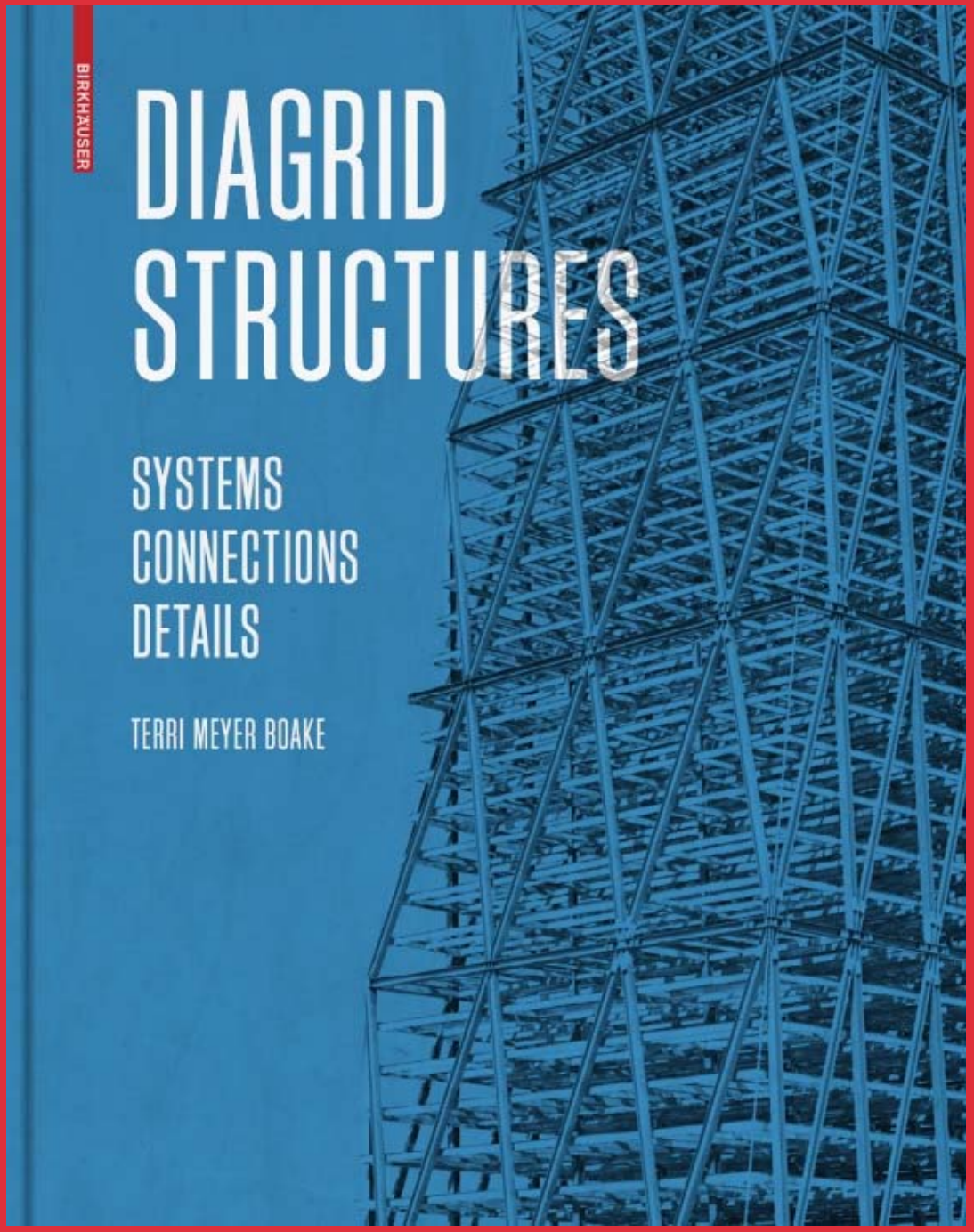
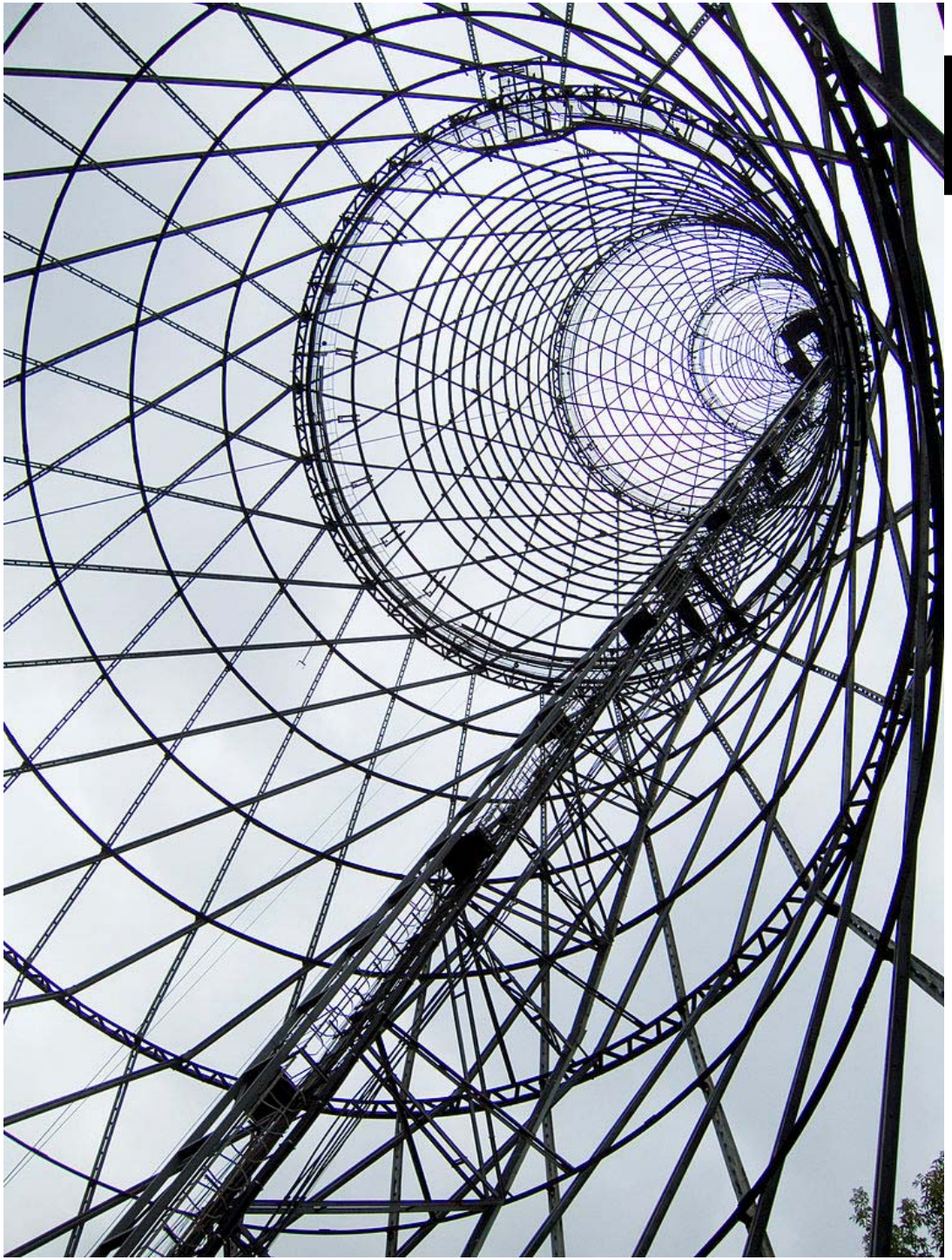


Arch 375: Architecturally Exposed Structural Steel

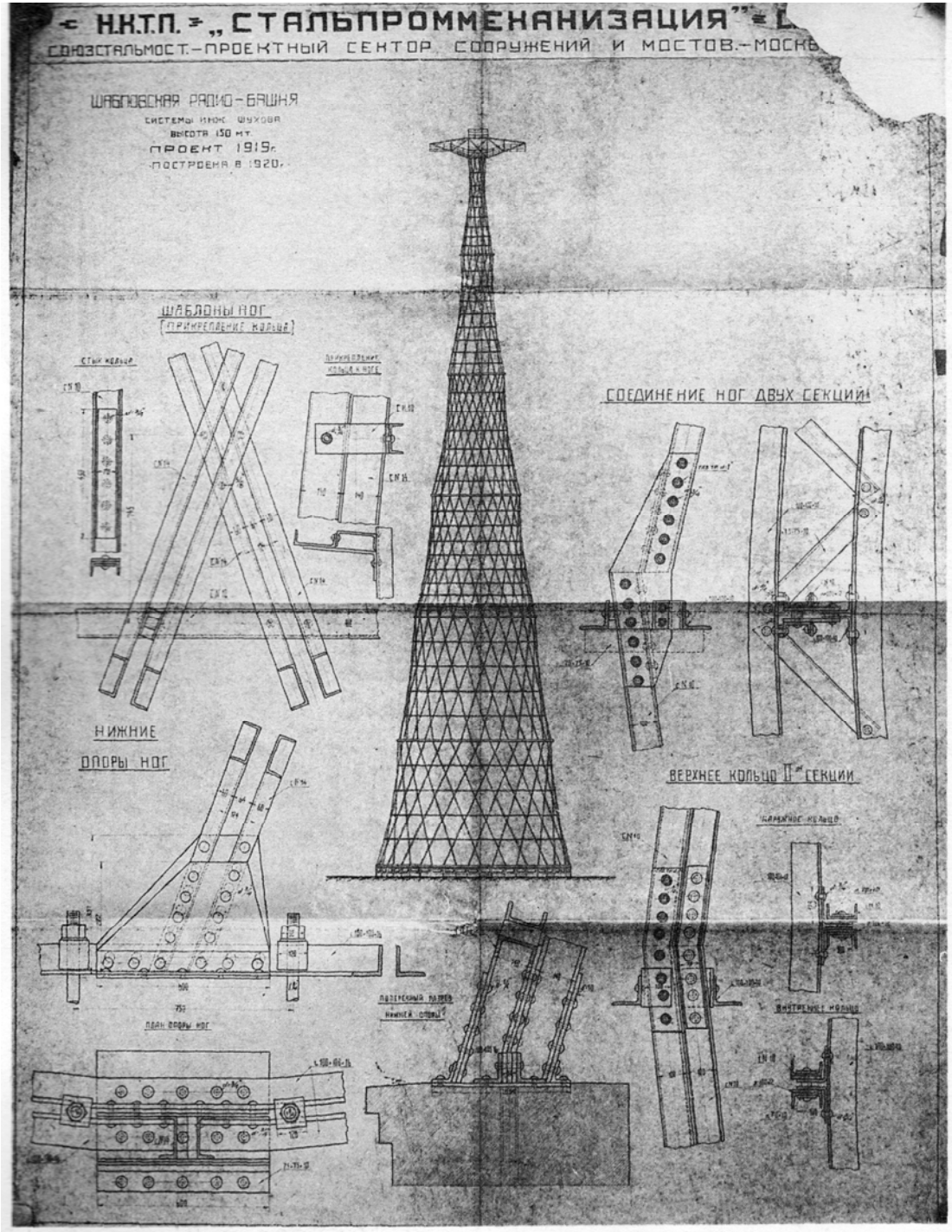
Terri Meyer Boake
University of Waterloo
School of Architecture

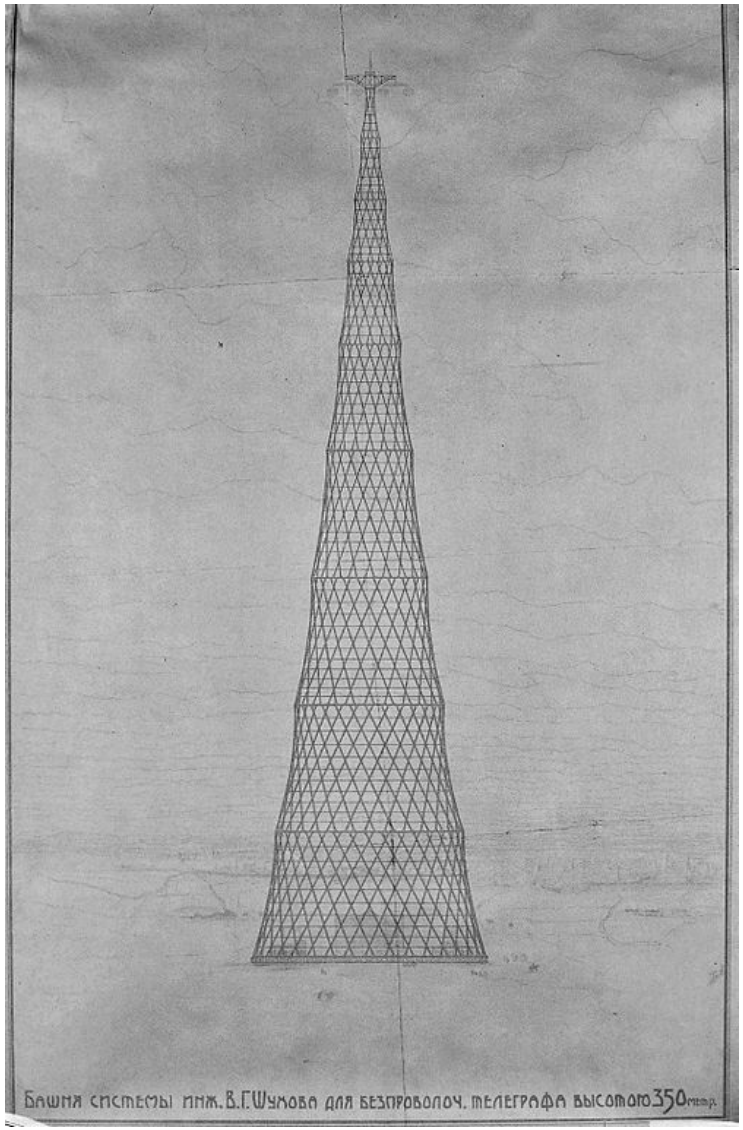


Vladimir Shukhov

- originated in the work of Vladimir Shukhov circa 1896
- creation of tall hyperbolic paraboloid structures to support water towers
- structure had no need of a core for lateral load resistance

Shukhov Towers





Evolution: Diagonal Bracing

- Diagonals re-appeared as expressions of bracing
- They provided lateral support for wind and seismic loads
- Columns carried the gravity loads
- Core was the primary means of lateral resistance

Evolution: Eliminating vertical columns

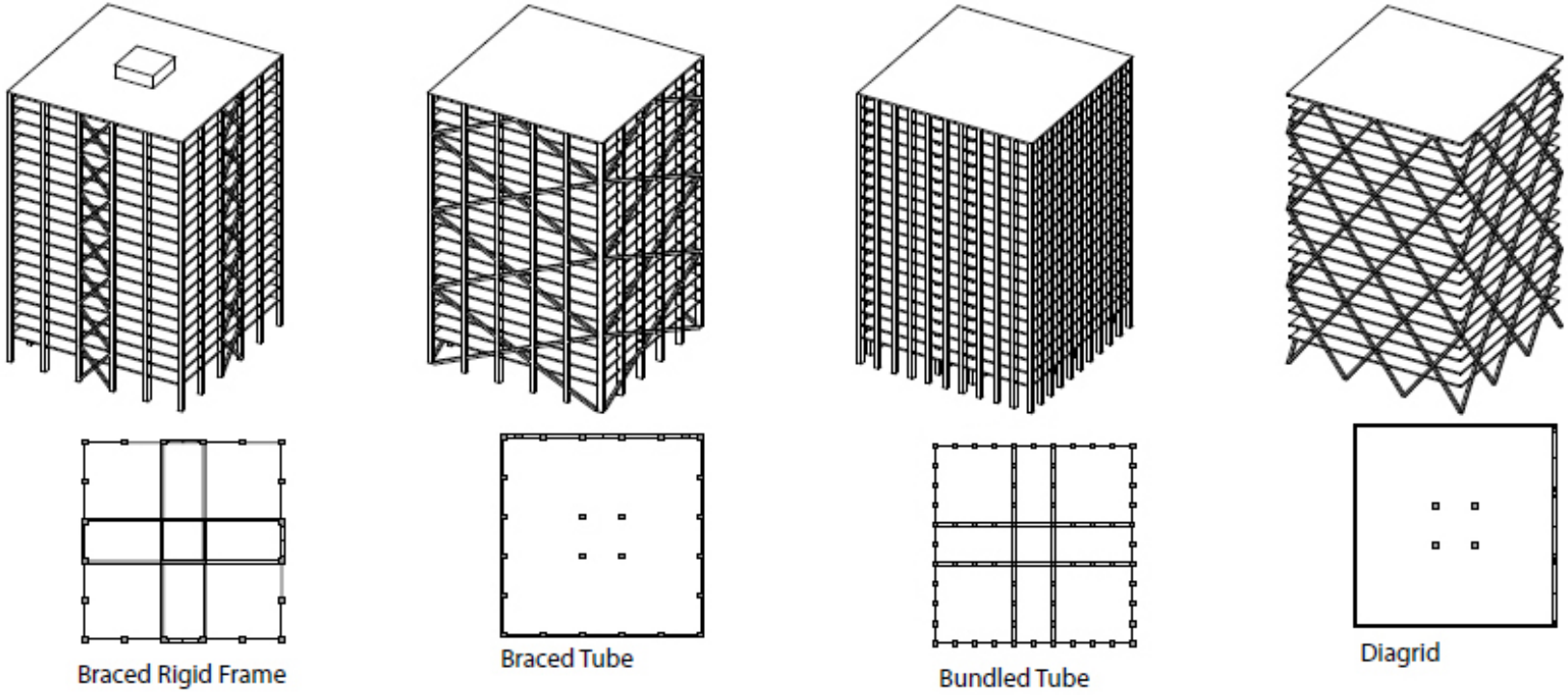
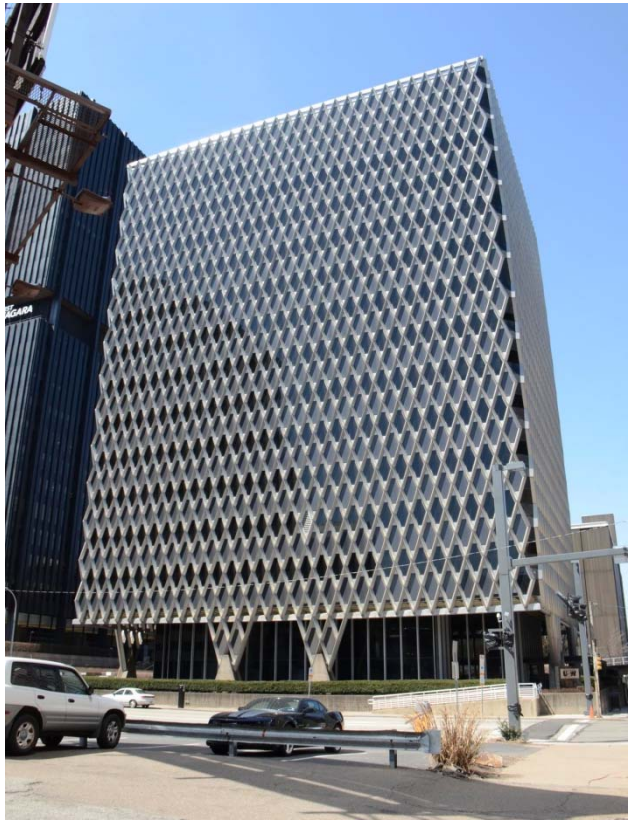


Image: Vincent Hui

Note: The core will be framed in steel or cast in concrete as a function of local practices and construction sequencing/erection priorities.
A pure steel diagrid tower does not require a core for lateral resistance.

