			
		B	C	D	S1
Ordinary Building All other than "Special buildings" below	1.0	-	-	Y	Y
Special Building • hospitals • fire stations • civil defense installations • government offices • institutional building	1.4	-	Y	Y	Y





Value of P as computed from paragraph 2.2 for soil in the upper 30m			Ground Type	Description of stratigraphic profile
Shear-Wave Velocity. $v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	Undrained Shear Strength, c_u (kPa)		
> 800	Not applicable	Not applicable	A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.
360 - 800	> 50	> 250	B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.
180 - 360	15 - 50	70 - 250	C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.
< 180	< 15	< 70	D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soils.
< 100	< 5	10 - 20	S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content.

Table 1 – Determining Ground Type from computed value of P

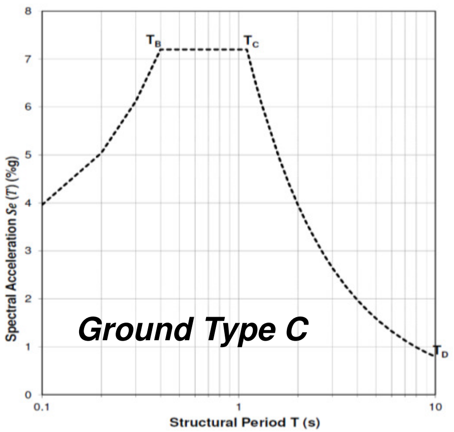
Overview of BC3

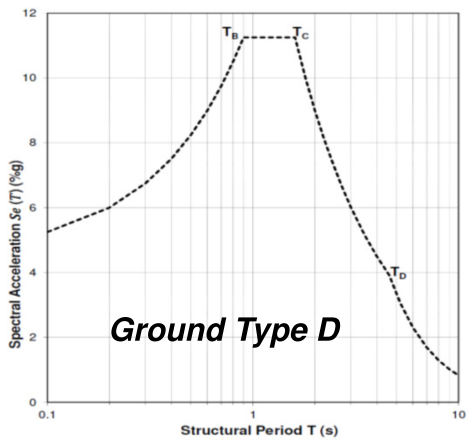
Design Spectra

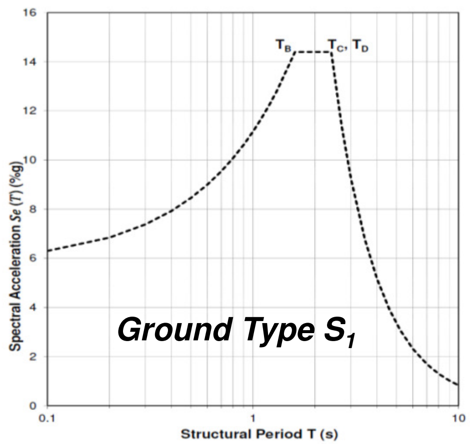
T (sec)	Spectral Acceleration $S_e(T)$ (%g)	T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	2.88	1.8	4.40
0.1	3.96	2.0	3.96
0.2	5.04	2.2	3.60
0.3	6.12	2.4	3.30
0.4	7.20	2.7	2.93
0.5	7.20	3.0	2.64
0.6	7.20	3.5	2.26
0.7	7.20	4.0	1.98
0.8	7.20	4.6	1.72
0.9	7.20	5.2	1.52
1.0	7.20	6.0	1.32
1.1	7.20	7.0	1.13
1.2	6.60	8.0	0.99
1.4	6.09	9.0	0.88
1.6	4.95	10.0	0.79

T (sec)	Spectral Acceleration $S_e(T)$ (%g)	T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	4.50	1.8	10.00
0.1	5.25	2.0	9.00
0.2	6.00	2.2	8.18
0.3	6.75	2.4	7.50
0.4	7.50	2.7	6.67
0.5	8.25	3.0	6.00
0.6	9.00	3.5	5.14
0.7	9.75	4.0	4.50
0.8	10.50	4.6	3.91
0.9	11.25	5.2	3.06
1.0	11.25	6.0	2.30
1.1	11.25	7.0	1.69
1.2	11.25	8.0	1.29
1.4	11.25	9.0	1.02
1.6	11.25	10.0	0.83

T (sec)	Spectral Acceleration $S_e(T)$ (%g)	T (sec)	Spectral Acceleration $S_e(T)$ (%g)
0.0	5.76	1.8	14.40
0.1	6.30	2.0	14.40
0.2	6.84	2.2	14.40
0.3	7.38	2.4	14.40
0.4	7.92	2.7	11.38
0.5	8.46	3.0	9.22
0.6	9.00	3.5	6.77
0.7	9.54	4.0	5.18
0.8	10.08	4.6	3.92
0.9	10.62	5.2	3.07
1.0	11.16	6.0	2.30
1.1	11.70	7.0	1.69
1.2	12.24	8.0	1.30
1.4	12.78	9.0	1.02
1.6	14.40	10.0	0.83

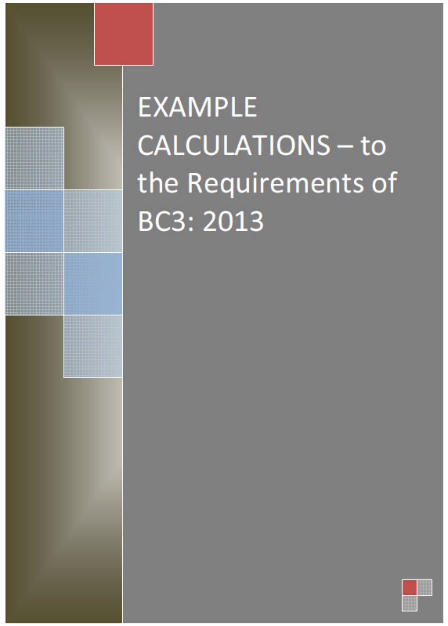


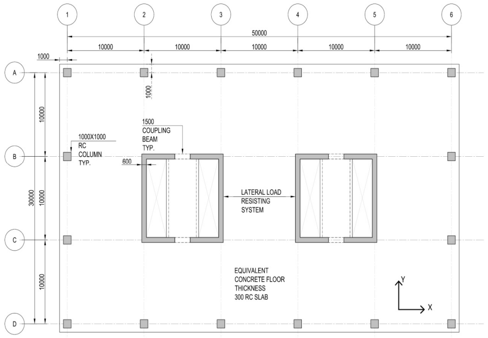


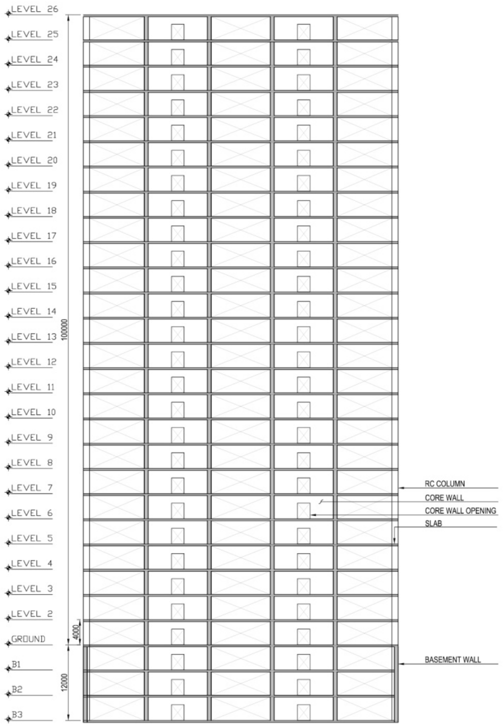


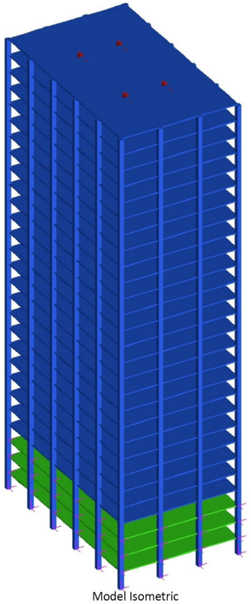
Overview of BC3

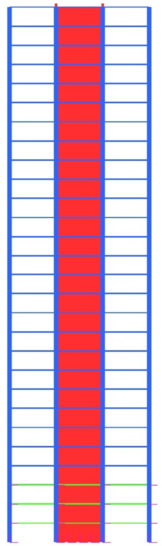
Design Example

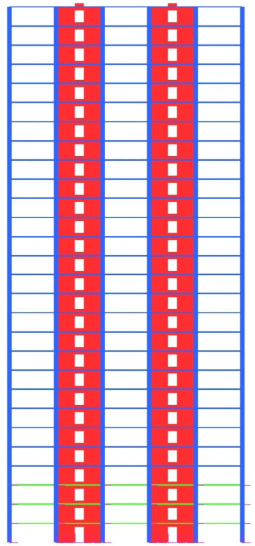







Model Isometric


Model Elevation

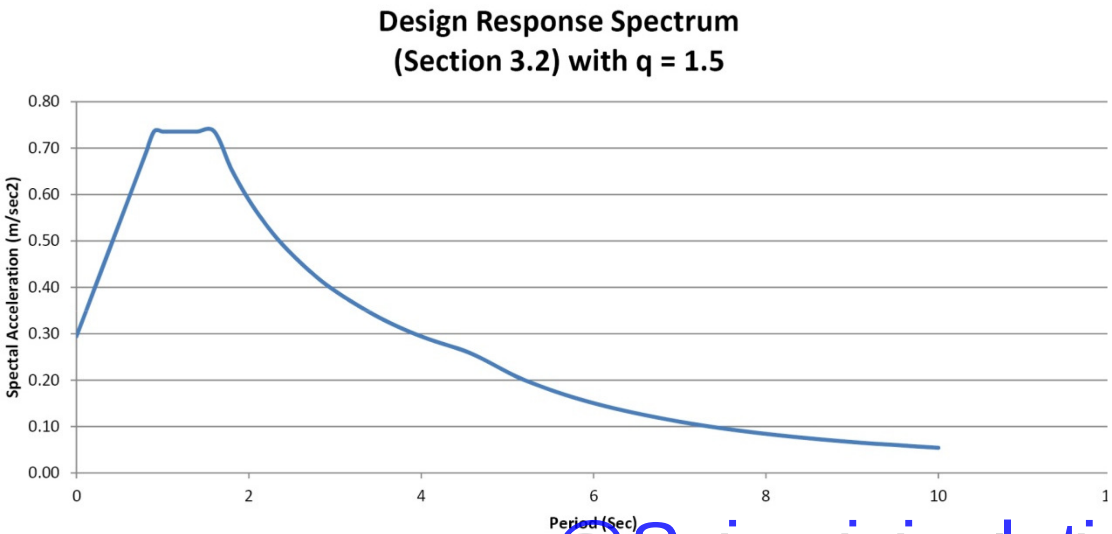

Model Elevation

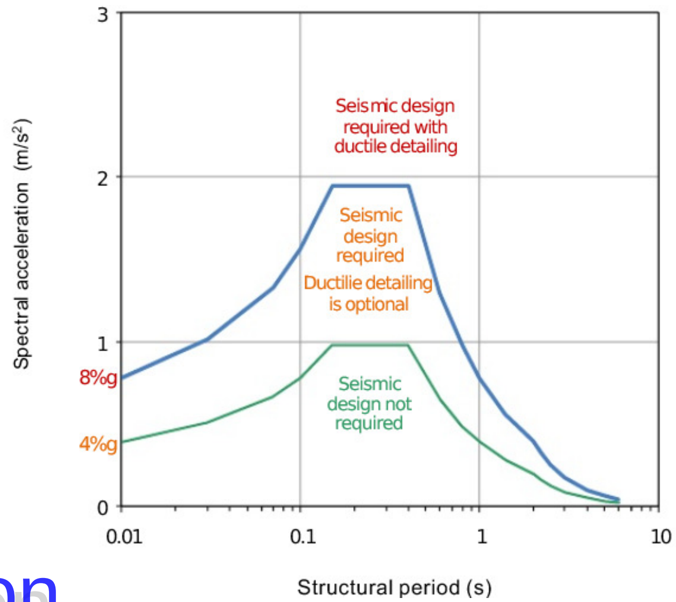
Overview of BC3

Modal Response Spectrum Analysis Method *(Para* 4.5)*

- The intent of a more rigorous dynamic analysis approach is to more accurately capture the vertical distribution of forces along the height of the building. The steps for a dynamic analysis are summarized below.
  - ✓ Solve for the building's period and mode shapes.
  - ✓ Ensure sufficient modes are used in the dynamic analysis by inspecting the cumulative modal participation.
  - ✓ Determine base shears obtained through response spectrum in each direction under consideration.

Determine Design Spectrum (Para 3.2)*

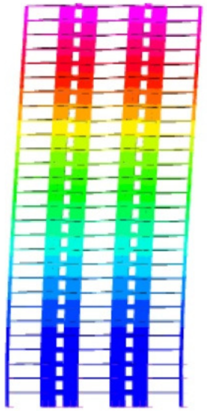




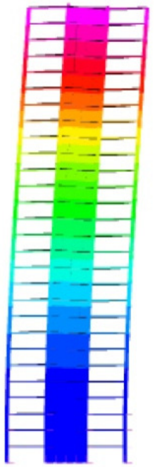
Overview of BC3

Modal Response Spectrum Analysis

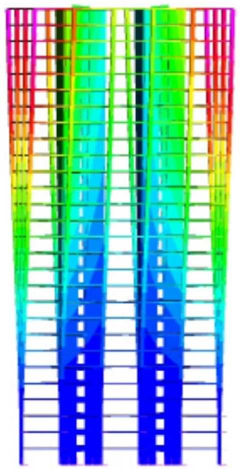
A response spectrum analysis is then run in two orthogonal directions.



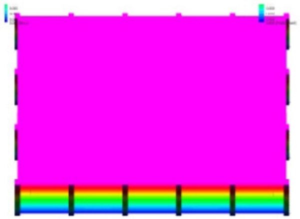
Mode 1
T = 3.3 sec

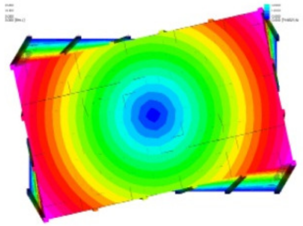


Mode 2
T = 3.3 sec



Mode 3
T = 2.0 sec





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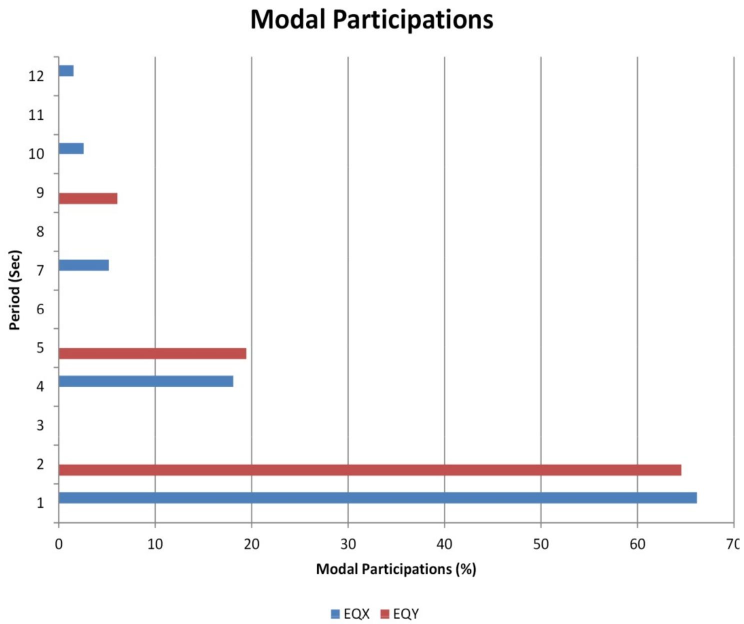
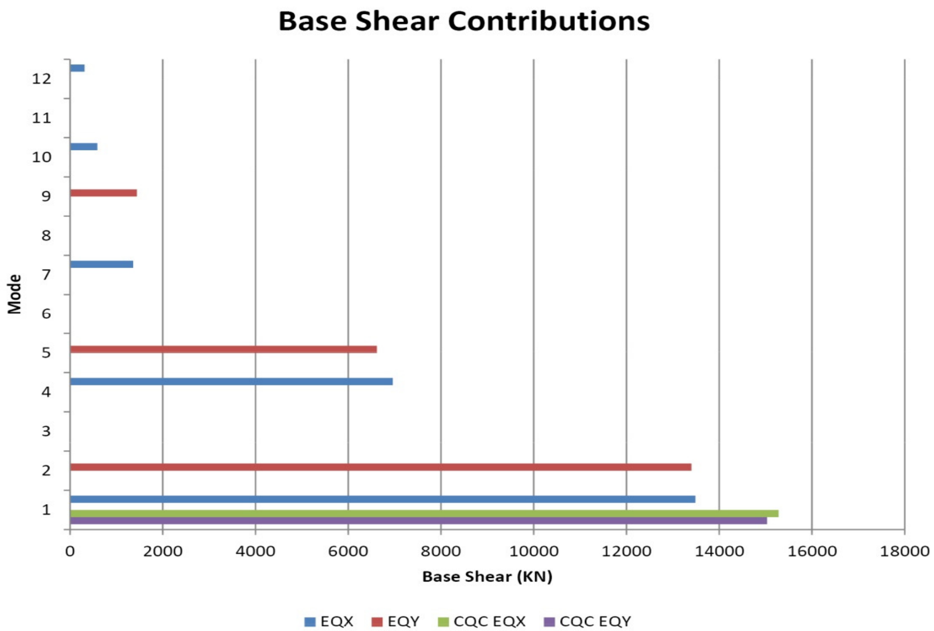
Overview of BC3

Modal Response Spectrum Analysis





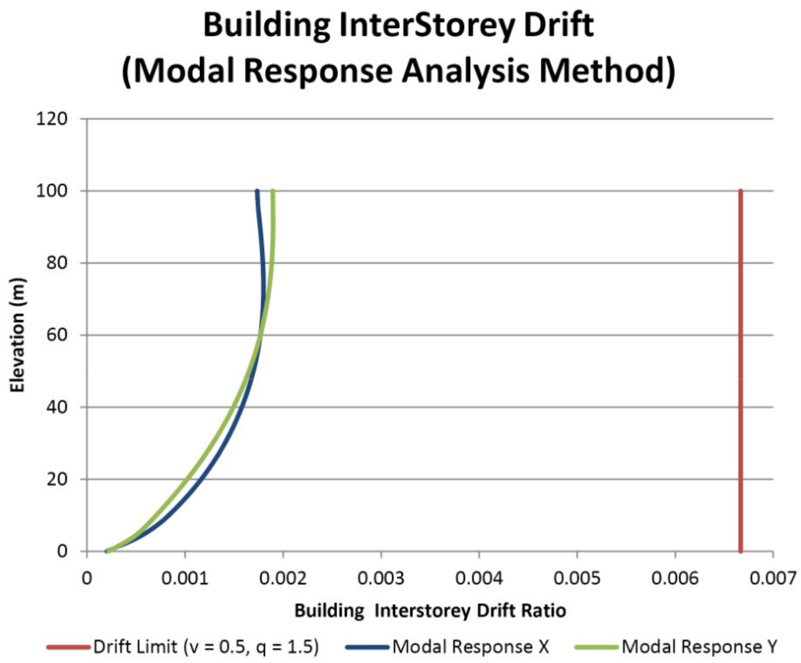
Overview of BC3

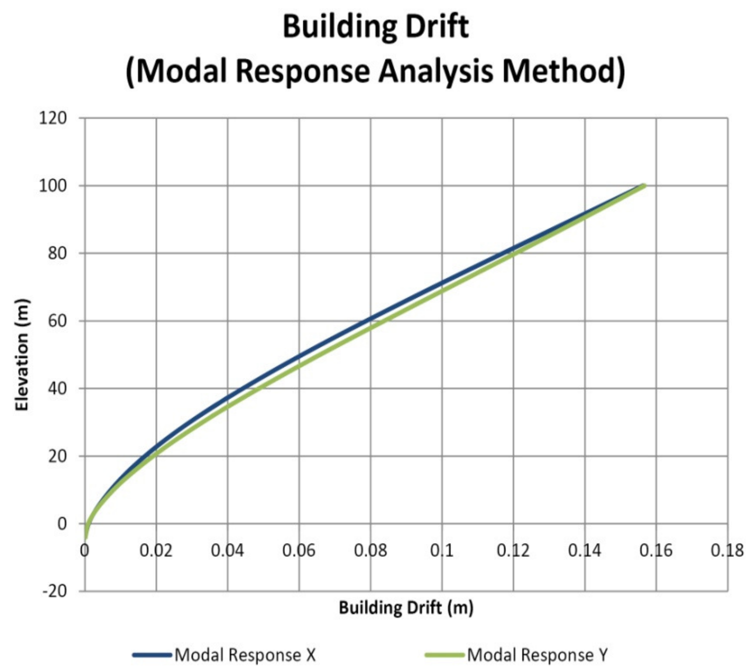
Required Combinations of Actions (Load Combinations) (Para 5.2)*

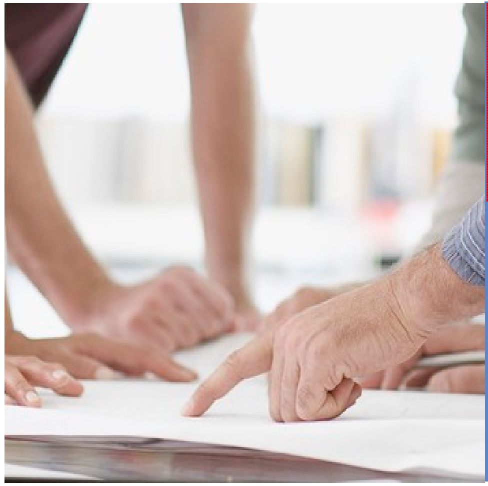
Load Combination Number	Dead	SDL	LL	Sesimic Action X	Sesimic Action Torque X	Sesimic Action Y	Sesimic Action Torque Y	Geometric Imperfection Effects (X direction)	Geometric Imperfection Effects (Y direction)
1	1.00	1.00	0.24	1.00	1.00	0.30	0.30	1.00	0.00
2	1.00	1.00	0.24	1.00	-1.00	0.30	0.30	1.00	0.00
3	1.00	1.00	0.24	-1.00	1.00	0.30	0.30	1.00	0.00
4	1.00	1.00	0.24	-1.00	-1.00	0.30	0.30	1.00	0.00
5	1.00	1.00	0.24	1.00	1.00	-0.30	0.30	1.00	0.00
6	1.00	1.00	0.24	1.00	-1.00	0.30	-0.30	1.00	0.00
7	1.00	1.00	0.24	-1.00	1.00	-0.30	0.30	1.00	0.00
8	1.00	1.00	0.24	-1.00	-1.00	0.30	-0.30	1.00	0.00
9	1.00	1.00	0.24	0.30	0.30	1.00	1.00	1.00	0.00
10	1.00	1.00	0.24	0.30	0.30	1.00	-1.00	1.00	0.00
11	1.00	1.00	0.24	0.30	0.30	-1.00	1.00	1.00	0.00
12	1.00	1.00	0.24	0.30	0.30	-1.00	-1.00	1.00	0.00
13	1.00	1.00	0.24	-0.30	0.30	1.00	1.00	1.00	0.00
14	1.00	1.00	0.24	0.30	-0.30	1.00	-1.00	1.00	0.00
15	1.00	1.00	0.24	-0.30	0.30	-1.00	1.00	1.00	0.00
16	1.00	1.00	0.24	0.30	-0.30	-1.00	-1.00	1.00	0.00

