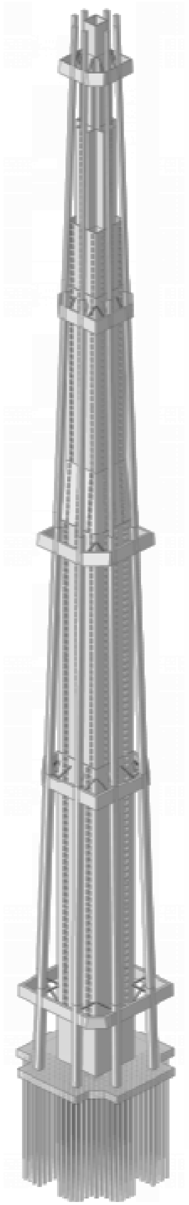
RECENT SUPERTALL CONCRETE TOWERS IN THE MIDDLE EAST

John Peronto and Robert Sinn

11th International Workshop on Structural Concrete

October 19, 2019



Uptown Dubai – Site of Supertalls

Uptown Dubai – Site of Supertalls

- 711m Supertall Tower and Structural System

- Concrete Material
  a. Strength (f'c)
  b. Modulus (MOE)
  c. Local Challenges

- Wind Tunnel Testing

- Site Challenges and Wake Buffeting

- Performance

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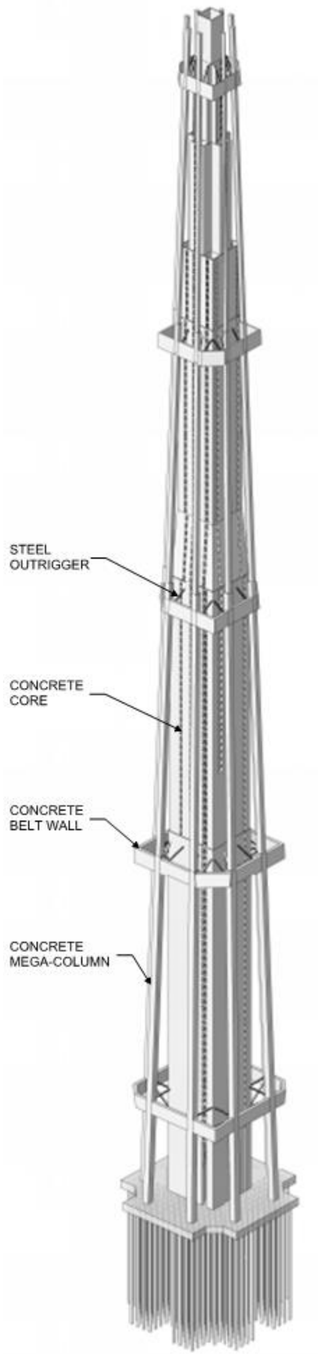
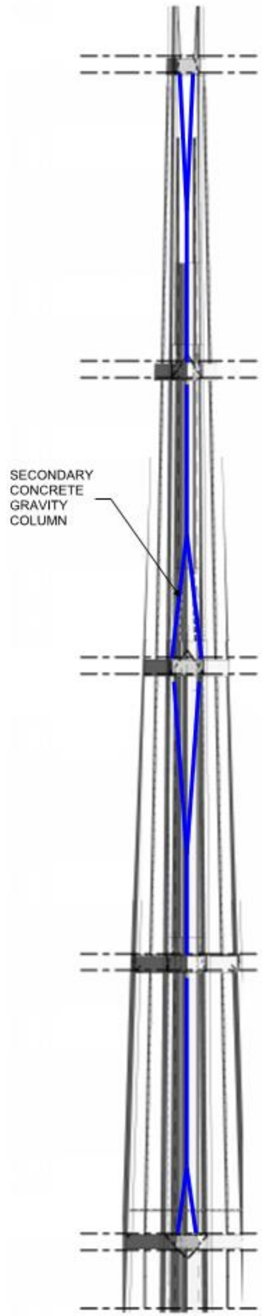
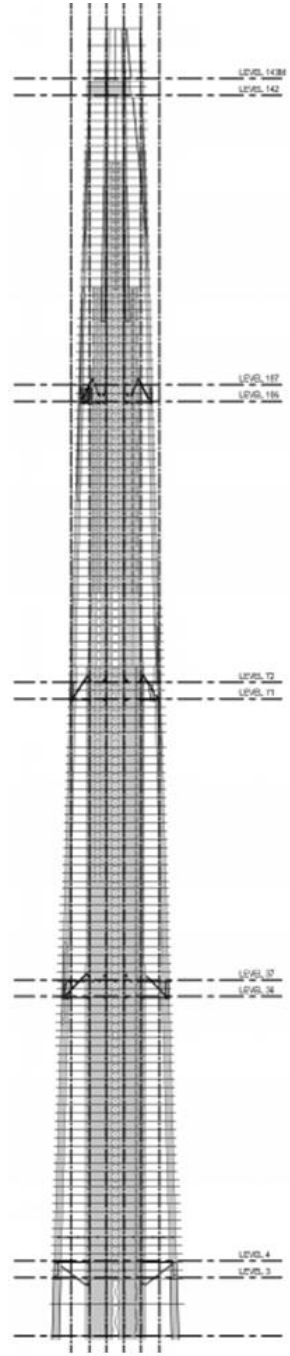


SYSTEM ISOMETRIC



CORNER ELEVATION



BUILDING SECTION

Structural System

- Concrete Core
- Concrete Mega-Columns
- Steel Outriggers
  (3 – Stories Deep)
- Concrete Belt Wall
  (2 – Stories Deep)
- Concrete Secondary
  Columns
- Concrete Floor Framing

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High-Strength Concrete Data

Mix		NORMAL	NORMAL	high pumping	high pumping	high pumping/NORMAL	high pumping/NORMAL	high pumping	high pumping
Grade (Cylinder)		C80/20	C80/20	C80/20	C80/20	C80/10	C80/10	C80/10	C80/10
Description		520-OPC+45%GGBS+8%MS GABRO	520-OPC+45%GGBS+8%MS LIMESTONE	520-OPC+45%GGBS+8%MS LIMESTONE	520-OPC+45%GGBS+8%MS GABRO	520-OPC+45%GGBS+8%MS GABRO	520-OPC+45%GGBS+8%MS LIMESTONE	520-OPC+25%PFA+8%MS LIMESTONE	520-OPC+25%PFA+8%MS GABRO
aggrgate Combination	20 mm	520	520	370	370	0	0	0	0
	10 mm	350	350	420	420	780	780	780	780
	5mm	560	560	580	580	550	550	550	550
	dune sand	320	320	390	390	430	430	430	430
@ 7Days	MOE Records (Mpa)	43700	43200	43900	44000	43400	43800	43600	44000
		45200	43200	44600	44700	44600	45100	45500	44400
		41200	43000	40700	40200	41300	40900	41300	41200
	Average	43367	43133	43067	42967	43100	43267	43467	43200
	Average Compressive strength (Mpa)	67.5	64.0	64.5	66.0	58.2	65.0	56.0	57.0
@ 28Days	MOE Records (Mpa)	53200	54300	53300	49900	54300	53100	50300	54500
		52400	52500	52900	52000	52400	52800	53100	52000
		54000	53100	54100	53700	54500	53500	54400	50200
	Average	53200	53300	53433	51867	53733	53133	52600	52233
	Average Compressive strength (Mpa)	80.0	82.0	80.5	72.5	74.5	76.0	70.0	72.5
@ 56Days	MOE Records (Mpa)	58400	60700	55500	58800	58900	59300	57400	54600
		56600	61000	56200	59500	60400	58600	56300	56200
		56700	60800	58400	62900	58700	60100	58500	59000
	Average	57233	60833	56700	60400	59333	59333	57400	56600
	Average Compressive strength (Mpa)	80.0	84.0	82.5	83.0	88.5	85.0	83.0	81.0

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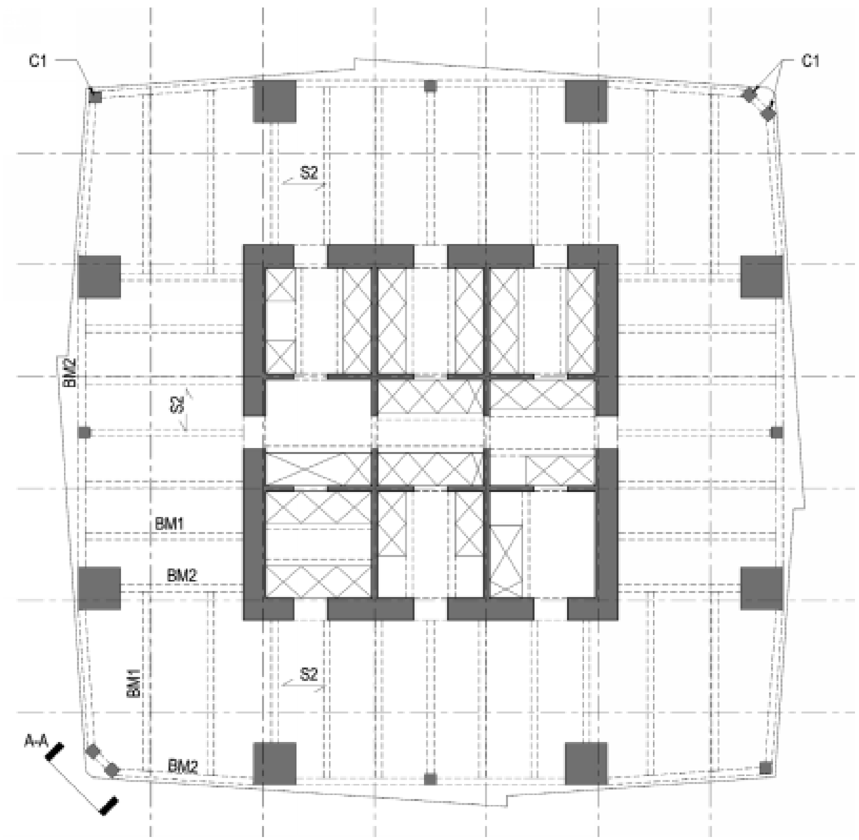
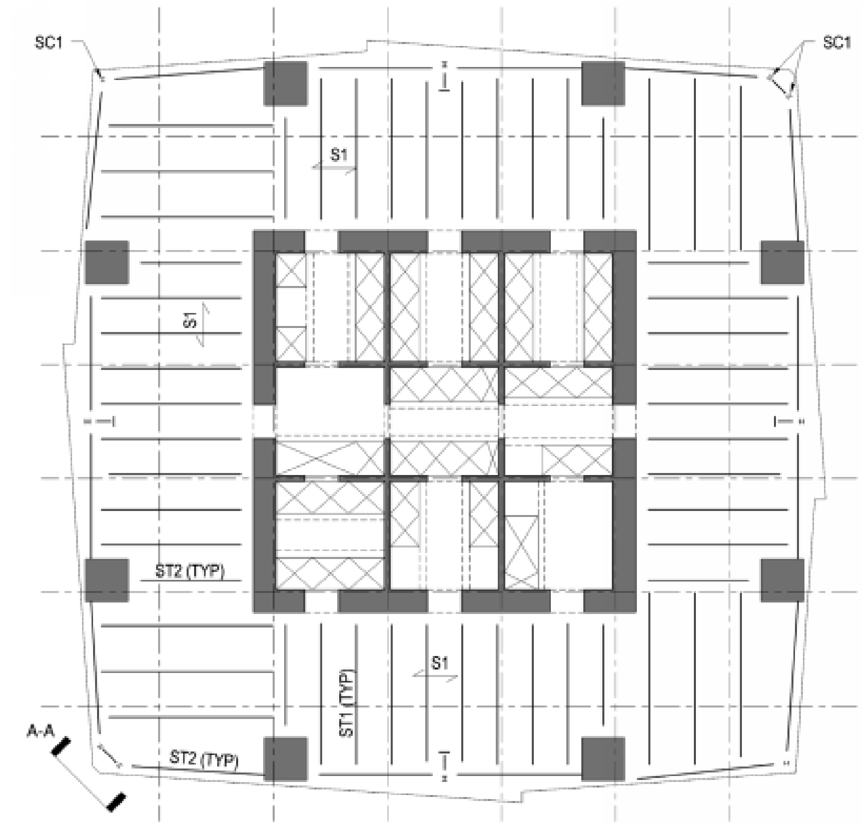
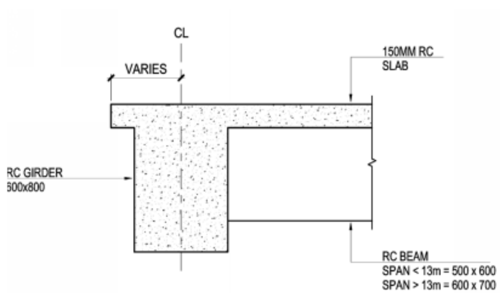
Floor Framing – Concrete vs Steel