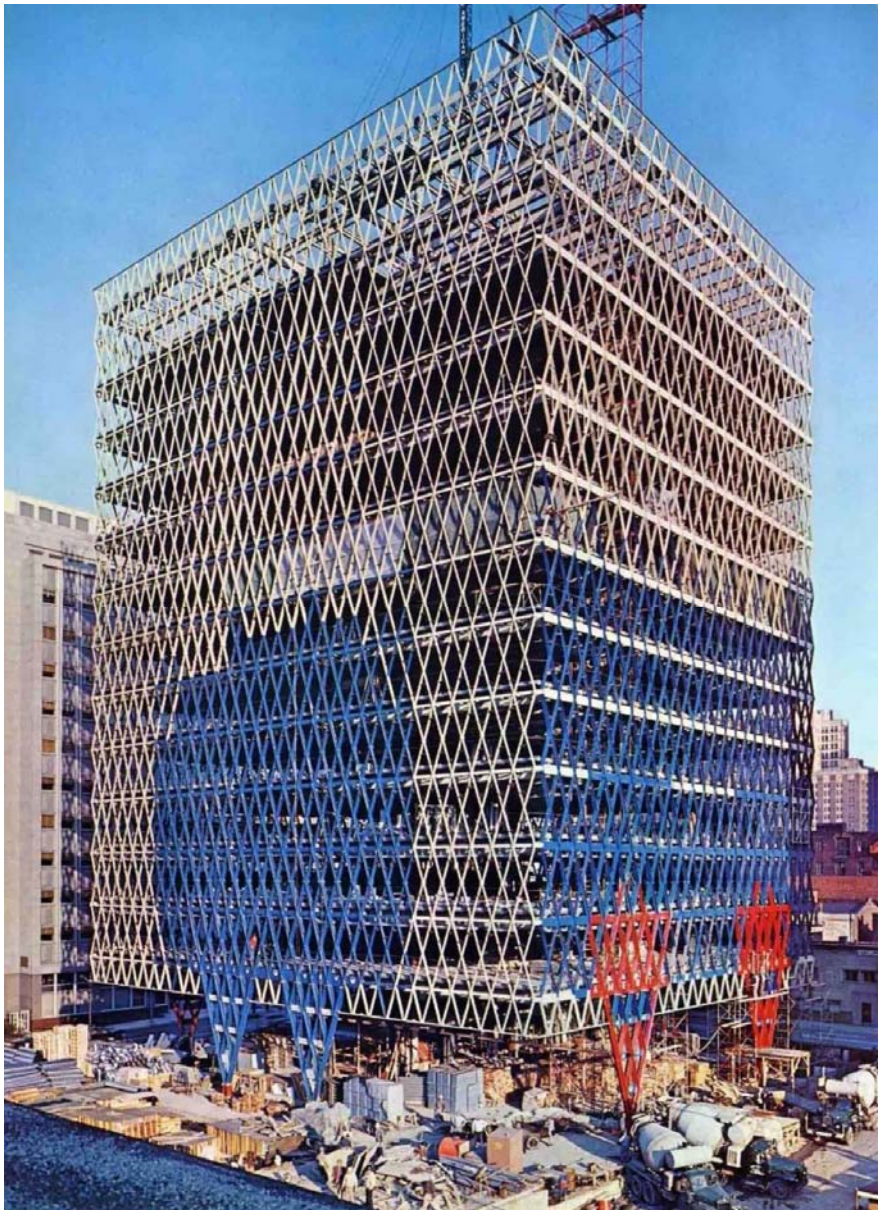
History: Early Diagrids



CURTIS AND DAVIS w/
LESLIE ROBERTSON ENGINEER
UNITED STEELWORKERS BUILDING 1963
Pittsburgh, Pennsylvania

- Exterior steel frame
- Aluminum clad
- Incorporated glazing system

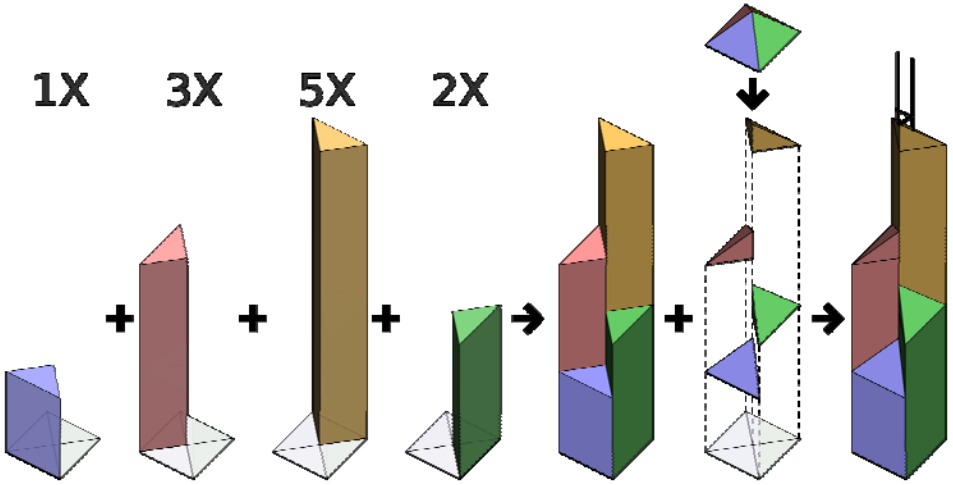
Prefabrication



- introduction of prefabrication of the exterior framing elements
- color coding of the frames according to their load carrying capacity
- quicker connections on site

Images: Leslie E. Robertson Associates

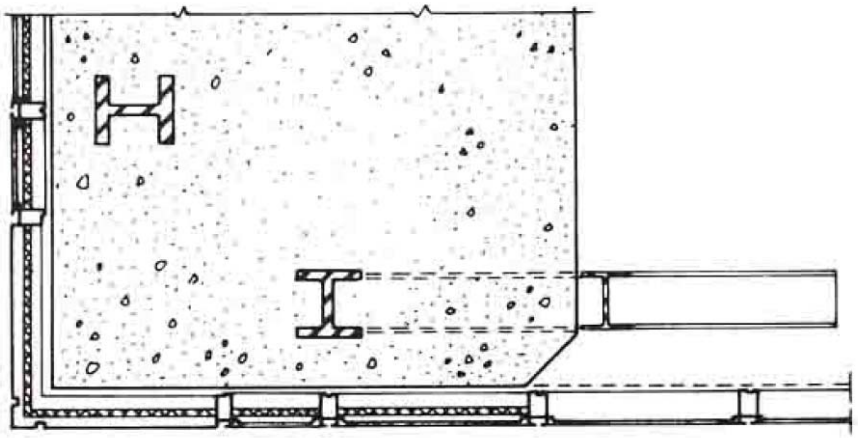
History:
Early Diagrids



I.M. PEI w/
LESLIE ROBERTSON ENG.
BANK OF CHINA 1989
Hong Kong

Diagonal geometry permitted unusual massing of the tower.

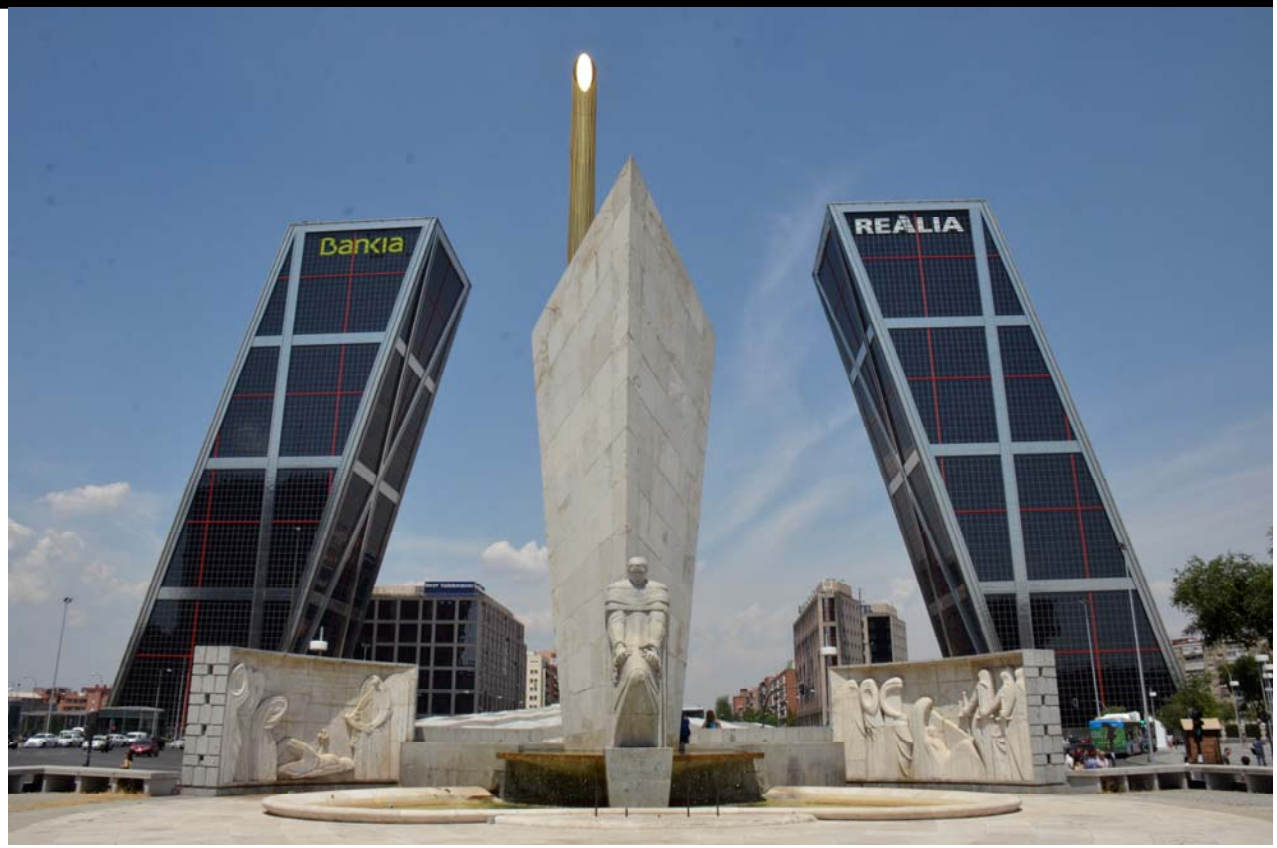
History:
Early Diagrids



I.M. PEI w/
LESLIE ROBERTSON ENG.
BANK OF CHINA 1989
Hong Kong

Diagonals were constructed of steel that was embedded in large masses of concrete at the major nodes.

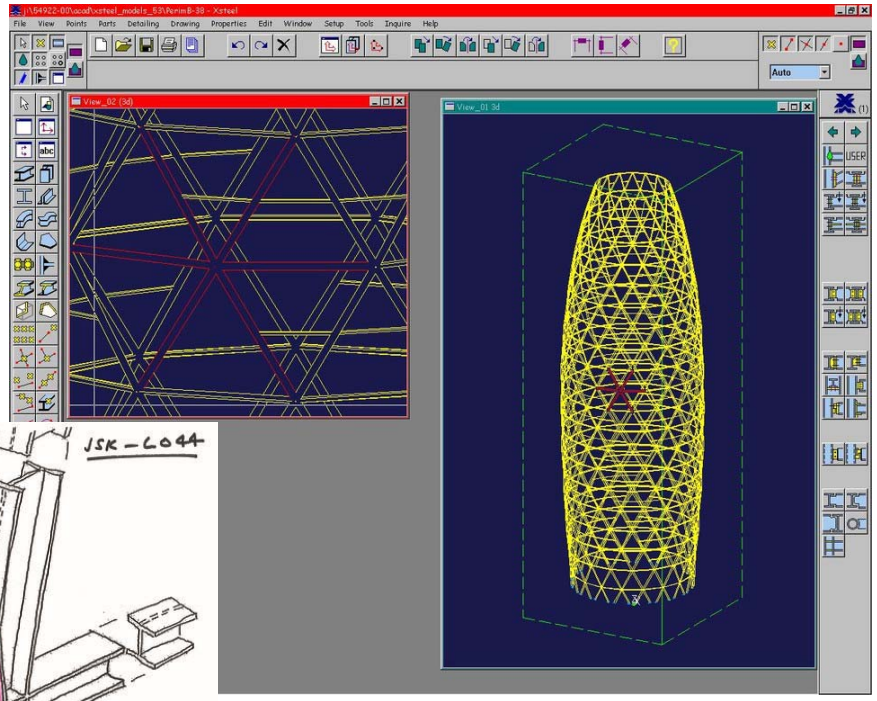
Early Expressions of Diagonal Bracing

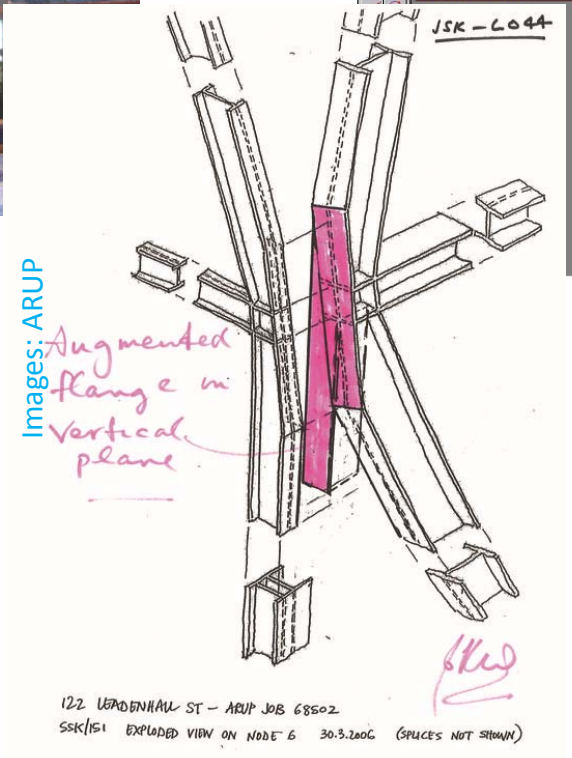


Johnson/Burgee w/
LESLIE ROBERTSON ENG.
Puerta de Europa Towers 1996
Madrid, Spain

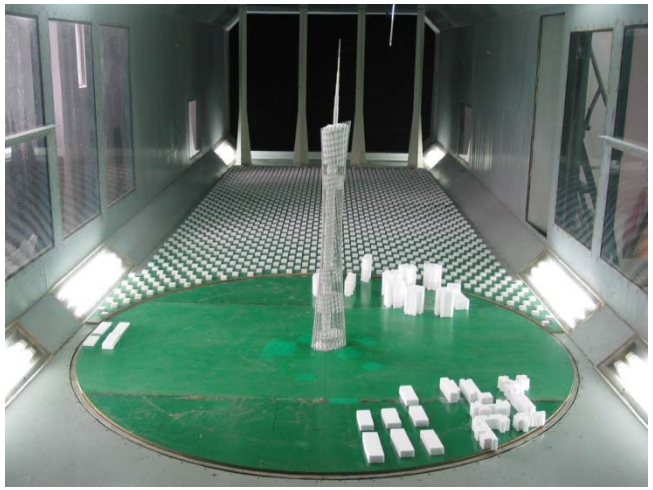
- Highly expressive use of diagonal bracing
- 15^{o} lean
- Steel frame with reinforced concrete core

Collaboration is critical for success





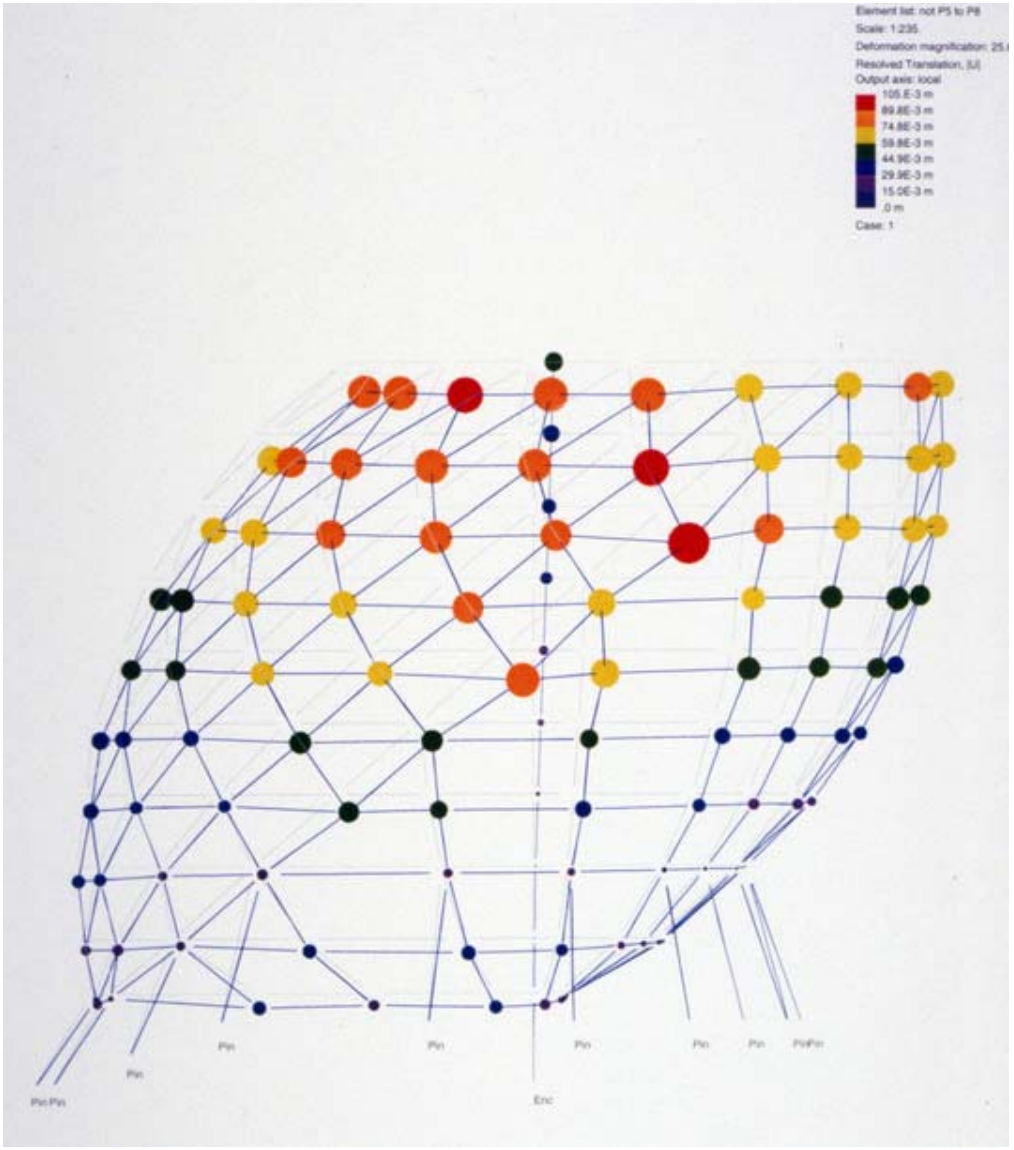
Images: ARUP



* New code issues!
Diagrids not in current seismic codes

ARCHITECT
ENGINEER
FABRICATOR

Early Diagrids



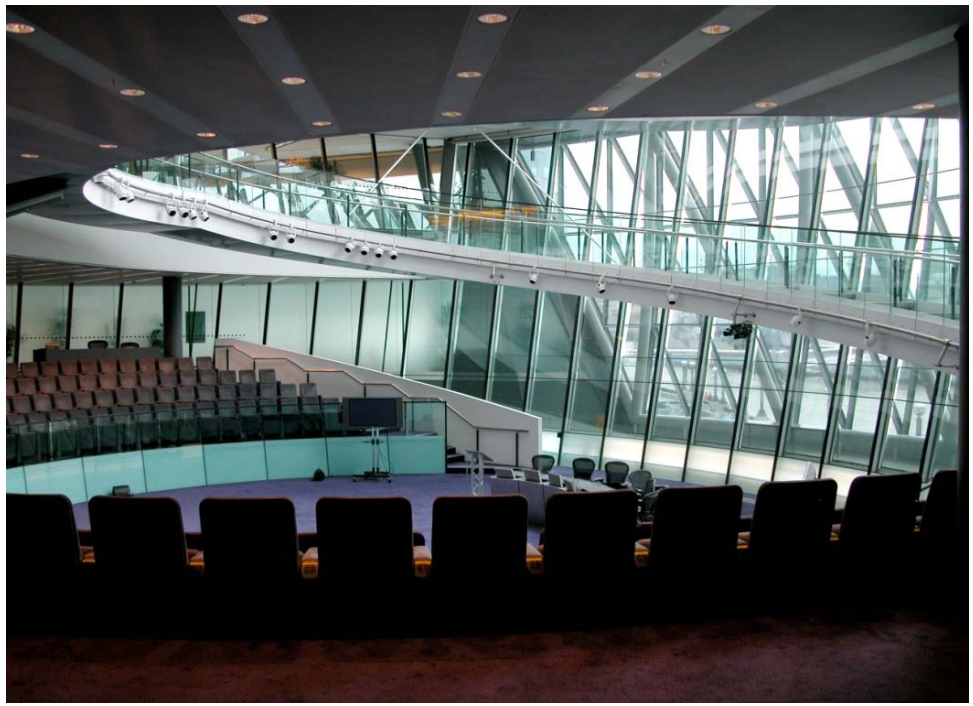
Adapted well to non rectilinear geometries.

FOSTER+PARTNERS
w/ARUP
LONDON GLA 2003
London, England

Images: ARUP

Early Diagrids

- diagrid not a complete system
- used to support the front glazed face
- combined with sloped columns to address “egg” shape
- structural system designed around the idea of the central void



FOSTER+PARTNERS
w/ARUP
LONDON GLA 2003
London, England

Early Diagrids

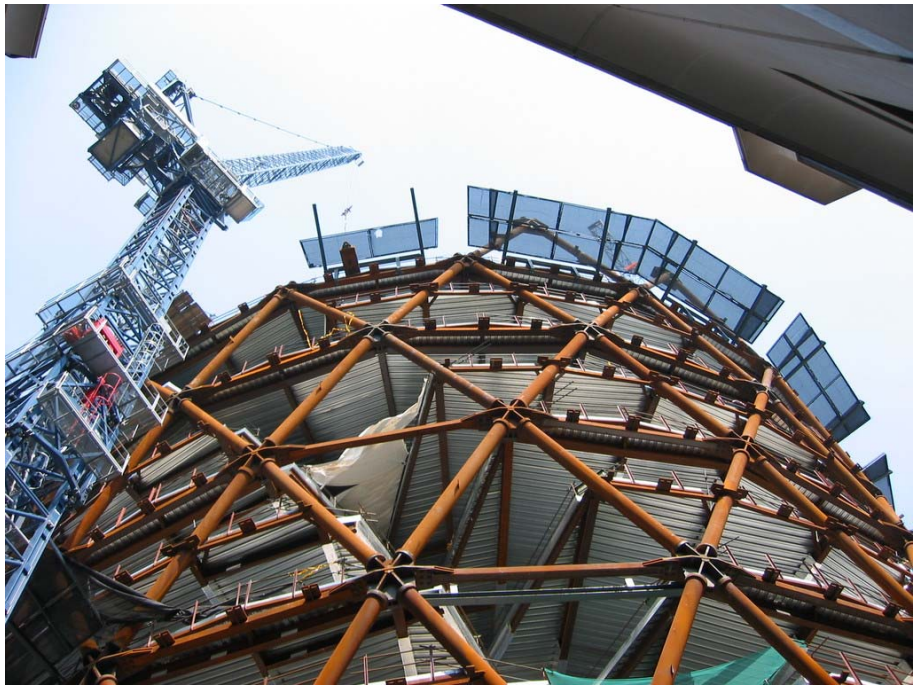


Photo: ARUP

Steel as the exclusive structural system for exterior, floors and core.