Overview of BC3

Building Response







05

Case Studies

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Case Studies

The Sail @ Marina Bay
Singapore
245m, 70 Story,
2008
Concrete
Residential

Ocean Heights
Dubai
310m, 82 Story
2010
Concrete
Residential

WTC II
Jakarta, Indonesia
160m, 30Story,
2012
Composite
Office

Capital Plaza
Abu Dhabi
210m, 45 Story
2012
Concrete
Residential, Hotel & Office

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Case Studies

Thamrin Nine,
Jakarta, Indonesia
325m, 71 Story,
Under construction
Composite
Office & Hotel

Nurol Life Tower
Turkey
250m, 60 Story,
Under construction
Composite
Residential & Office

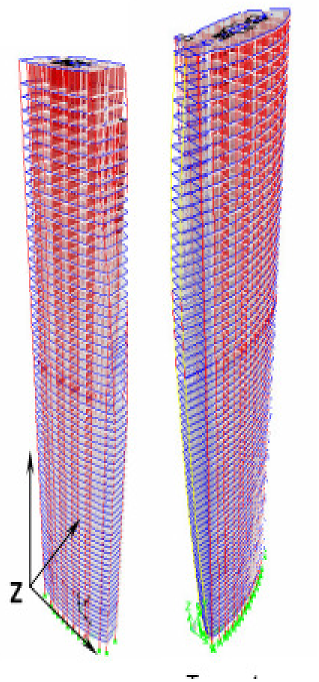
Izmir Ova Centre,
Turkey
112m, 27 Story,
Under construction
Composite
Office

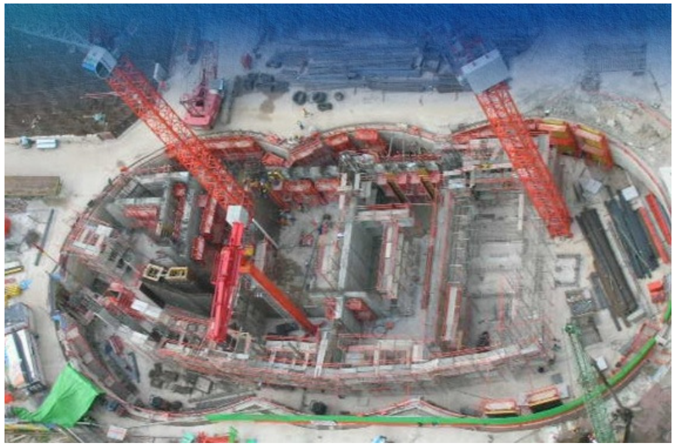
IFC ISGYO Office Tower
Turkey
111m, 27 Story,
Under construction
Composite
Office

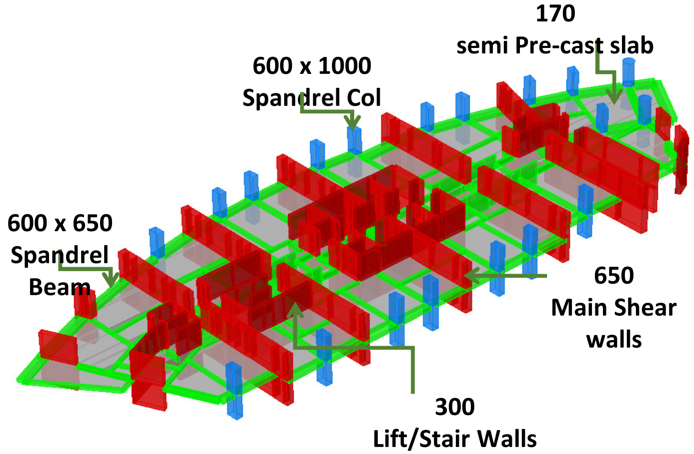
Case Studies

The Sail @ Marina Bay, Singapore

- Two residential towers, 70 (245m) & 63 (216m) story.
- Towers have extreme slenderness ≈ 13
- Unique coupled-outrigger-shear wall structural system.
- Seismic design, super high strength concrete & unique strut-free retention system.







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Case Studies

The Sail @ Marina Bay, Singapore

- Seismic design adopted for enhanced safety & robustness

Select Structure System & Materials

↓

Modal Analysis → **Building Dynamic Properties**

↓

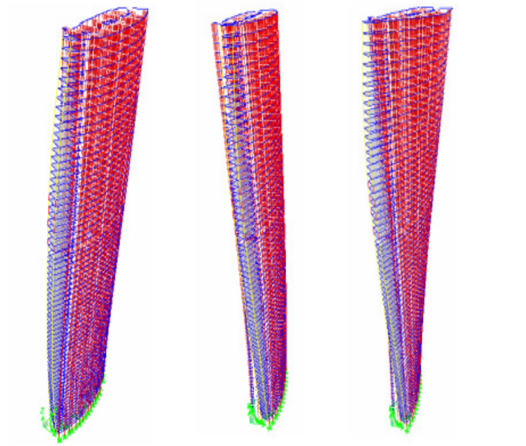
Lateral Loads (wind, seismic), WTT

↓

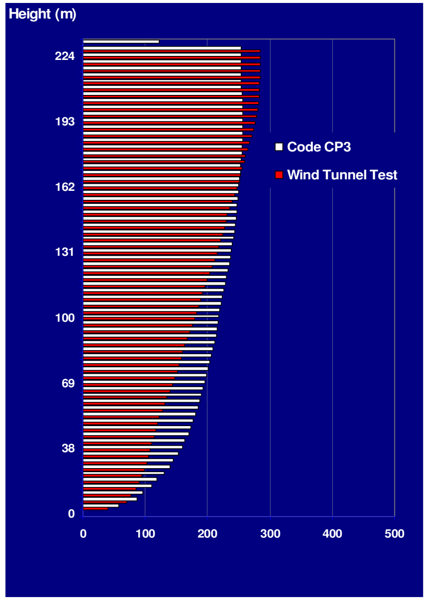
Dynamic Analysis (Response Spectrum Analysis)

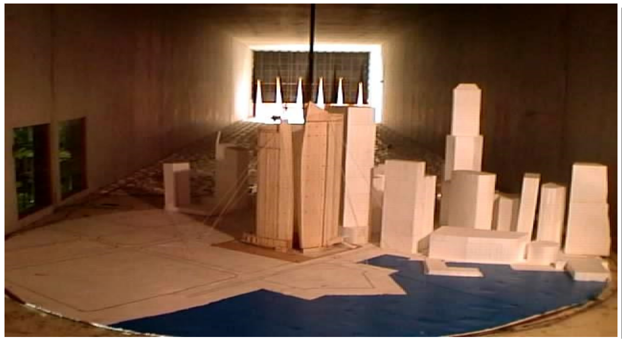
↓

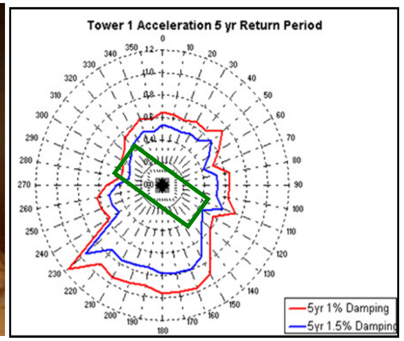
Building Performance/Strength (Seismic Design to UBC 97)



T1 = 6.4s *T2 = 5.5s* *T3 = 4.9s*







Case Studies

The Sail @ Marina Bay, Singapore

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)*
  - ✓ $(0.11 C_a I)\, W \leq \underline{\mathbf{V} = (C_v I / R\, T)\, W} \leq (2.5\, Ca\, I / R)\, W$, where
    - *Z represents expected ground acceleration at bedrock*
    - *C_a & C_v are coefficients depending on Soil Profile and Zone*

Seismic Zone	Zone Factor, Z	Base Shear, V
Zone 2A	0.15g	2.4% W * (with special detailing)

*Governed by minimum load required by code

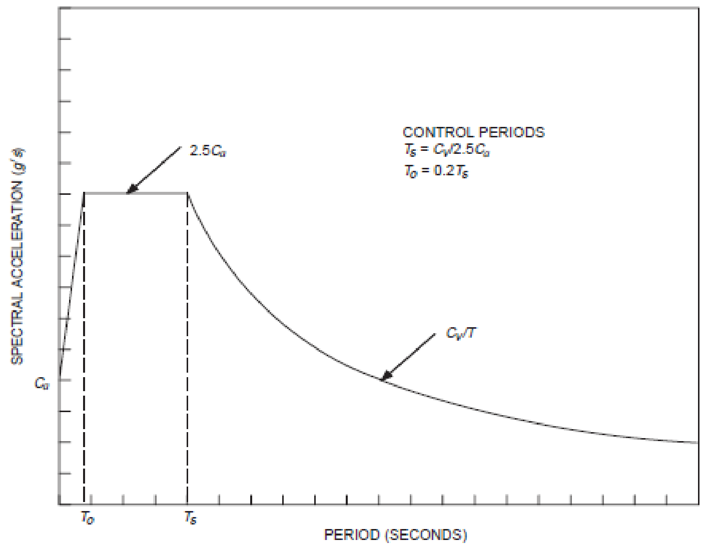


FIGURE 16-3—DESIGN RESPONSE SPECTRA

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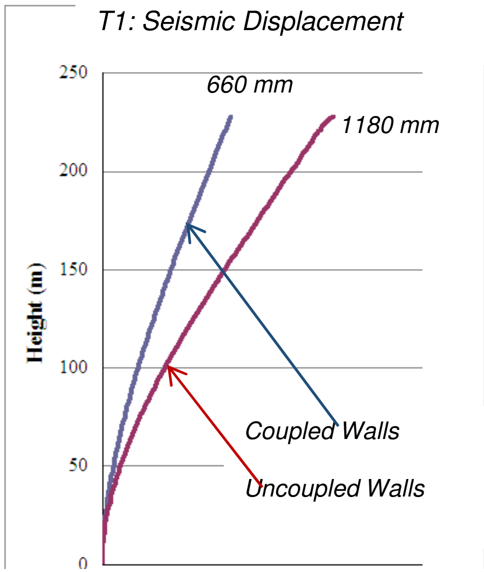
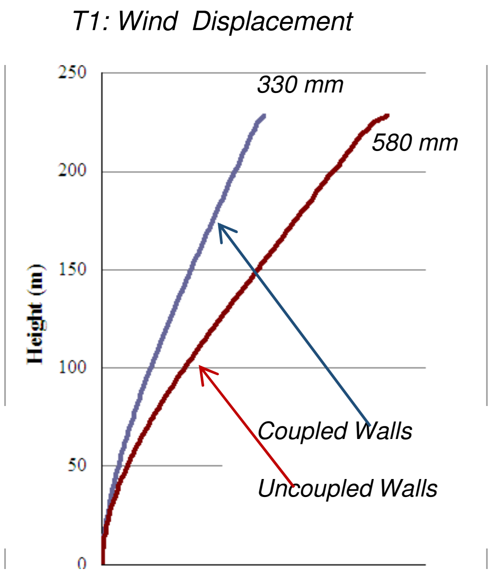
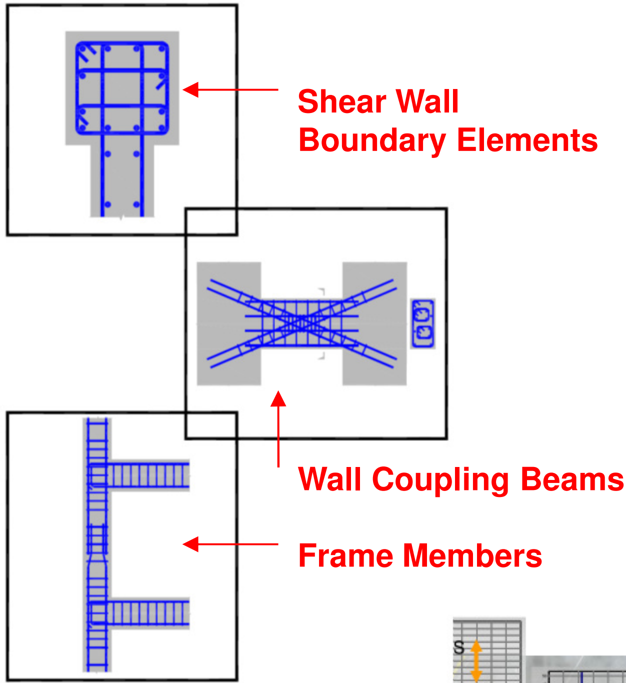
Case Studies

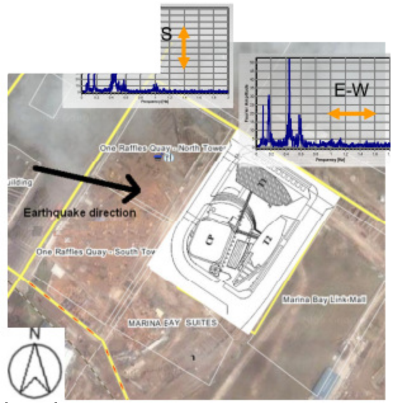
The Sail @ Marina Bay, Singapore

- ≈ 60% higher loads
- Special detailing

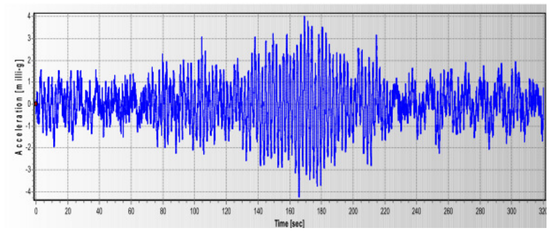








Tower 1 acceleration sensors triggered by Sumatra EQ on 11 April 2012, 4:56PM



Structural Performance Indicators	Tower 1 (245m)
Fundamental Period	6.4 secs
Building Acceleration	14. 1 milli-g
Inter-storey Drift under Wind	h / 550
Inter-storey Drift under Seismic	h / 280 (elastic), h / 70 (in-elastic)

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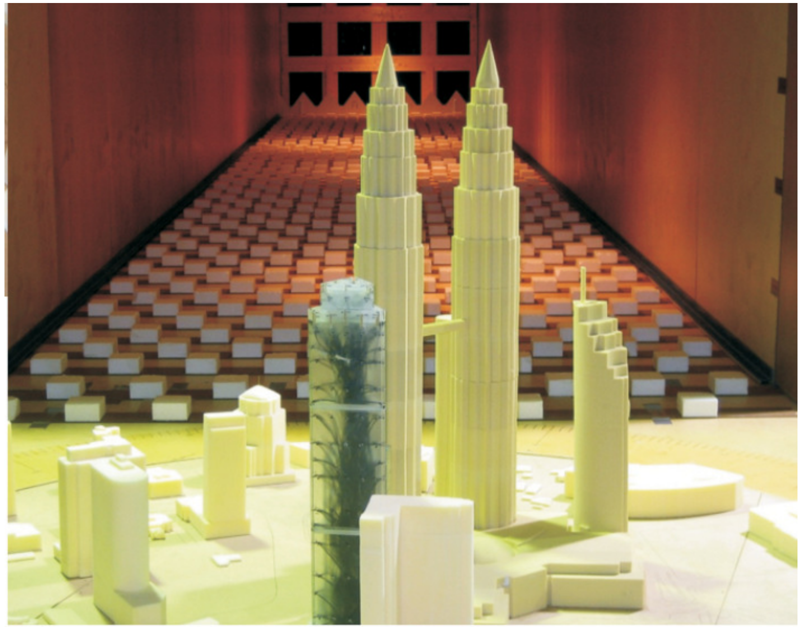
Case Studies

Four Seasons Place, KL, Malaysia

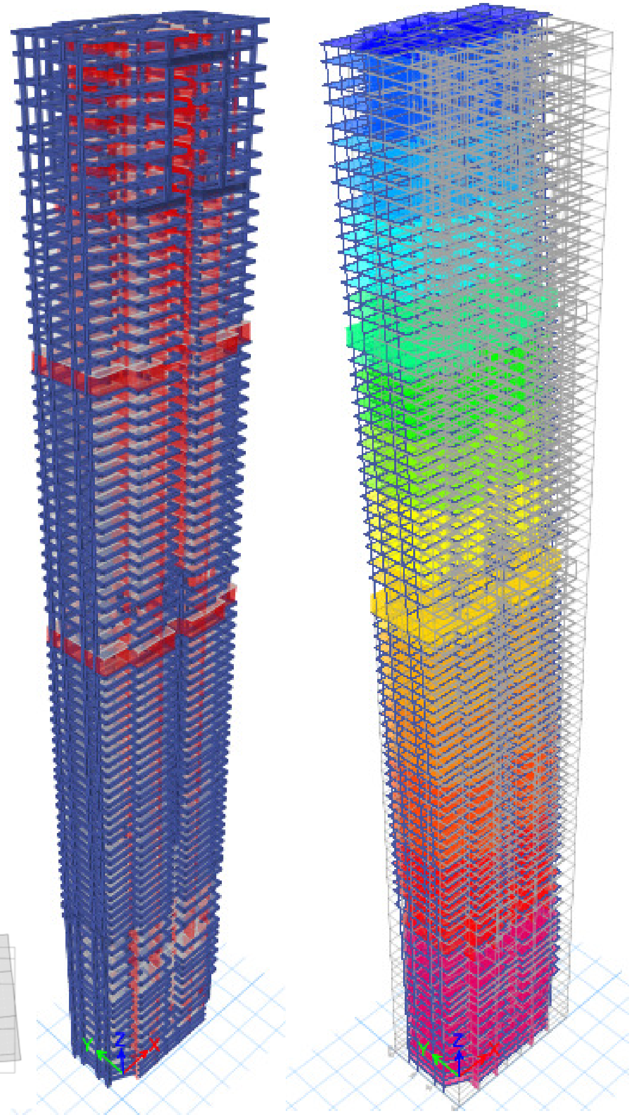
- The 75-storey, 342m tower will be 2nd tallest building in Malaysia when completed in 2017.
- Challenging project due to 12.5 slenderness ratio.
- WT studies revealed significant wake vortices and strong cross wind effects.

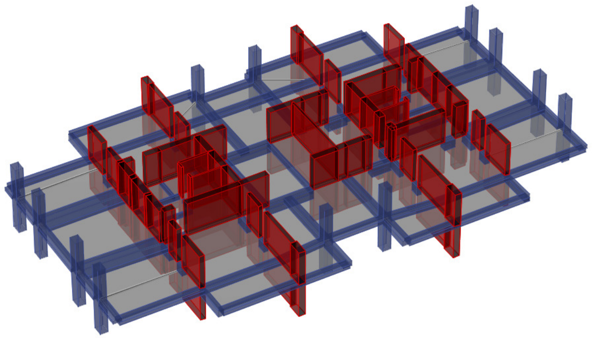


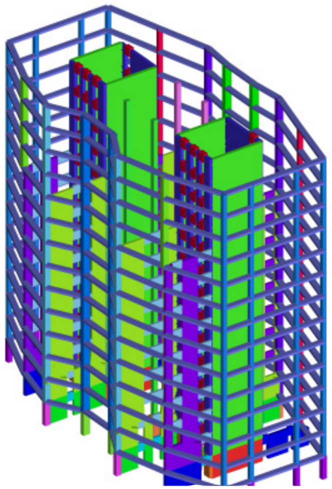
Case Studies

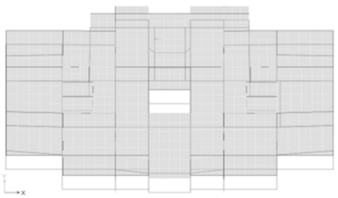
Four Seasons Place, KL, Malaysia

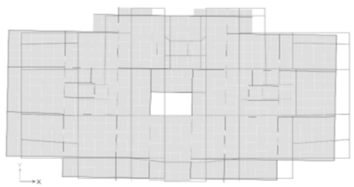
- An innovative lateral load resisting system was devised incorporating
  - ✓ suitably located fin walls
  - ✓ two levels of concrete outrigger and perimeter belt walls,
  - ✓ all coupled with the central core-walls.











Ty = 10.1s

Tx = 6.4s

Tr = 6.0s

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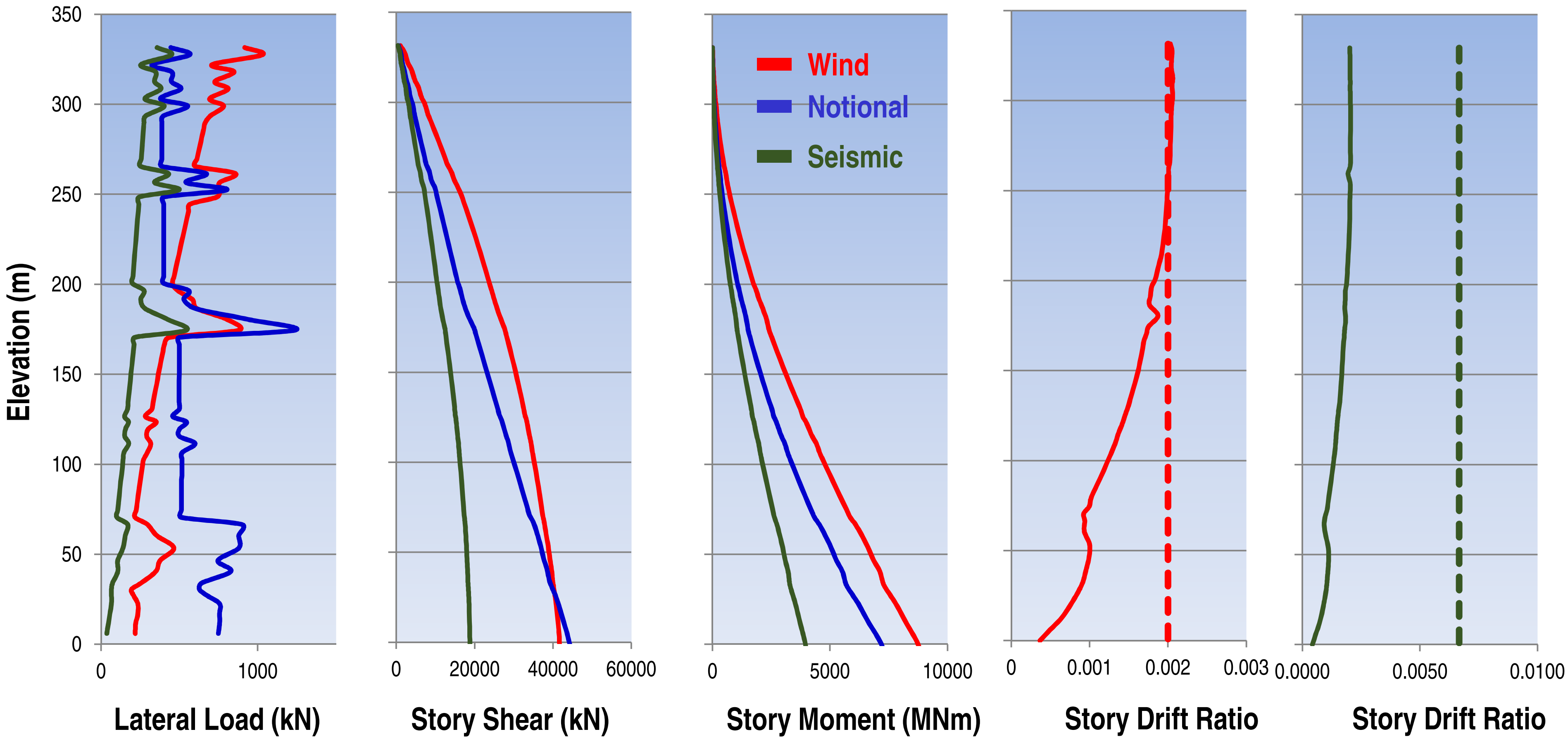
Case Studies

Four Seasons Place, KL, Malaysia

Structural Performance



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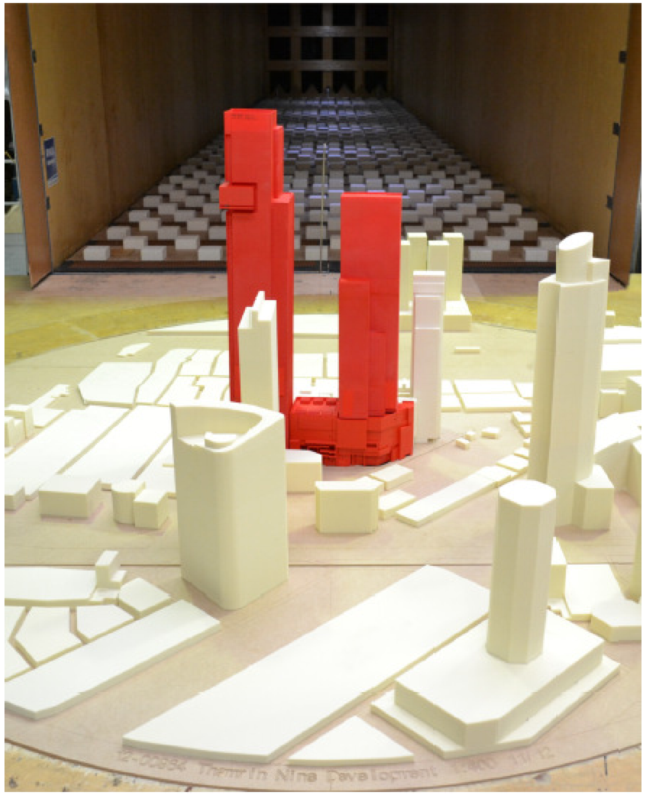
Case Studies

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.