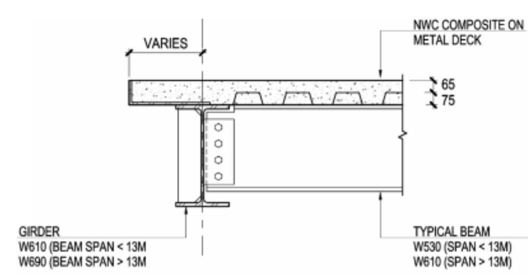
Typical Reinforced Concrete Floor Framing



Typical Composite Steel Beam Floor Framing (Alternate)



Spandrel Beam RC Option Section



Spandrel Beam Steel Option Section

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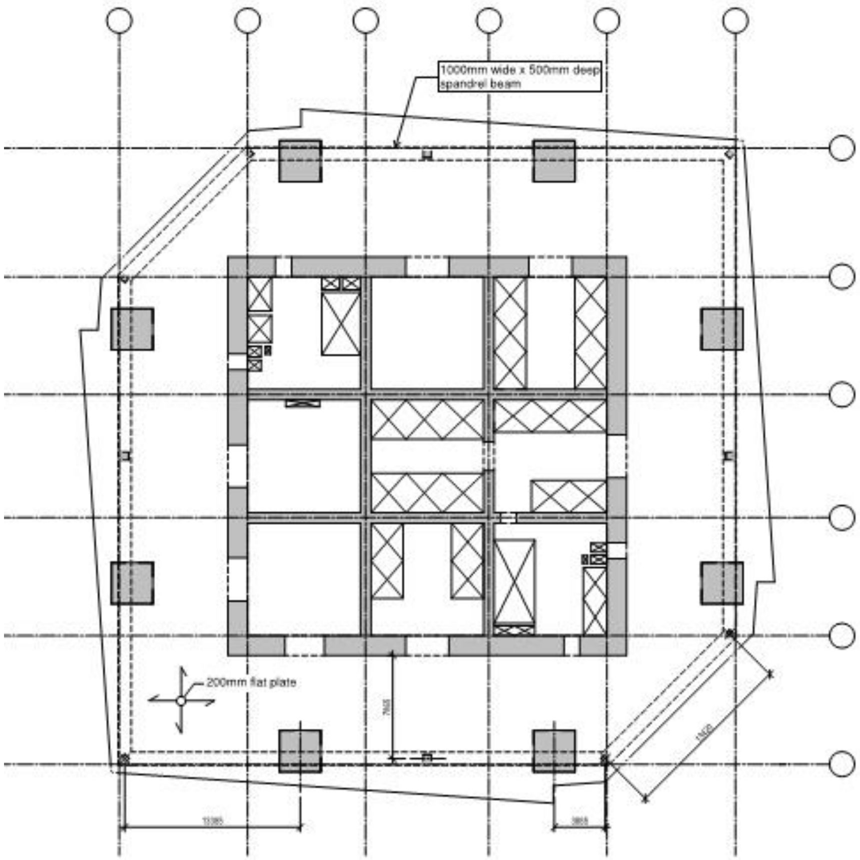
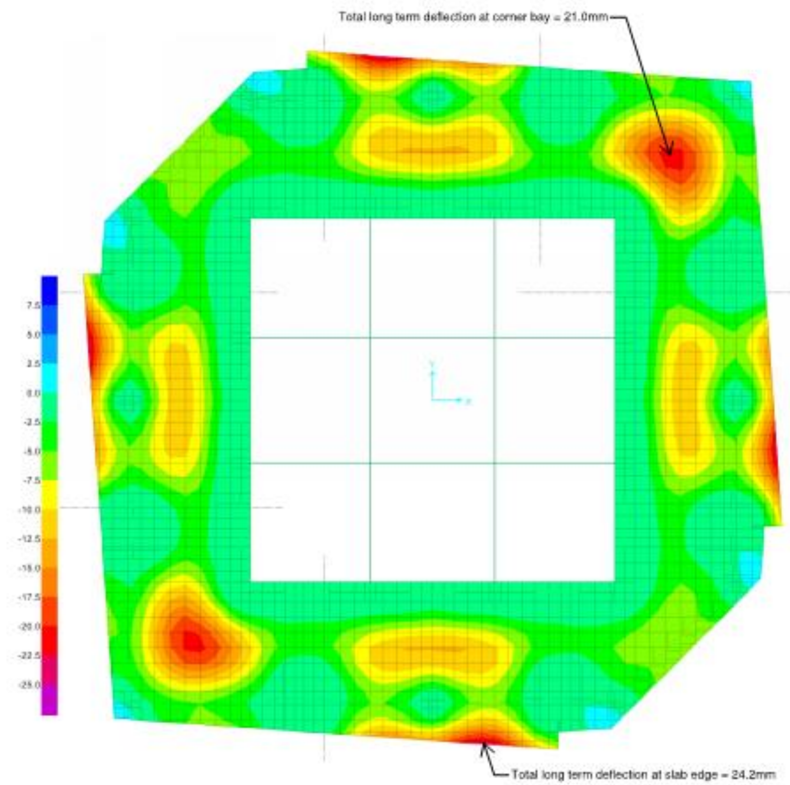
Floor Framing – Flat Slab Analysis



LEVEL 70 FLOOR FRAMING PLAN
Scale: not to scale



LEVEL 70 DEFLECTION DIAGRAM
Scale: not to scale

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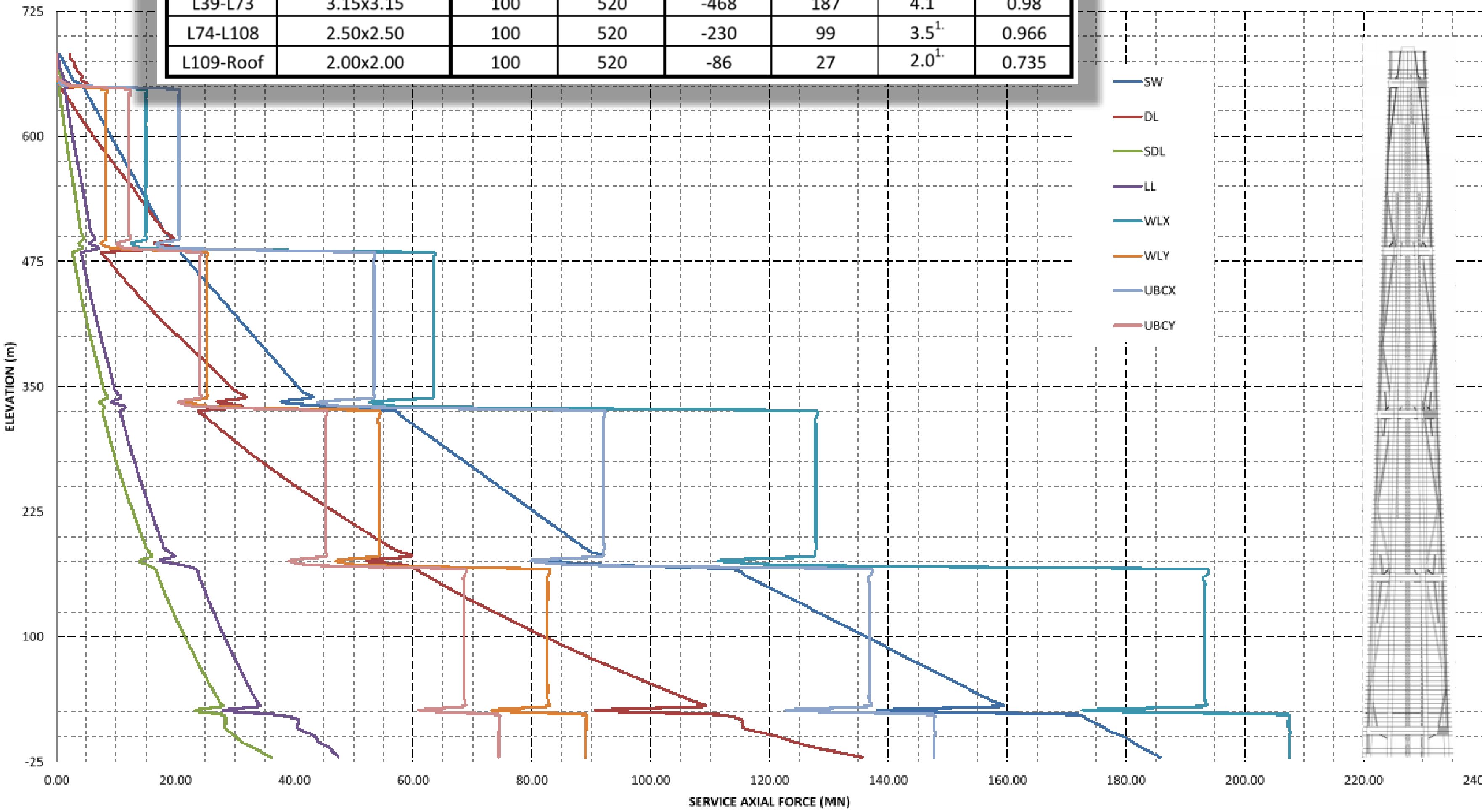
Mega-Column Design

MEGA COLUMNS							
Levels	Mega Column Size	fc'	fy	Pu_max	Pu_min	ρ	DCR
	(m)	(MPa)	(MPa)	(MN)		(%)	
BASE-L5	4.25x4.25	100	520	-892	230	2.87	0.975
BASE-L5	4.00x4.00	100	520	-892	230	5.3	0.993
L5-L38	3.75x3.75	100	520	-773	230	5.36[1.]	0.975
BASE-L38	3.75x3.75	100	520	-892	230	8.7	0.993
L39-L73	3.15x3.15	100	520	-468	187	4.1[1.]	0.98
L74-L108	2.50x2.50	100	520	-230	99	3.5[1.]	0.966
L109-Roof	2.00x2.00	100	520	-86	27	2.0[1.]	0.735



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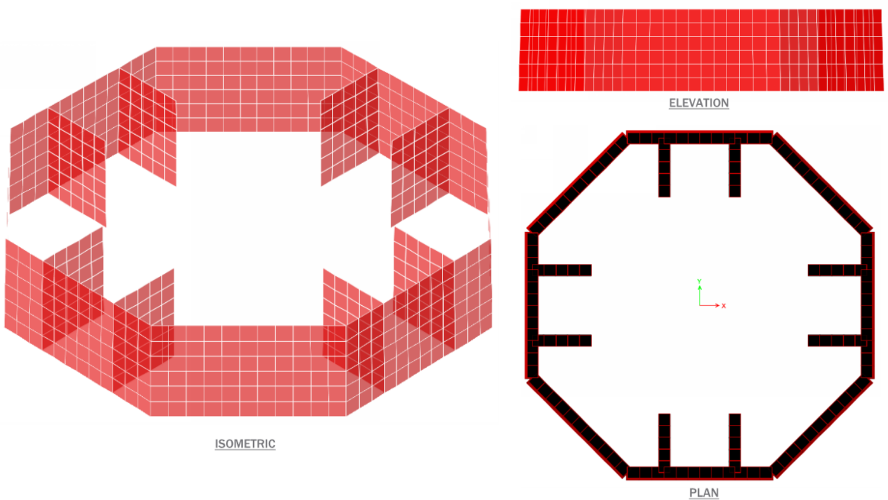
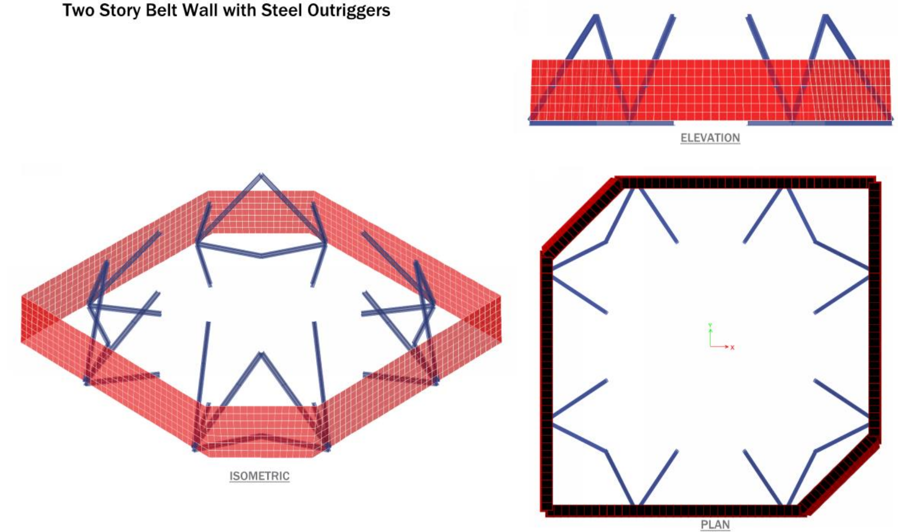
Structural System