FOSTER+PARTNERS
w/ARUP
SWISS RE 2004
London, England

Early Diagrids

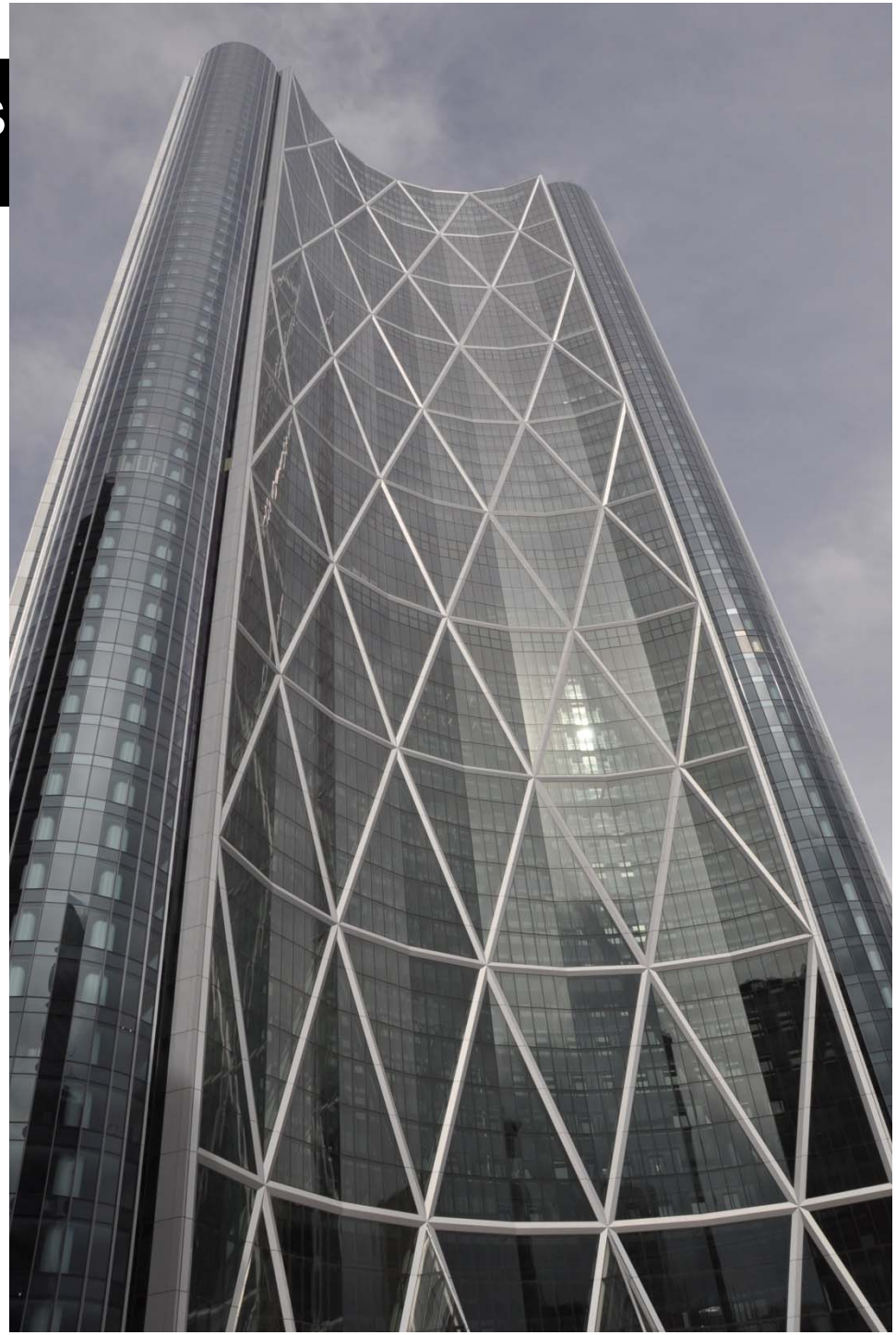
- Used for a rectilinear building
- Expression of the diagrid on the detailing of the corners
- Exclusive steel structure for core, exterior diagrid support and floor system

FOSTER+PARTNERS w/
WSP GROUP
HEARST MAGAZINE TOWER 2006
New York, New York

Potential benefits

- Increased stability due to triangulation
- diagrids combine the gravity and lateral load bearing systems, thereby providing more efficiency
- provision of alternate load paths in the event of a structural failure
- *some* buildings noting a 20% reduction in the amount of structural steel required

FOSTER+PARTNERS w/ ZEIDLER
HALCROW YOLLES
BOW ENCANA 2012
Calgary, Alberta



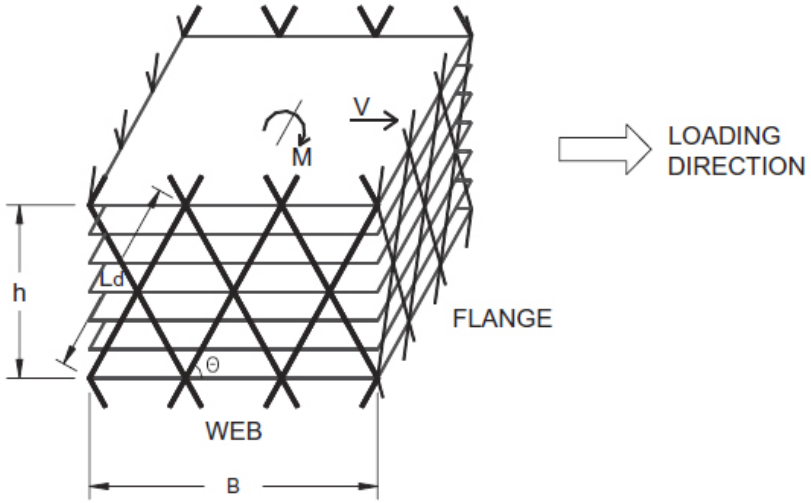
Potential benefits

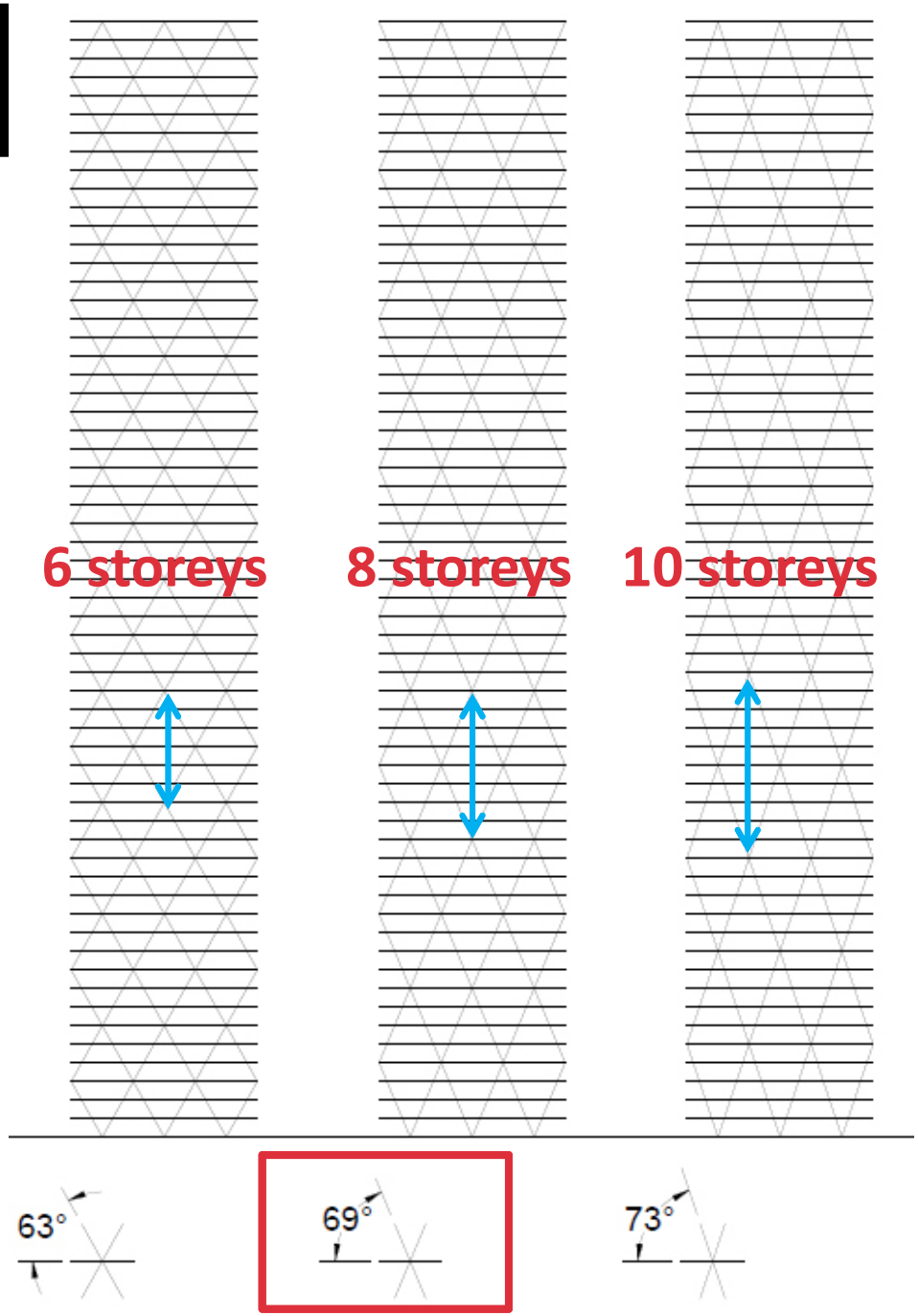
- reduced use of structural materials which translates into “carbon” or environmental savings
- reduced weight of the superstructure translates into reduced load on the foundations
- ability to provide structural support for a myriad of shapes

- MOST APPLICATIONS ARE ARCHITECTURALLY DRIVEN

ROGERS STIRK HARBOUR + PARTNERS
w/ ARUP
THE LEADENHALL BUILDING 2013
London, England

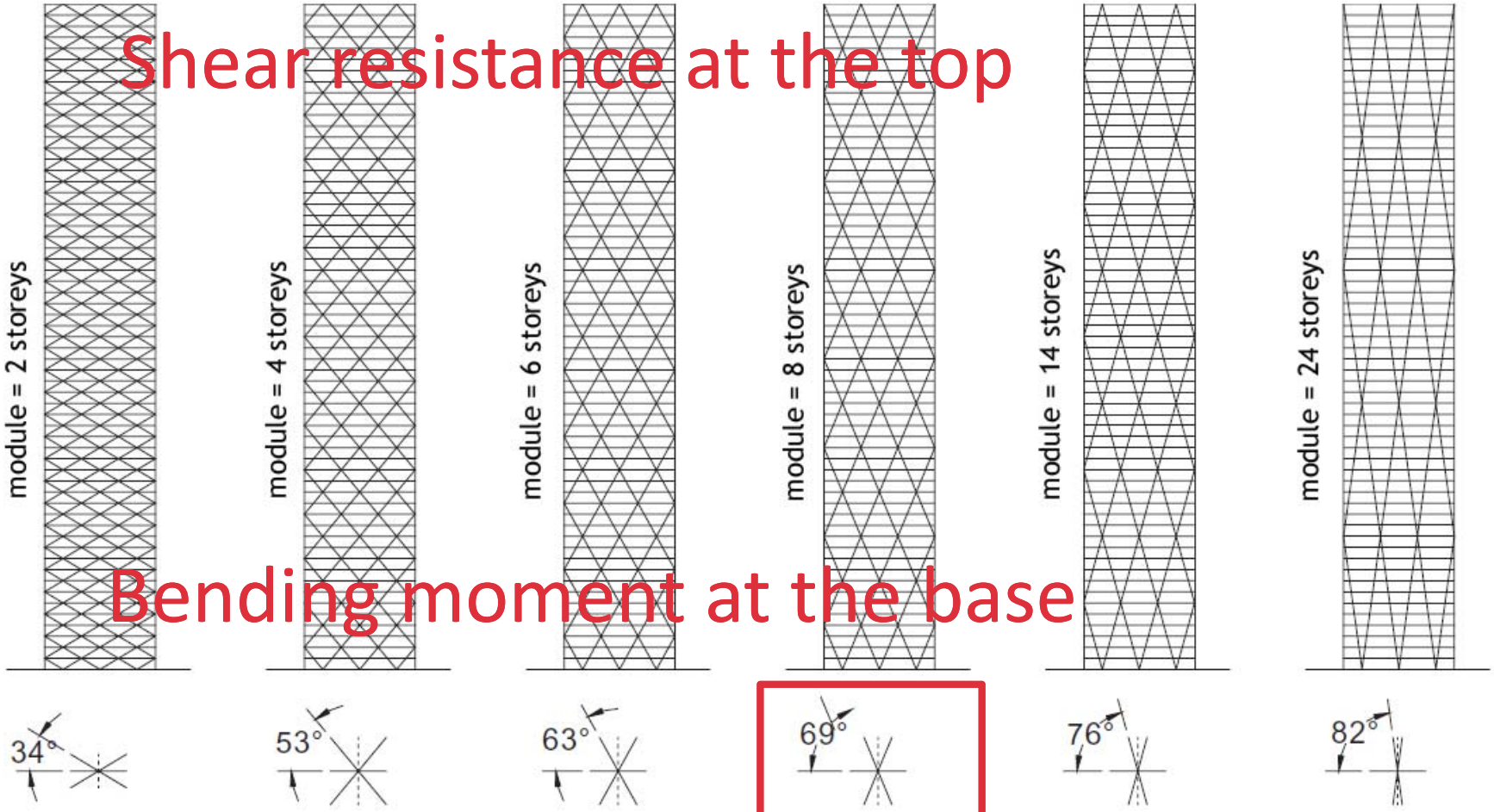
Optimization





KYOUNG SUN MOON
YALE UNIVERSITY
OPTIMIZATION WORK
2007 TO PRESENT

Optimization + Modularity



KYOUNG SUN MOON
OPTIMIZATION WORK

A tower is a tall cantilever. It experiences moment towards the base and shear towards the top.

Primary areas of concern for design

- Modules and modularity
- Node and member design
- Core design
- Façade design

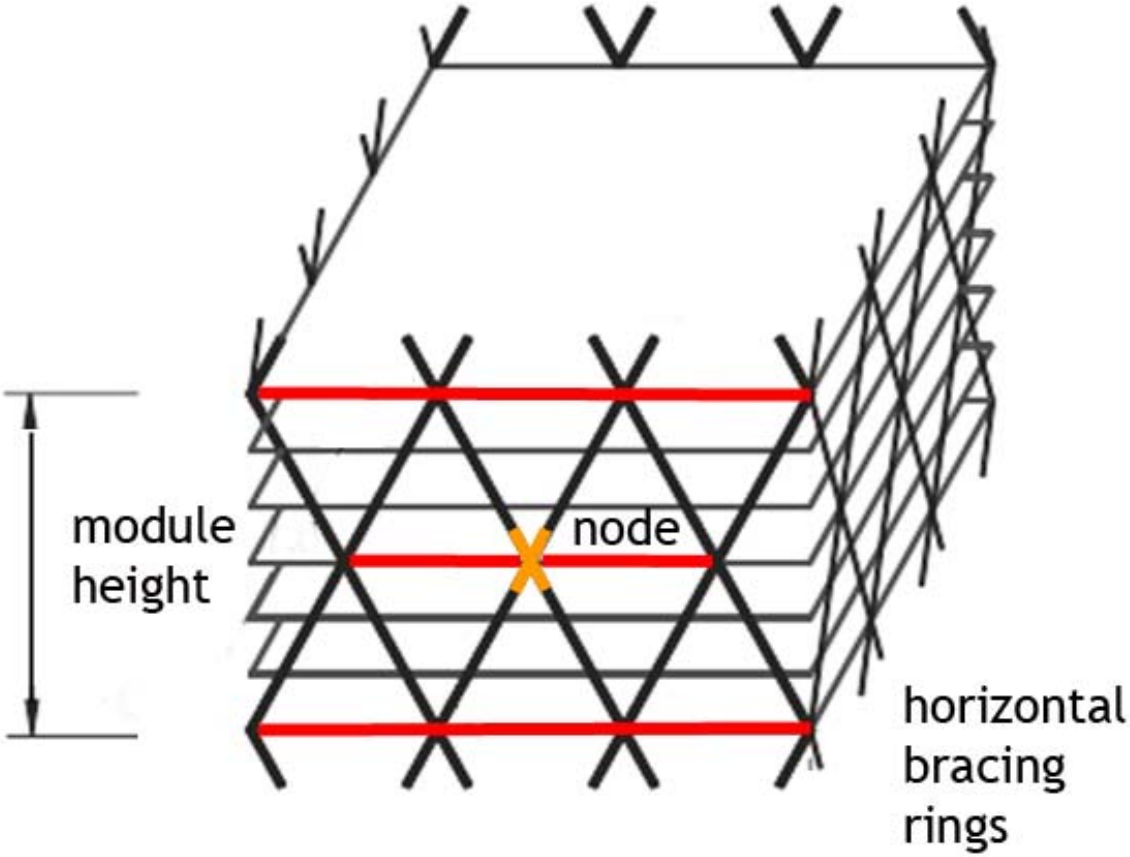
Modules

- How frequent are the nodes?
- How long are the diagonals?
- What sort of spacing angle is appropriate?
- What is the spacing between the points of connection with the floor edge beam that creates the triangulation between the diagrid members?

Additional module considerations

- geometry of the building
- occurrence of eccentric loading
- structural efficiency
- floor-to-floor heights
- requirements for fenestration pattern and window sizes
- selection of AESS or concealed steel structure

Terms



Note the unsupported condition of the corner. This becomes a major concern when designing the planimetric shape of the tower.

Bracing of the members?

Aldar HQ, UAE. Floor edge beams brace diagonals.

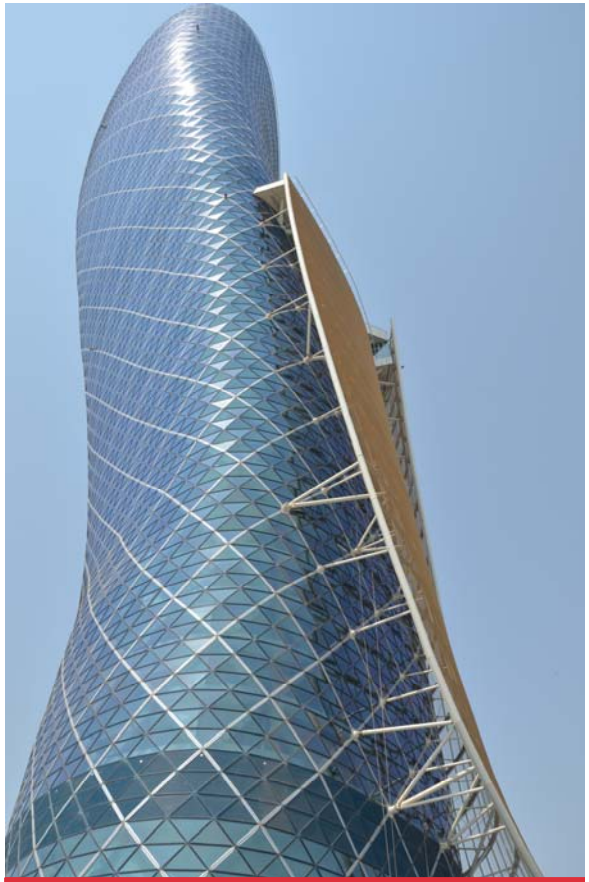
Bow Encana, Calgary. No bracing, double façade behind.