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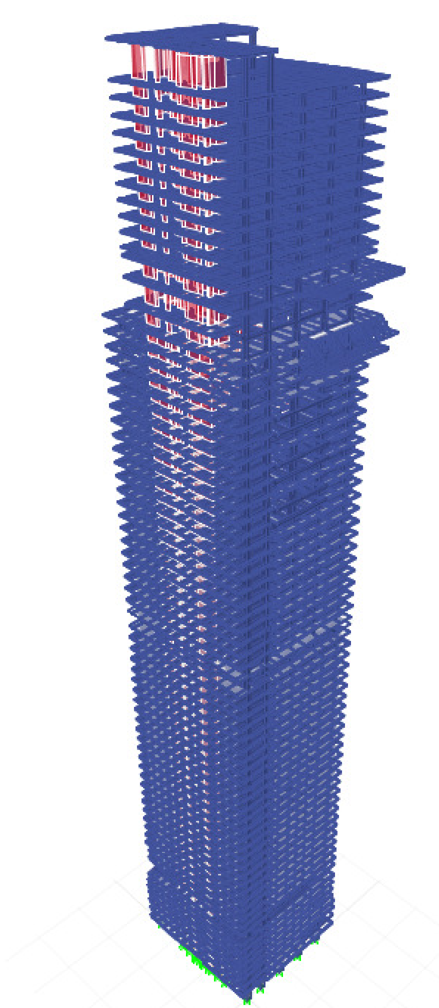
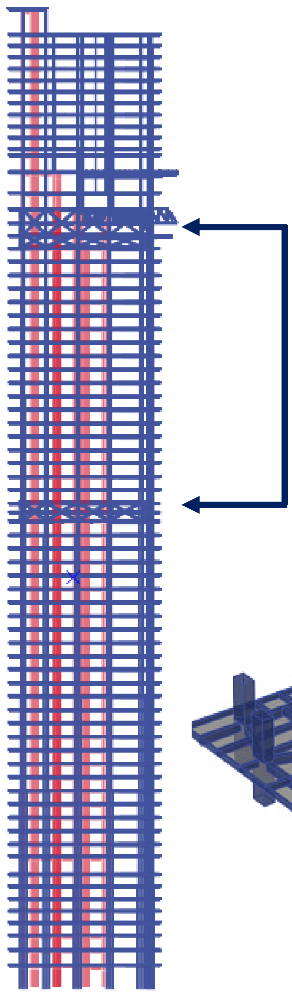
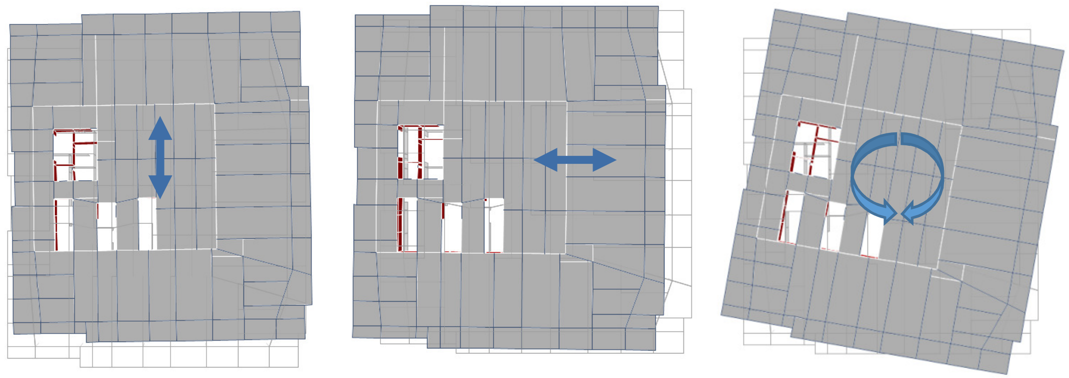
Case Studies

Thamrin Nine, Jakarta, Indonesia

Structural System



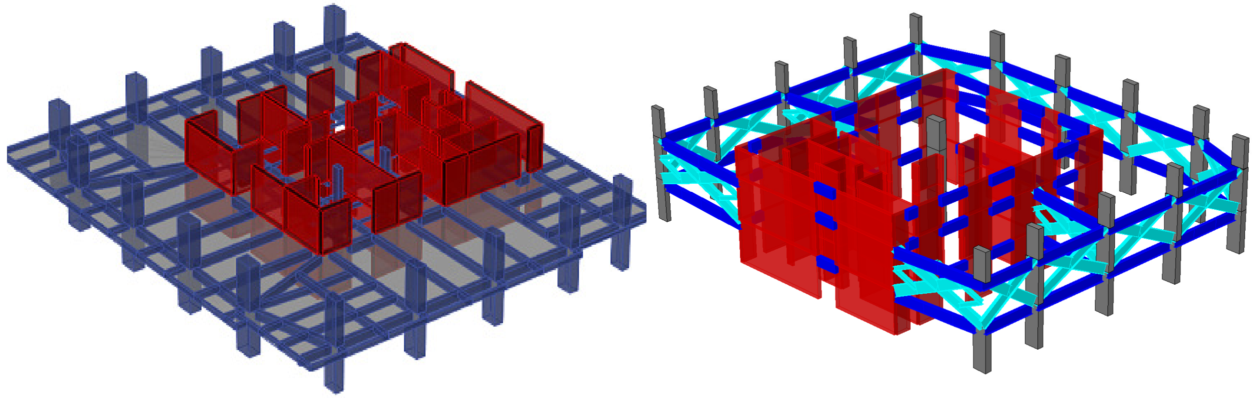




Ty = 7.2s   Tx = 6.8s   Tr = 3.2s

Outriggers & Belt Trusses

RC Walls/Columns/Beams/Slabs



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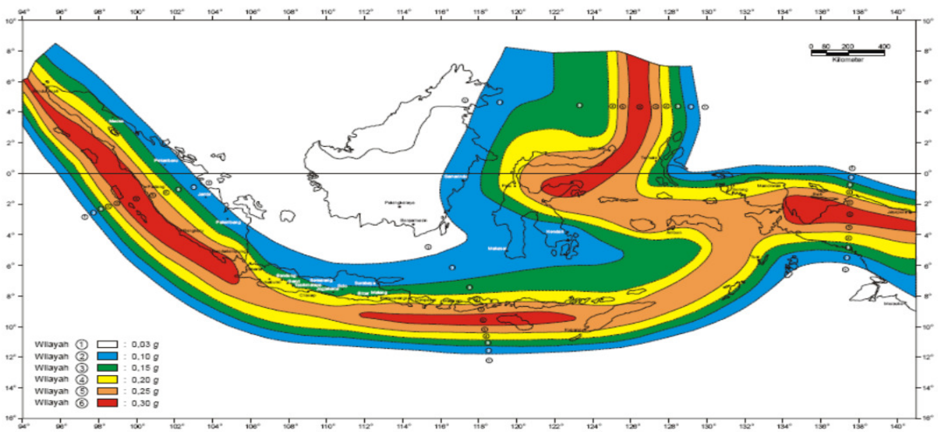
Case Studies

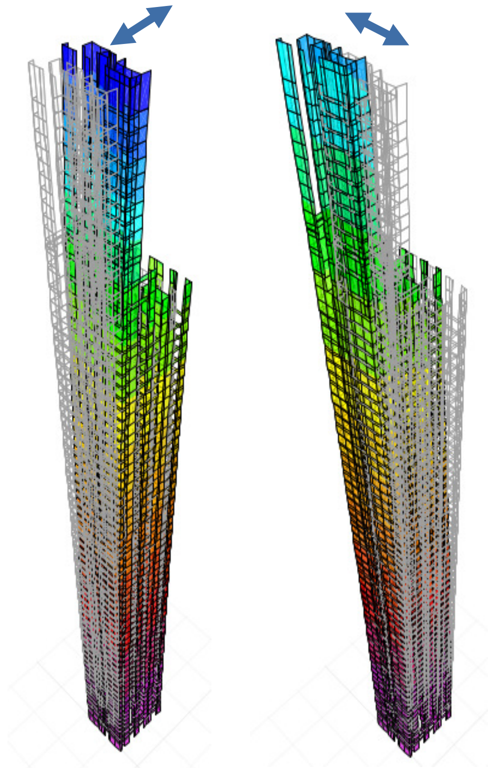
Thamrin Nine, Jakarta, Indonesia

Seismic Design Parameters

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

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



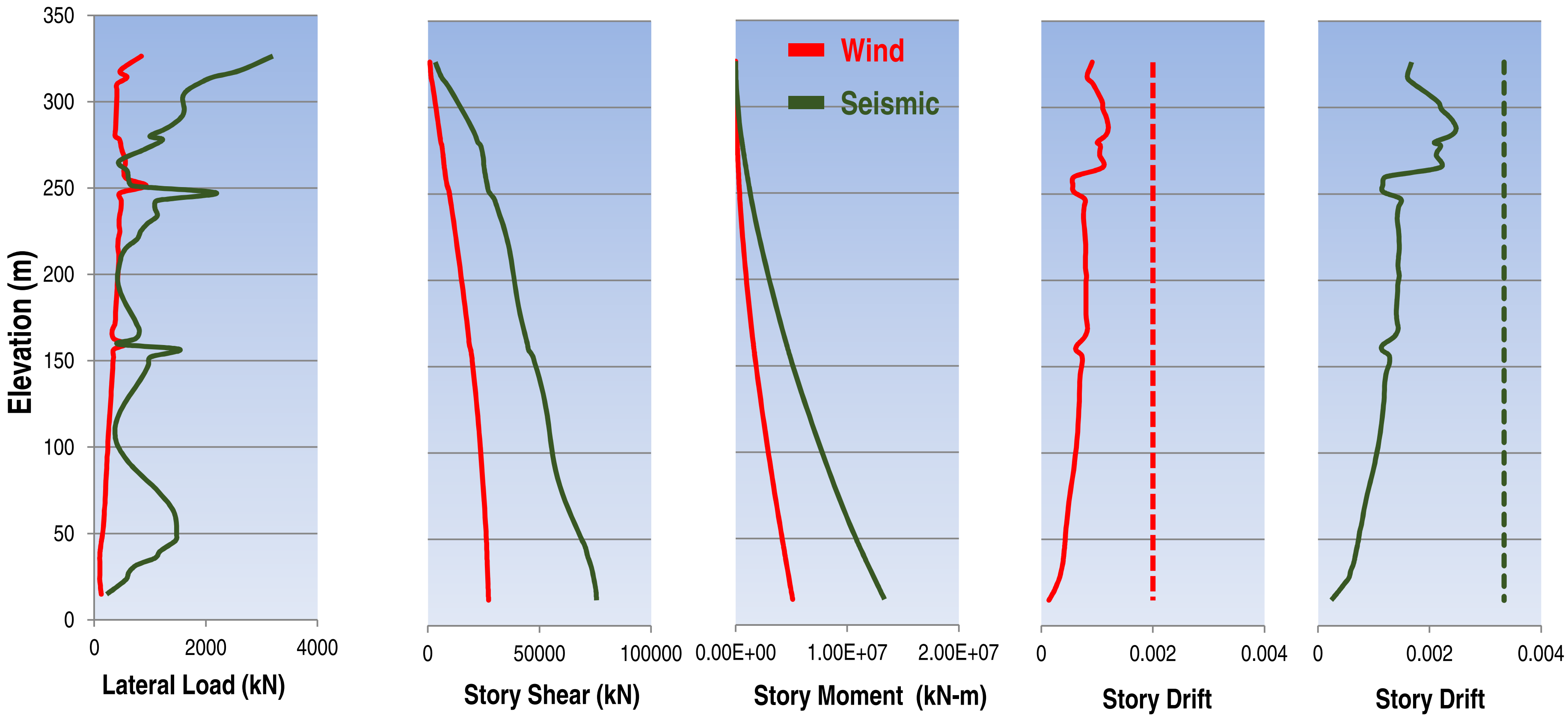


Seismic Building Drift

Case Studies

Thamrin Nine, Jakarta, Indonesia

Structural Performance



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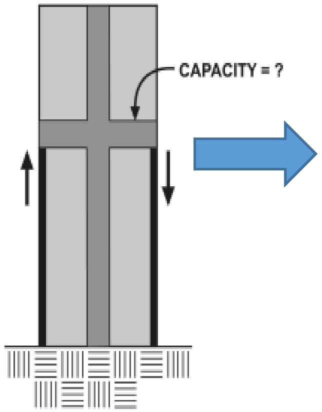
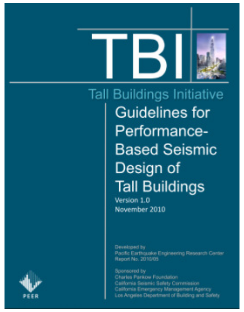
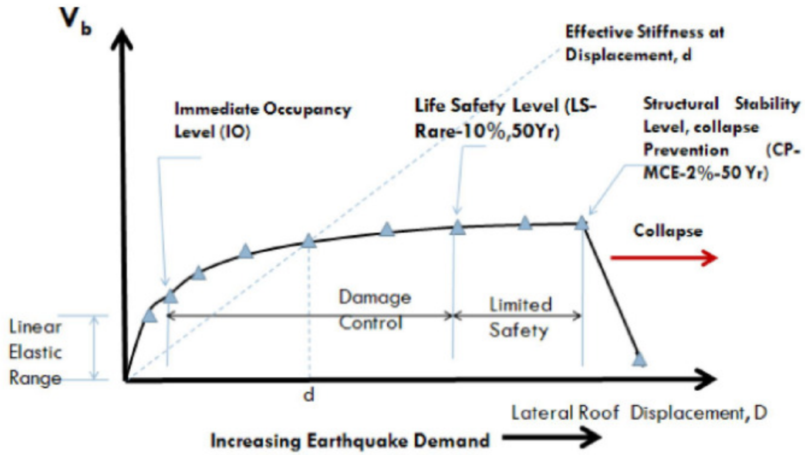
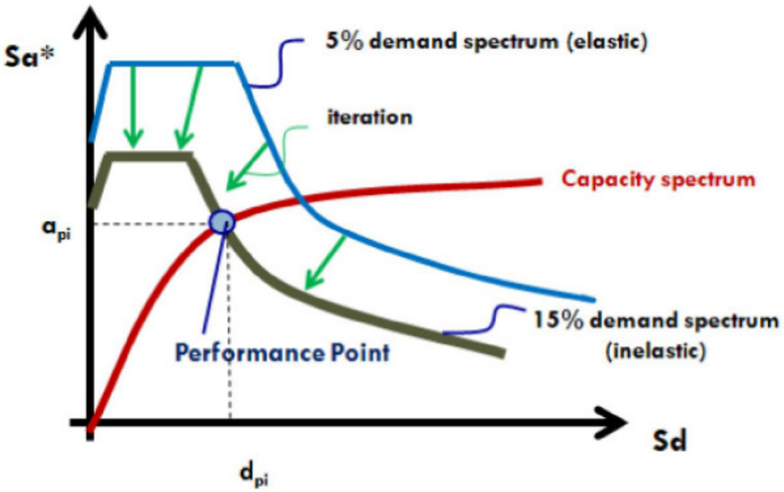
Thamrin Nine, Jakarta, Indonesia

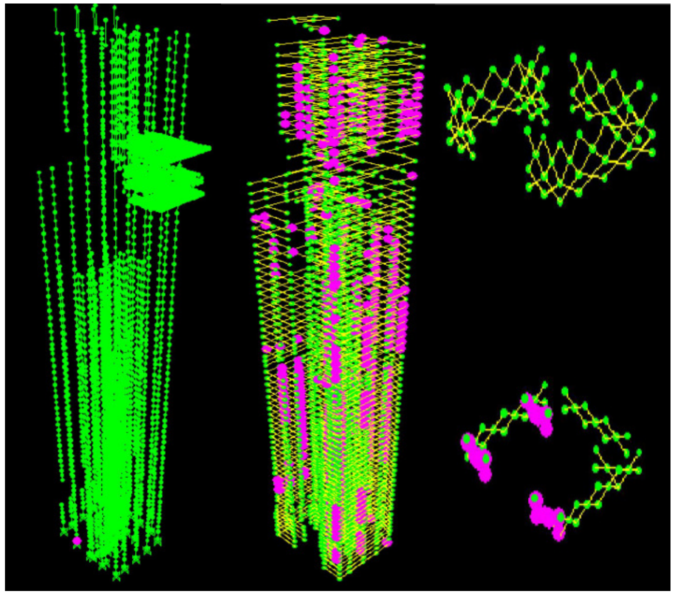
Non-Linear Static Push-Over Analysis











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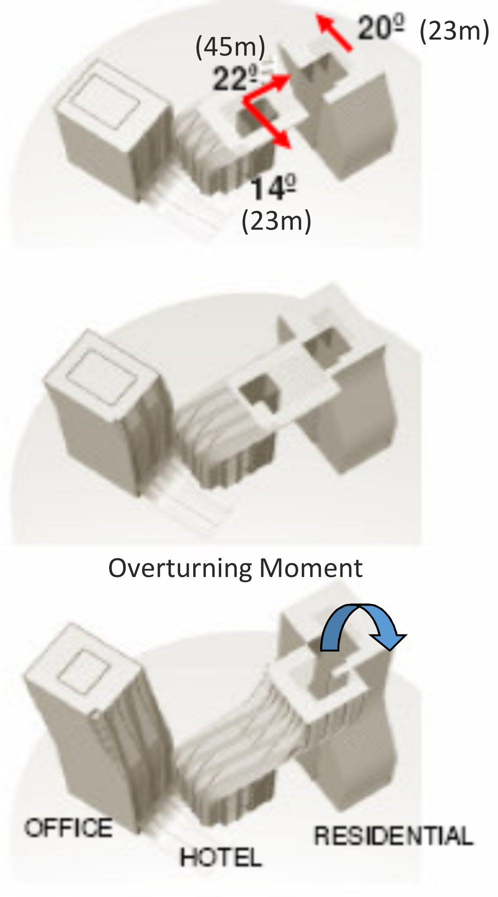
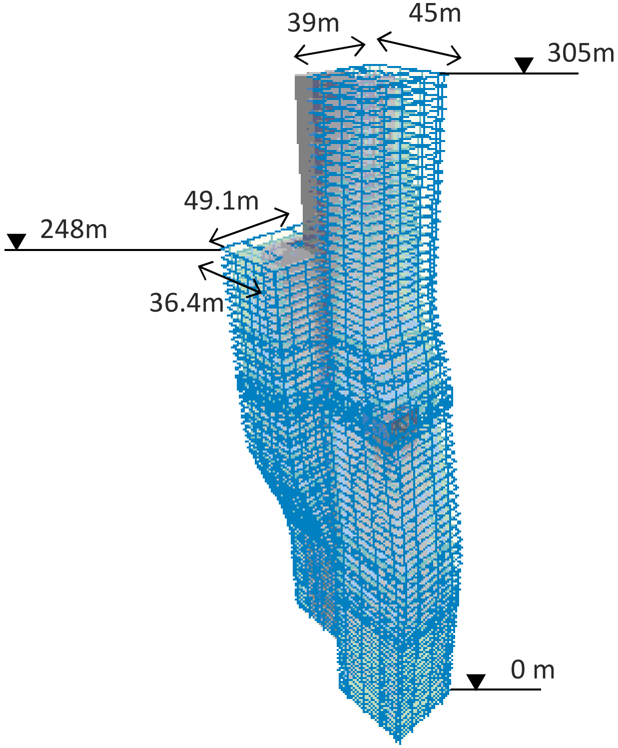
Signature Towers, Dubai

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

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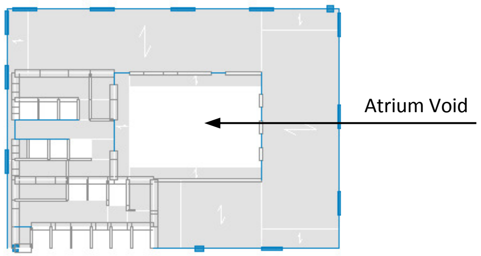

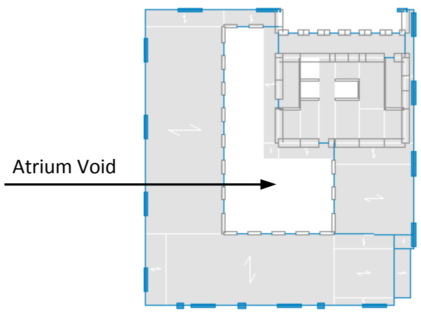

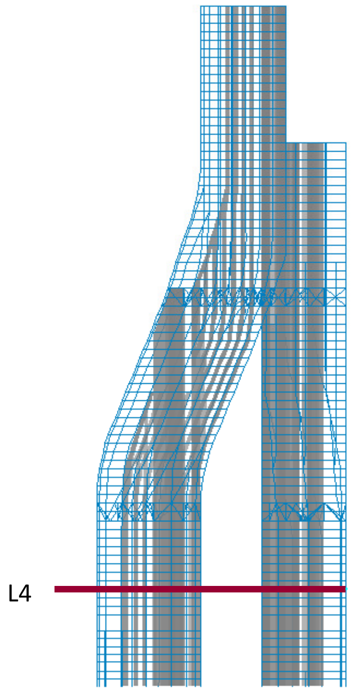

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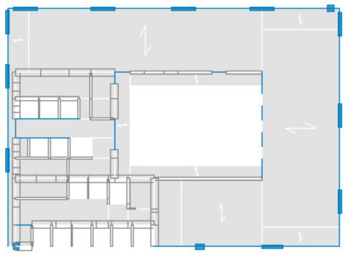