Concrete Core with Mega-Column and Outrigger Schemes

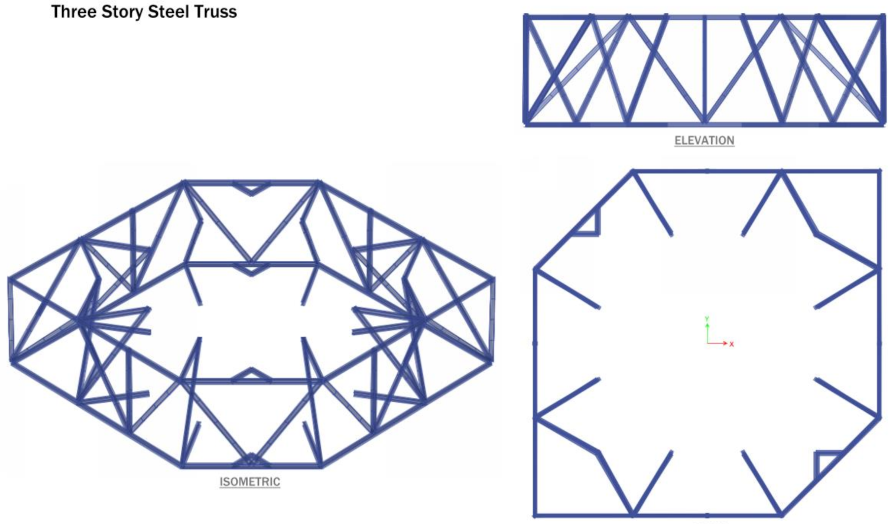
Concrete Wall with Concrete Outriggers



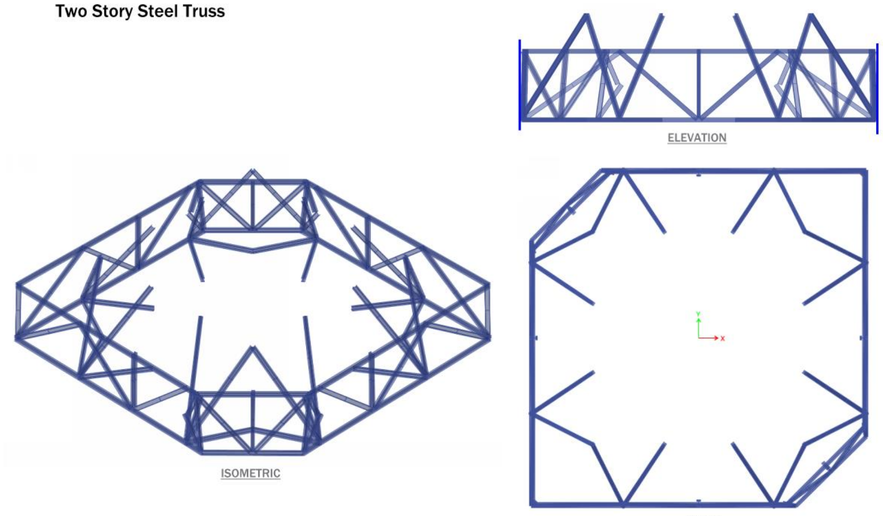
Two Story Belt Wall with Steel Outriggers



Three Story Steel Truss



Two Story Steel Truss



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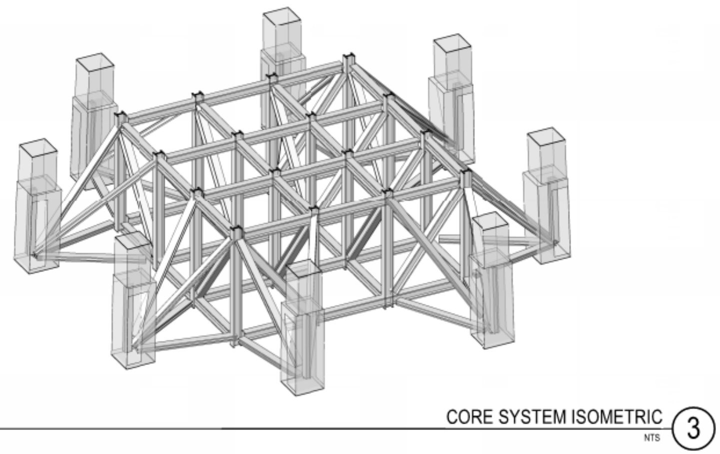
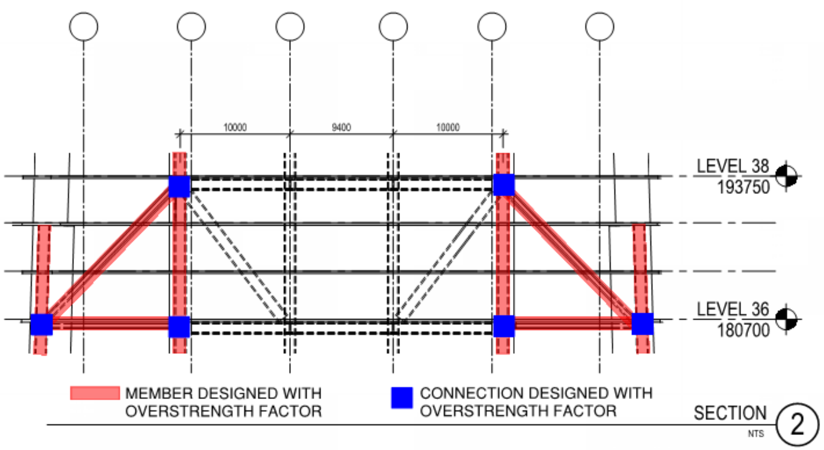
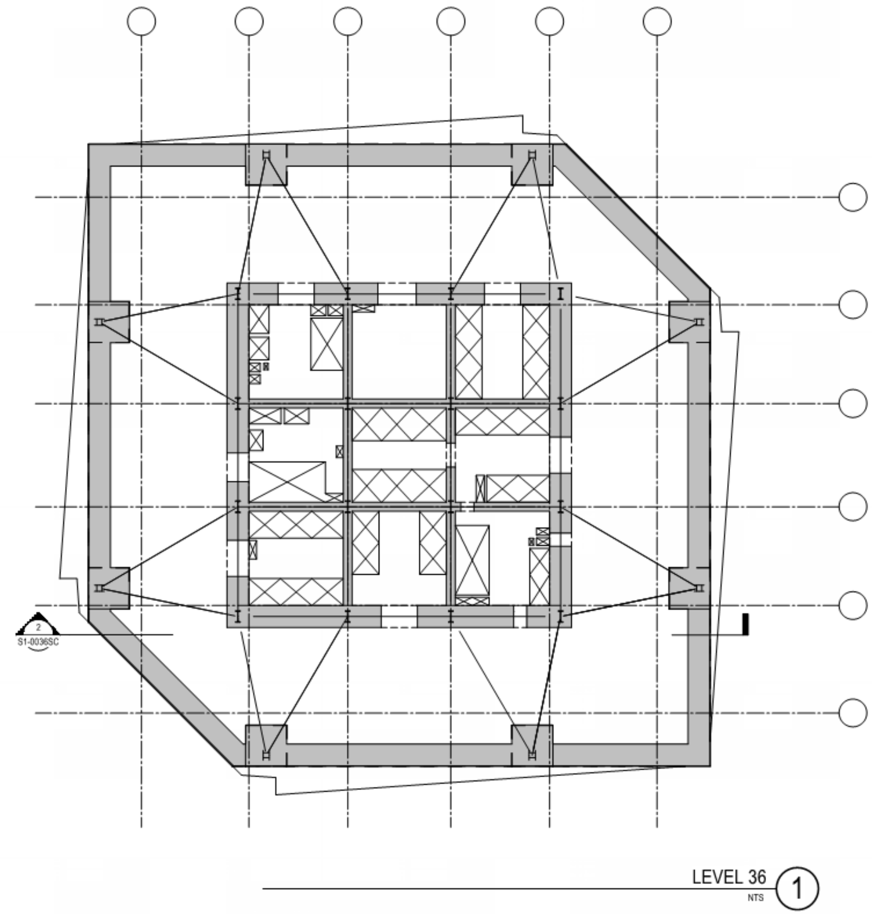
Outriggers and Seismic Overstrength







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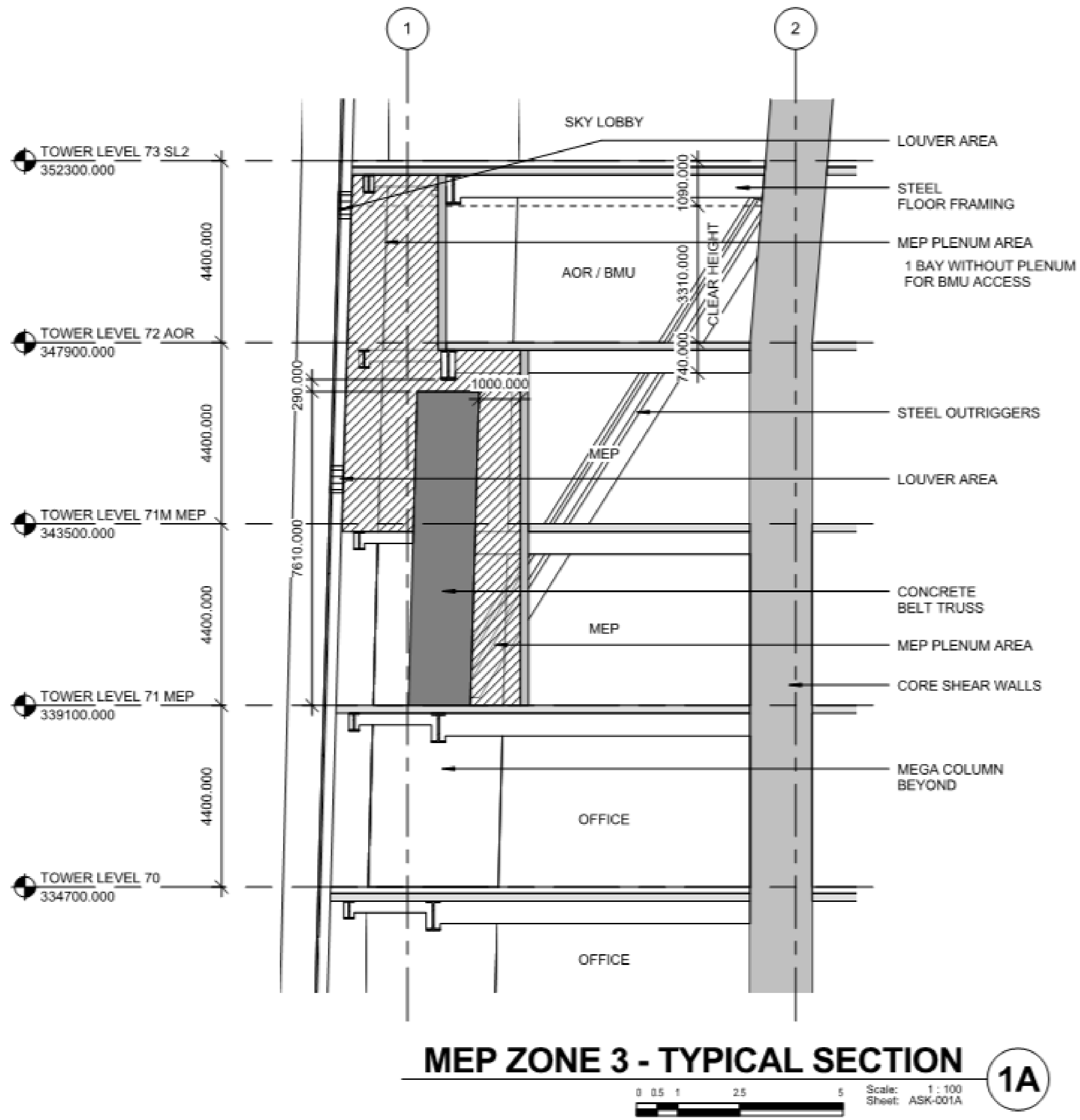
Outrigger MEP Coordination