Small Modules: 2 to 4 storeys

Swiss Re – 4 storeys

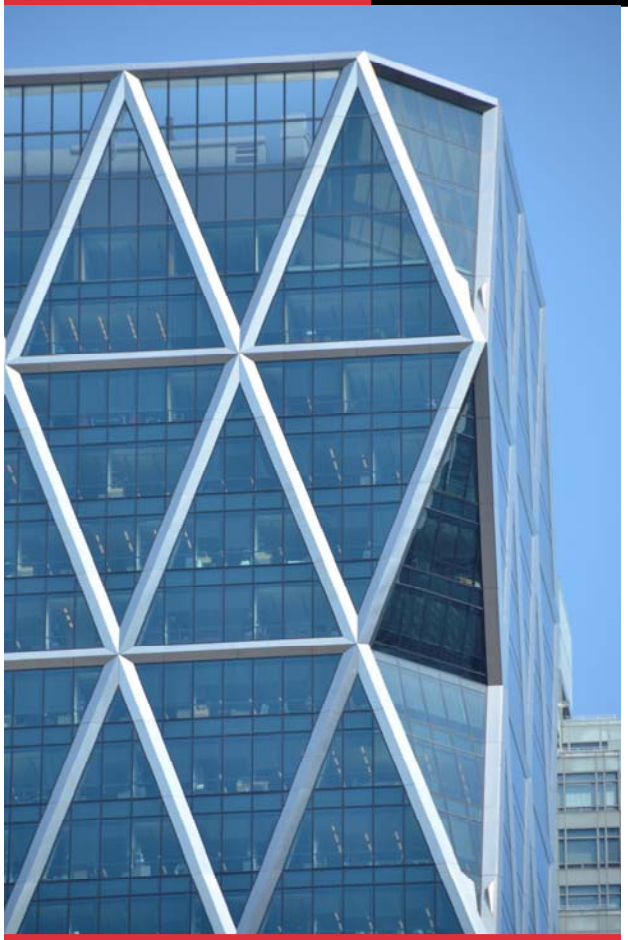
Shelley Street – 4 storeys

Tornado Tower – 4 storeys



Capital Gate – 2 storeys

Midrange Modules: 6 to 8 storeys

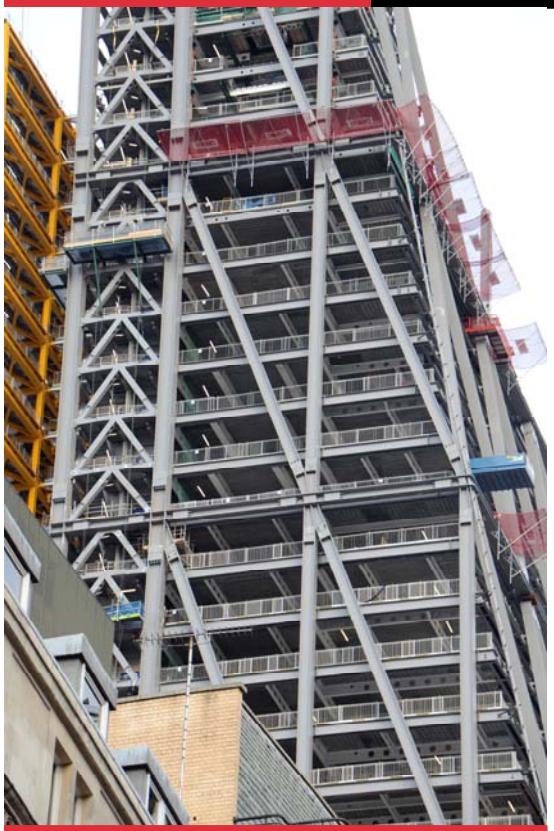


Hearst – 6 storeys

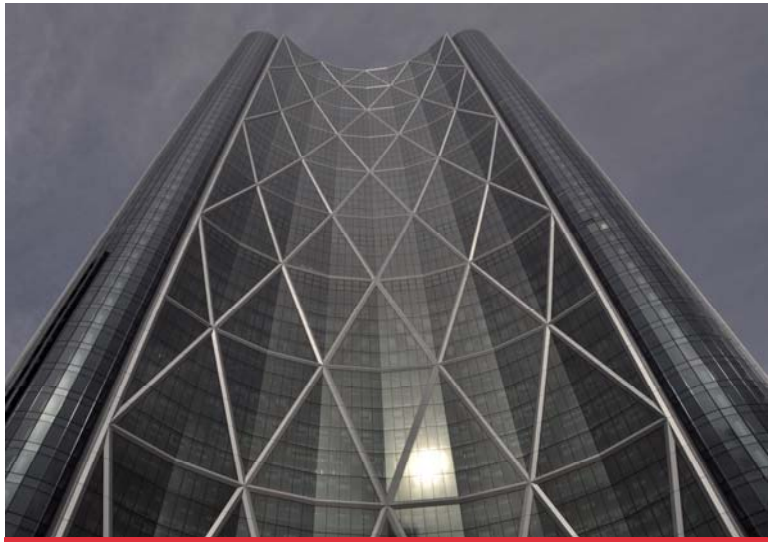
Aldar HQ – 6 storeys

Doha – 6 storeys

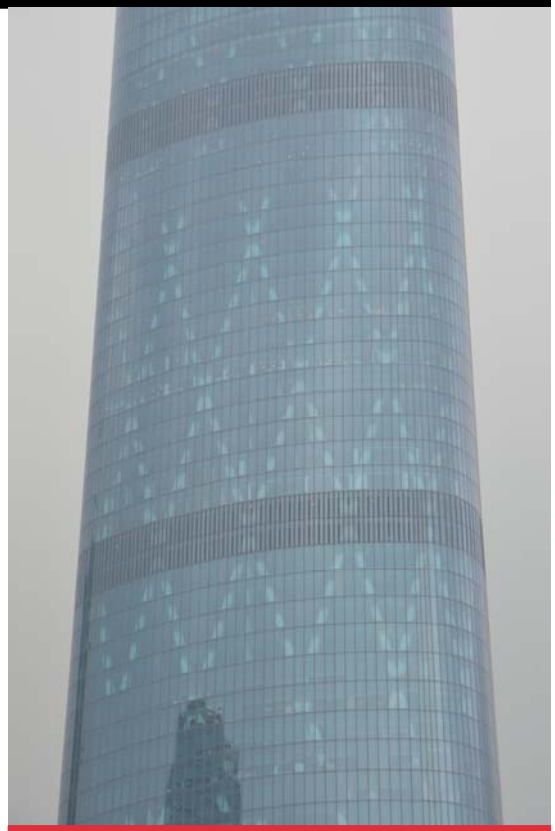
Large Modules: 10+ Storeys



Leadenhall – 14 storeys



Bow Encana – 12 storeys



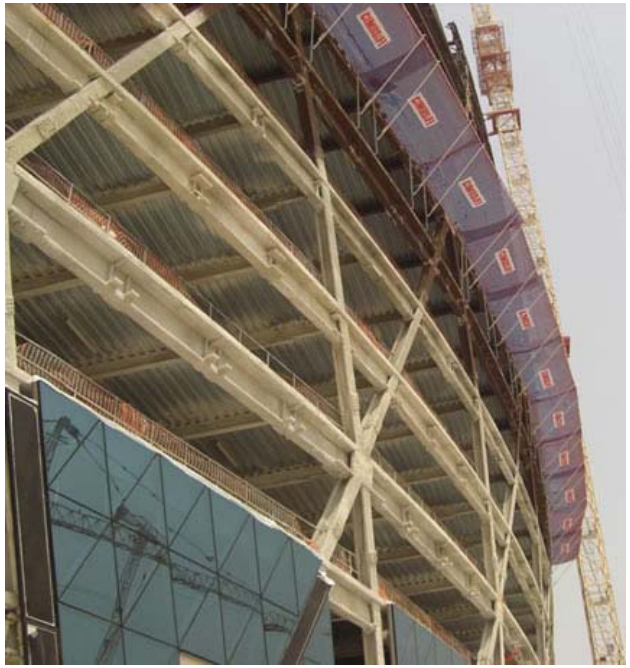
Guangzhou IFC – 12 or 16 storeys

Module

- 400m Supertall tower
- Taper towards top
- Rounded triangular plan
- Large scale for large building

WILKINSON + EYRE w/ARUP
GUANGZHOU IFC 2010
Guangzhou, China

Module



- Concealed steel
- Gently curved shape
- floor edge beams brace diagrid along its length

MZ ARCHITECTS w/ARUP
ALDAR HQ 2012
Abu Dhabi, UAE

Module

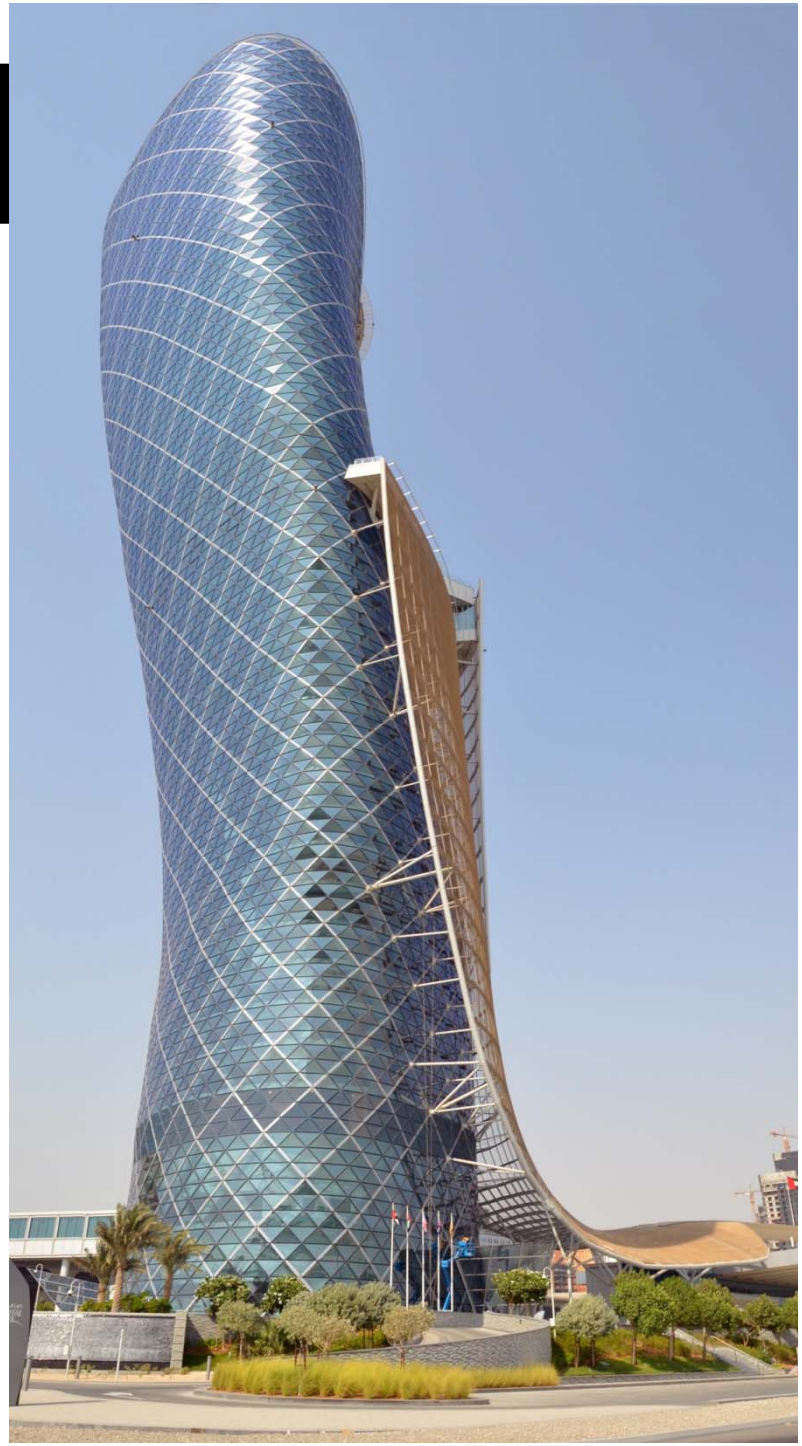
- exposed steel
- double façade
- sloped face
- module height linked to trapezoidal shape/height of building

ROGERS STIRK HARBOUR+PARTNERS
w/ ARUP
LEADENHALL 2013 London, England

Module

RMJM ARCHITECTS
SELF ENGINEERED
CAPITAL GATE 2012
Abu Dhabi, UAE

- Eccentric geometry
- 18^{o} backwards lean
- Offset concrete core
- Large diagonals on close spacing for structural reasons



Module

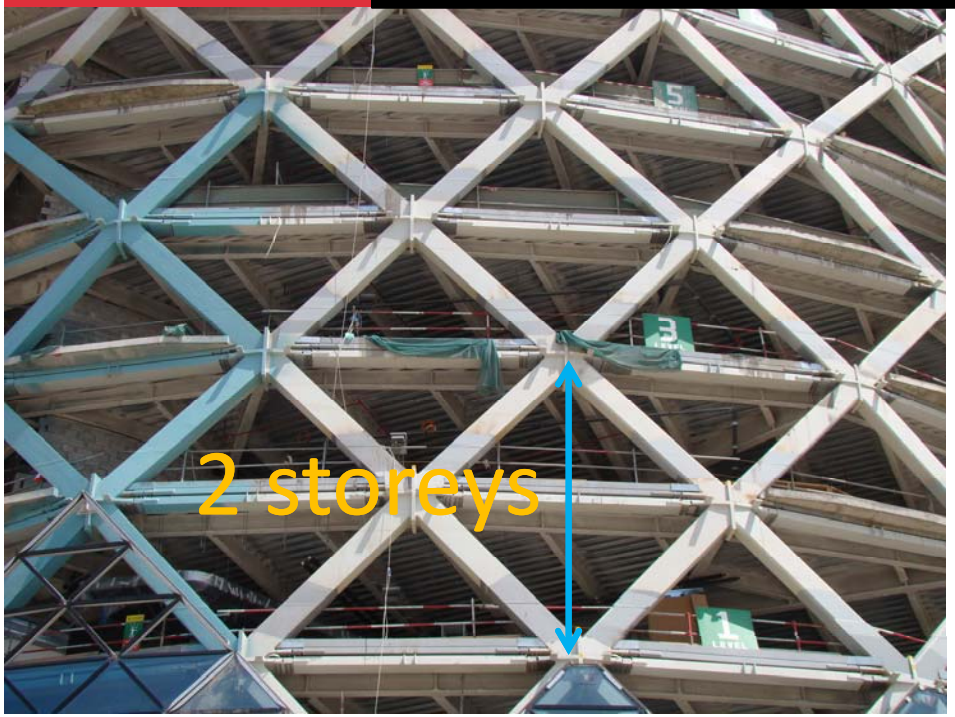
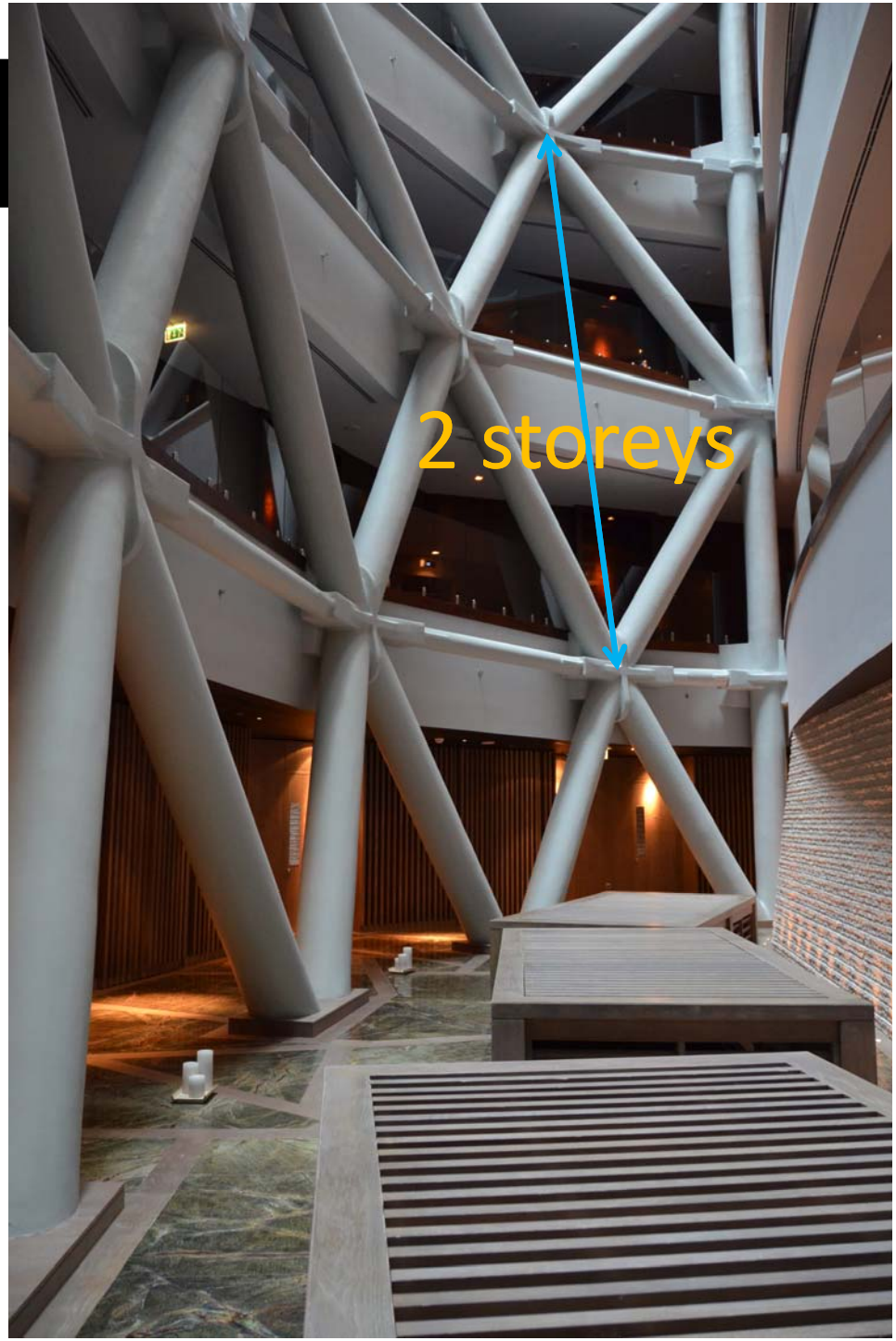


Image: Miroslav Munka

Module in atrium matches module for exterior support system.

RMJM ARCHITECTS
SELF ENGINEERED
CAPITAL GATE 2012
Abu Dhabi, UAE



Module

- 555m Supertall tower
- Taper towards top
- Rounded plan at the top
- Square plan at the bottom
- steepness of the diagrid shifts from moment resisting (steep) at the base to shear resisting (shallow) at the top

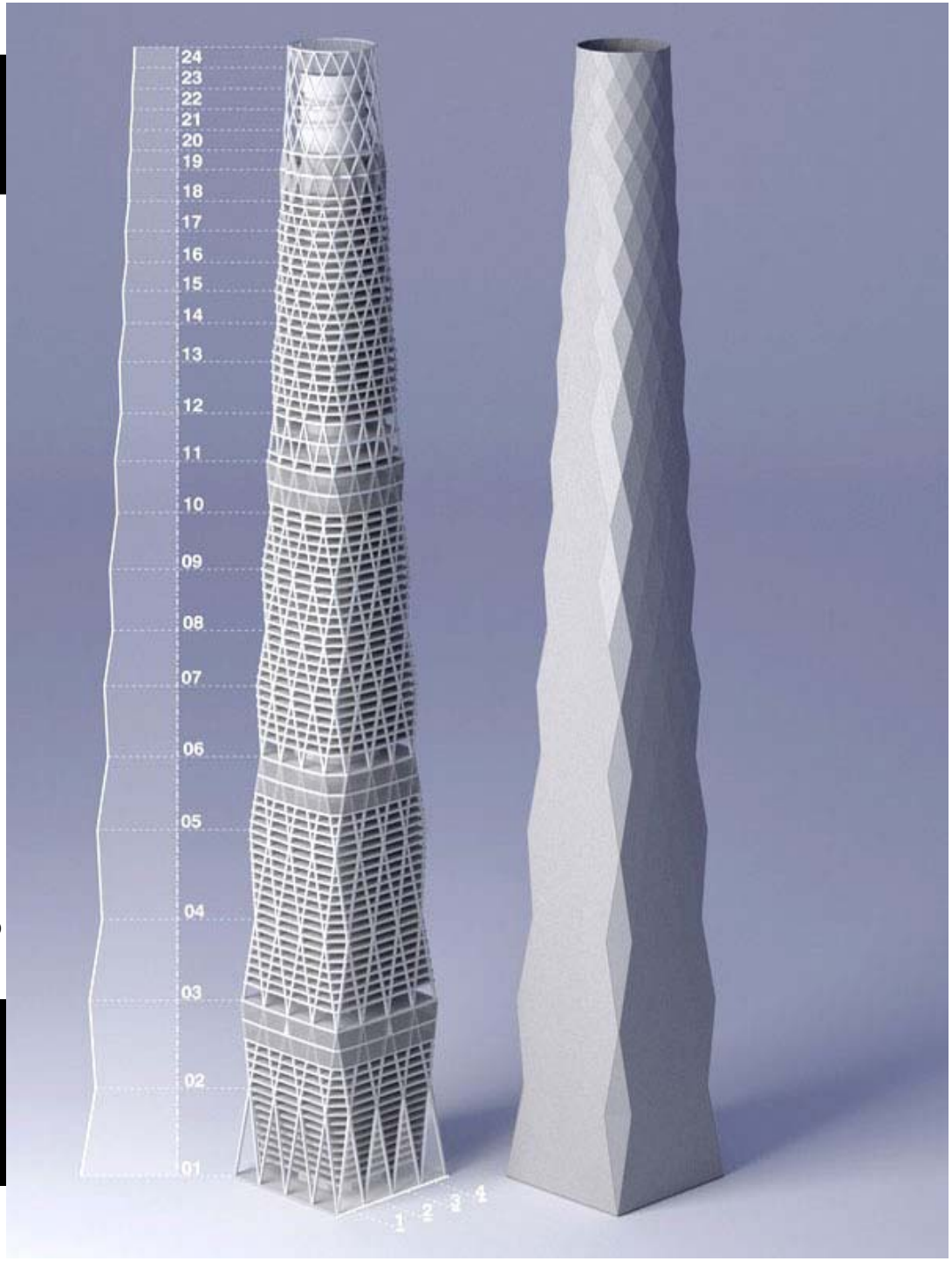


Image: SOM

SOM
Lotte Super Tower (visionary)
Seoul, Korea

Module

- plan changes from square at the bottom to round at the top
- module height changes from 10 storeys at the bottom to 2 storeys at the top
- round open lattice at the top good for vortex shedding
- angle is steeper at bottom and shallower at top