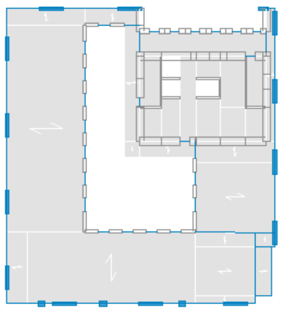

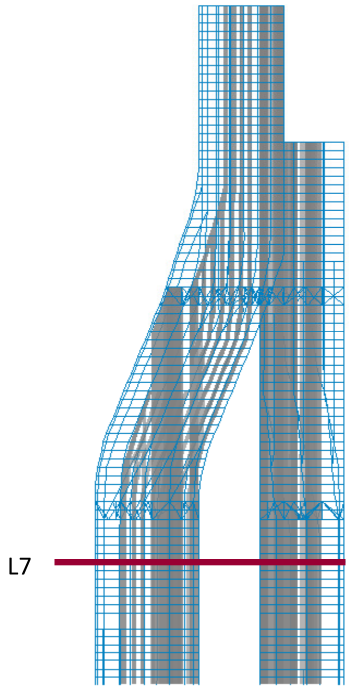

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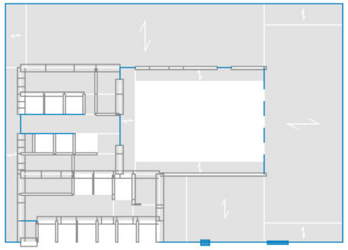

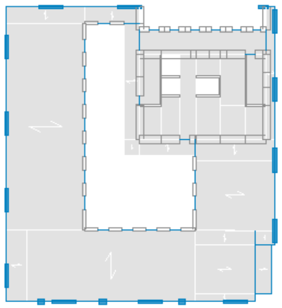

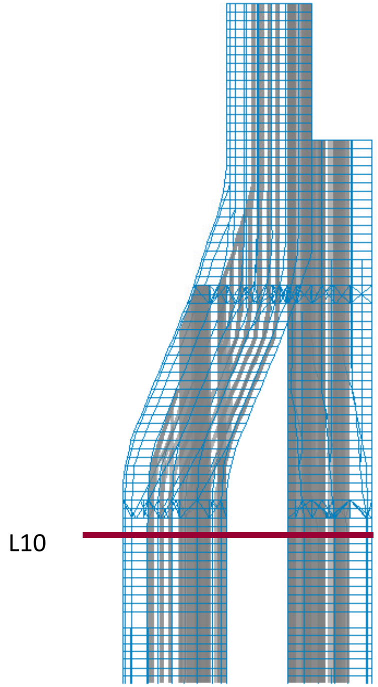

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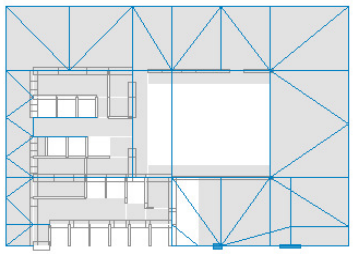

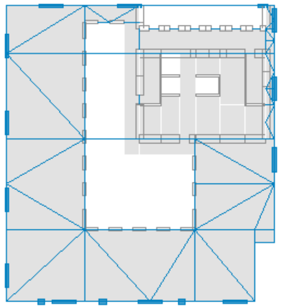

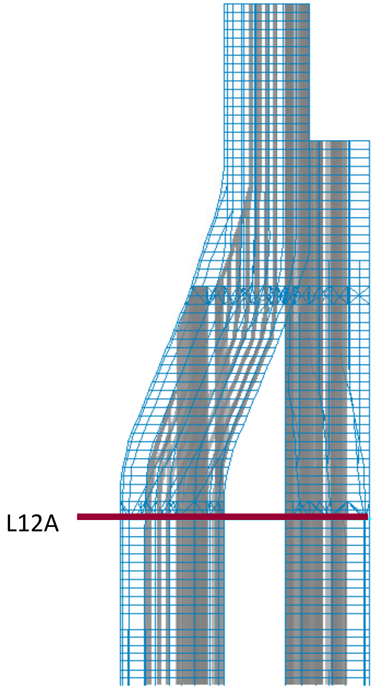

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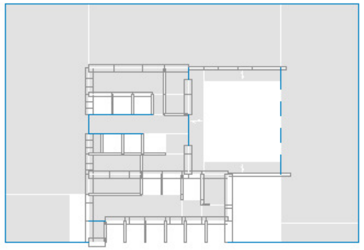

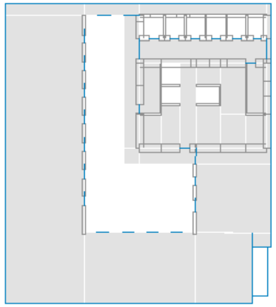

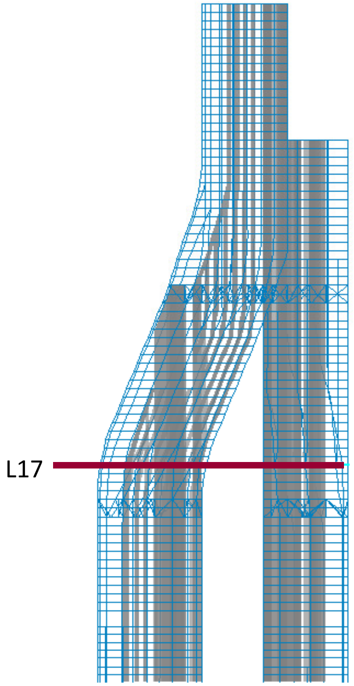

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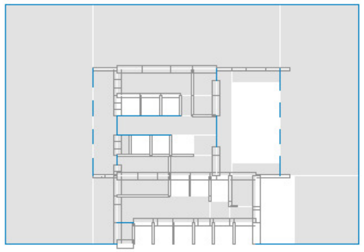

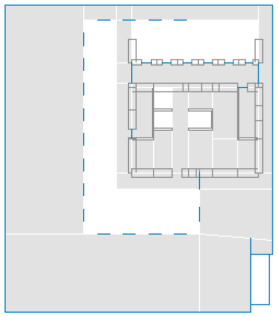

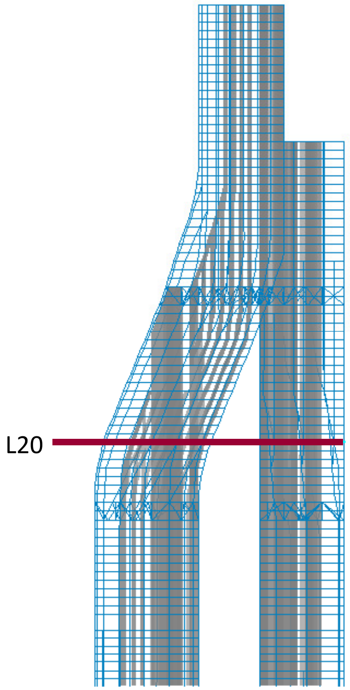

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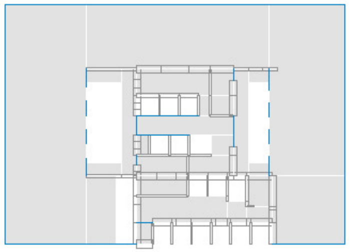

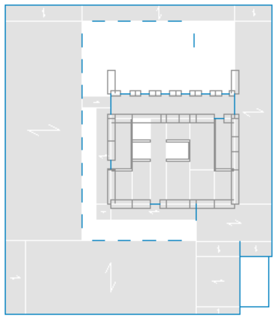

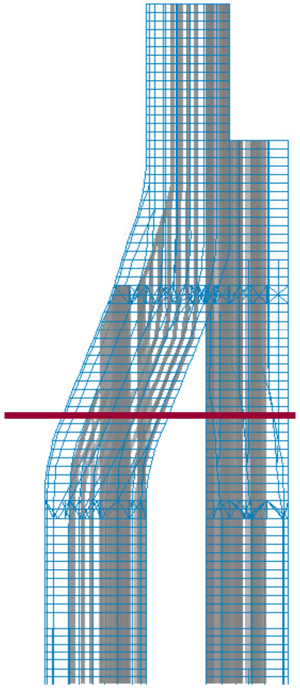

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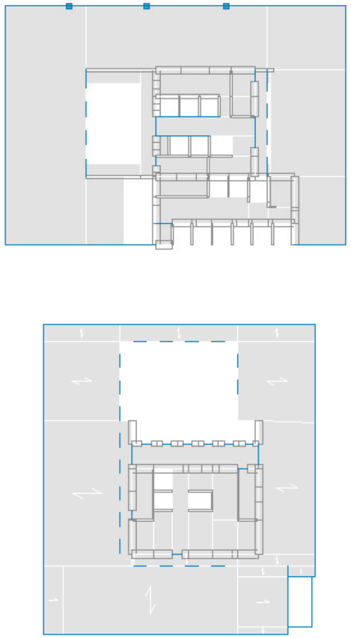

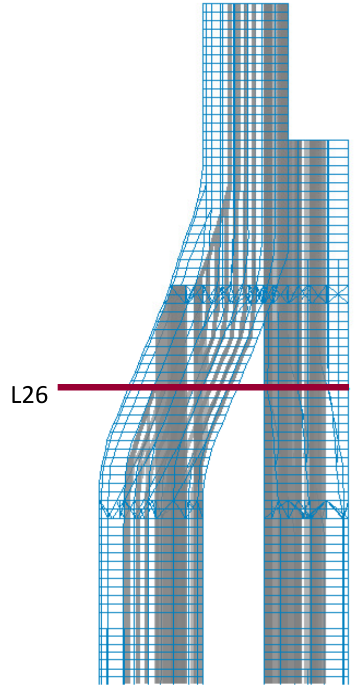

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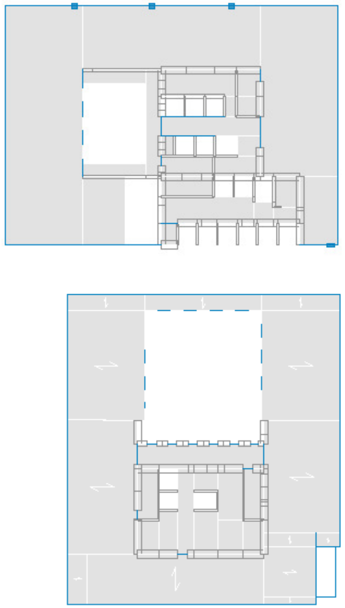

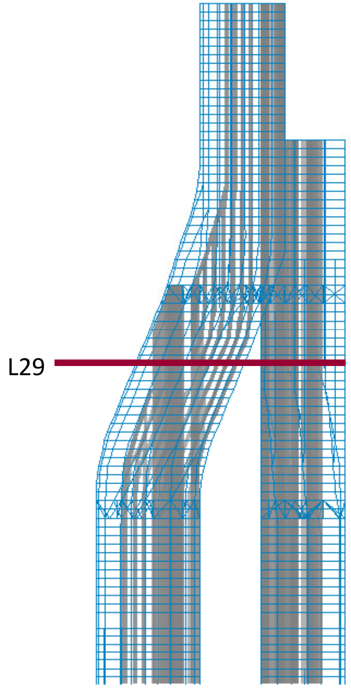

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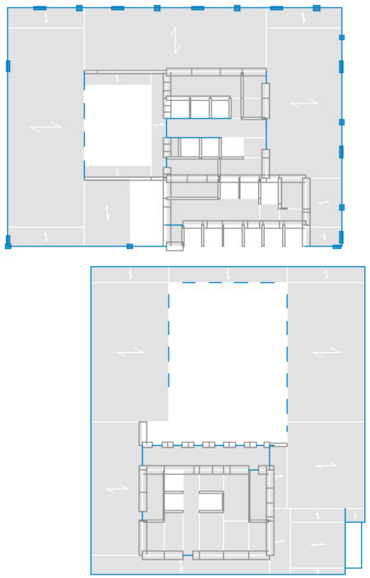

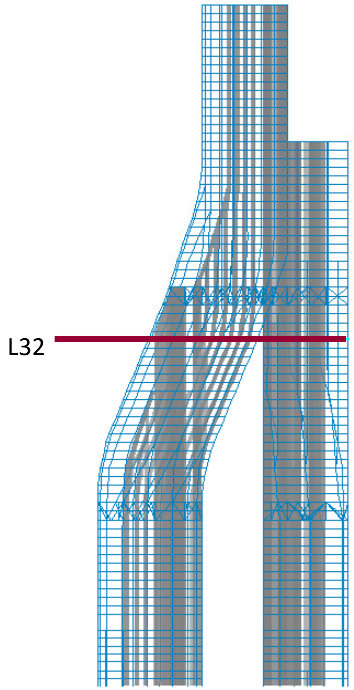

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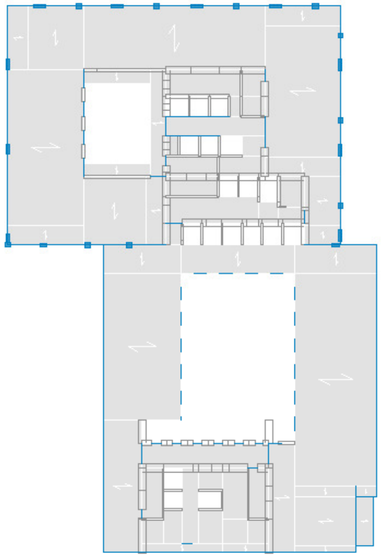

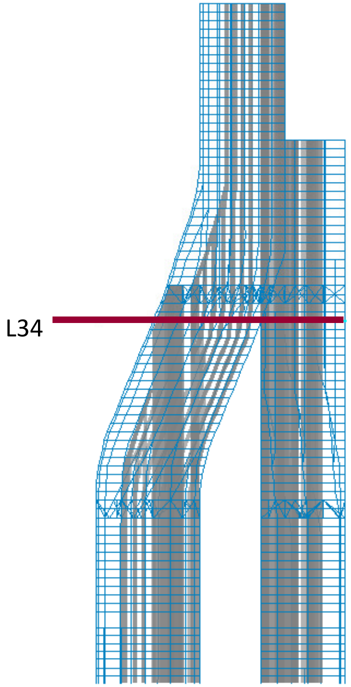

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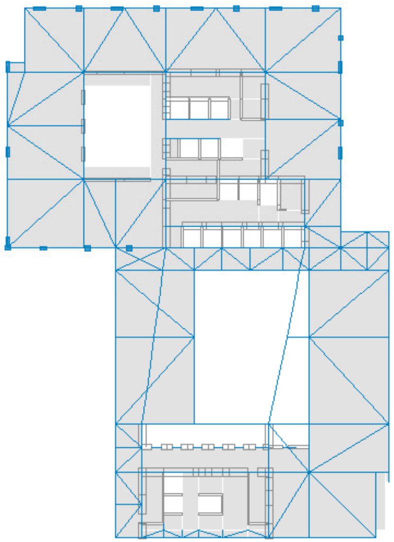

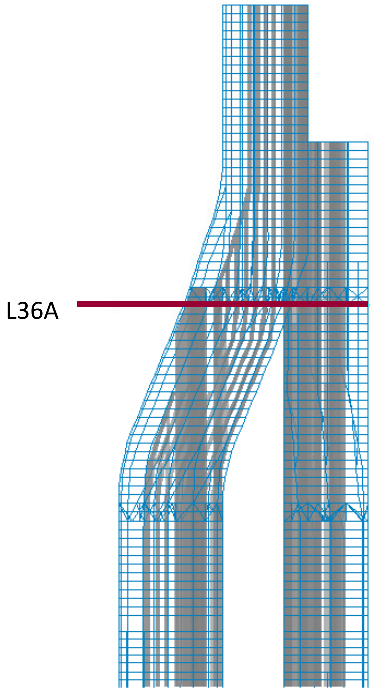

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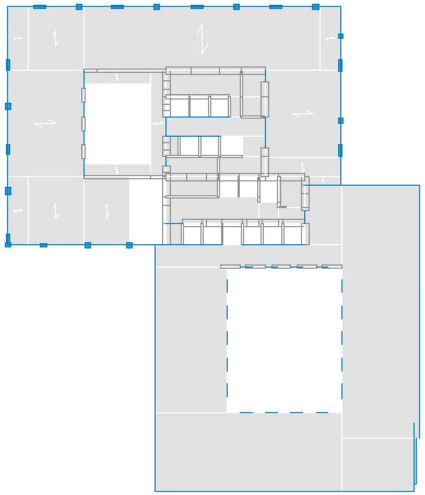

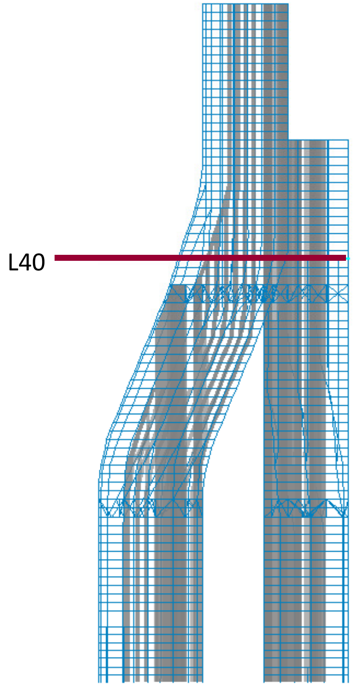

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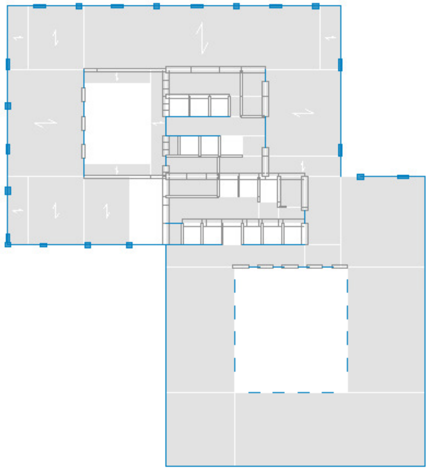

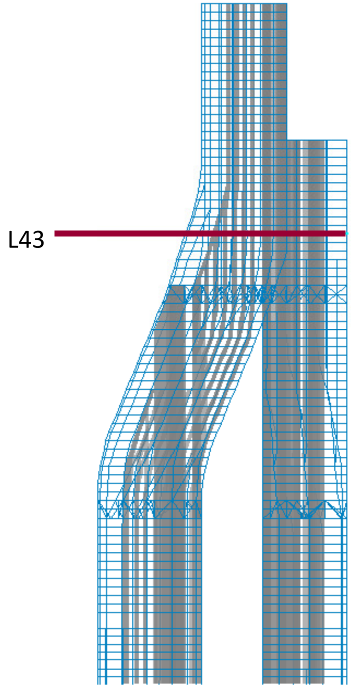

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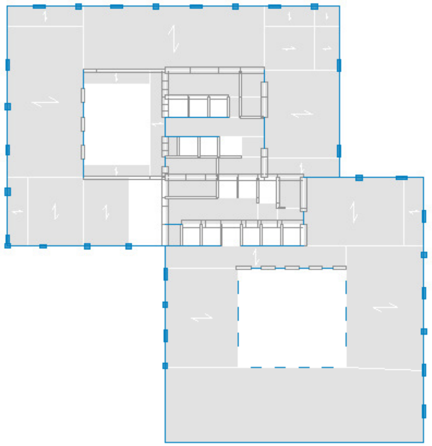

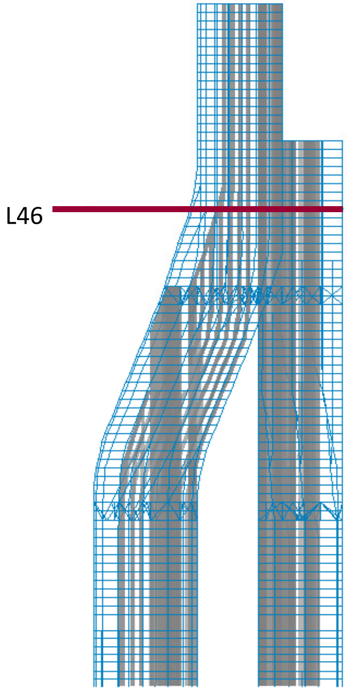

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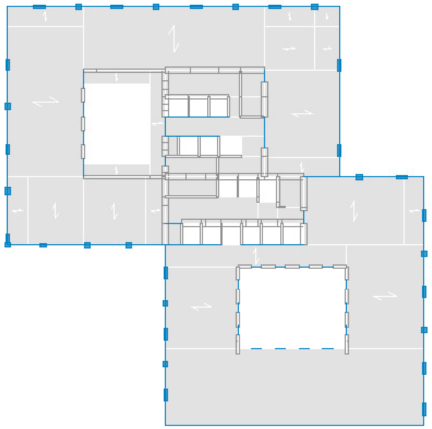

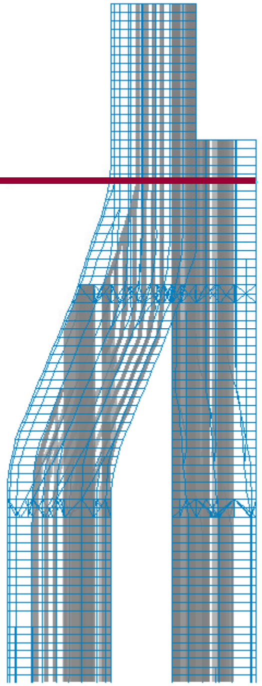

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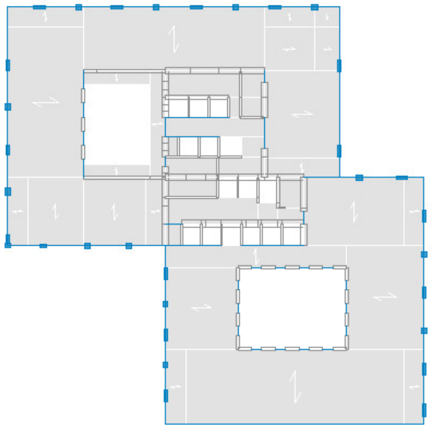

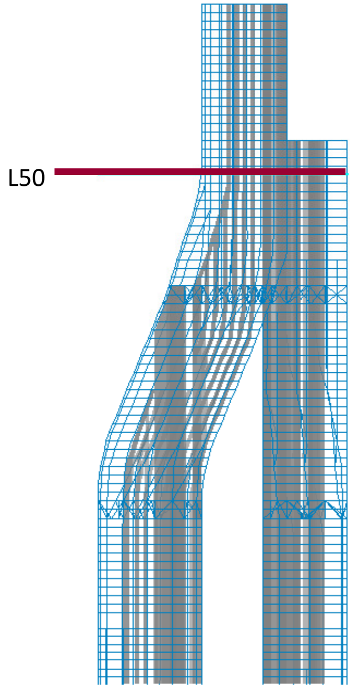

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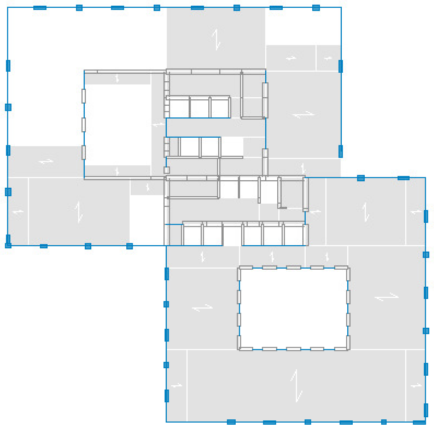