Section per ASGG sketch

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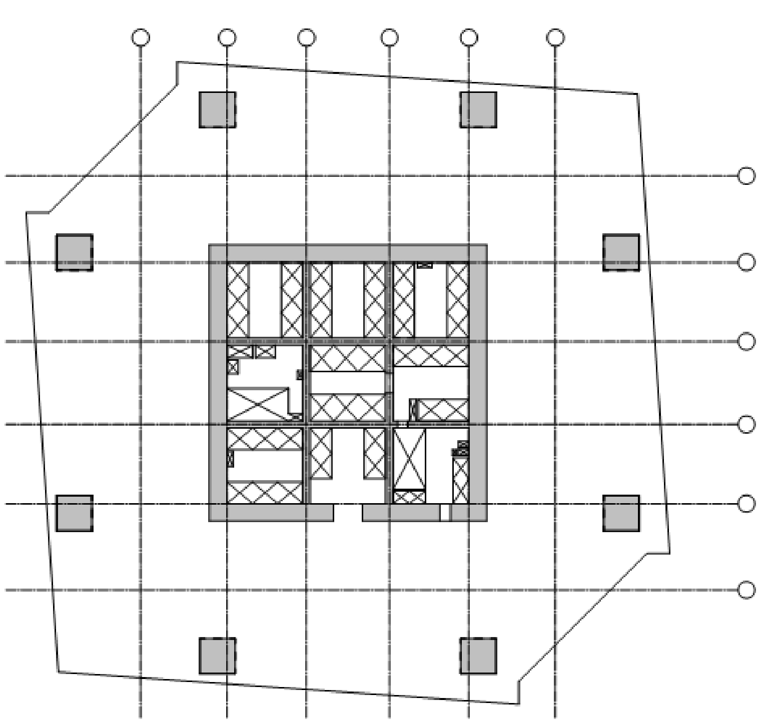
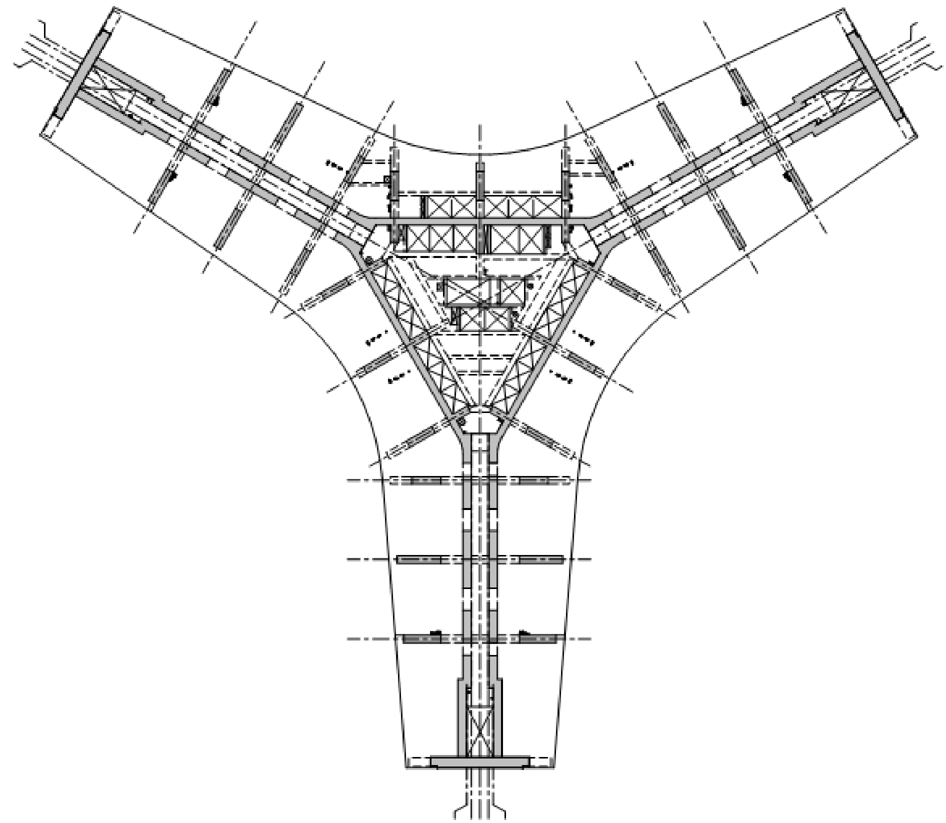
Footprint Comparison



Uptown Dubai T1– Floor Plan



Jeddah Tower – Floor Plan

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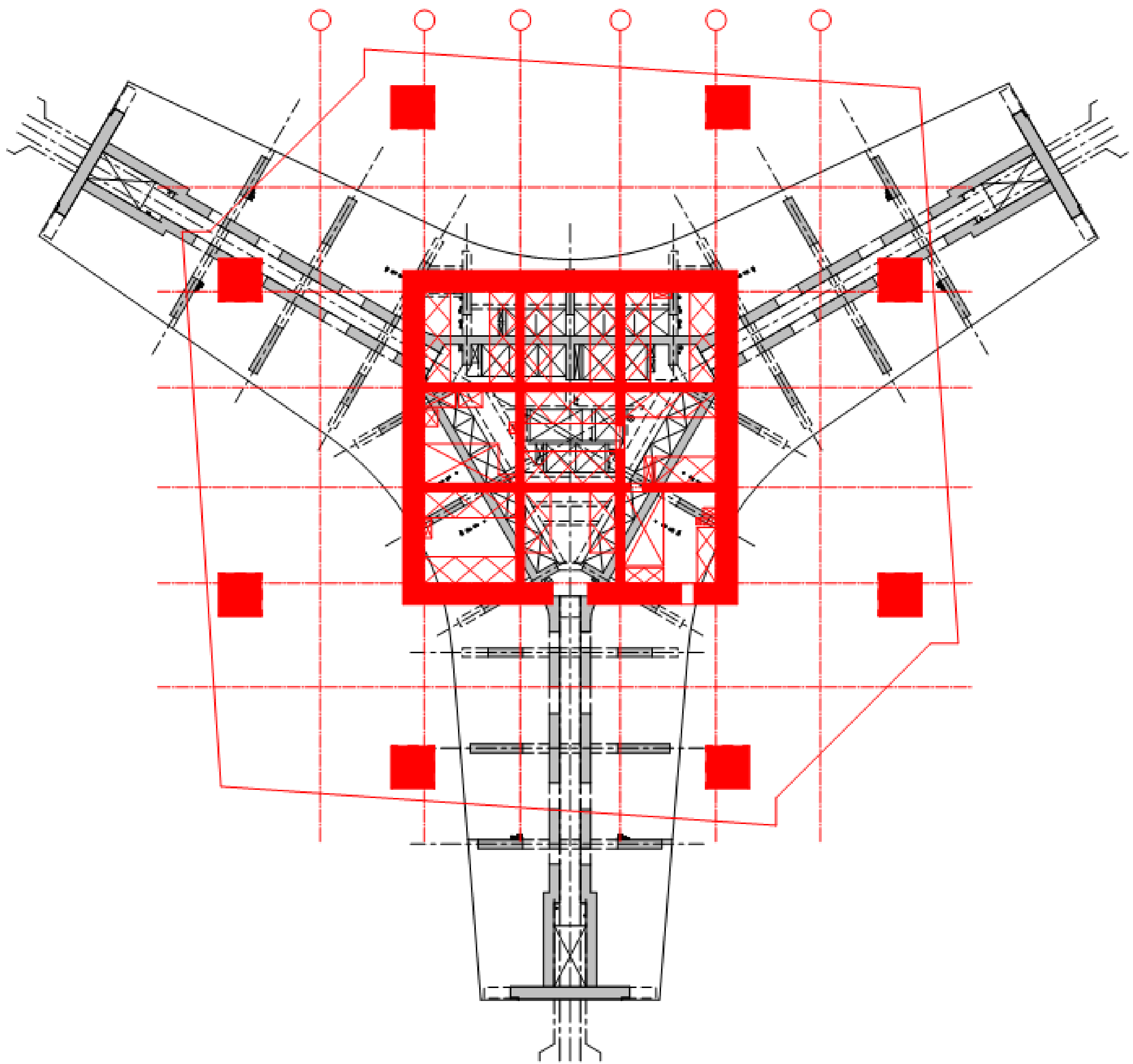
Footprint Comparison



Uptown Dubai T1 and Jeddah Tower – Floor Plan Overlay

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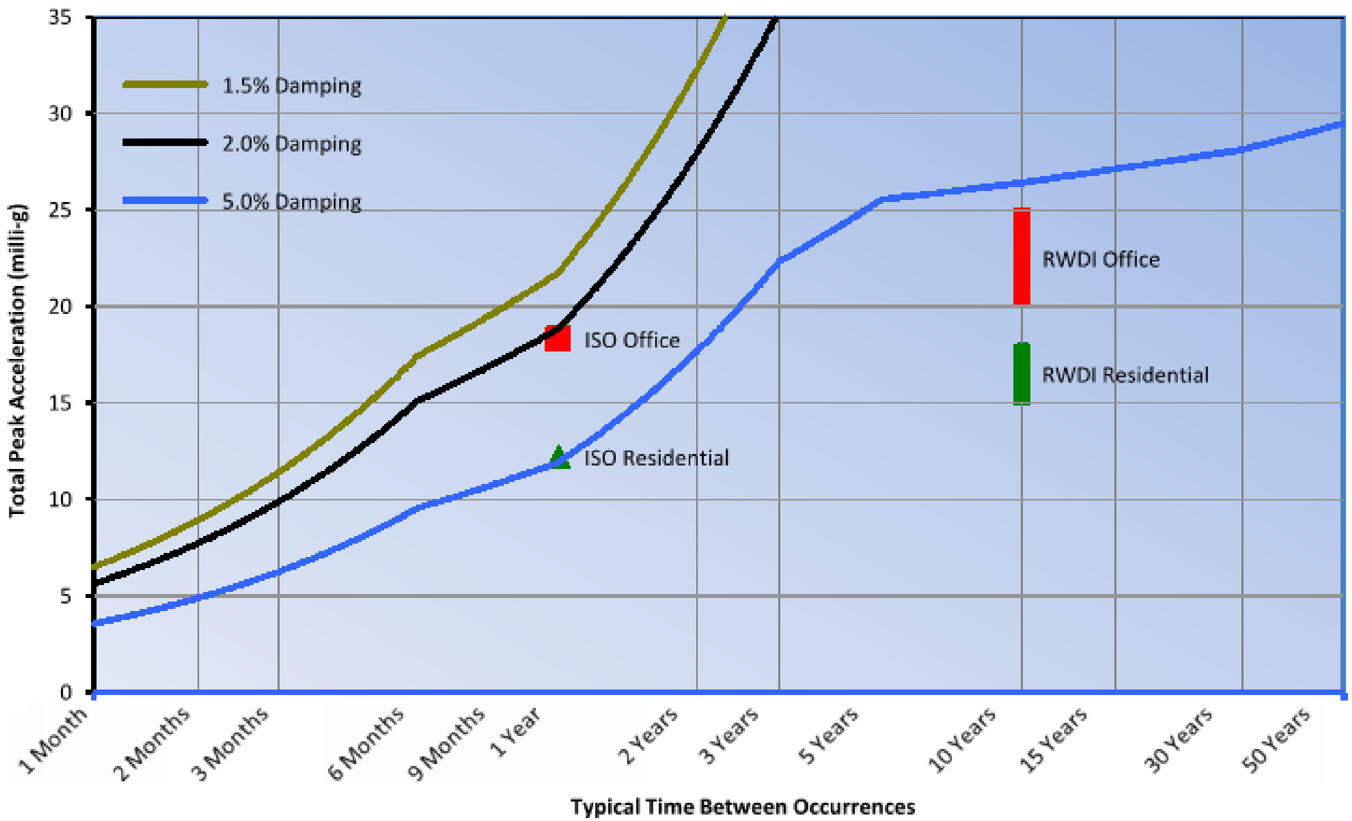
Wind Tunnel Testing - RWDI