SOM
Lotte Super Tower
(visionary)
Seoul, Korea

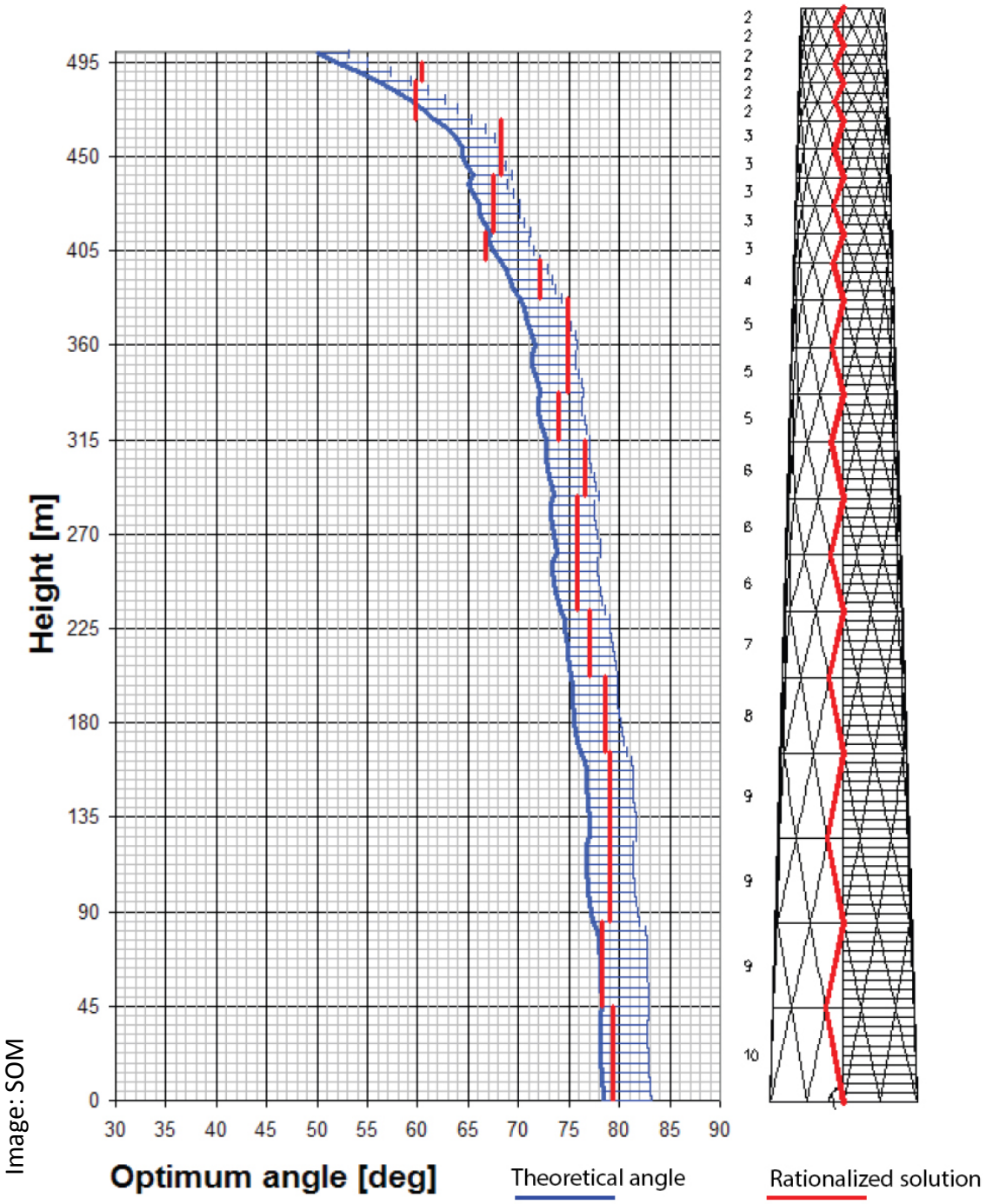
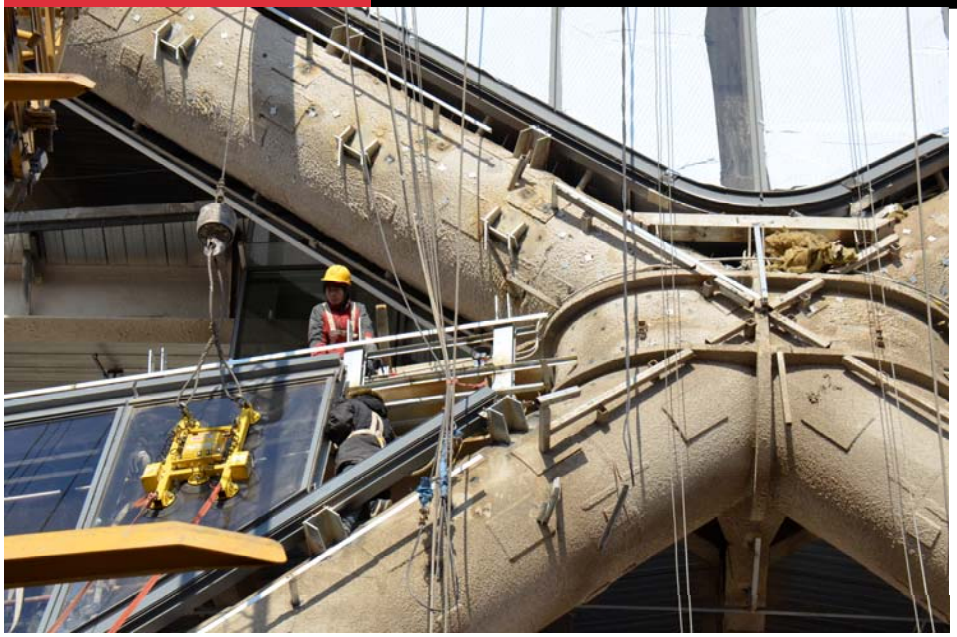


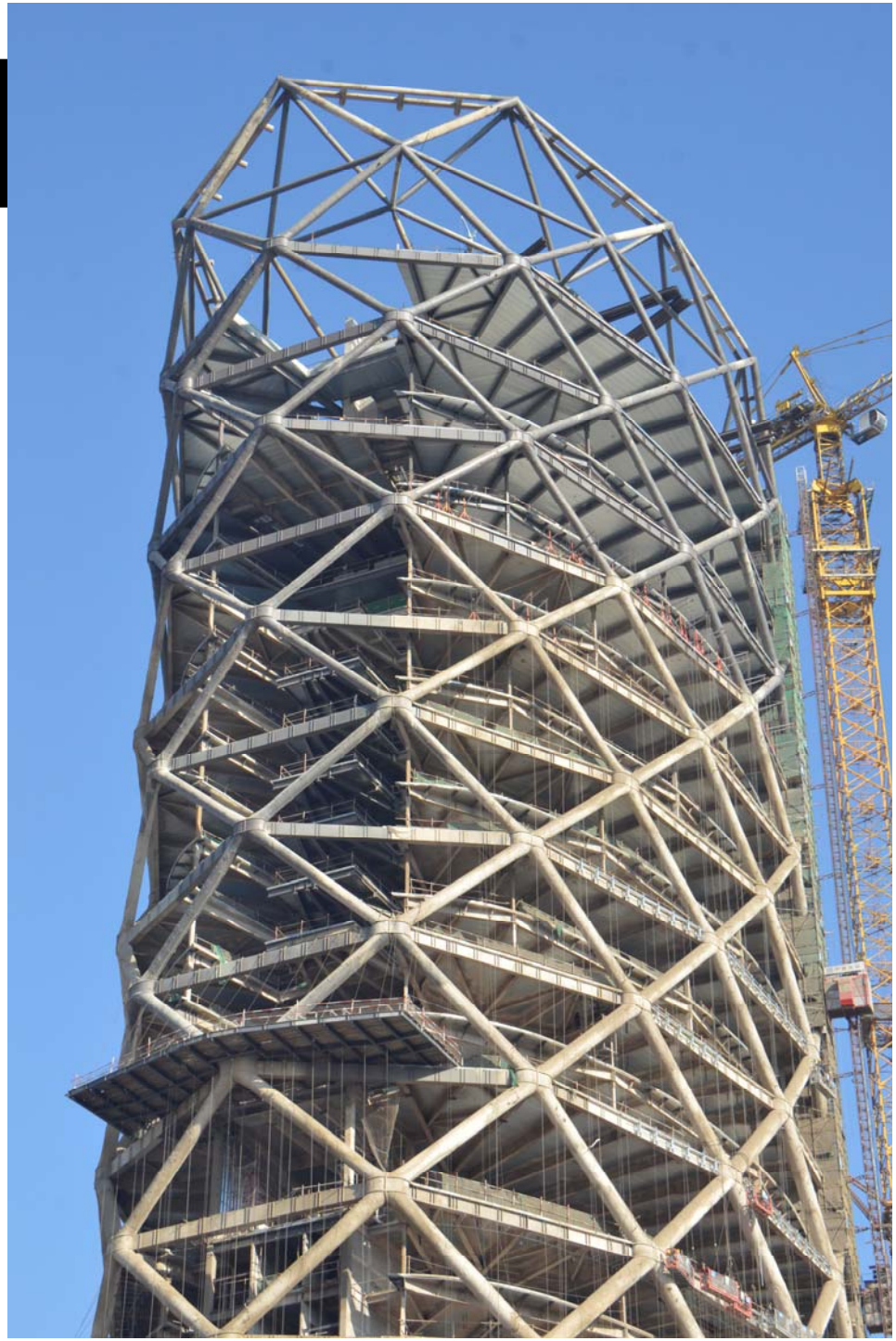
Image: SOM

Module

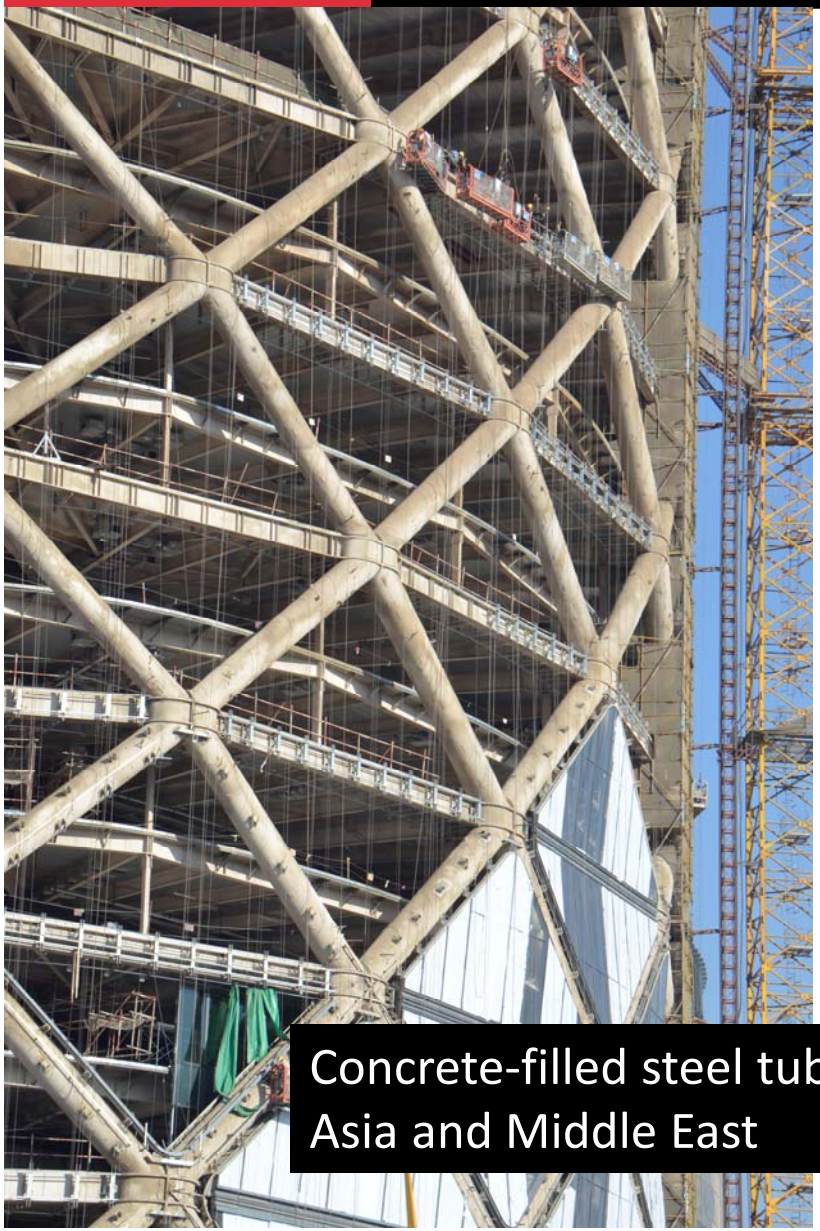


- 4 storey module
- Unbraced diagonals due to double façade
- Alternate floors hung from floor above
- Low angle with floor

SOM
Diamond Lantern
Beijing, China

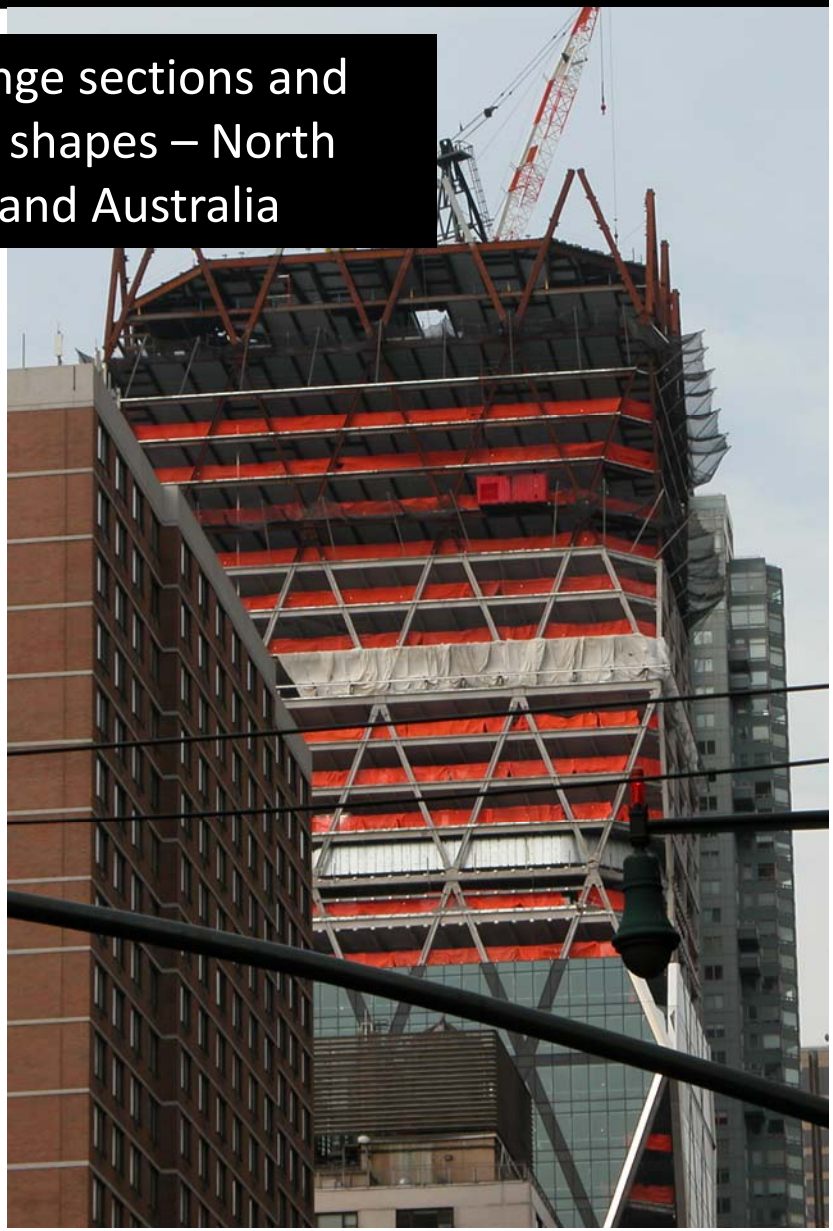


Shape choices for members



Concrete-filled steel tubes
Asia and Middle East

Wide flange sections and standard shapes – North America and Australia



Shape choices for members

Wide flange sections and bolting – worker safety

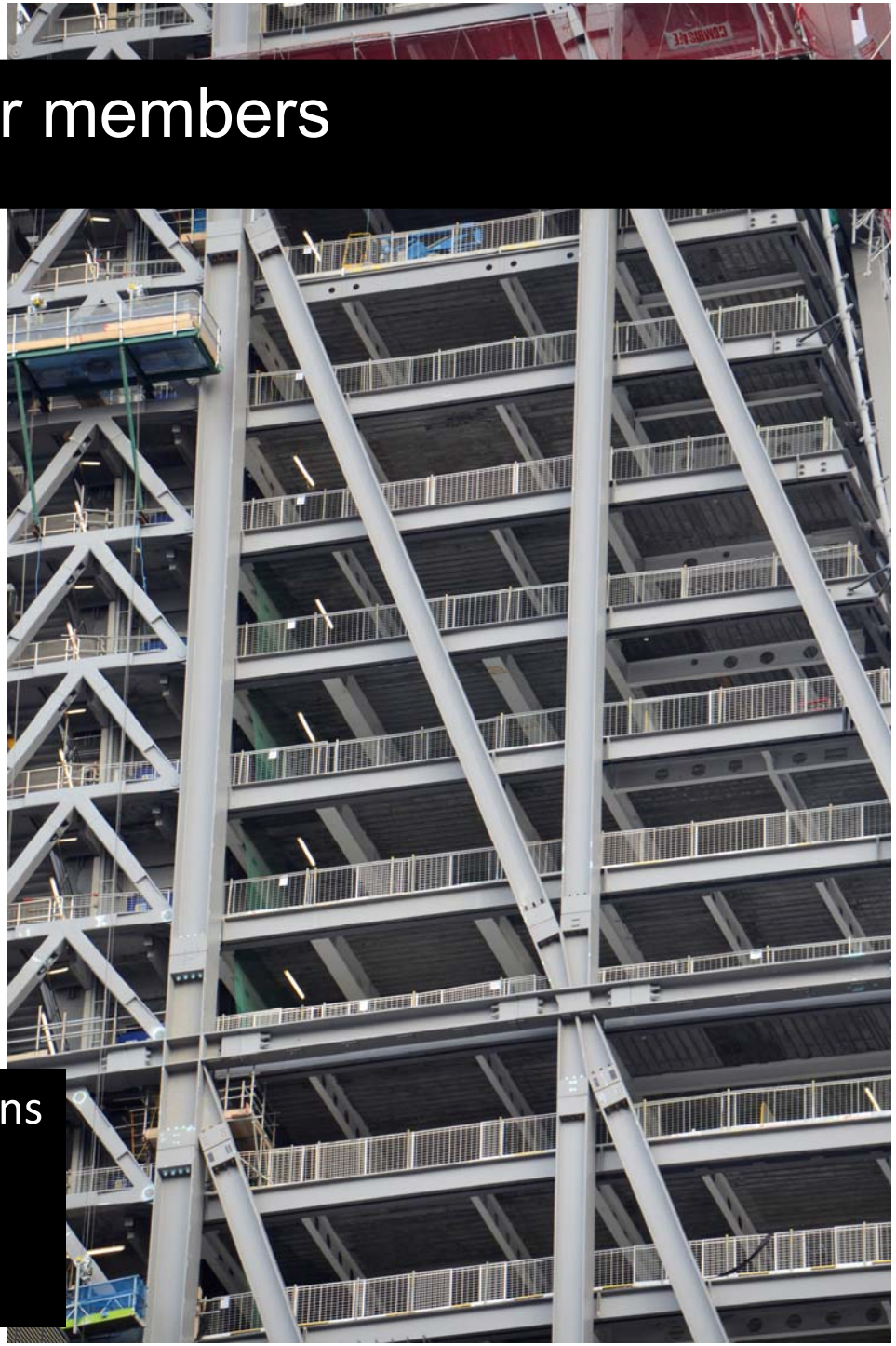


Image: Brookfield Multiplex Australasia

Completely custom sections fabricated from plate to attain sharp corners for exposure

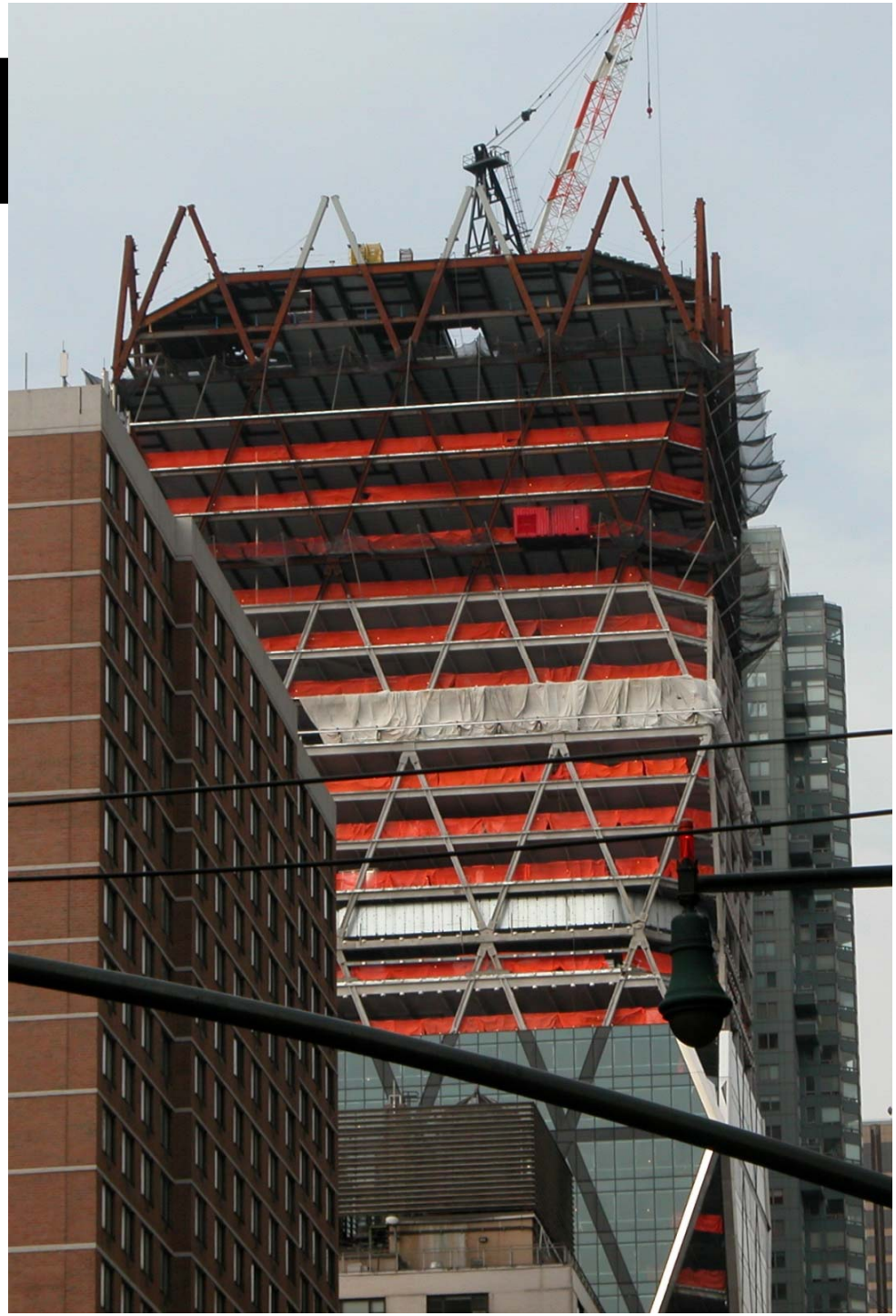
Node design criteria

- Concealed or AESS project?
- Shape of incoming members
- Site bolting or welding
- Independent element or integrated with member
- Usually fabricated in shop
- How many incoming members to accommodate?