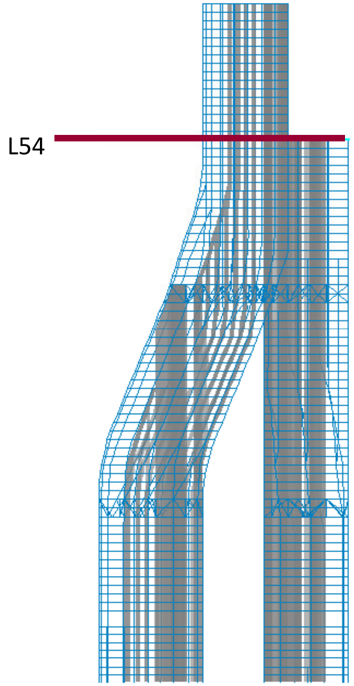

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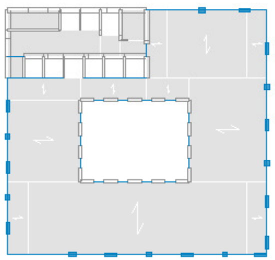

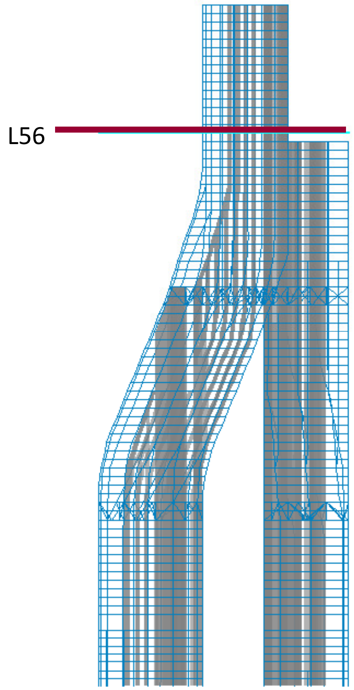

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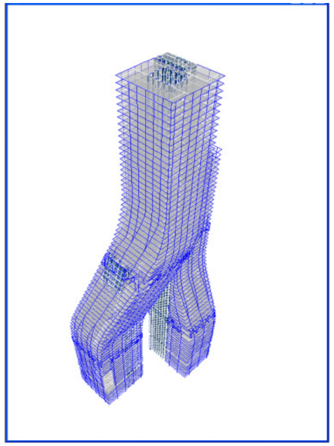
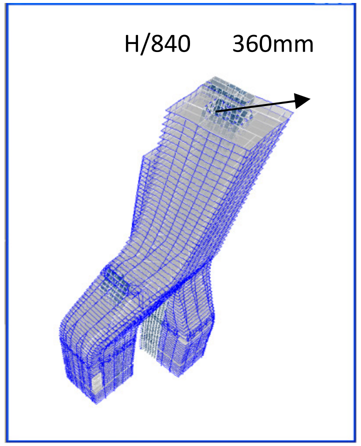
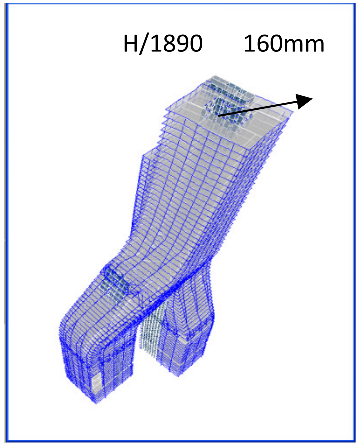


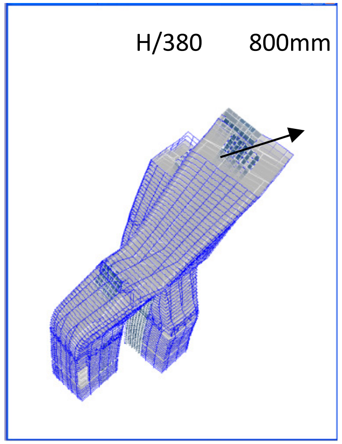
Un-deformed Shape



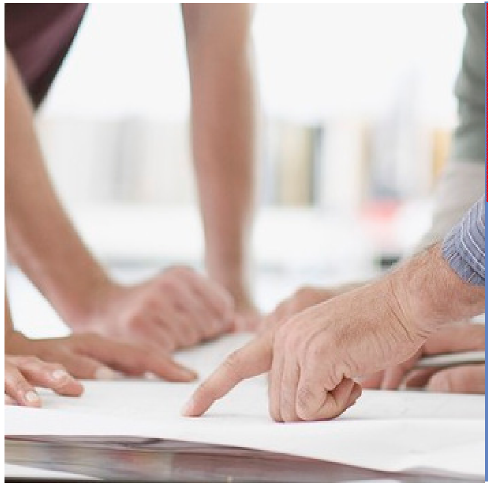
Self-WT Drift



Wind Load Drift



Earth-Quake Drift



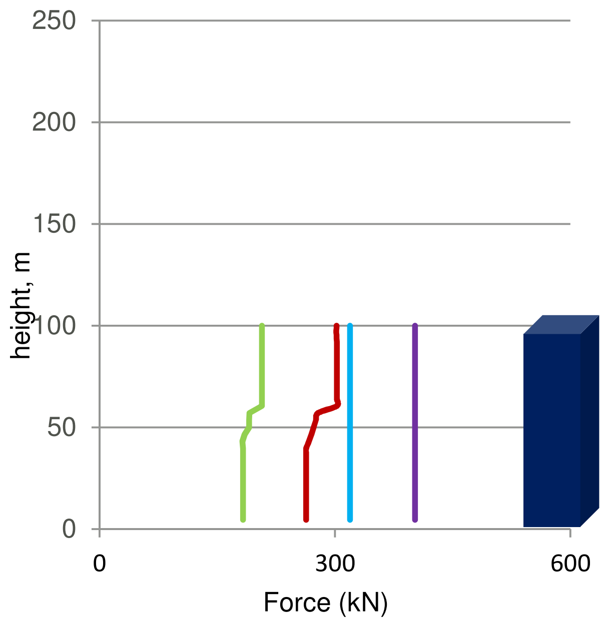
06

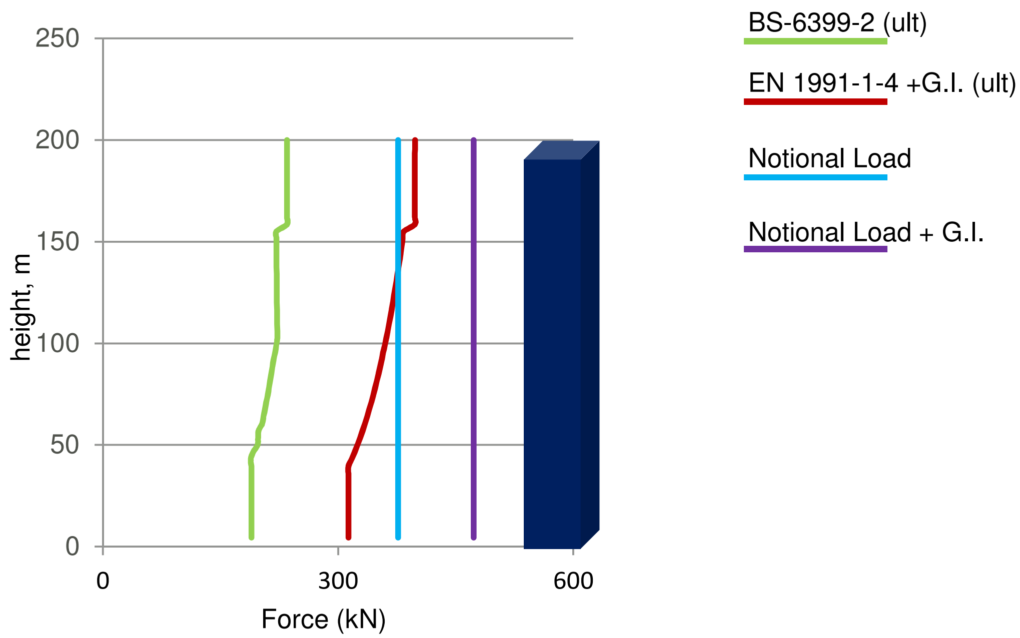
Comparison of Wind & Seismic Effects

Comparison of Lateral Loads

Ultimate Force

RC building,
L x W x H =
40m x 40m x 100m / 200m

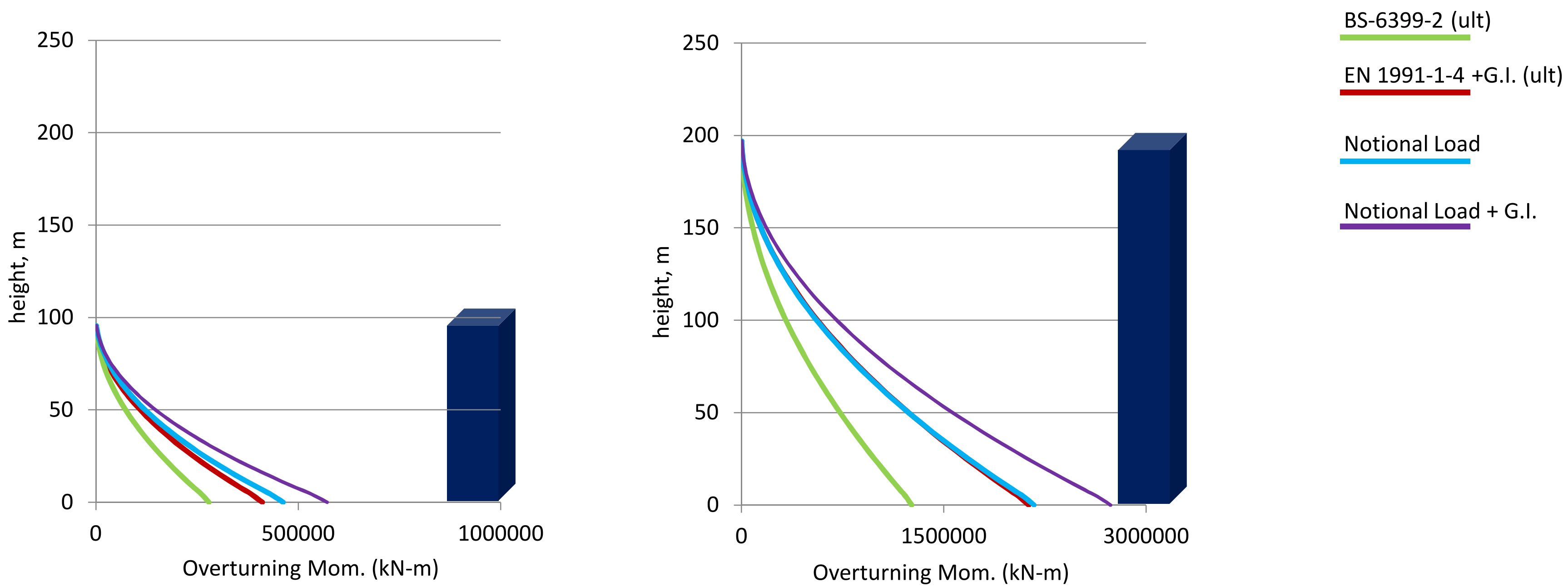




Comparison of Lateral Loads

Ultimate Over Turning Moment

RC building,
L x W x H =
40m x 40m x 100m / 200m



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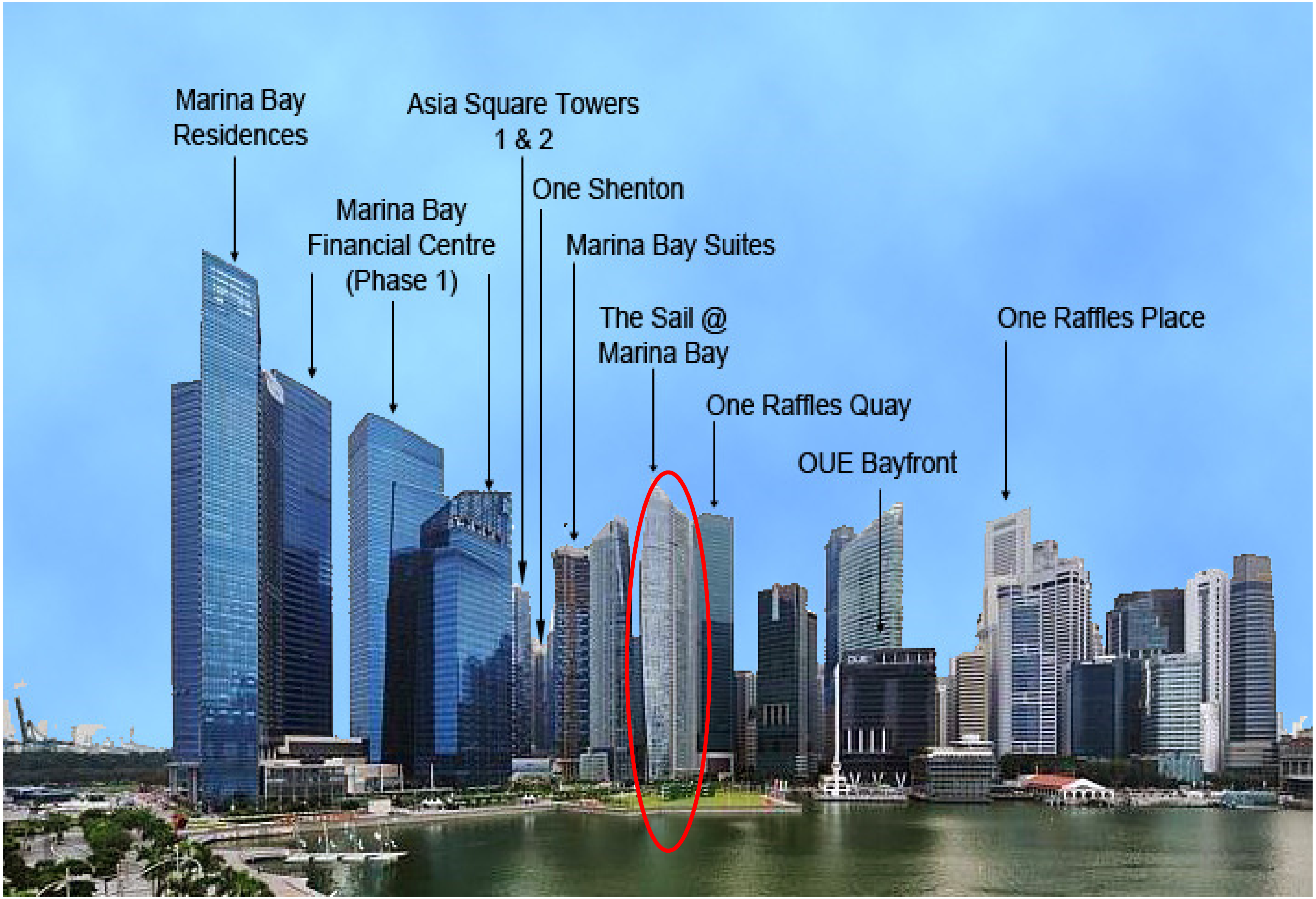

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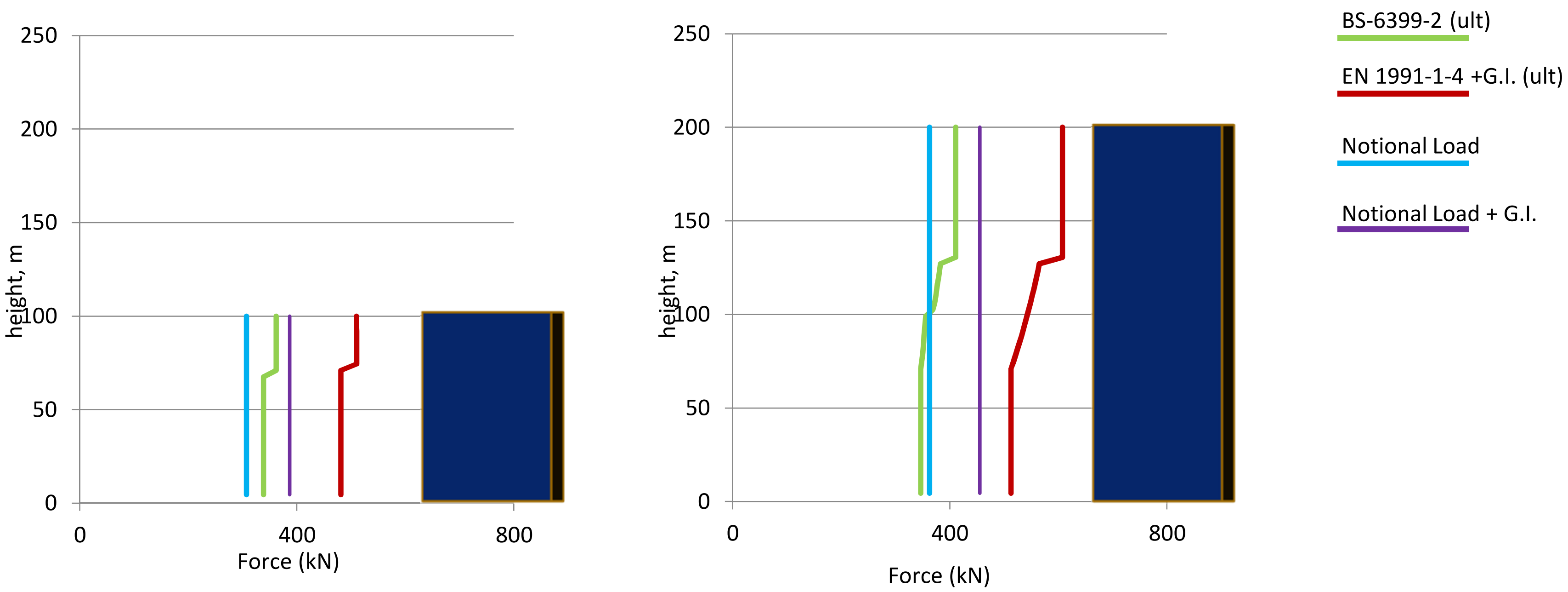
Comparison of Lateral Loads

Ultimate Force

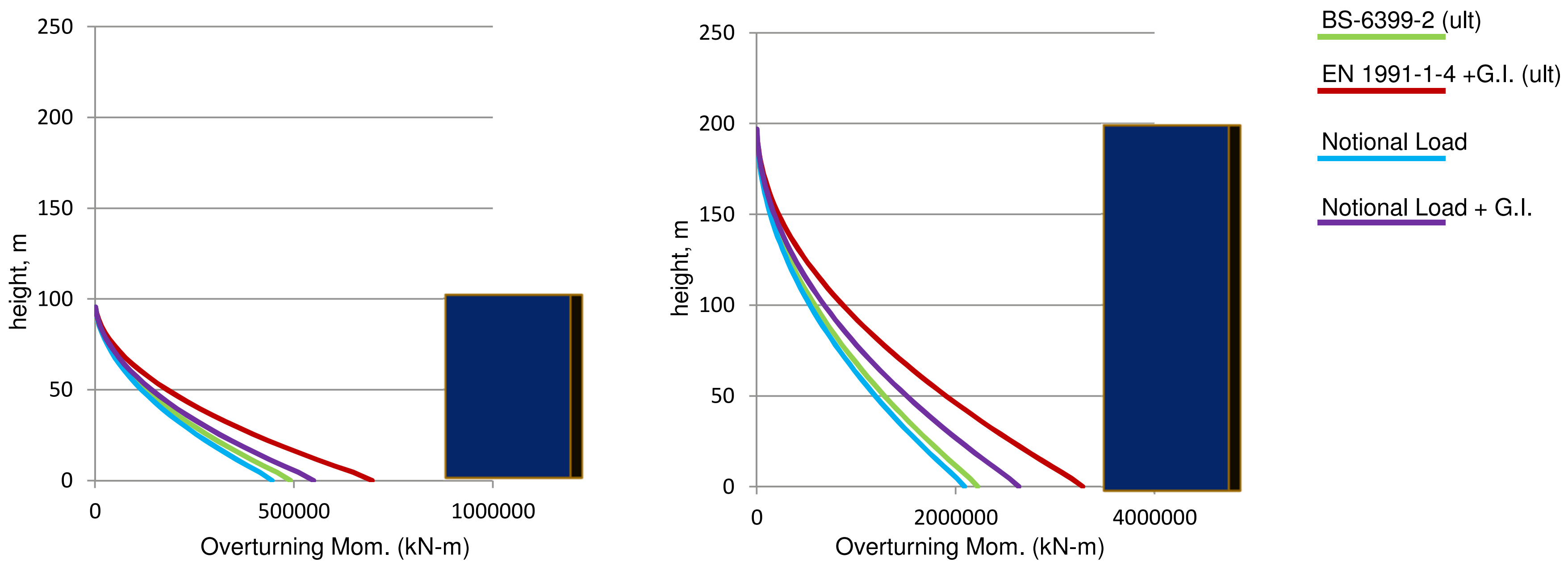
RC building,
L x W x H =
22m x 70m x 100m / 200m



Comparison of Lateral Loads

Ultimate Over Turning Moment

RC building,
L x W x H =
40m x 40m x 100m / 200m



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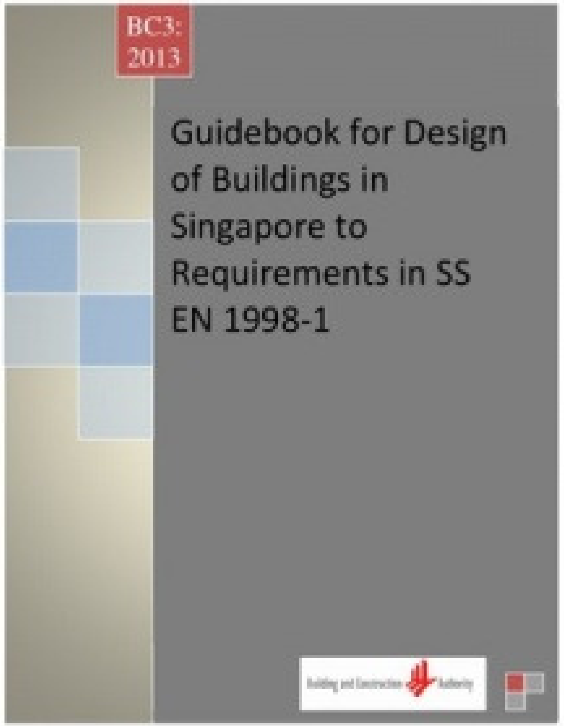
Comparison of Lateral Loads