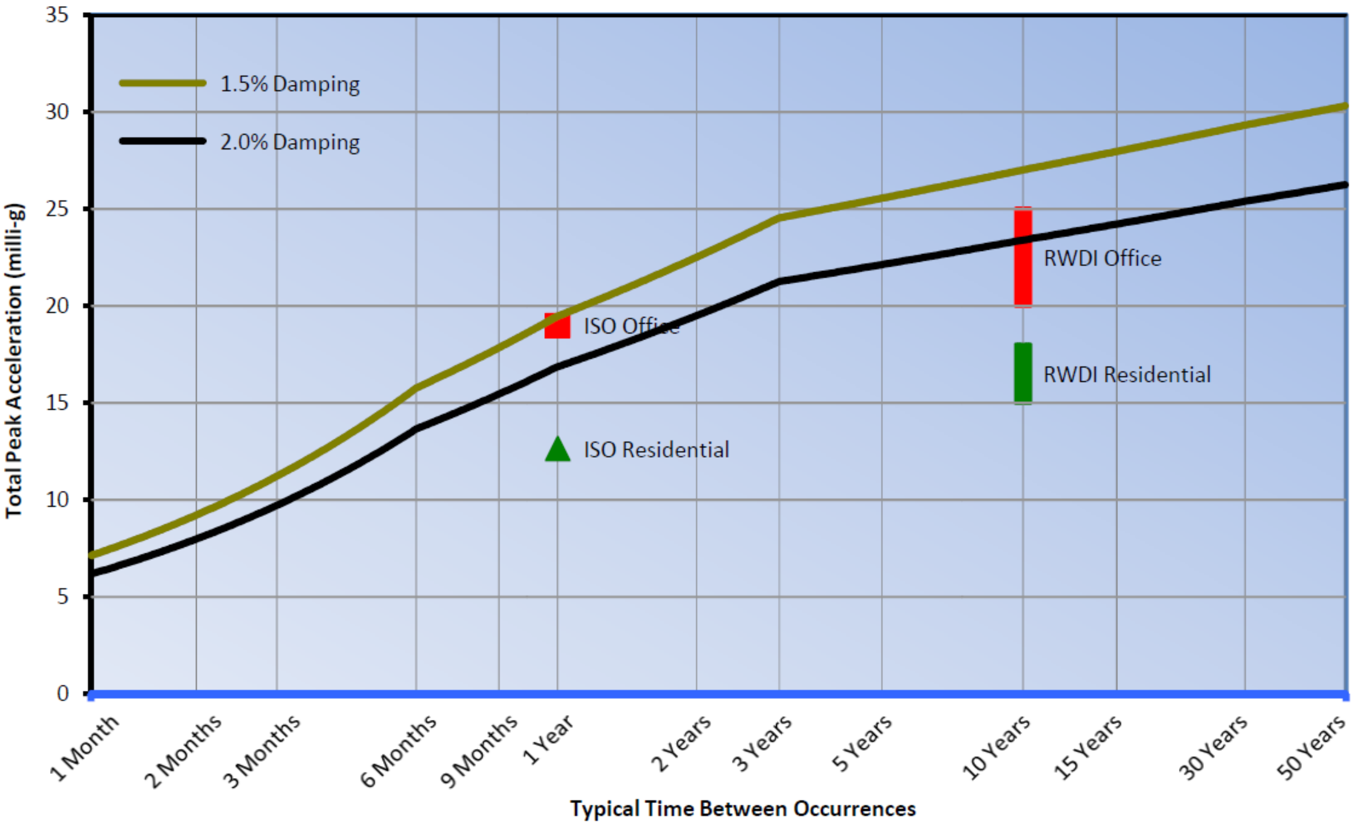
Initial HFFB Wind Tunnel Test Response



Return Period (Years)	Peak Accelerations[2] (milli-g) Total - [X, Y and torsional components]			Peak Torsional Velocities (milli-rads/sec)			
	1.5% Damping	2.0% Damping	5.0% Damping	1.5% Damping	2.0% Damping	5.0% Damping	CTBUH[5] Criteria
1	22 - [20, 20, 0.6]	19 - [17, 17, 0.5]	12 - [11, 11, 0.3]	0.3	0.2	0.1	1.5
5	47 - [45, 26, 0.9]	40 - [39, 22, 0.8]	26 - [25, 14, 0.5]	0.4	0.3	0.2	-
10	48 - [47, 26, 1.0]	42 - [41, 22, 0.9]	26 - [26, 14, 0.6]	0.4	0.4	0.2	3

Images per RWDI report (Figure 6a)

Aeroelastic Wind Tunnel Test Refined Response



Return Period (Years)	Peak Accelerations(2) (milli-g) Total - [X, Y and torsional components]		Peak Torsional Velocities (milli-rads/sec)		
	1.5% Damping	2.0% Damping	1.5% Damping	2.0% Damping	CTBUH(5) Criteria
1	19 - [19, 13, 0.54]	17 - [16, 11, 0.47]	0.3	0.3	1.5
5	26 - [25, 16, 0.80]	22 - [21, 14, 0.69]	0.4	0.4	-
10	27 - [26, 19, 0.95]	23 - [22, 16, 0.82]	0.5	0.4	3

Images per RWDI report (Figure 6a)

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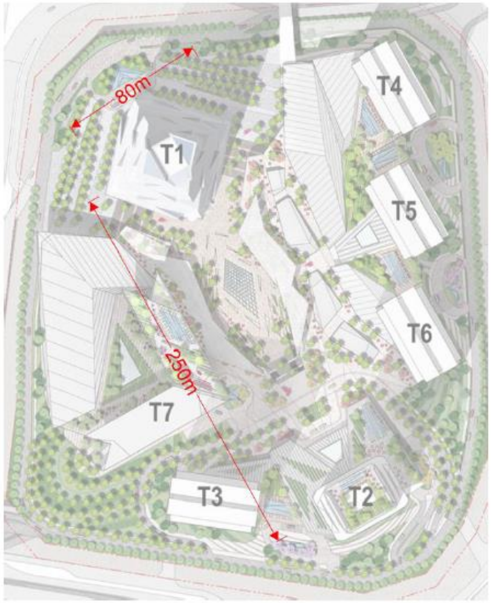
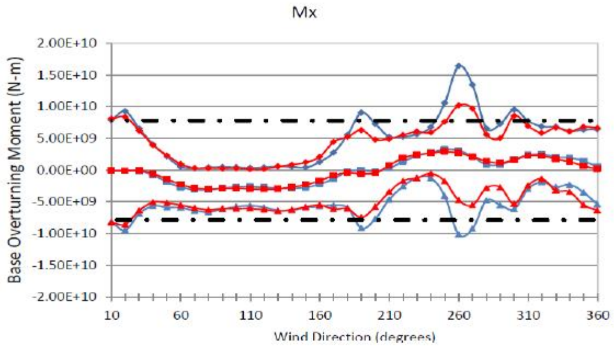
Tower 2 (340m) – WAKE BUFFETING !!

Tower T2

1) Site Orientation
2) Inter-Tower Spacing
3) T1 Relative Height
4) T1 Wake in Resonance with T2
5) T2 Structural Properties
6) T2 Geometry



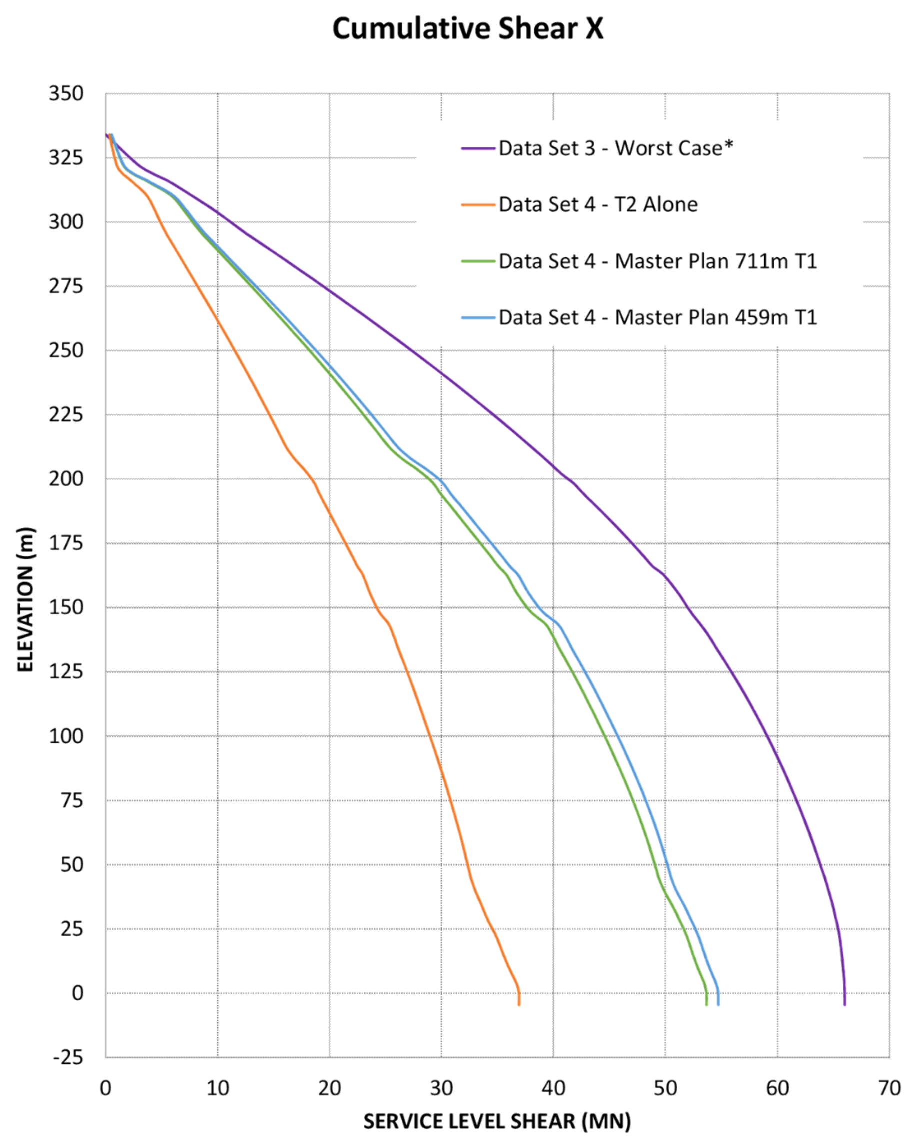
Tower Spacing



Site Orientation

Tower 2 (340m) – WAKE BUFFETING !!

Results



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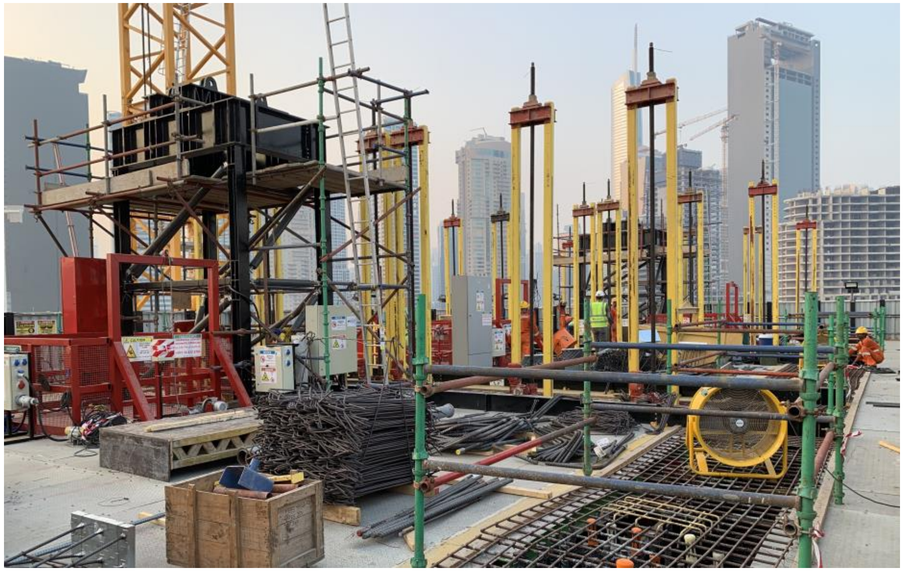
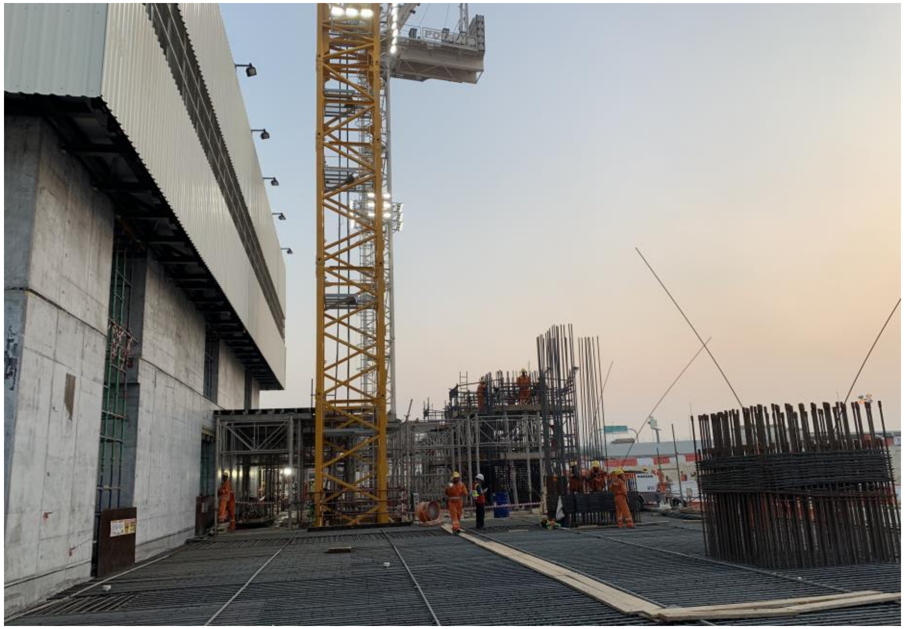
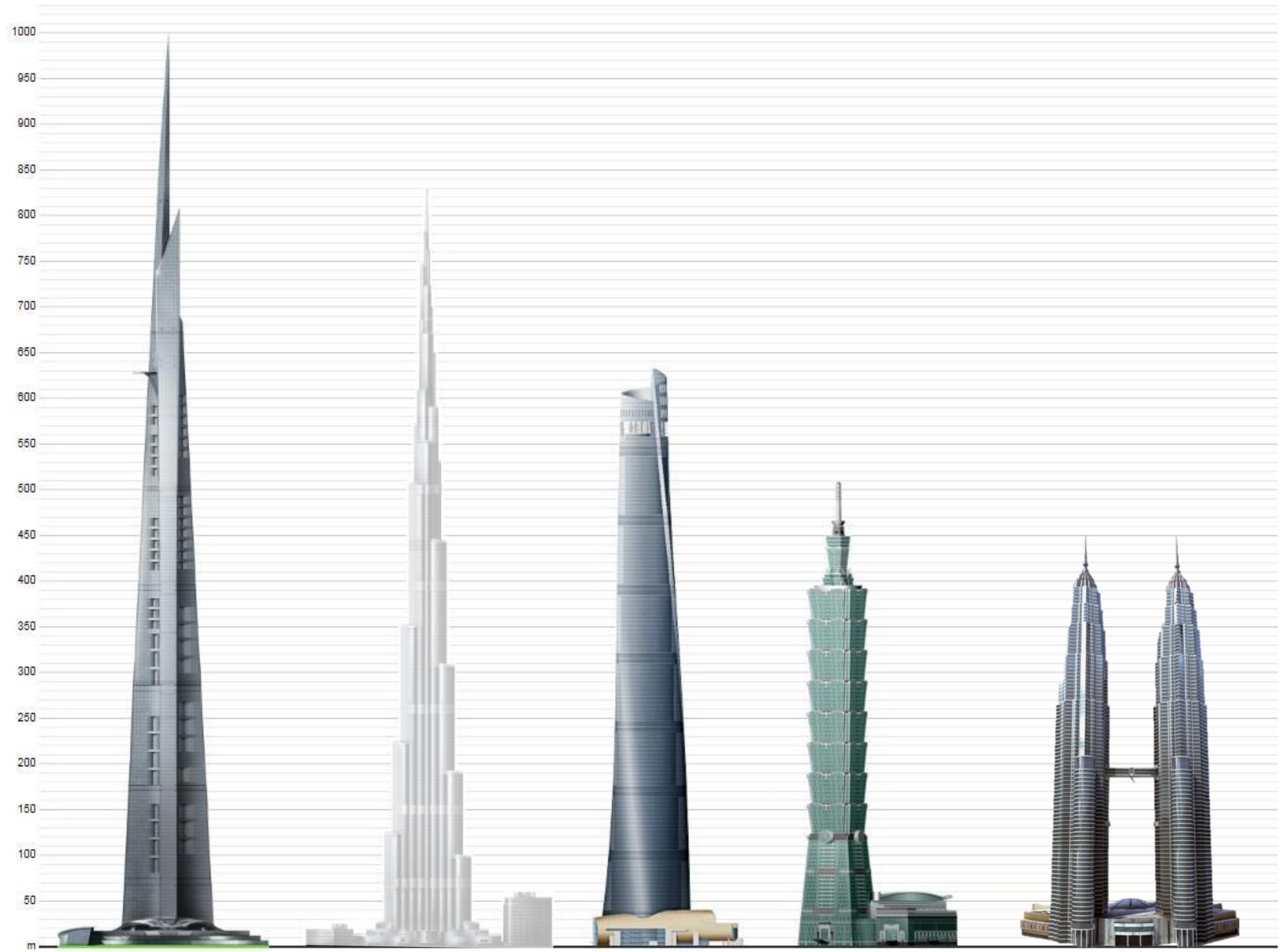
Phase 1 - Construction Progress (Raft)