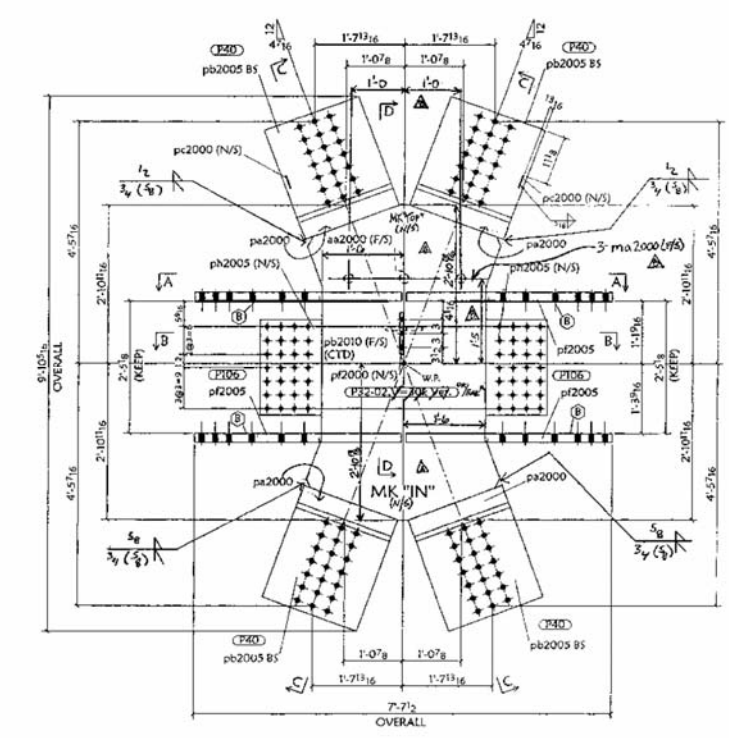
Node design

- Concealed steel
- Fixed node
- No shoring
- Shop fabricated
- Bolted on site

FOSTER+PARTNERS w/ WSP GROUP
HEARST TOWER 2006

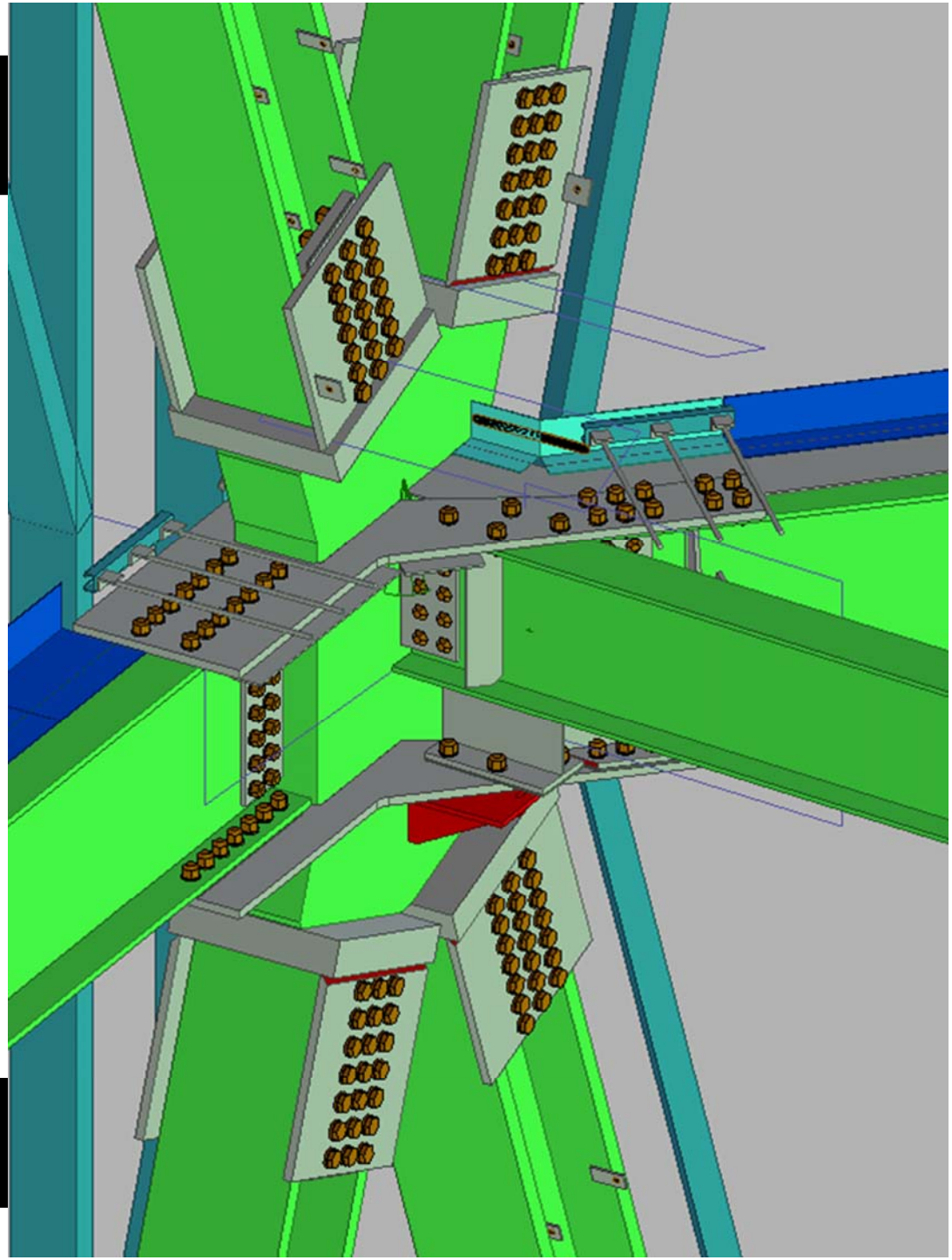


Node



Concealed steel but tight detailing to keep a slim profile for cladding.

Images: WSP Group



FOSTER+PARTNERS w/ WSP GROUP
HEARST TOWER 2006

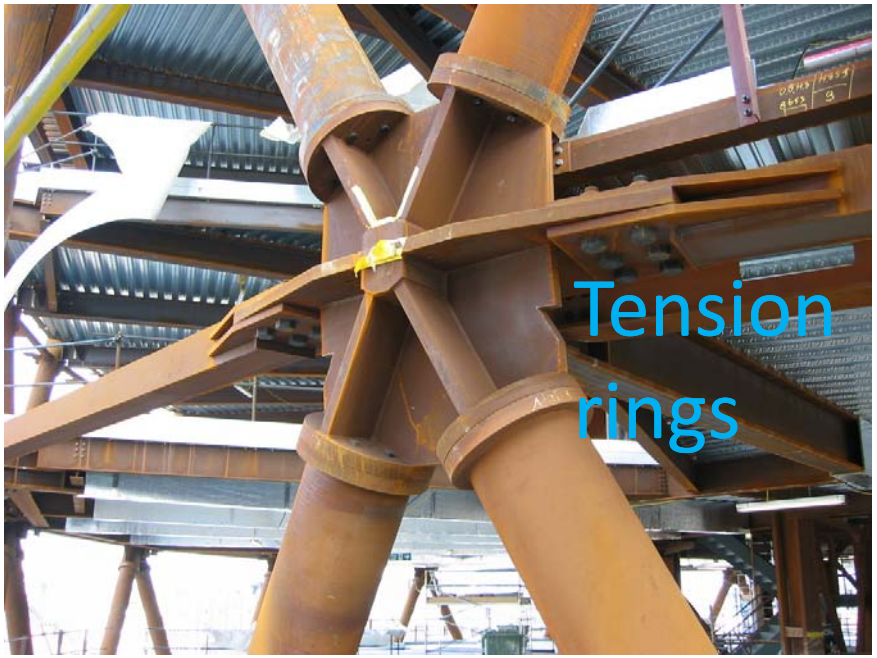
Node design

Images: ARUP

- AESS (intumescent coating)
- Concrete filled tubes
- No shoring
- Shop fabricated
- Welded on site (temp bolts)

WILKINSON + EYRE w/ARUP
GUANGZHOU IFC 2010

Node design



- Concealed
- Fixed node
- No shoring
- Shop fabricated
- Bolted on site

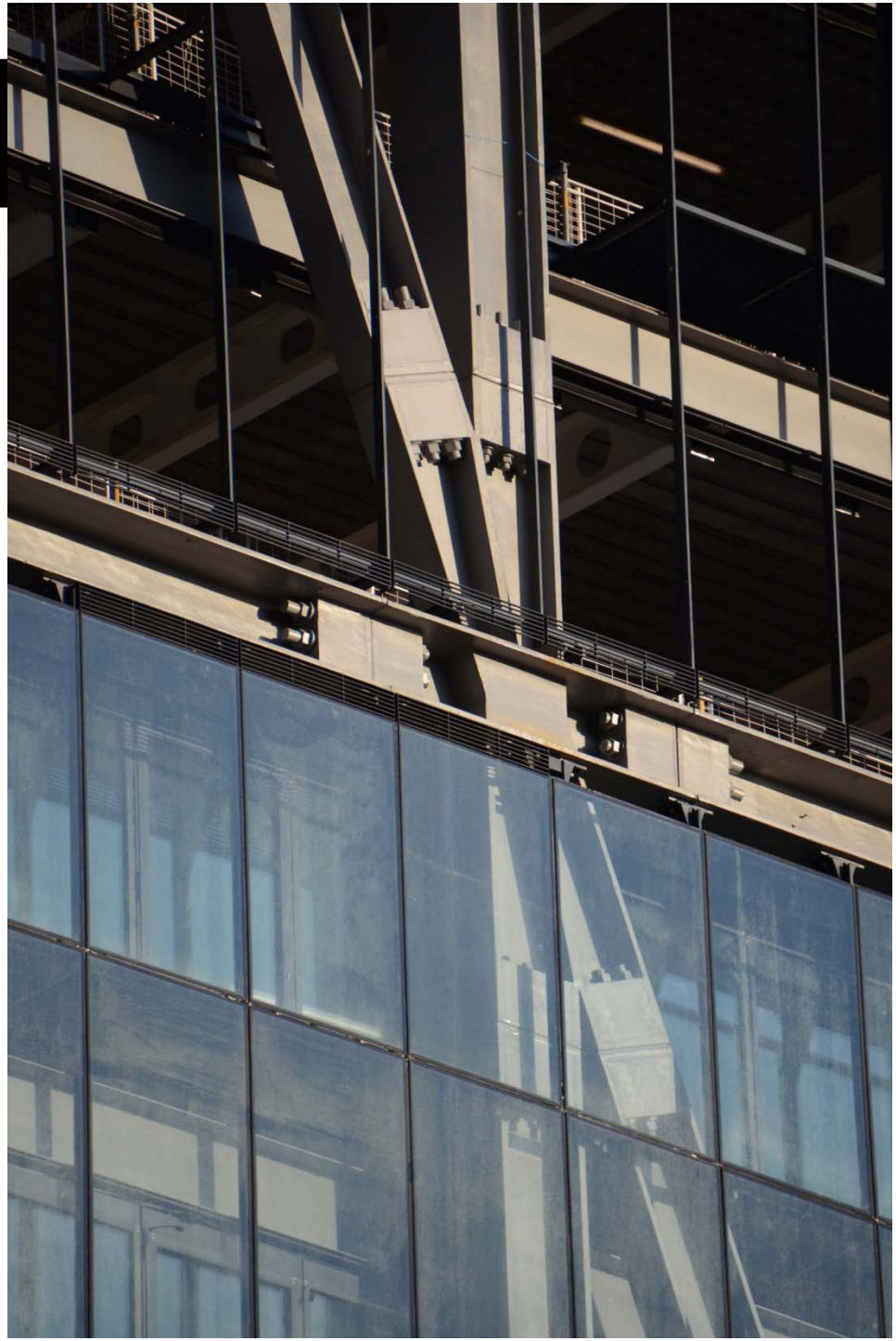
FOSTER+PARTNERS w/ARUP
SWISS RE 2004

Images: ARUP

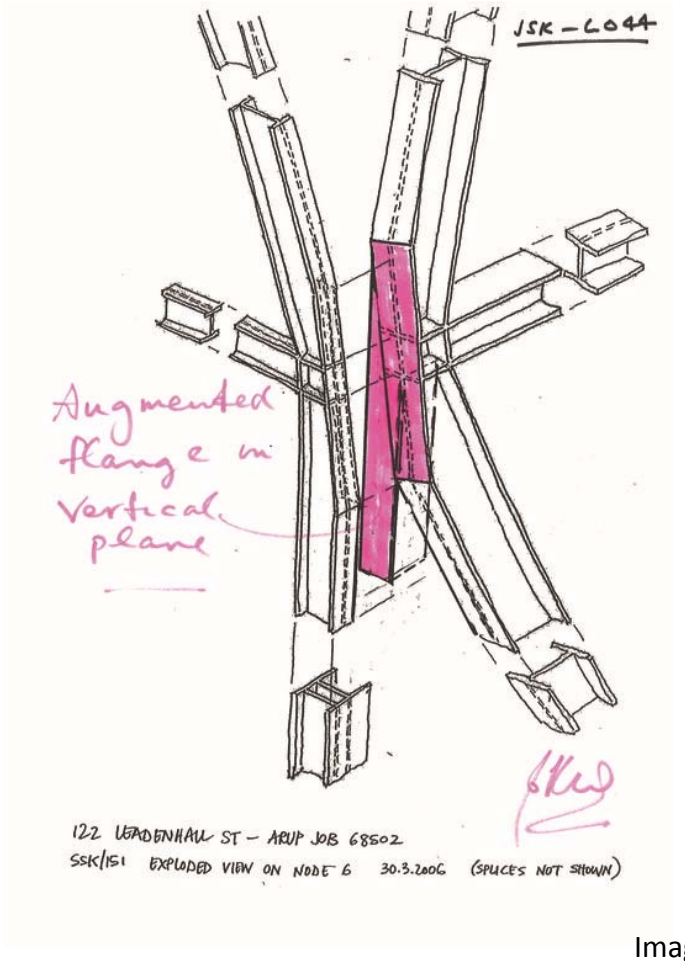
Node design

- AESS
- Tensioned connection
- Adjusted during construction to correct lean of building
- Node types vary per location
- Bolted on site

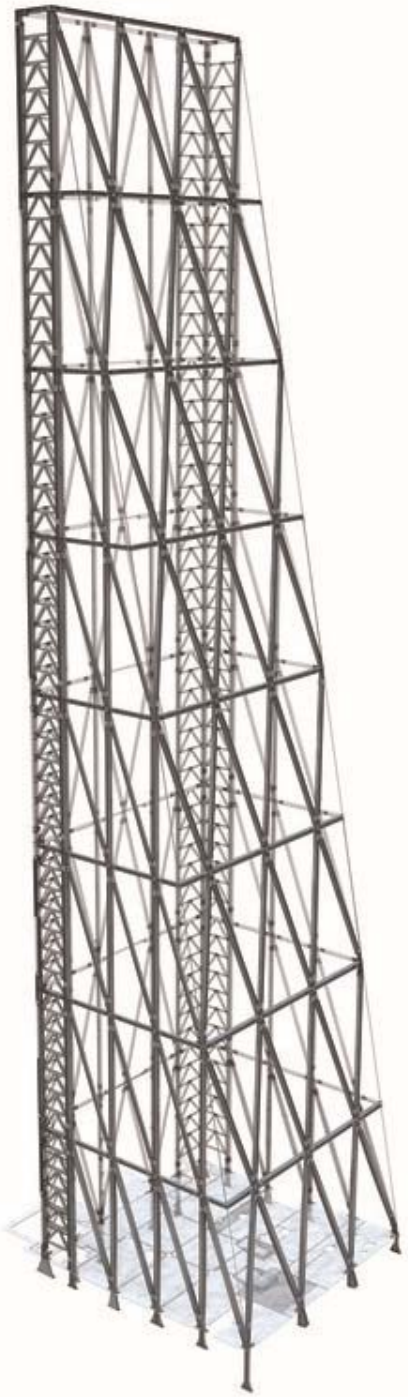
ROGERS STIRK HARBOUR+PARTNERS
w/ ARUP
LEADENHALL 2013



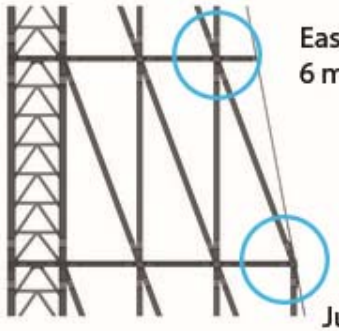
Node design



Images: Arup

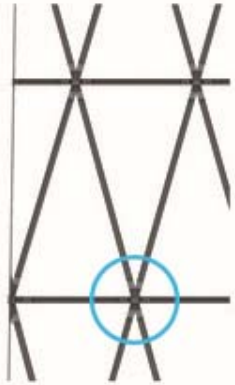


North face node
8 members



East/west nodes
6 members

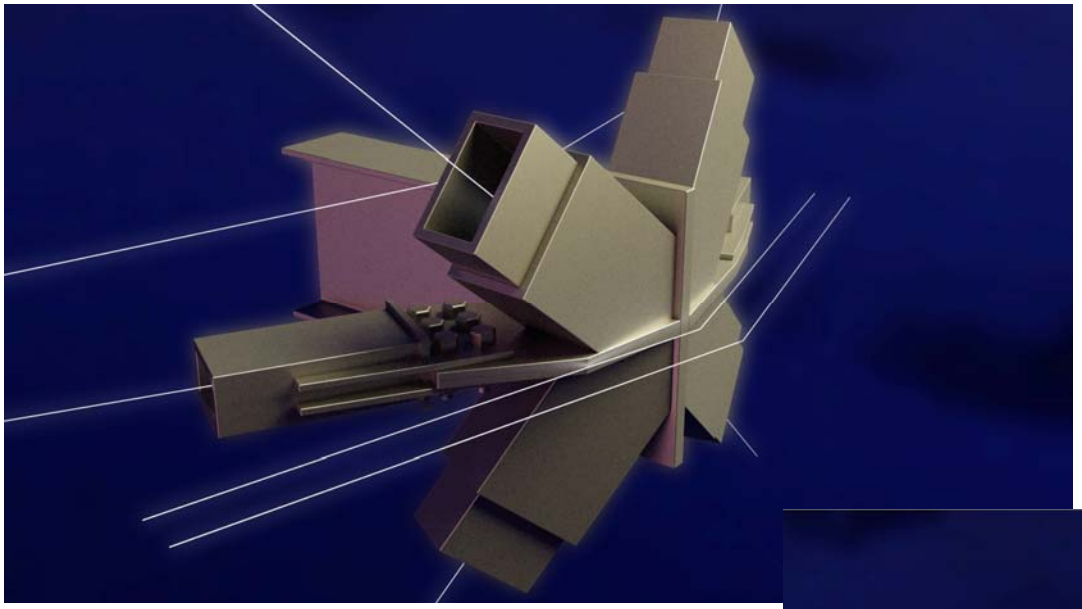
Junction node
most difficult
geometry

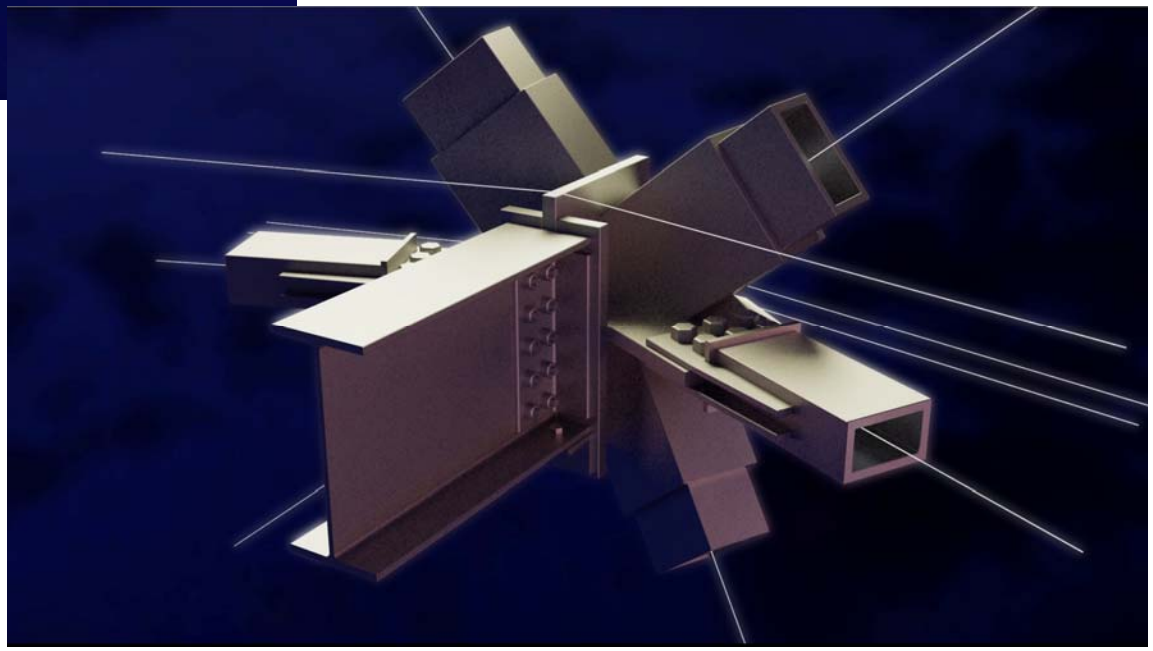


South face node
6 members

ROGERS STIRK
HARBOUR+PARTNERS w/ ARUP
LEADENHALL 2013

Node design – renderings and actual





Images: Jeff Schofield

Node attached to member

Image: ArcelorMittal

C. BALMOND w/ ARUP
ORBIT TOWER 2012

The node and member may be erected as a unit for reasons of constructability.