Impact of Seismic Loads



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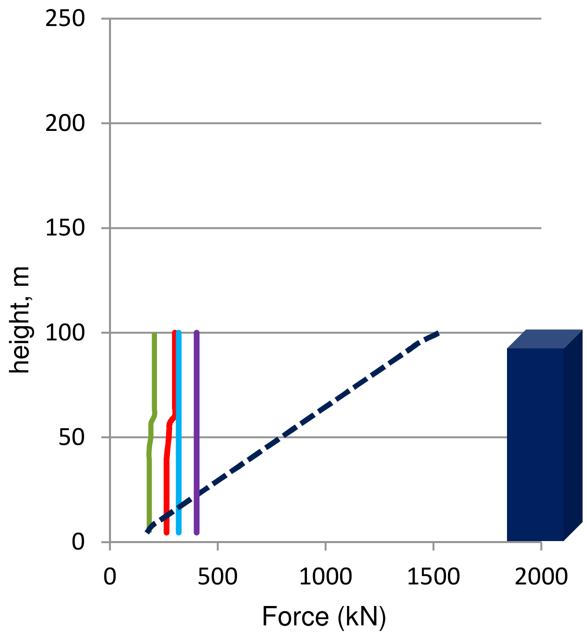
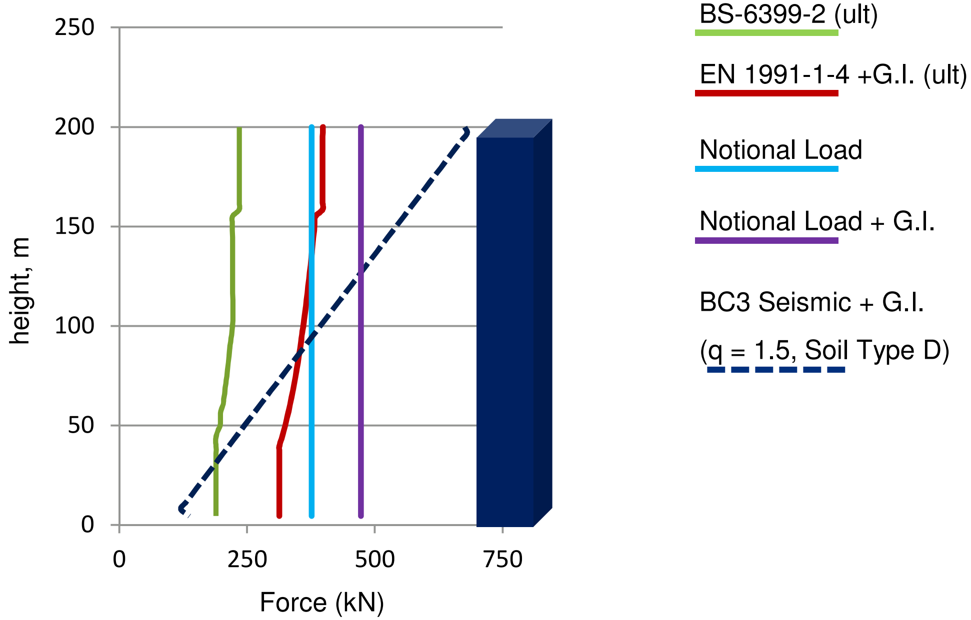
Comparison of Lateral Loads

Ultimate Force

RC building,
L x W x H =
40m x 40m x 100m / 200m





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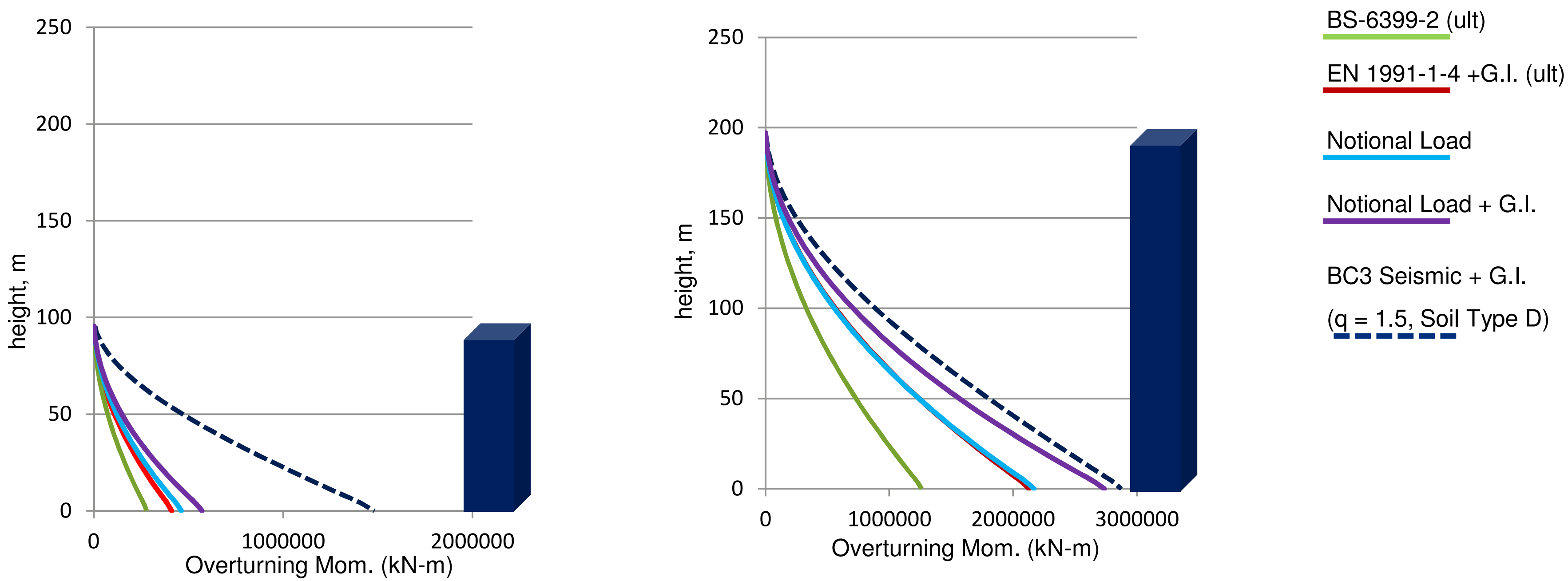
Comparison of Lateral Loads

Ultimate Over Turning Moment

RC building,
L x W x H =
40m x 40m x 100m / 200m



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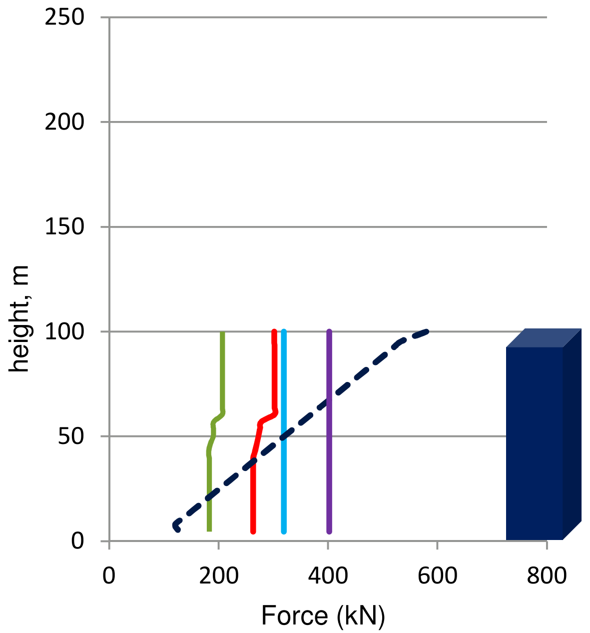
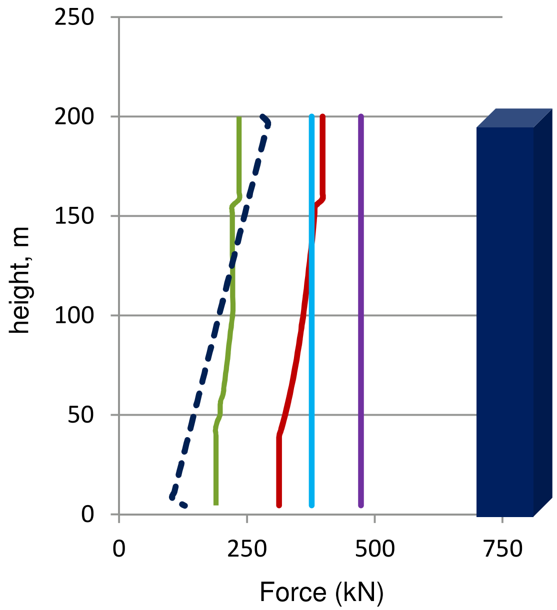
Comparison of Lateral Loads

Ultimate Force

RC building,
L x W x H =
40m x 40m x 100m / 200m





BS-6399-2 (ult)

EN 1991-1-4 +G.I. (ult)

Notional Load

Notional Load + G.I.

BC3 Seismic + G.I.
(q = 4.5, Soil Type D)

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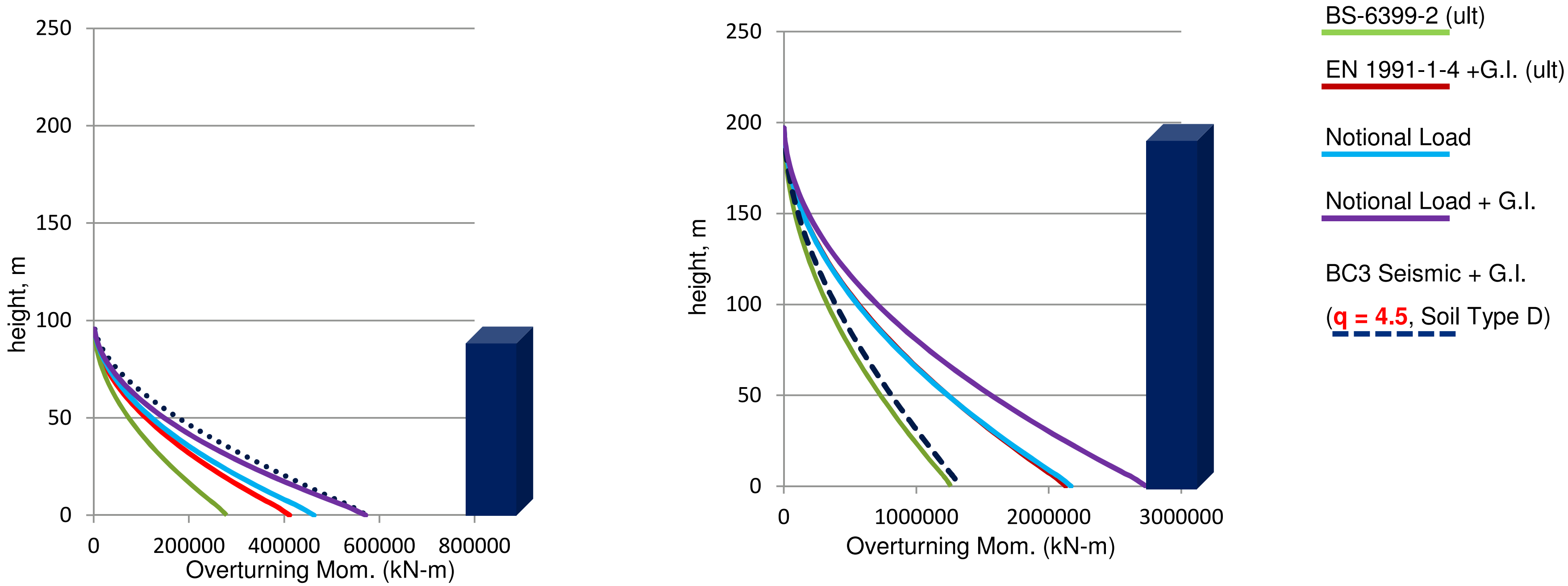
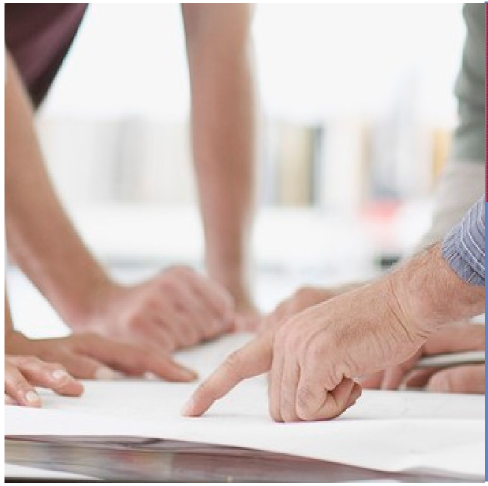
Comparison of Lateral Loads

Ultimate Over Turning Moment

RC building,
L x W x H =
40m x 40m x 100m / 200m



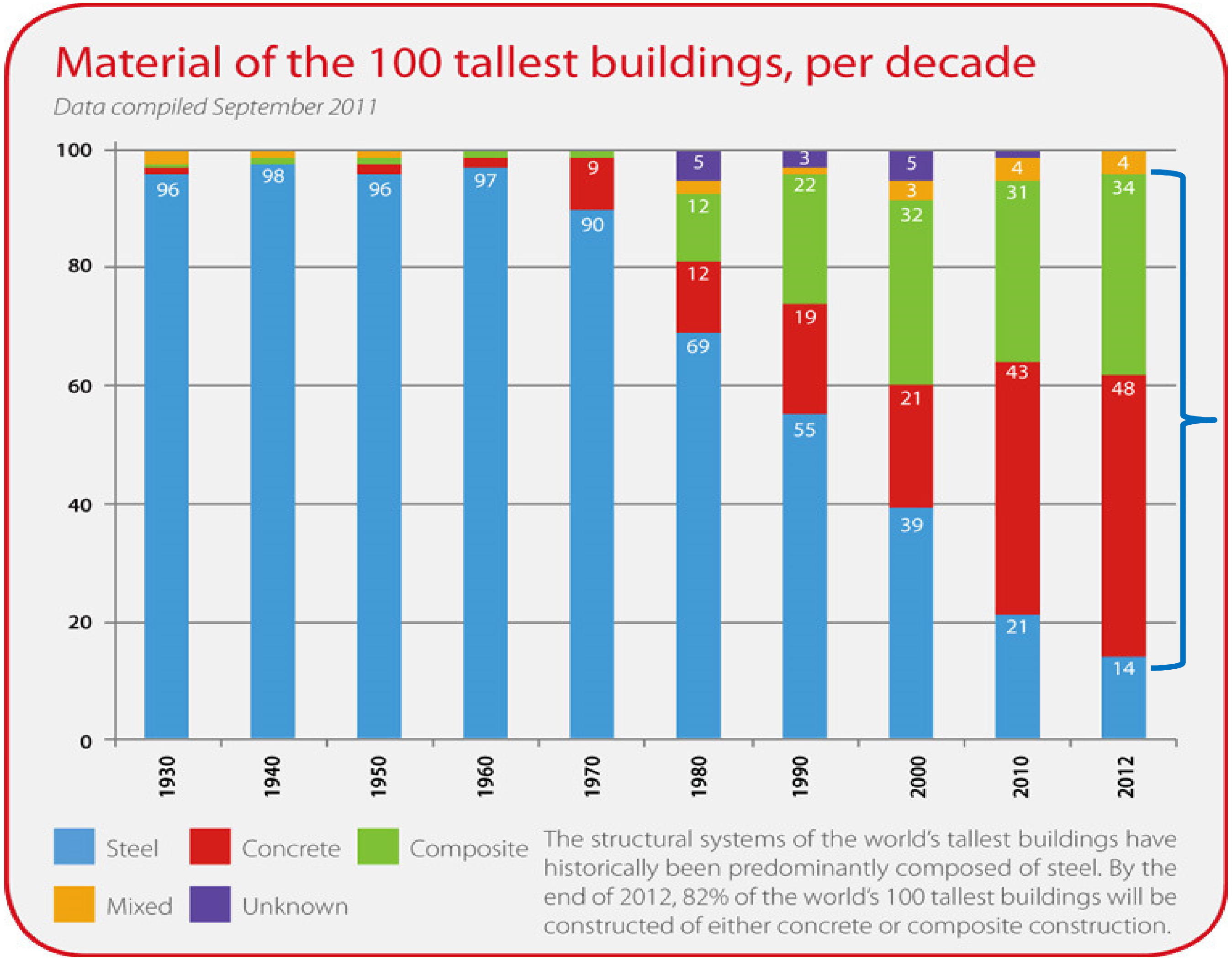


07

Cost Comparison of Concrete vs. Composite Tall Building

Cost Comparison

- **82% of the 100 tallest buildings are** either **concrete** or **composite**.



Source: CTBUH

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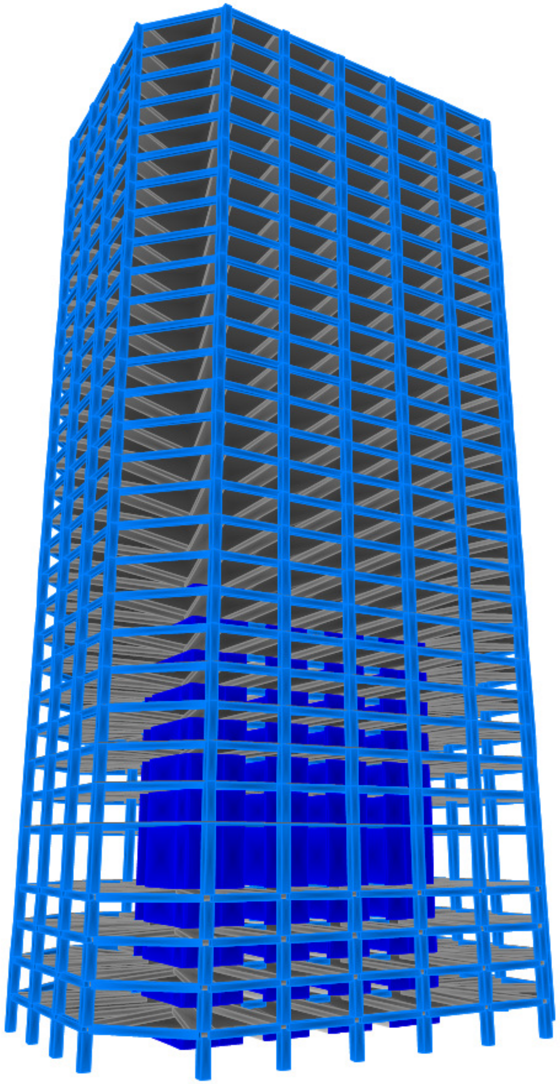
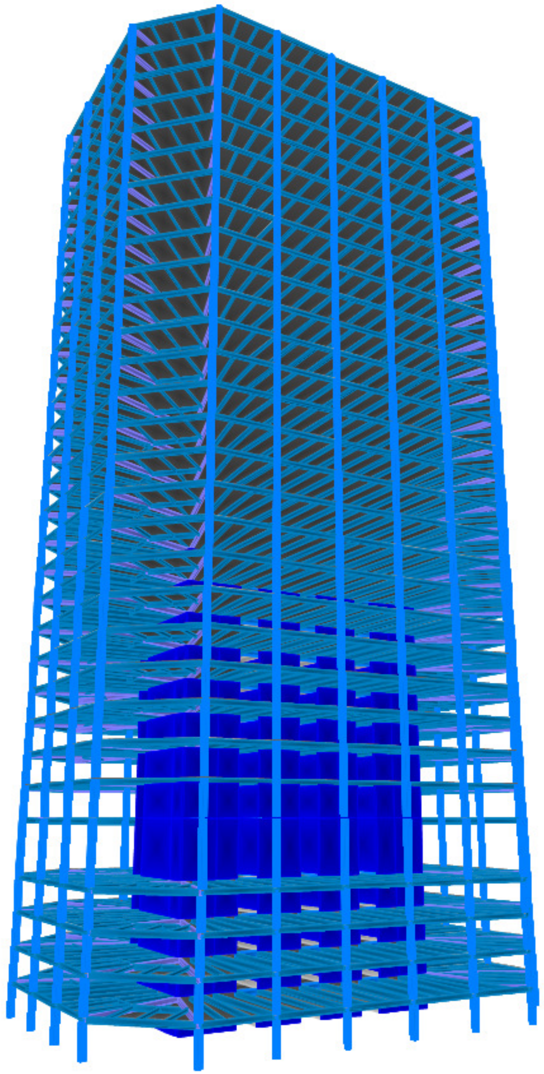
Comparative Case Study of a Typical Tall Building in Singapore



RC Building

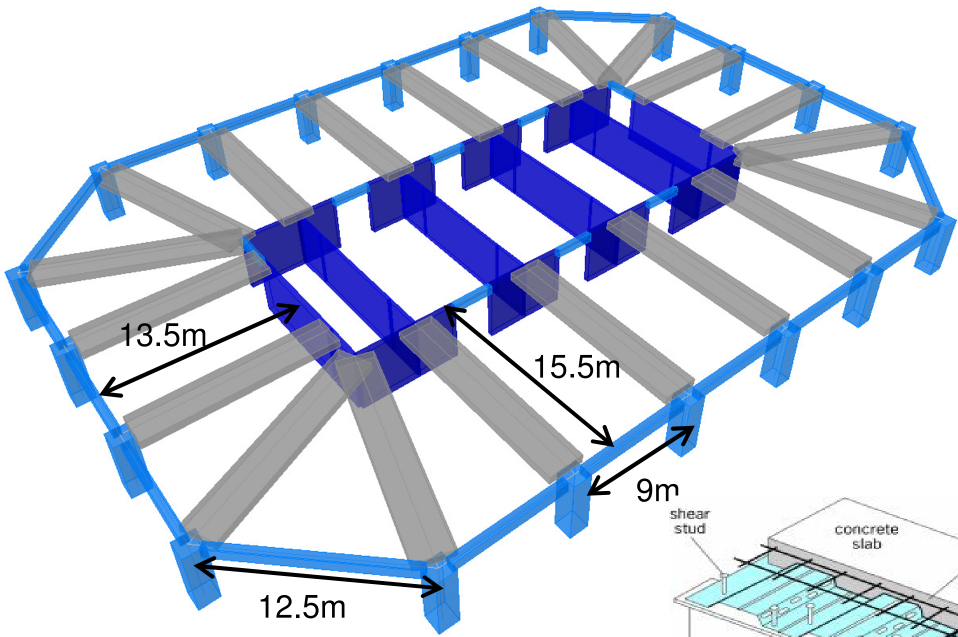


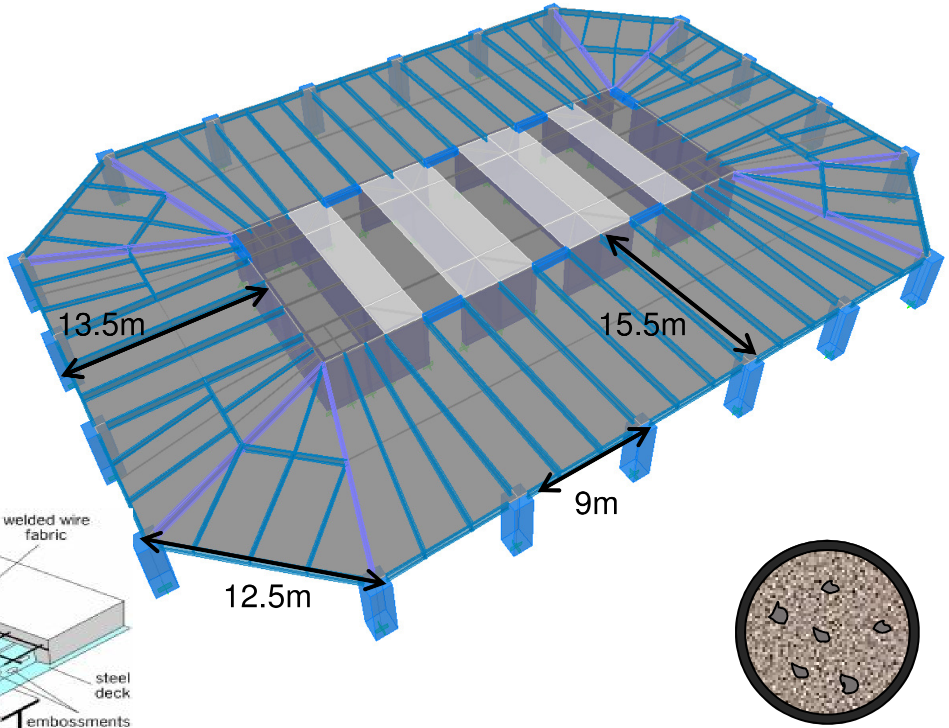
Steel-Concrete Composite Building

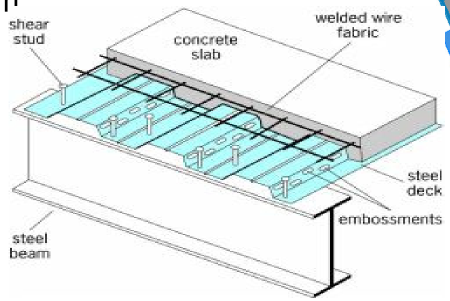
<u>Building Description</u>

GFA:	85,000 m^2
Height:	130m
No. of Floors:	30
Typ. Floor Height:	4.3m
Typ. Floor Area:	2800 m^2
Clear Span:	up to 15.5m
Lateral System:	Dual System - RC Core + Frames