Phase 1 - Construction Progress (Tower Rising)





Jeddah Tower – 1st 1km Tall Structure



Name	Jeddah Tower	Burj Khalifa	Shanghai Tower	Taipei 101	Petronas Towers
City	Jeddah	Dubai	Shanghai SH	Taipei	Kuala Lumpur
Country	Saudi Arabia	United Arab Emirates	China	Taiwan	Malaysia
Height	1000m	828m	632m	508m	452m

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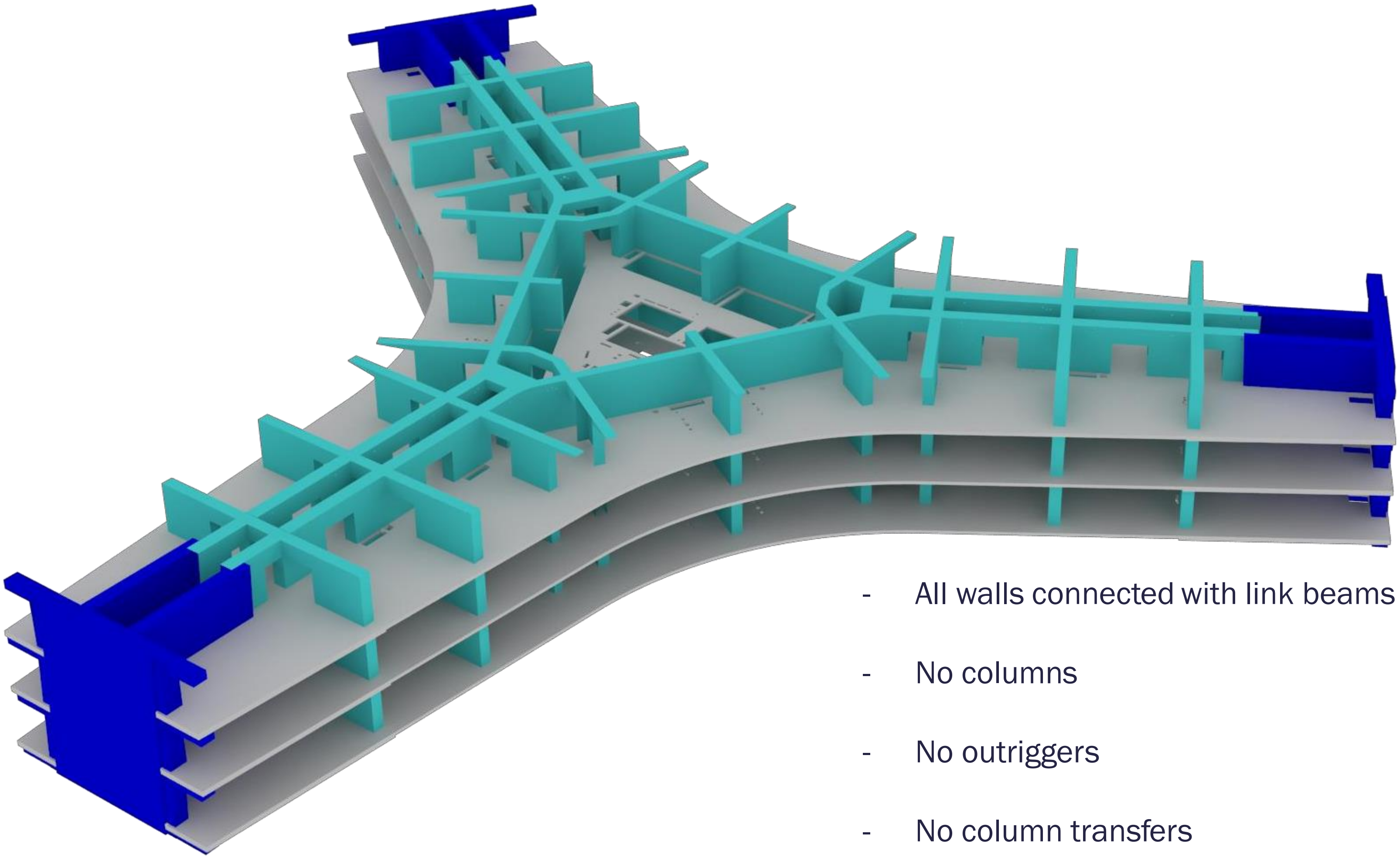
Team/Code Recap

- Structural Engineer: Thornton Tomasetti (TT)
- Architect: Adrian Smith + Gordon Gill Architecture (AS+GG)
- Developer Jeddah Economic Company (JEC)

- Competition Start : June 2009
- Complete Design Docs: August 2013
- Reinforced Concrete: Design to ACI 318
- General Contractor: Saudi BinLaden Group (SBG)
- Employers Engineer: Dar Al-Handasah

Structural System



- All walls connected with link beams
- No columns
- No outriggers
- No column transfers
- Flat plate floors
- No spandrel beams

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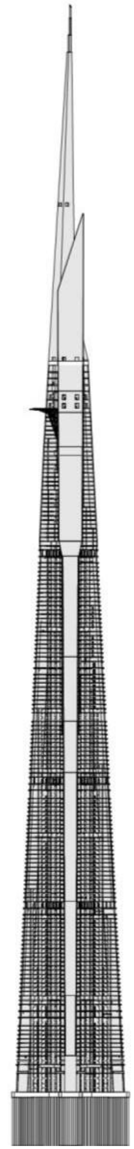
High Strength Concrete and Reinforcing Bar Materials

Vertical Rebar

420 MPa
60 KSI

520 MPa
75 ksi



Concrete (f'c) Cylinder

65 MPa
9,500 psi

75 MPa
11,000 psi

85 MPa
12,500 psi

60 MPa /
9,000 psi

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85 MPa Concrete Spec

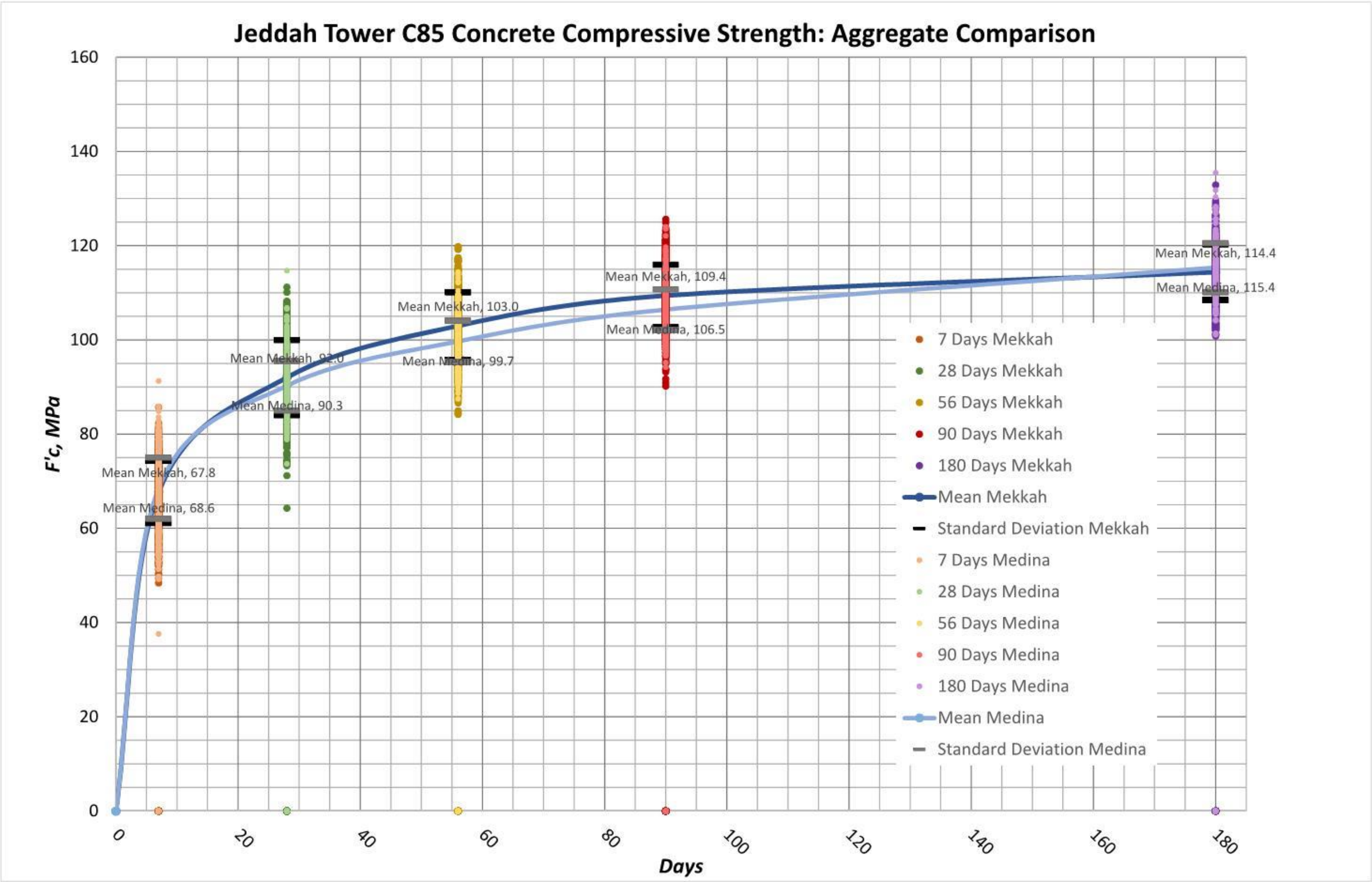
- f'c =85 MPa (12,3000 psi) at 90d
- MOE =43.3 GPa (6300 ksi) at 90d
- Mix: Near SCC

OPC	696	lb
SF	76	lb
PFA	170	lb
3/8" CA	1580	lb (Medina)
Fine Agg	1245	lb
Water/Ice	235	lb
HRWR		Polycarboxylate
VMA		