Image: Arup

IBA ARCHITECTS w/ ARUP
CANTON TOWER 2010

Core Design

- A true/simple diagrid tower does not NEED a core for structural stability
- Diagrid structure can have all of the gravity and lateral loads assumed by the perimeter framing
- Lower rise towers can choose not to have a “structural core”
- Skyscrapers will need a “structural core” to assist the perimeter diagrid
- Choice between steel and concrete

Core design

Steel core types:

- Centered core
- Offset core
- Core outside of building

Concrete core types:

- Centered core
- Narrow plan
- Highly eccentric loading
- Supertall towers

Other issues:

- Regional preferences for materials
- Seismic performance
- Excessive wind loads

Centered steel core

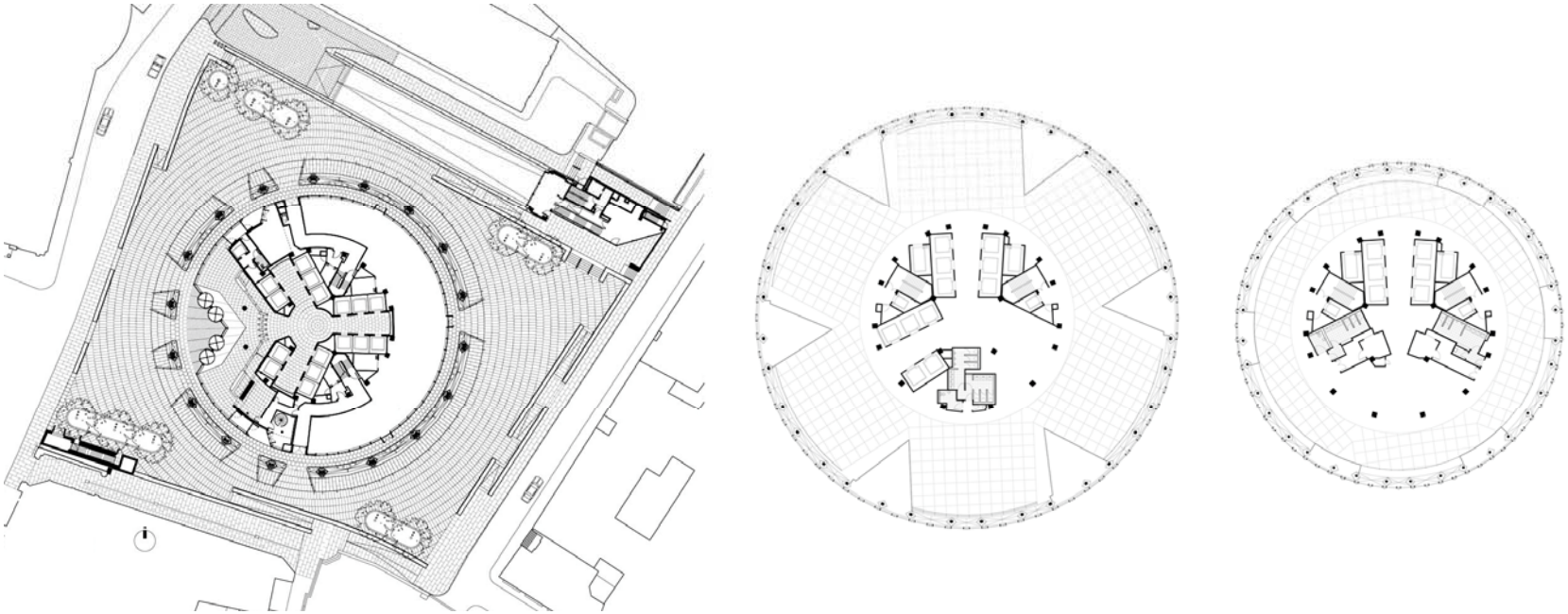


Image: Foster + Partners

- Swiss Re the most “pure” diagrid tower as core is NOT used for lateral stability
- Plan allowed to open up towards the top due to steel only taking gravity loads
- No seismic issues

Offset steel core

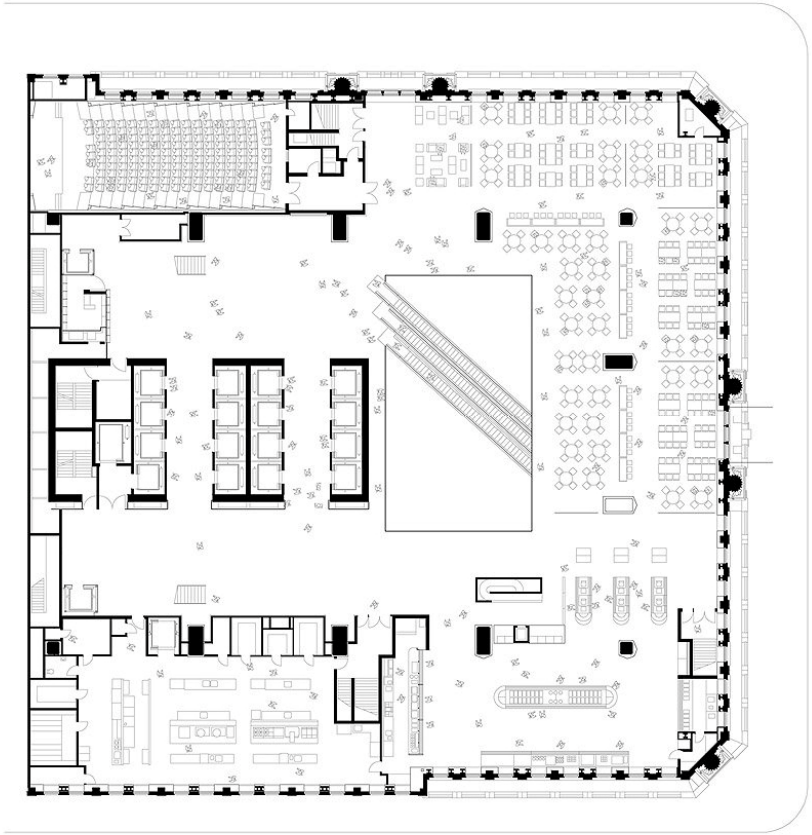


Image: Foster + Partners

- Core offset due to preferred exposure on 3 sides
- Added some steel bracing but diagrid doing most of the structural work
- NYC is in a seismic zone, so additional stability issues

External core

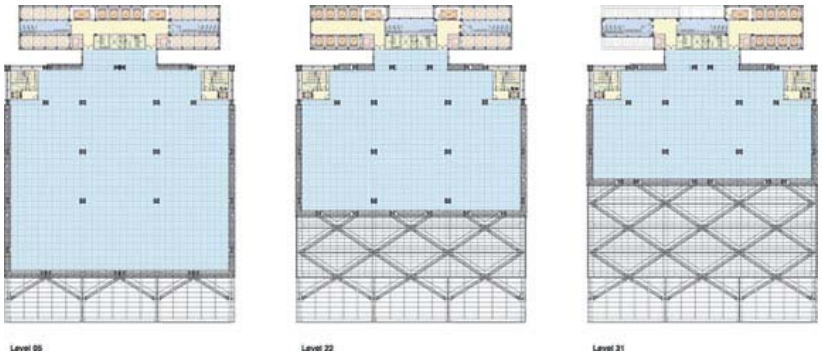
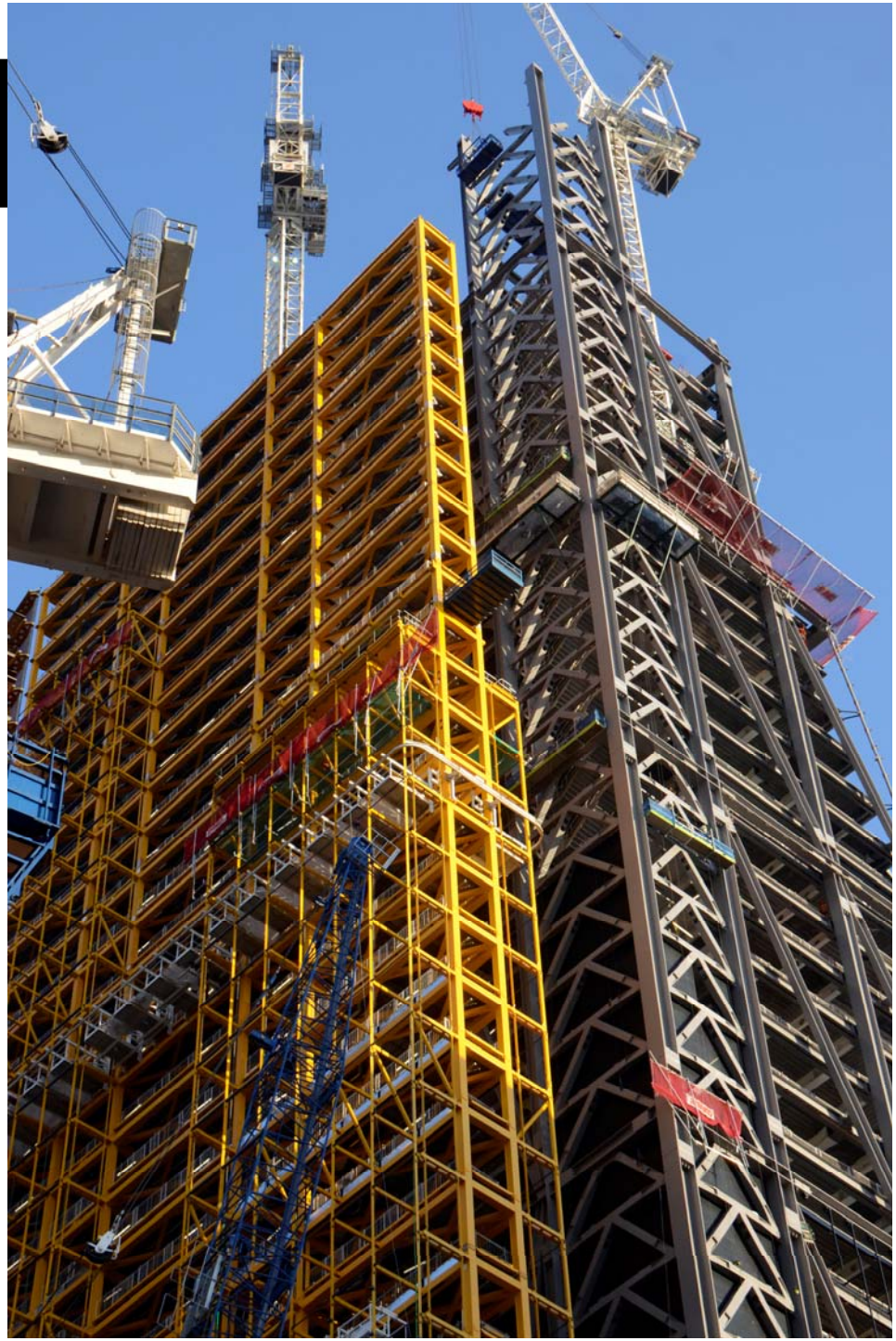


Image: Rogers Stirk Harbour + Partners

- Strength of diagrid/megaframe allows for core to be external
- Core houses elevators and W/C
- Provides no lateral stability
- K bracing at rear bay adds stability to the megaframe

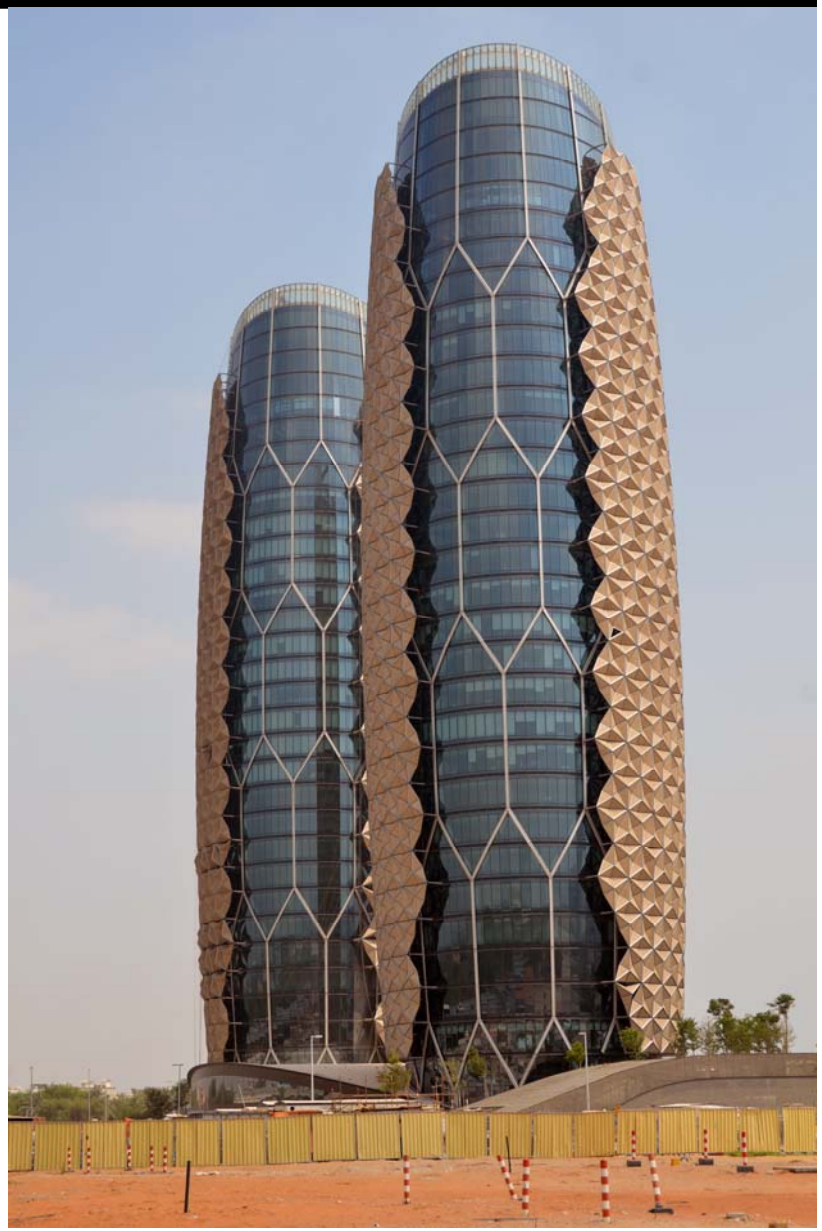


Centered concrete core

Image: William Hare

AEDAS w/ ARUP

AL BAHAR TOWERS 2012



Concrete core for a narrow plan

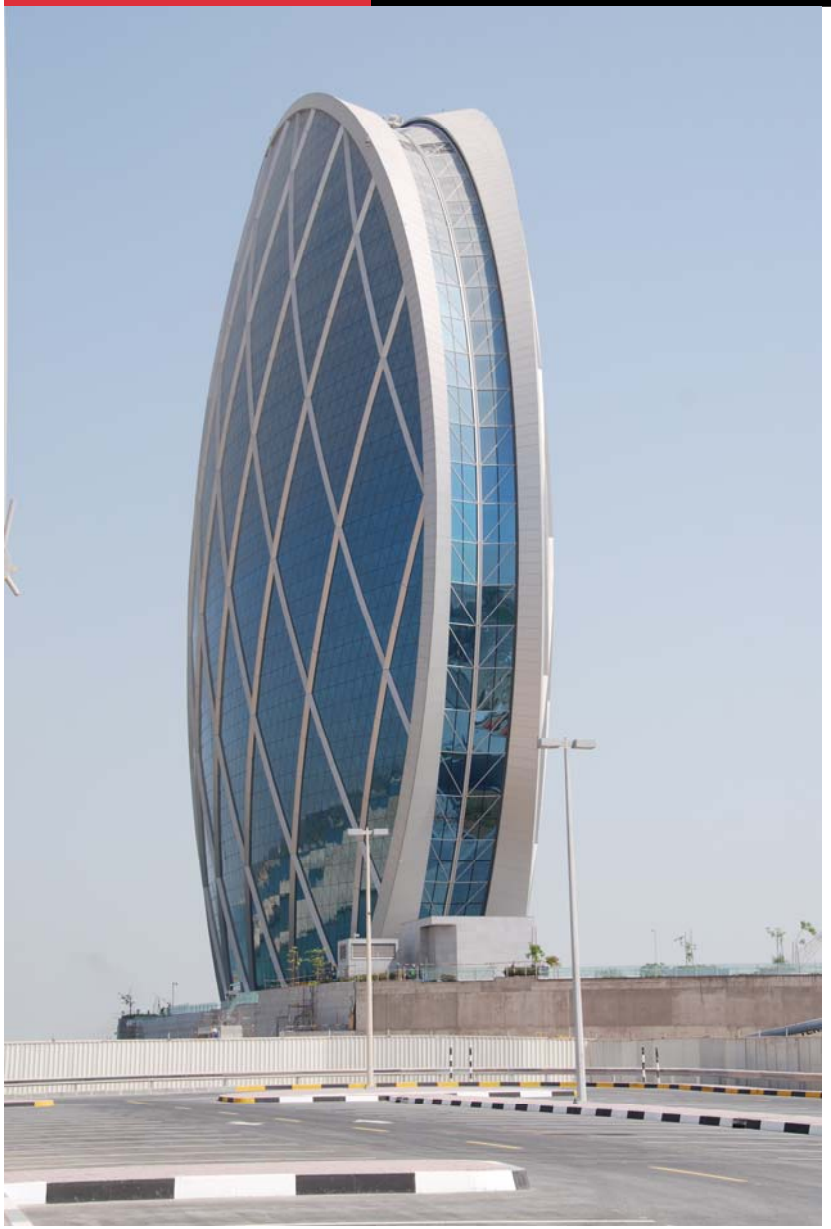
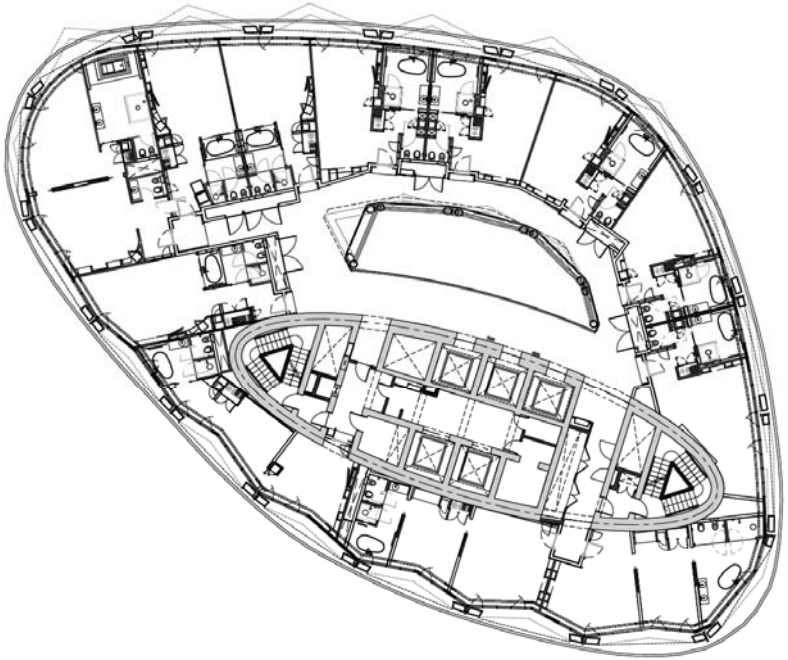


Image: William Hare

Concrete core for eccentric load



- 18^{o} lean
- Core pre-cambered 350mm off vertical to compensate
- Core pretensioned on one side to balance load