Comparative Case Study of a Typical Tall Building in Singapore







RC Building – Typical Parameters
Long Span PT Band Beam: 2400x 600 Deep
Short Span PT Band Beam: 2400x 550 Deep
Edge Beam: 500x600 Deep
PT Slab Thickness: 200 Typical
Primary Core Wall Thickness: 350
Secondary Core Wall Thickness: 250
Columns : 1.0m x 1.0m

Composite Building - Typical Parameters
Long Span Steel Beams: UB610 x 229 x 92
Short Span Steel Beams: ***UB610 x 229 x 113***
Edge Steel Beams: UB533 x 210 x 66
Slab: 130 on Re-Entrant Deck
Primary Core Wall Thickness: 300
Secondary Core Wall Thickness: 250
Columns : 0.8m dia. CHS

Comparative Case Study of a Typical Tall Building in Singapore

Design Criteria

Gravity Loading:

Dead Load (DL)	: Self-weight of elements
Superimposed Dead Load (SDL)	: 1.5 kPa
Live Load (LL)	: 3.5 kPa + 1 kPa for Partitions = 4.5 kPa Total
Cladding (SDL)	: 1.0 kPa (on elevation)

Lateral Loading:

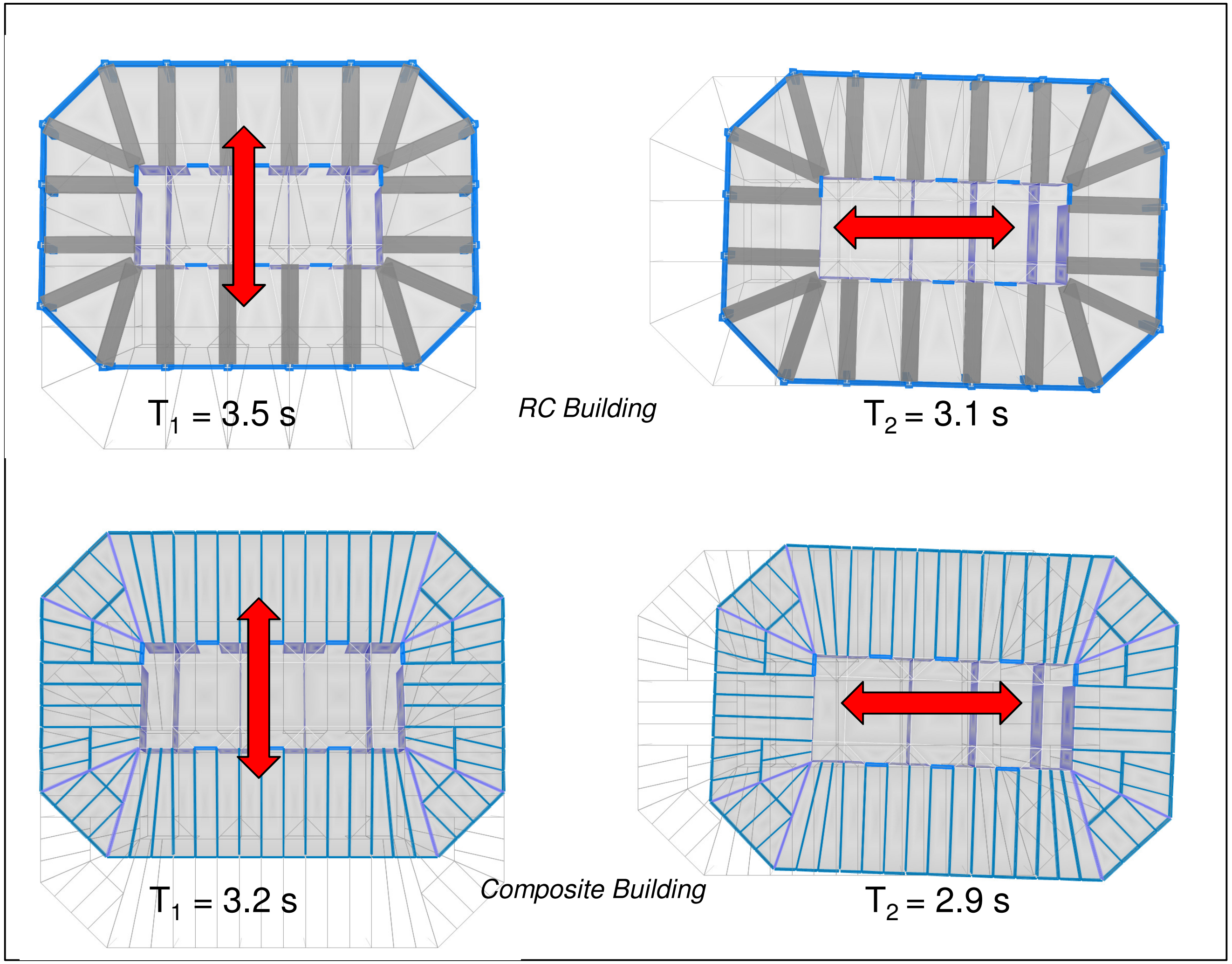
Wind Speed	: 22m/s Mean Hourly, 50-year Return Period
Wind Load Pressure	: Max Pressure ~ 1.3 kPa
Seismic	: SS-EN 1998-1, BC3, q=1.5, Ground Type D

Deflections and Drift Parameters:

Interior Beams, Live Load	: L / 250, 20 mm maximum
Interior Beams, Incremental Deflection	: L / 350
Perimeter Beams, Live Load	: L /500, 10 mm maximum
Wind Inter-story Drift	: H / 500

Floor Vibrations and Acceleration:	: Frequency ≥ 4 Hz & / or Acceleration ≤ 0.5%g

Comparative Case Study of a Typical Tall Building in Singapore



Comparative Case Study of a Typical Tall Building in Singapore

Building Performance Comparison

$$S_d\,(T) = \frac{S_e\,(T).\,\gamma_I}{q}$$

[γ_I = 1.0, q=1.5]

RC Building:

V_{eq1} = 3.41%*W = 35.9 MN

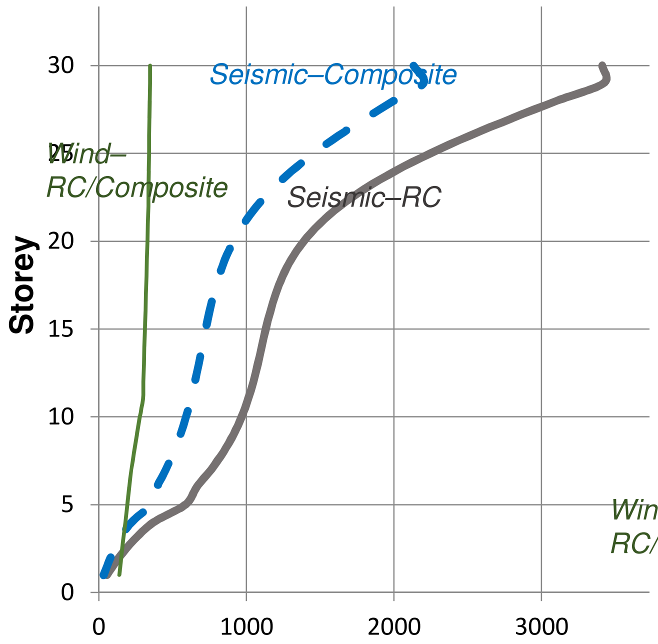
V_{eq2} = 3.95%*W = 41.6 MN

Composite Building:

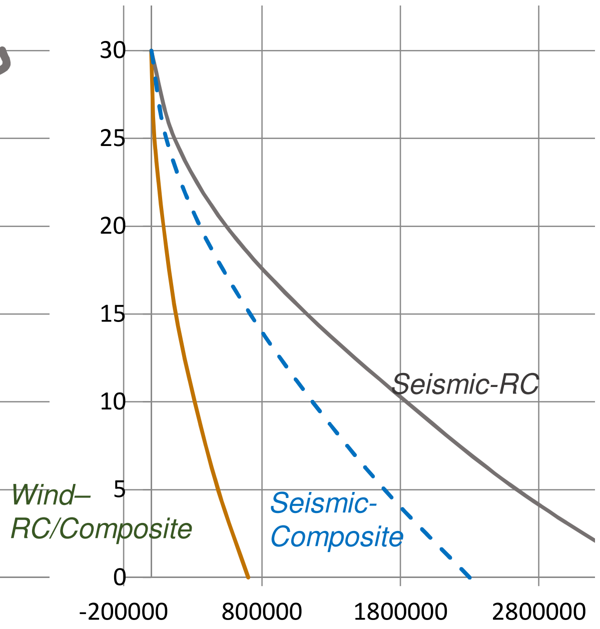
V_{eq1} = 3.81%*W = 24.9 MN

V_{eq2} = 4.05%*W = 26.5 MN

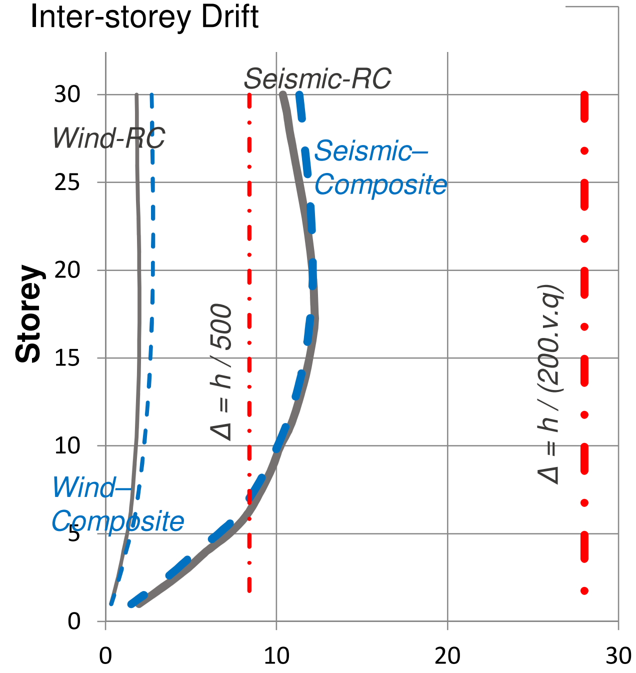
Lateral Storey Forces



Overturning Moment



Inter-storey Drift



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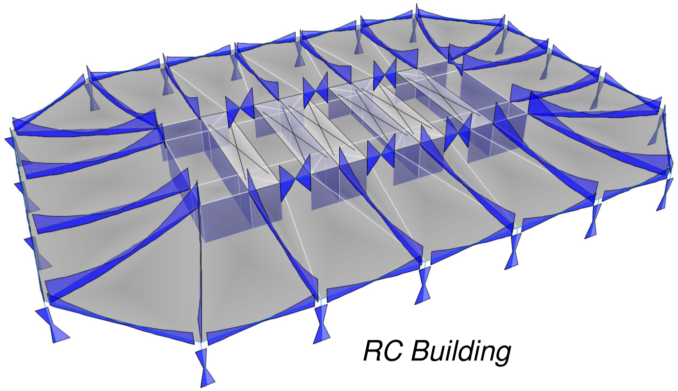
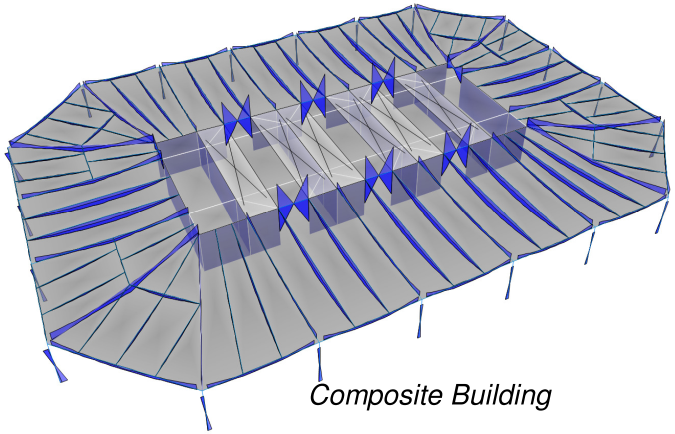
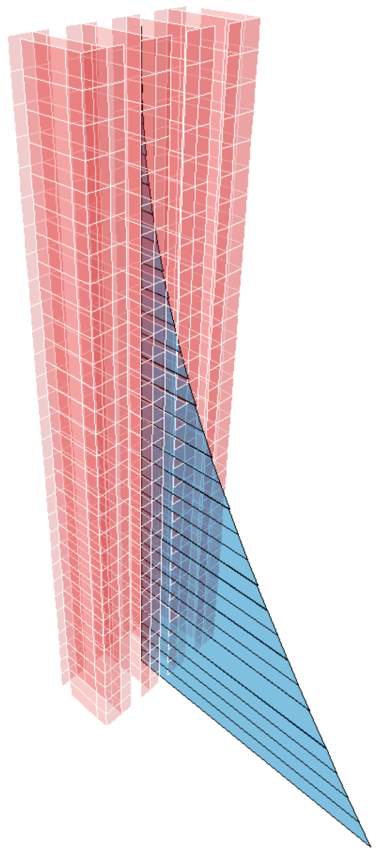
Comparative Case Study of a Typical Tall Building in Singapore



RC Building



Composite Building



Comparative Case Study of a Typical Tall Building in Singapore

Costing Assumptions:

Pricing information was collated & verified through a combination of local sources (based on 2013 prices)

Baseline Unit Costs ("All-in," incl. labour)

Concrete Grade (f_{cu})	**Cost (S$/m3)**
30	$ 155
40	$ 160
50	$ 165
60	$ 170
Rebar Cost (S$/T)	$ 1,500
Post-tensioning (S$/T)	$ 6,000
Formwork (S$/m2)	$ 35
Structural Steel *incl. studs* **(S$/T)**	$ 5,000
Metal Deck (S$/m2)	
1 mm Bondek	$ 40
Steel Fireproofing (S$/m2)	$ 25
Foundation Costs (S$/ ton / m)	$ 0.60

Material Cost Information Courtesy of :

- *Langdon & Seah*
- *Bluescope Lysaght*
- *Hyundai E&C*
- *Yongnam*

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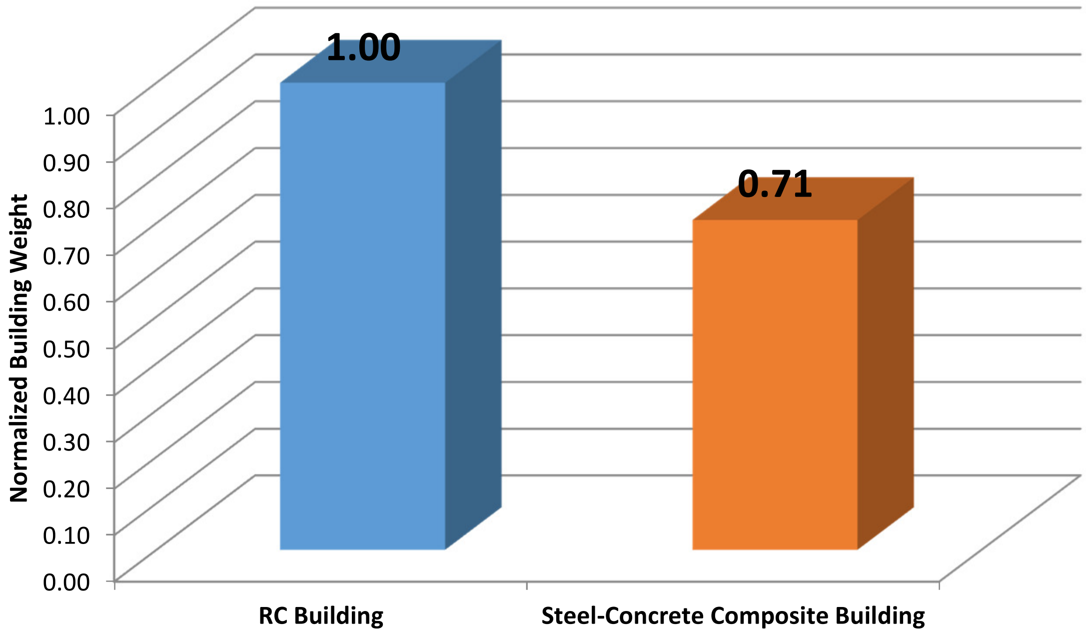
Comparative Case Study of a Typical Tall Building in Singapore

Building Weight *(Normalized; including imposed loads)*



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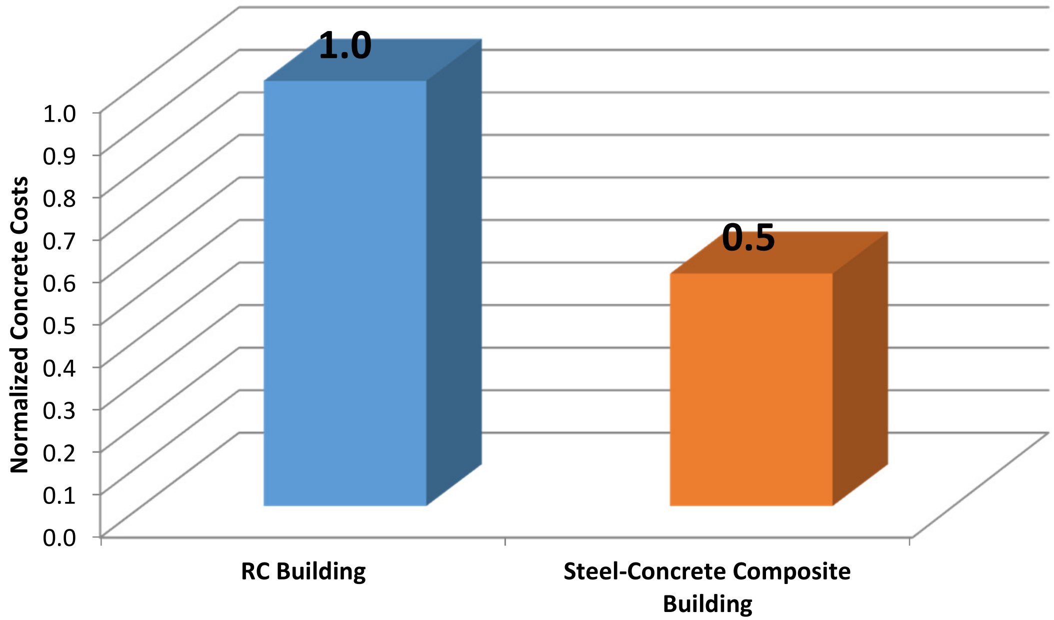
Comparative Case Study of a Typical Tall Building in Singapore

Concrete Costs *(Normalized; excluding rebar & PT)*



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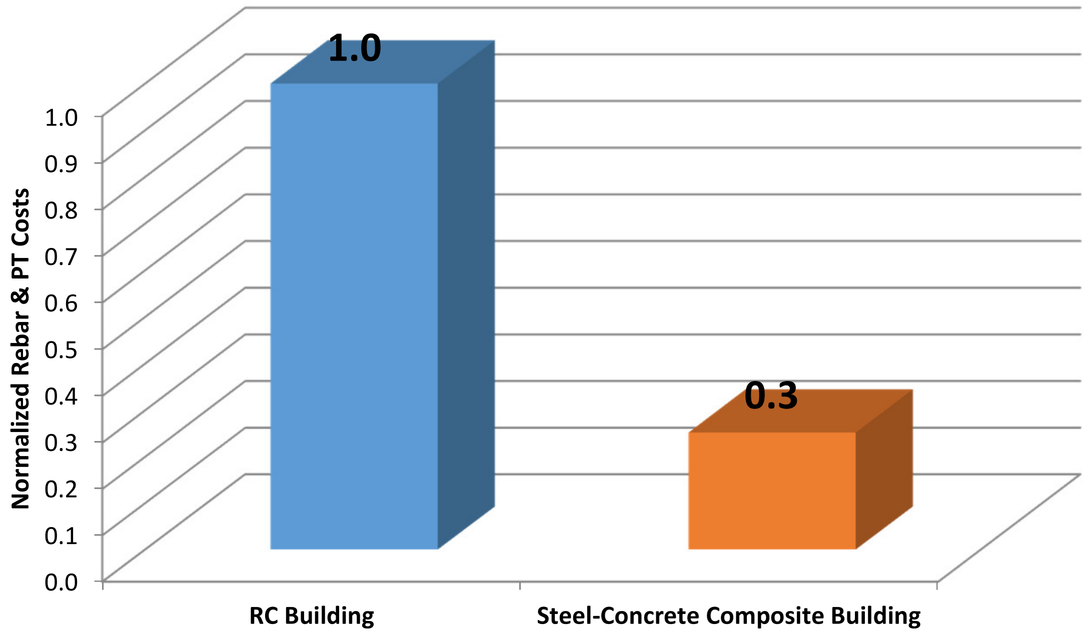
Rebar and Post-tensioning Costs *(Normalized)*



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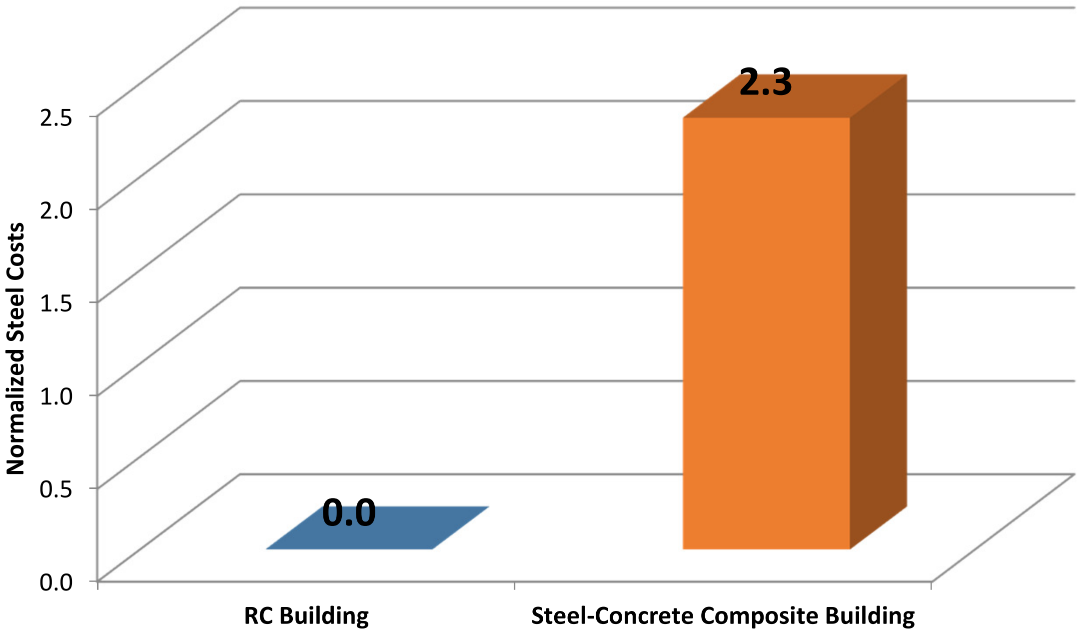
Structural Steel Costs *(Normalized; including Decking and FP)*