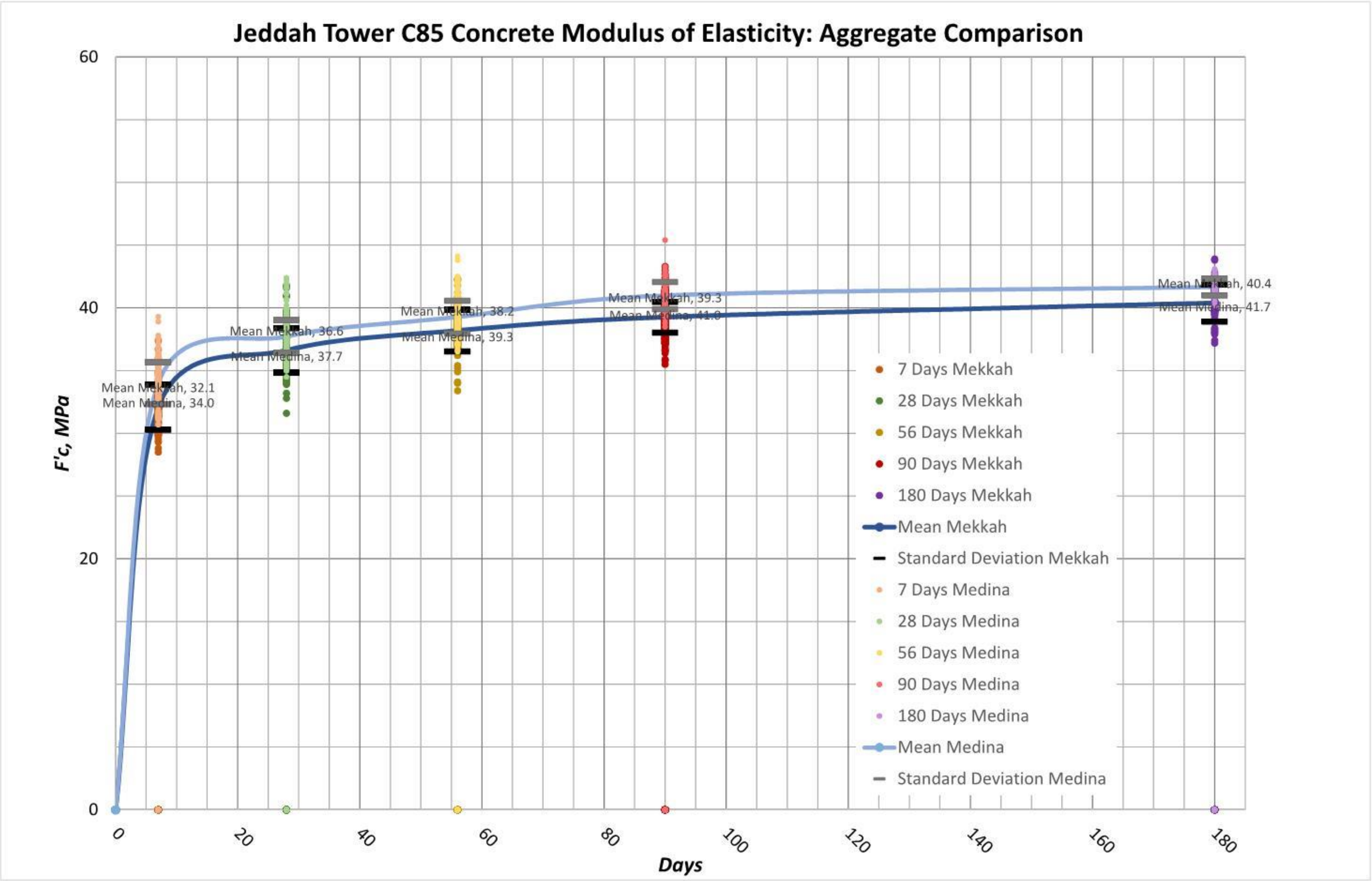
Water/Cementitious Ratio 0.25

Density 156 pcf

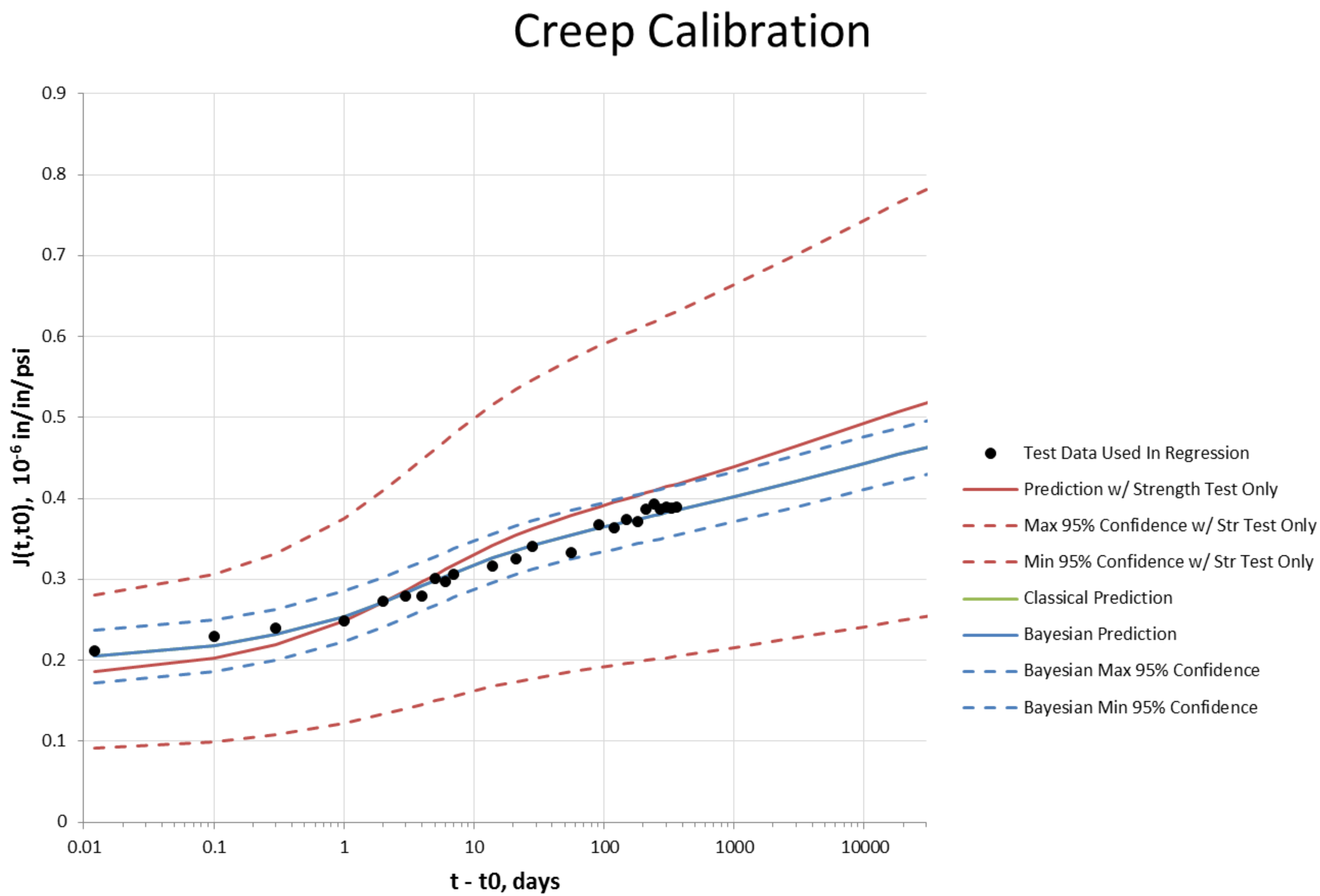
High Strength Concrete – Site Testing for f'c



High Strength Concrete – Site Testing for MOE



Bayesian Statistical Analysis



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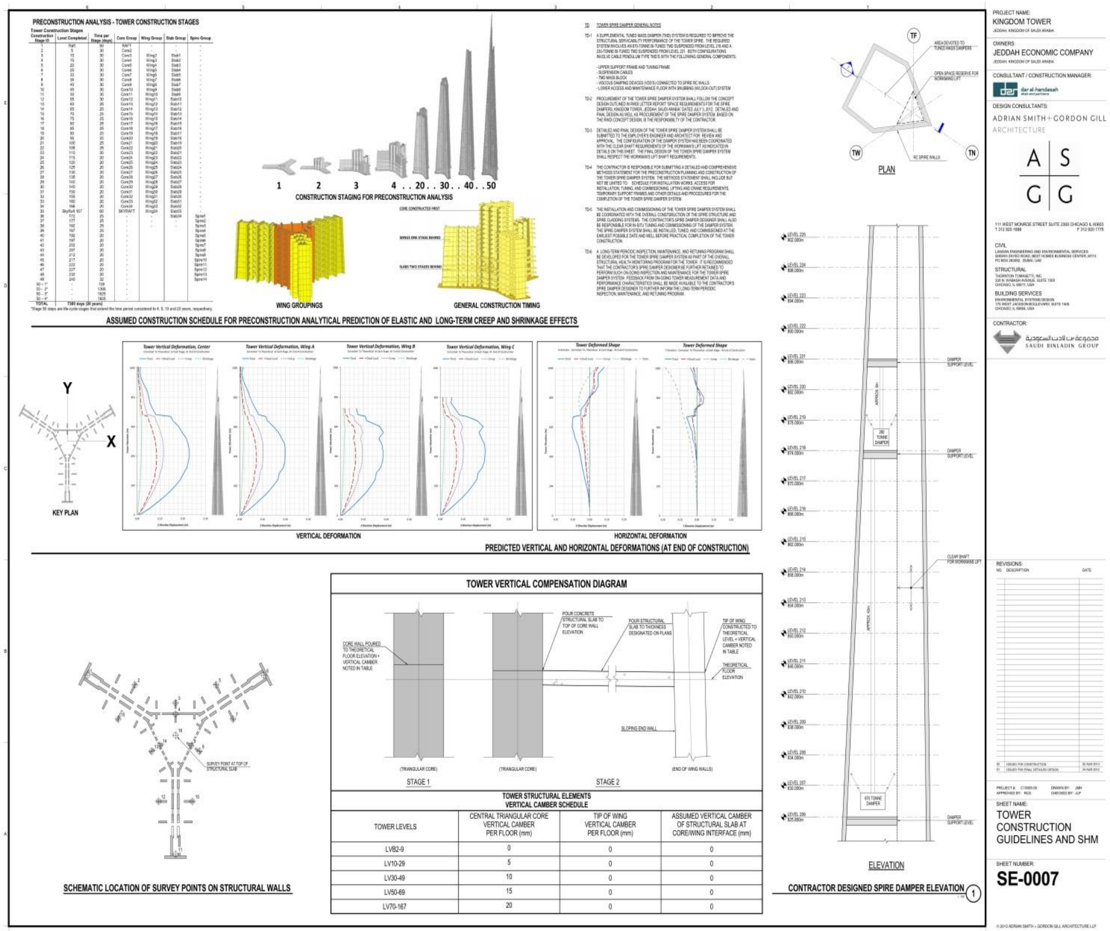
Construction Guidelines & Monitoring

Kingdom Tower



*PreConstruction Testing Program

*Full Construction Concrete Testing Program
- Modulus
- Strength
- Creep

*Surveying/Monitoring Requirements

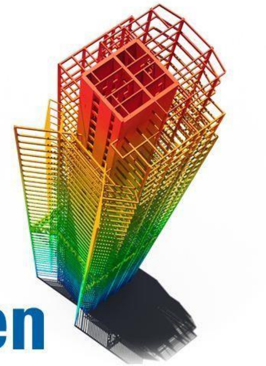
*Reporting

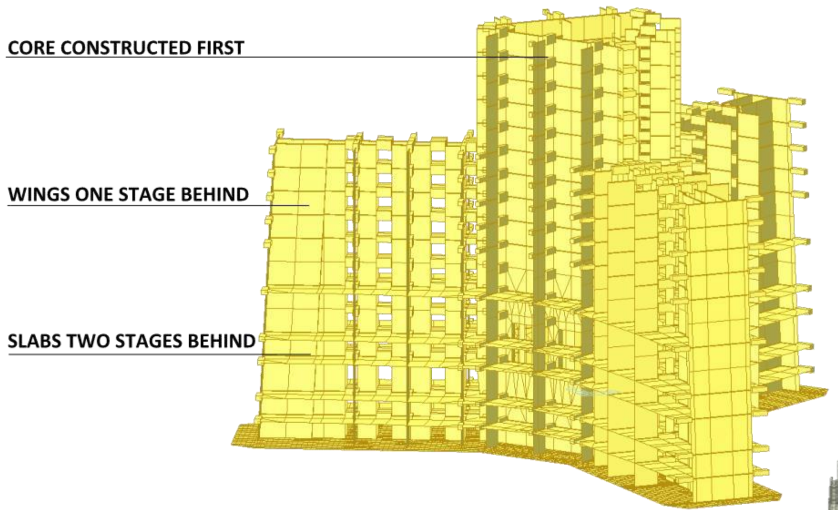
*Compensation Instructions
- Vertical
- Horizontal

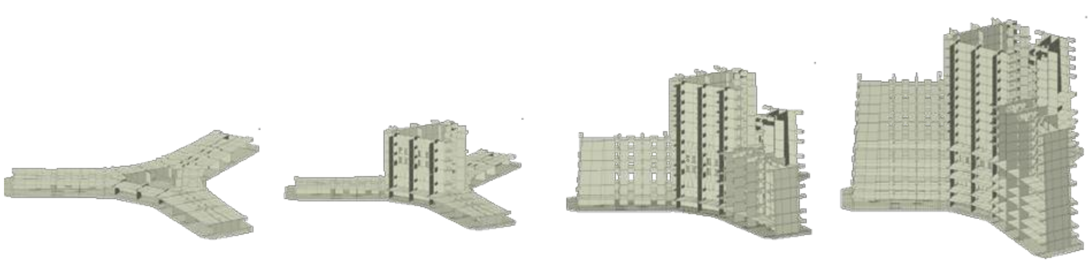
*Assumed Sequence of Construction

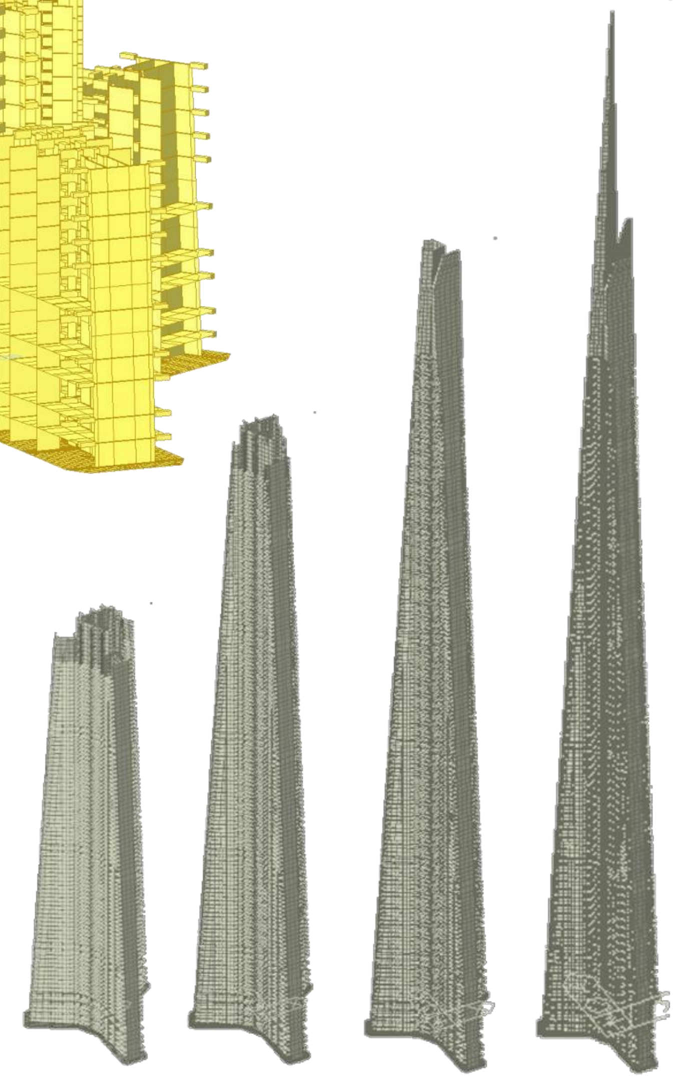
Kingdom Tower-Staging Assumptions

midas Gen









Representative Stages – Construction Sequence

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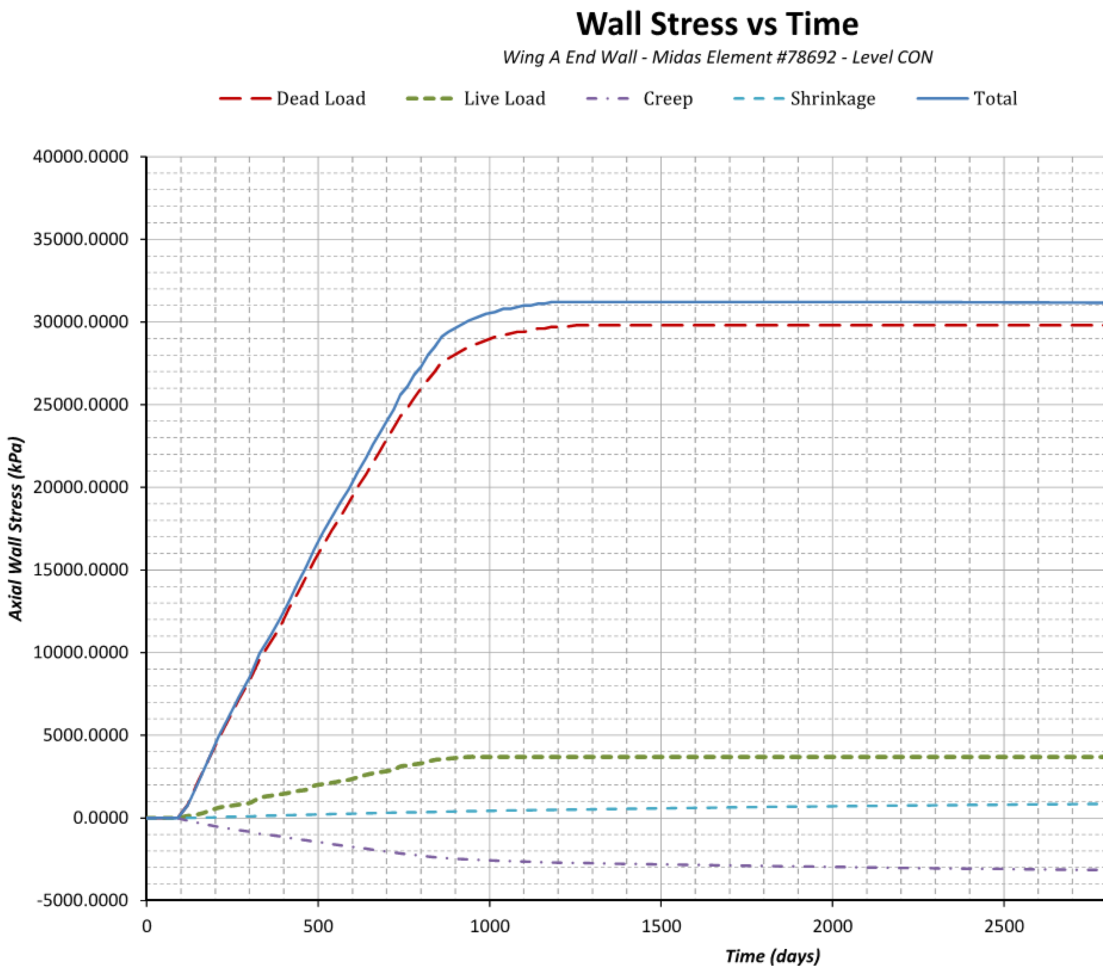
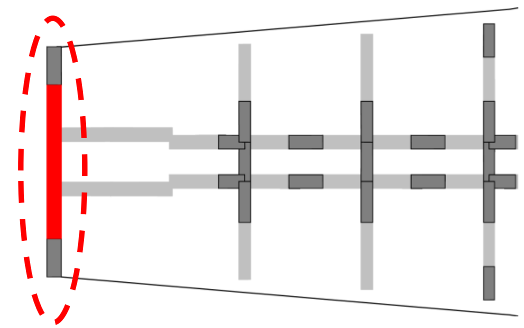
Results – Kingdom Tower

Wall Stress vs. Time





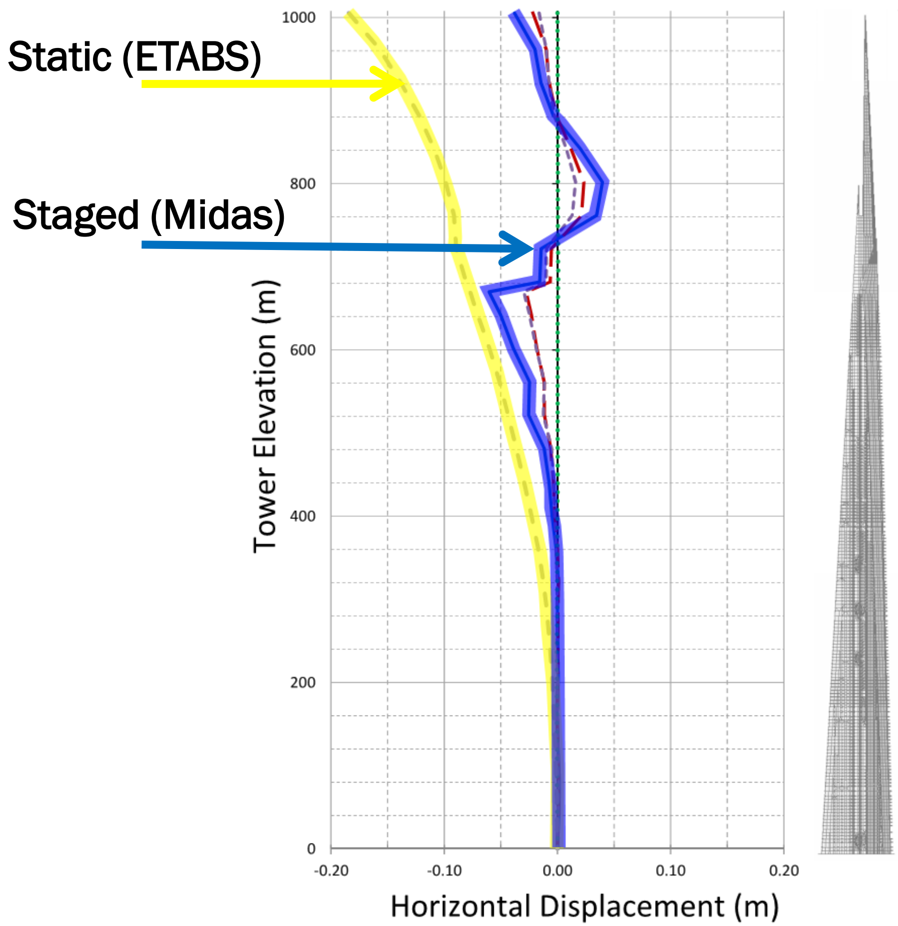
Effect of Creep & Shrinkage may redistribute load over time

Results – Kingdom Tower

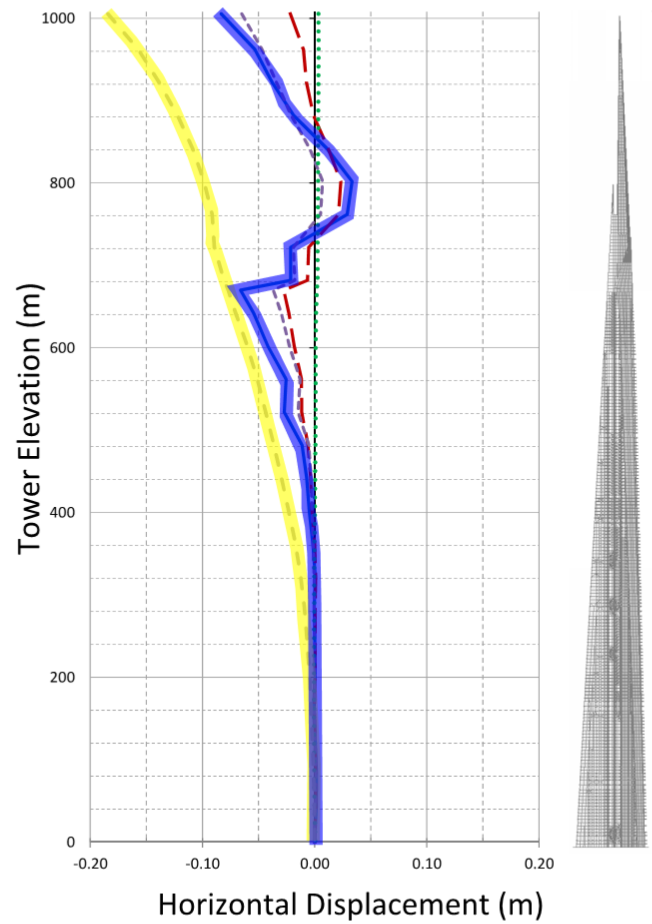
Horizontal Displacement

Total   Dead Load   Creep   Shrinkage   Static

At End of Construction



At 10 Years



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Construction – January 2014

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Construction – February 2014

Mat Concrete

- f'_c= 60 MPa (8,7000 psi) at 56d
- MOE = No requirement
- Mix: Self-Consolidating Concrete

Portland C	454	lb
SF	66	lb
PFA	305	lb
1/2,3/8” CA	1440	lb (Mecca)
Fine Agg	1390	lb
Water/Ice	250	lb
HRWR	Polycarboxylate	
VMA		

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Mat Foundation – Steel Fixing

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Tower Mat Formwork

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Tower Mat Concrete Pour

Mat Foundation – Insulation / Curing

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Construction Progress

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Sequence of Construction

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Wing/Corridor Wall Formwork

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October 2019 Progress:

- Height 265m
- Exterior Wall Installation Commenced
- First Column Setback Reached
- ~40% Concrete placed