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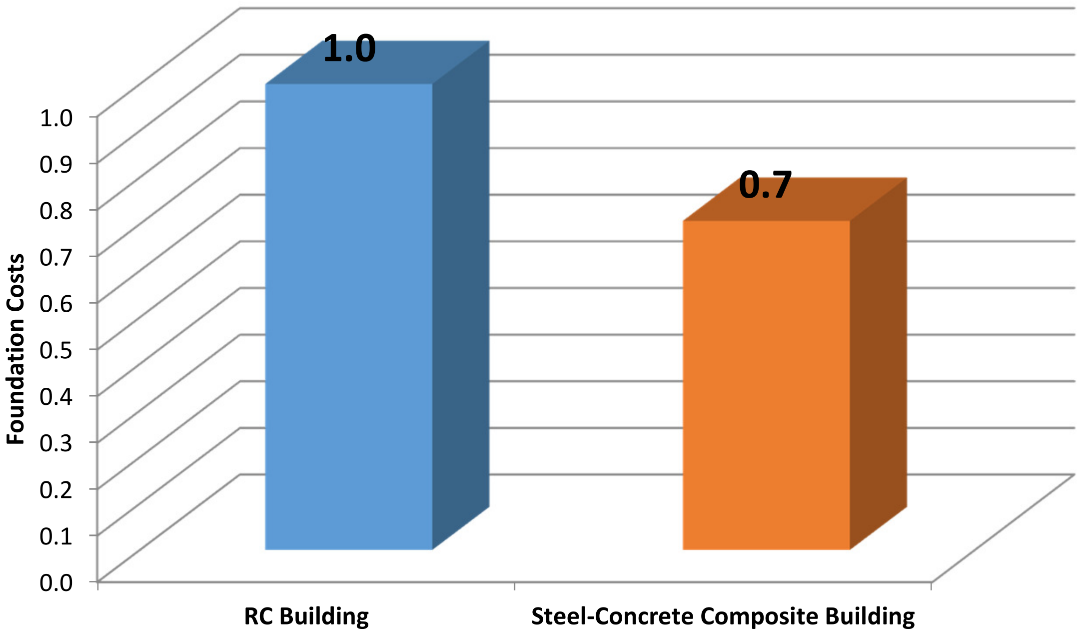
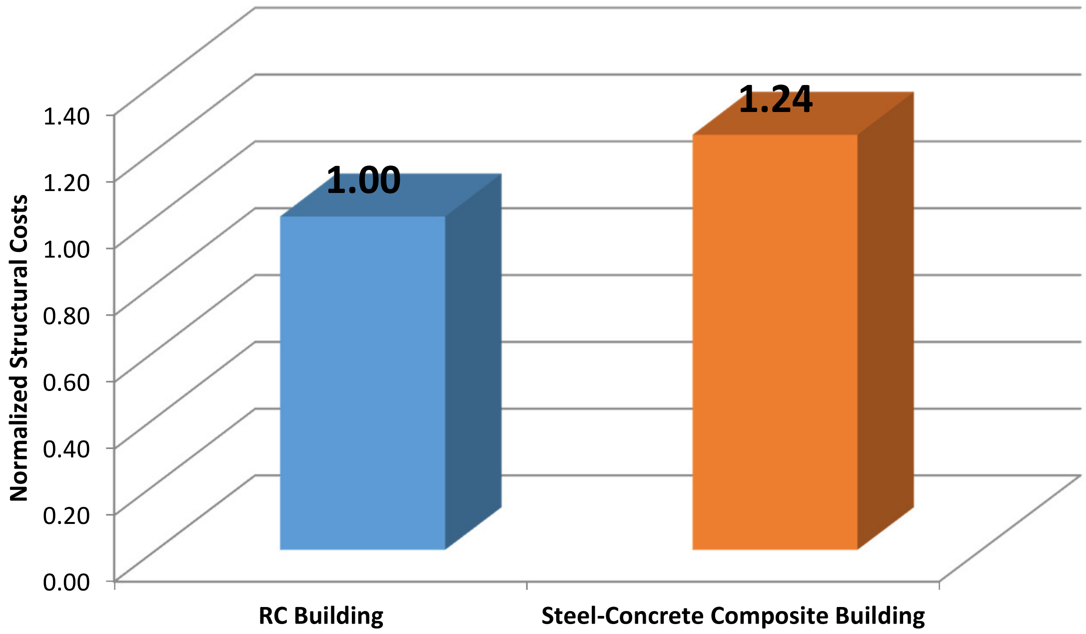
Comparative Case Study of a Typical Tall Building in Singapore

Foundation Costs *(Normalized)*



Comparative Case Study of a Typical Tall Building in Singapore

Total Structural 'Material' Costs *(Normalized)*



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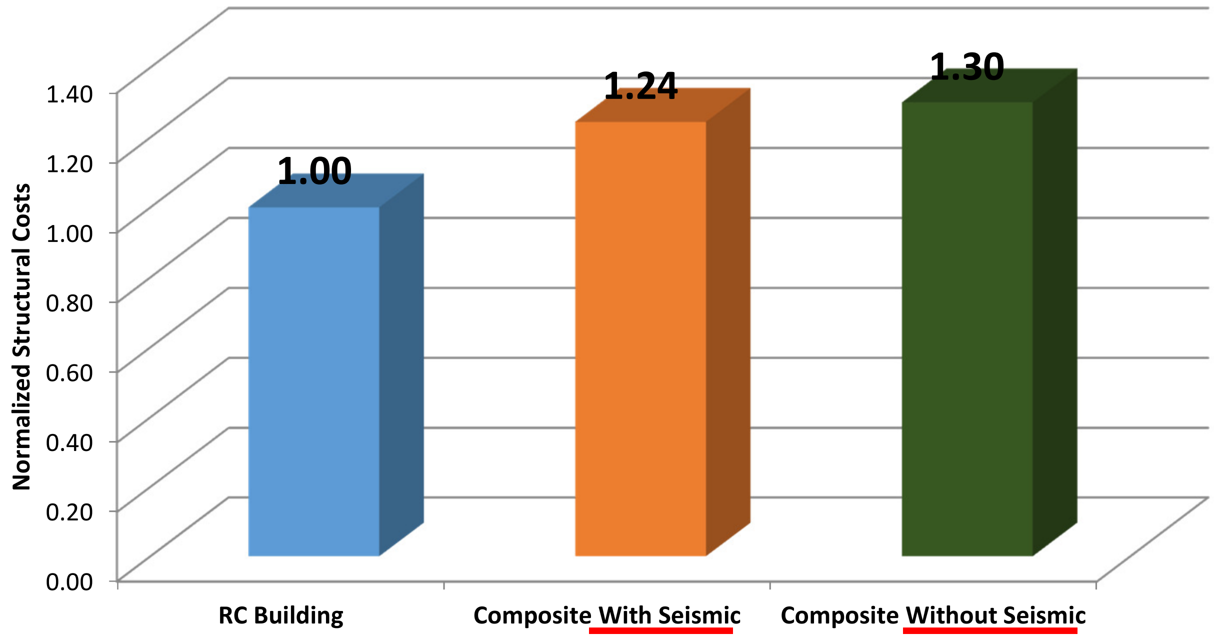
Comparative Case Study of a Typical Tall Building in Singapore

Total Structural ‘Material‘ Costs *(Normalized)*



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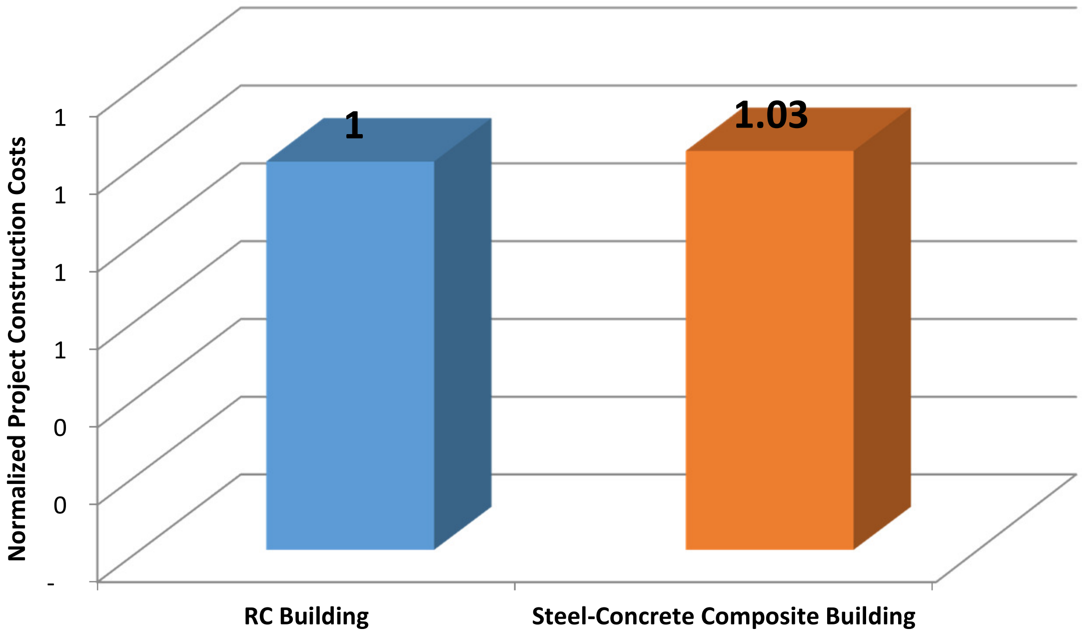
Comparative Case Study of a Typical Tall Building in Singapore

Total Project Construction Costs *(Normalized)*



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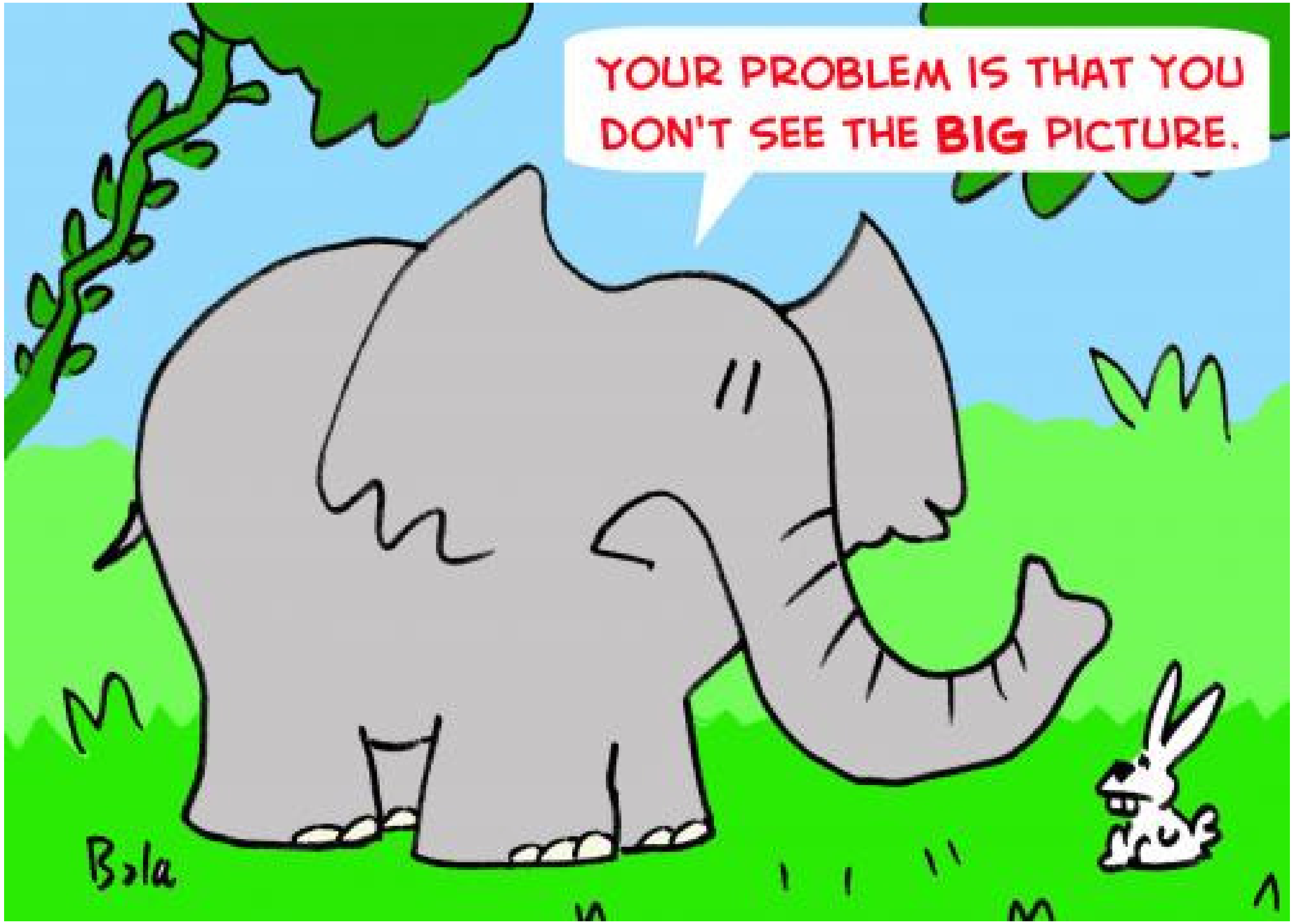
The Big Picture ……..



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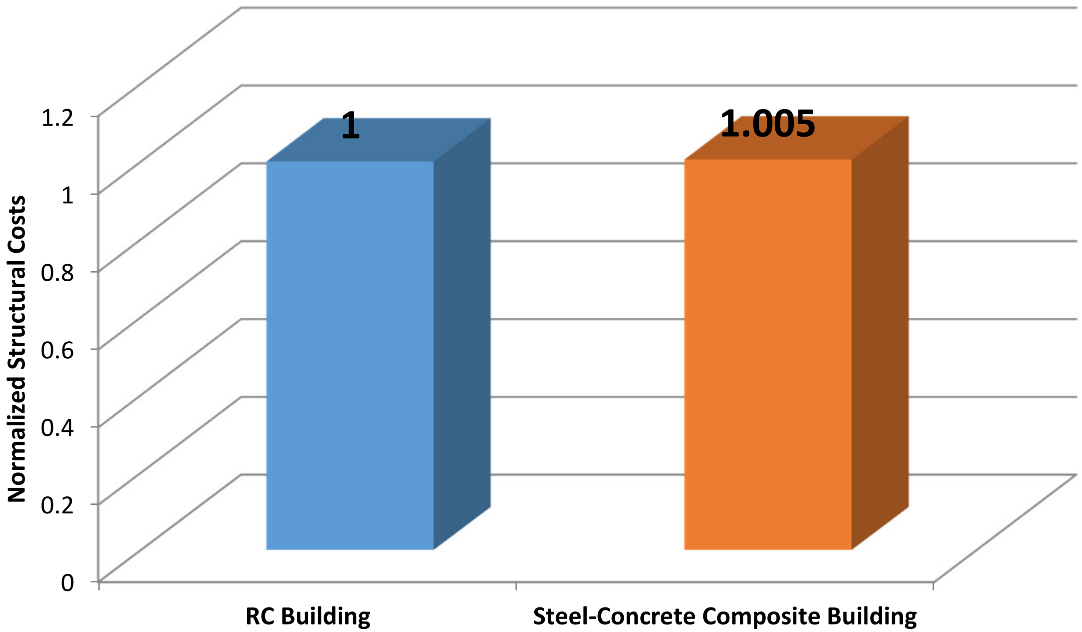
The Big Picture ……..

Other Costs and Revenues

PROJECT COSTS	
GFA =	85,000 sq-m
Land Cost =	$19,000 per sq-m of GFA
Legal Fee & Stamp Duty =	4% of land cost
Total Project Duration (including Design Period)=	33 months
Property Tax =	0.5% x land cost x duration)($)
Associated Costs (Prof. & Site Supervision Fee) =	~ 8% of Total Construction Cost
Marketing & Advertisement =	~ 5% of Total Construction Cost
GST =	7% of Construction & Associated Costs
Interest of Financing Cost for Land =	5% of Land Cost, Legal Fee & Property Tax
Interest of Financing During Construction =	5% of Construction & Associated Costs x 0.5
RENTAL RETURN + PRELIMINARIES	
Net Efficiency=	80%
Occupancy Rate=	80%
Rental Rate $$/sq-ft/month=	$12 per sq-ft per month
Preliminaries / month =	10% of Total Construction Cost

The Big Picture ……..

Total Development Construction Costs *(Normalized)*



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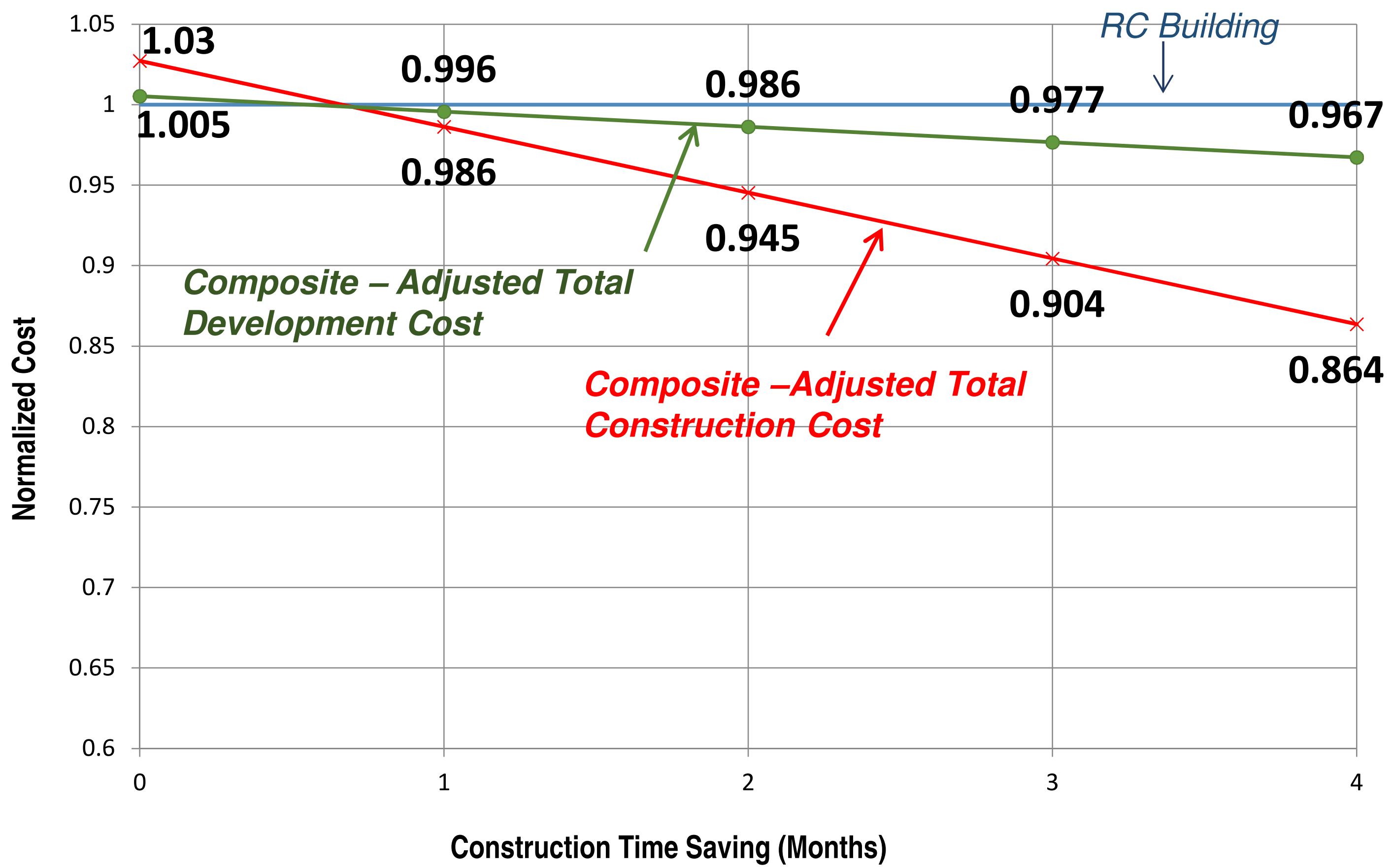
The Big Picture ……..

Total Project Construction / Development Costs *(Normalized)*



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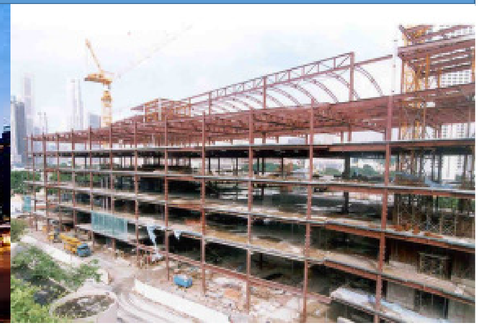
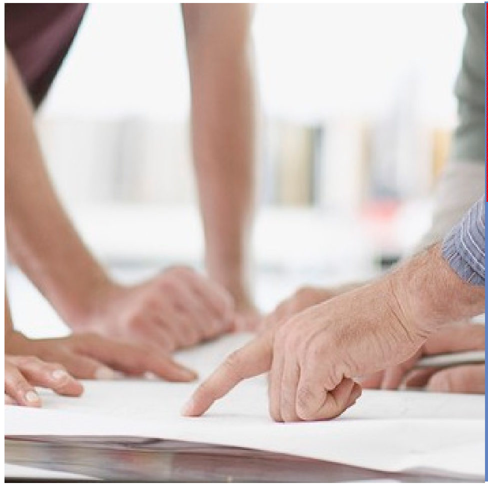
Composite Construction Benefits

- Besides productivity & costs what are the other intangible benefits of utilizing steel?
  - ✓ Higher quality
  - ✓ Lesser maintenance
  - ✓ More functional spaces
  - ✓ Flexibility to adaptation
  - ✓ Higher sustainability
  - ✓ Better performance under seismic actions

08

Concluding Remarks

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In Summary

- Tall buildings present special challenges to design & construction.
- The challenges from wind and seismic loads can be addressed through innovative design concepts.
- Composite buildings offer far higher potential for greater productivity & hence lower costs.
- Moving forward, more complex & taller buildings will be conceived & constructed.
- Structural engineers have the biggest contribution to make in making buildings safe & economical.

How will these future tall buildings be designed & constructed?

The choice is yours ………