Images: Jeff Schofield

Concrete core for a Supertall tower

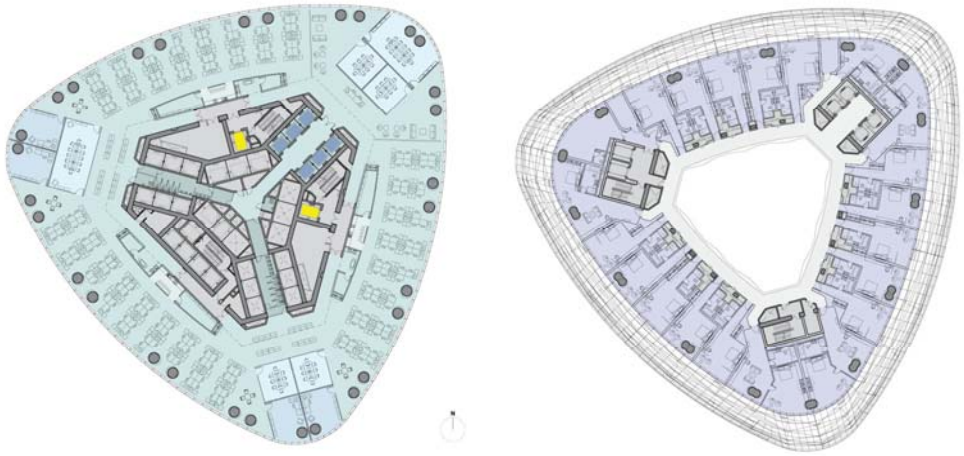
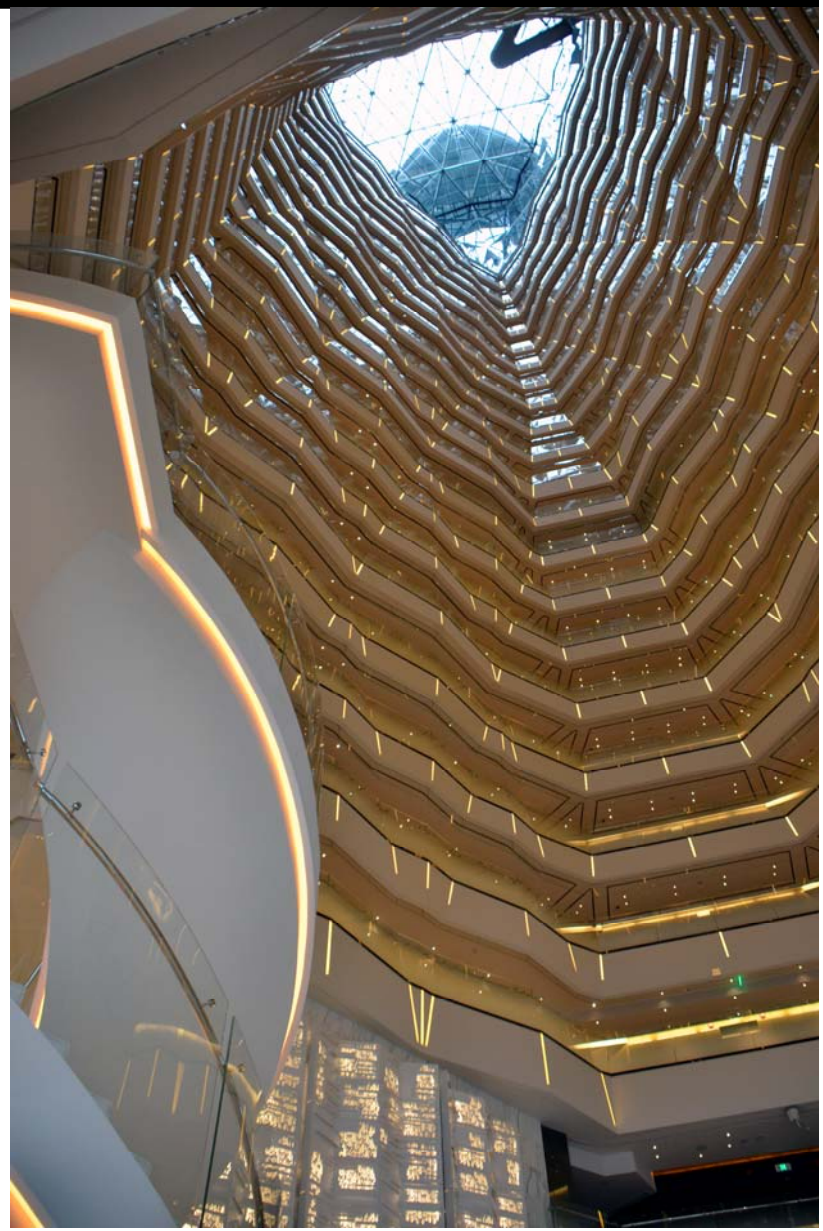


Image: Wilkinson Eyre Architects

- Core required at bottom 2/3 of tower
- Core split from floors 69 – 103 to allow for atrium at center
- Diagrid allows for “something special” to happen at top of tower
- Suits new tendency to mix hotel and office occupancies



Constructability

GENERAL ISSUES:

- Eliminate shoring
- Quick (bolted) site connections
- Staging area
- Highly skilled labour

LIBESKIND w/
ARUP CANADA/HALSALL
ROM CRYSTAL 2006
Toronto, Canada

ROM SPECIFIC ISSUES:

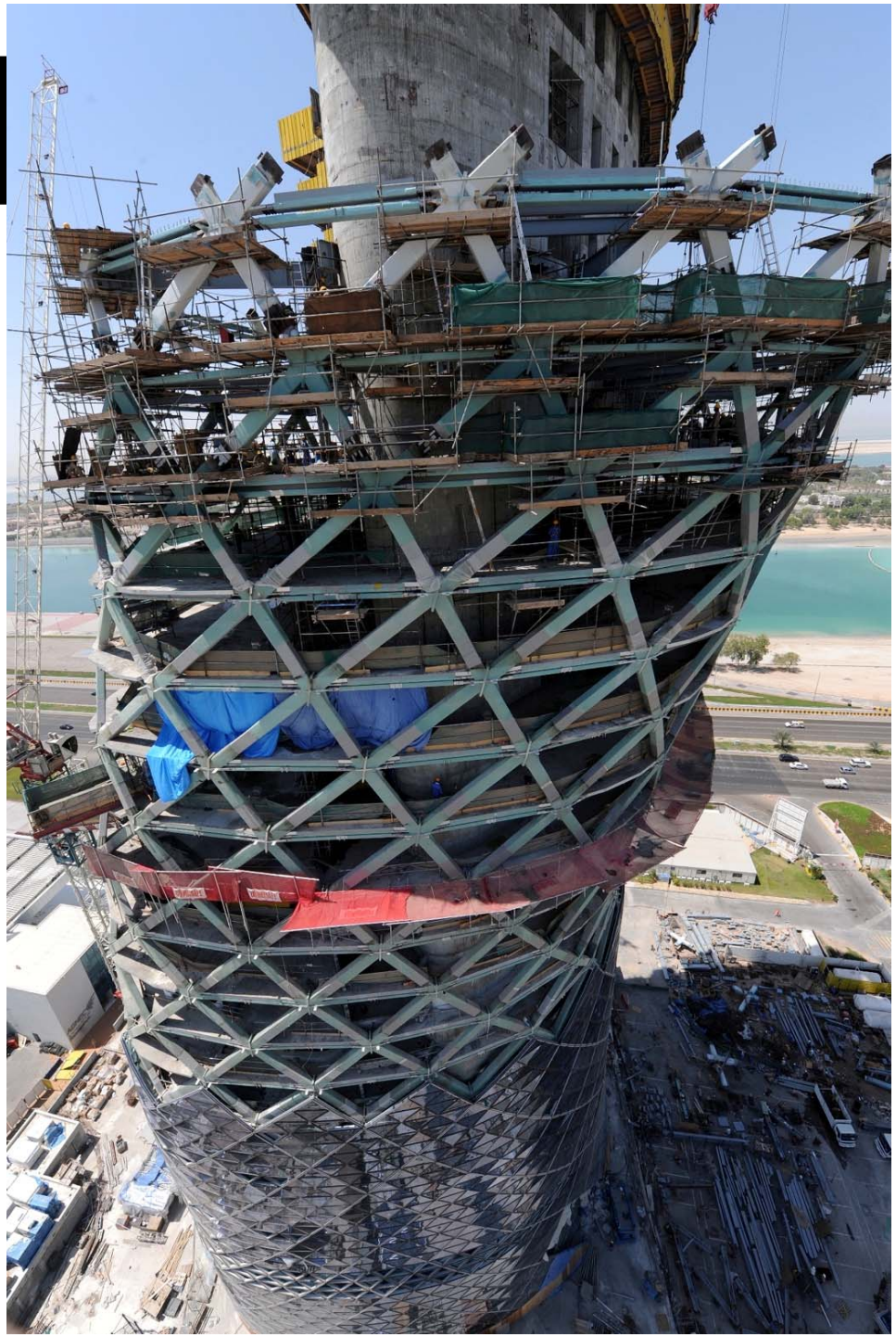
- Geometrical challenges due to lack of uniformity
- Gravity working against erection (eccentric pieces)
- Abundance of unique situations

Constructability

ISSUES:

- eccentric geometry
- no two nodes alike (822 unique)
- all welded – welding access
- tensioned core to offset lean

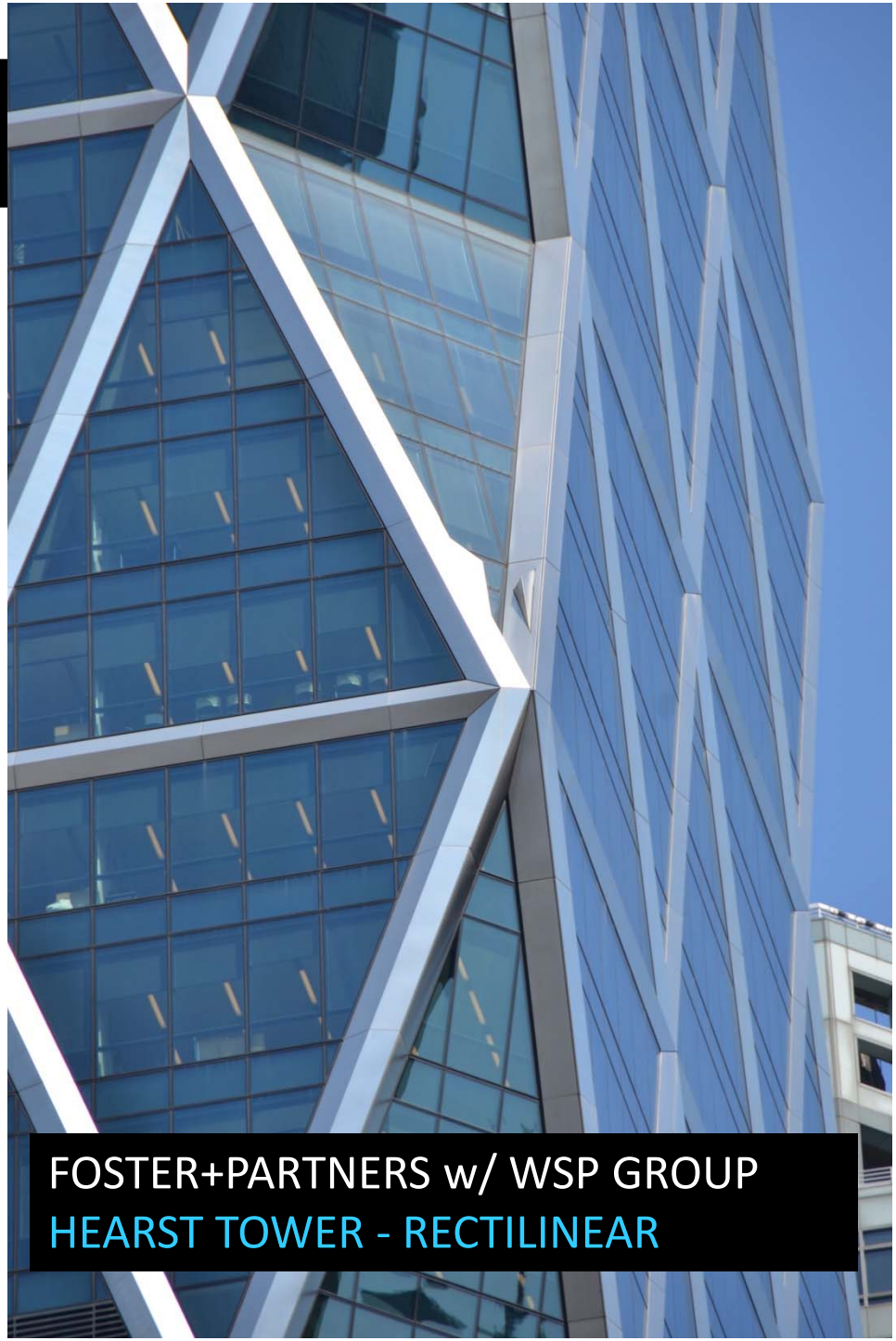
RMJM ARCHITECTS
CAPITAL GATE 2011
Abu Dhabi, UAE



Constructability

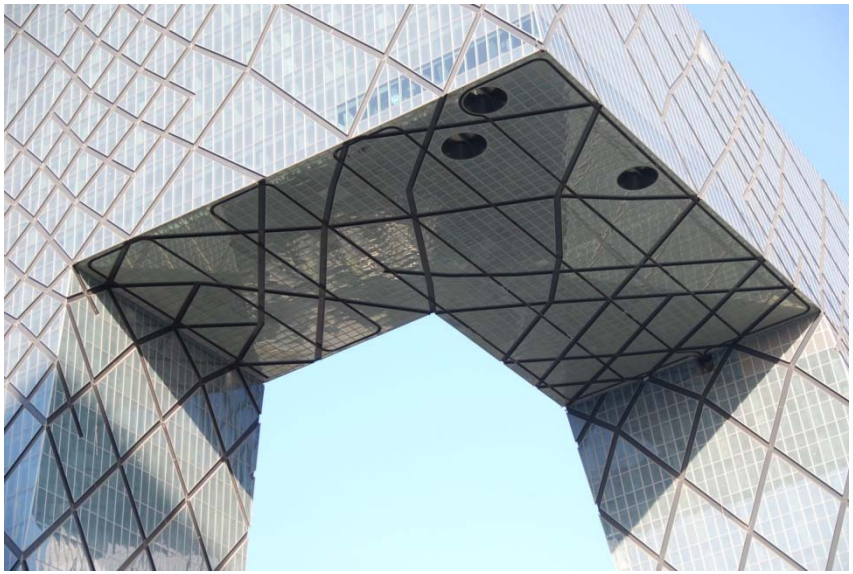
Façade design

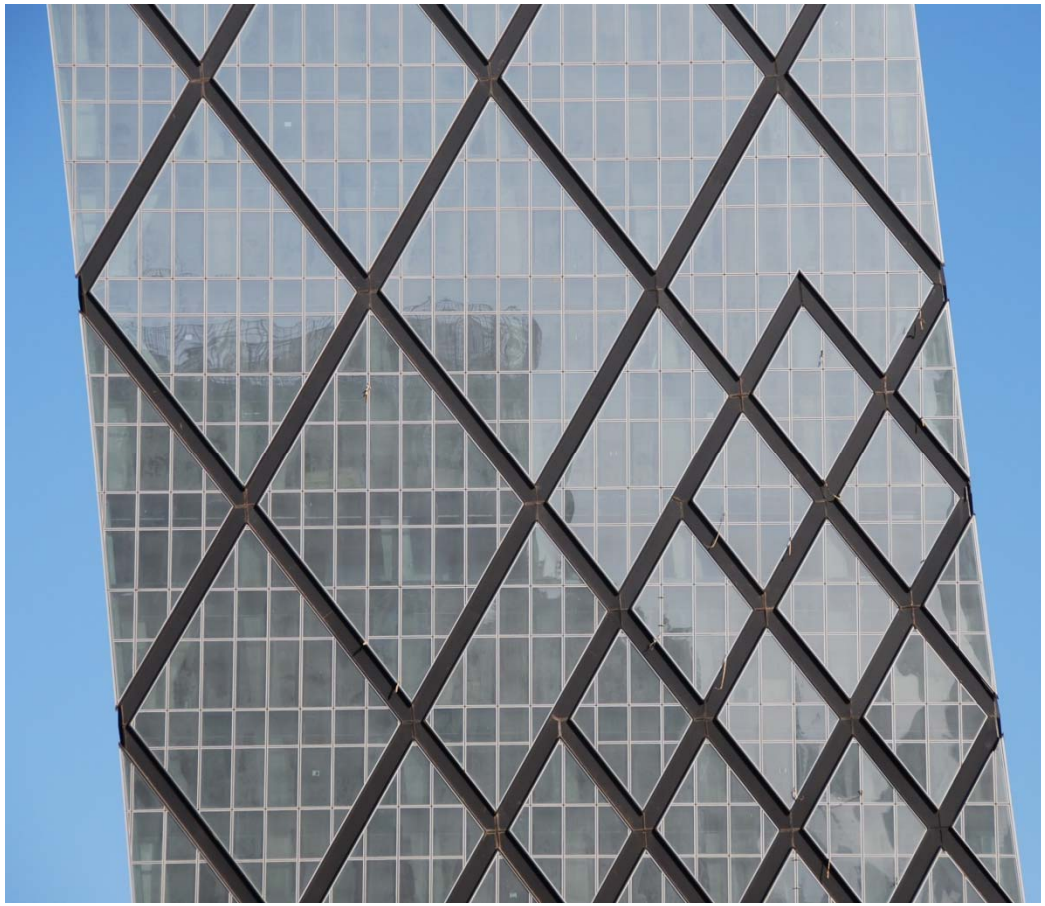
- Geometry of building
- Expression of diagrid?
  - diagrid emphasized in curtain wall design
  - curtain wall in front of structure
- Use of space
  - open floor area behind
  - partitions abutting glazing
- Budget for curtain wall
  - size of units
  - type of glass (# of panes)
  - double façade
- Shading strategies
- Operable units?
- Rectilinear vs. triangulated



FOSTER+PARTNERS w/ WSP GROUP
HEARST TOWER - RECTILINEAR

Façade design



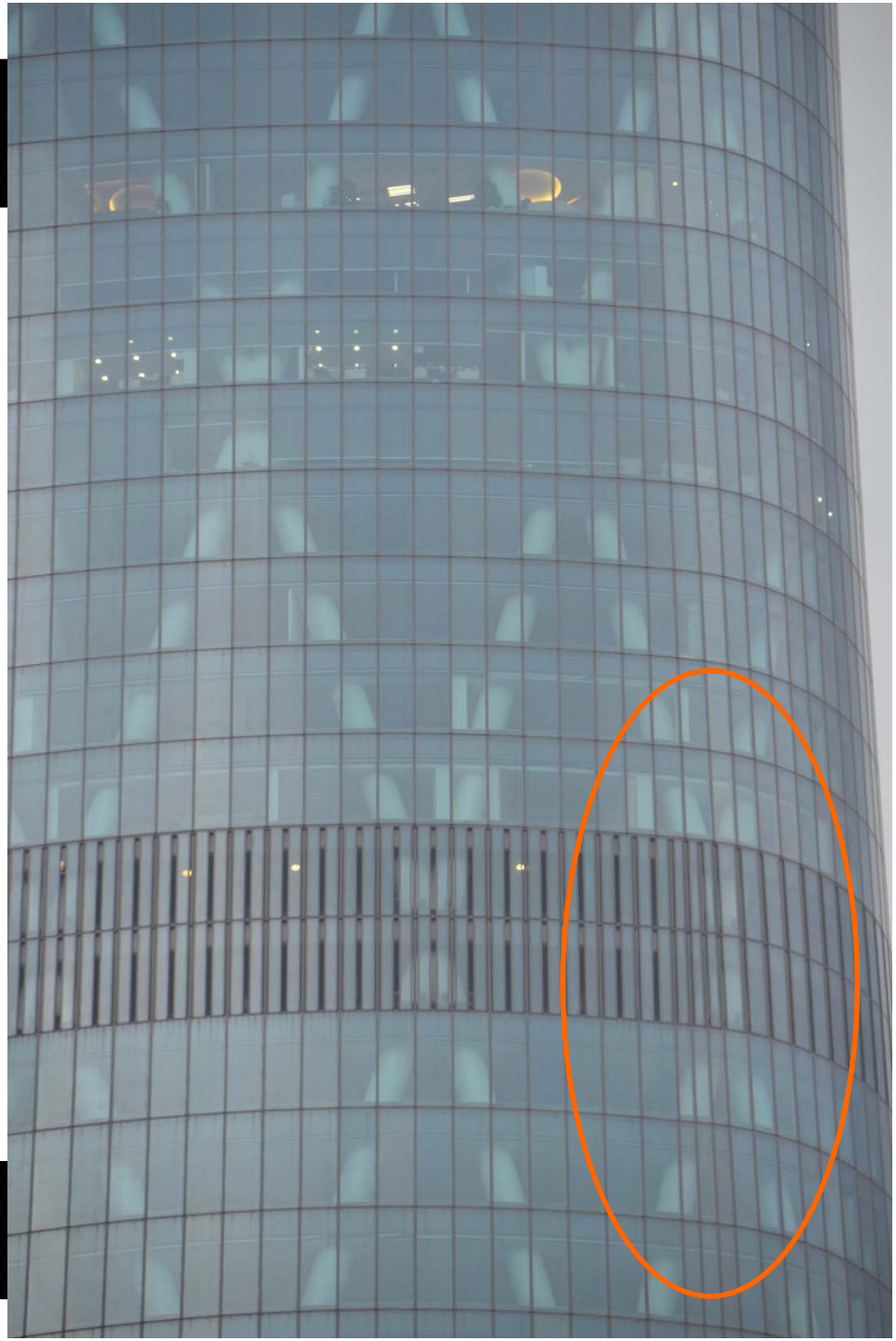


- Diagrid expressed showing its true irregularity for reinforcement
- Tilted but square geometry
- Curtain wall wraps large soffit

OMA w/ARUP
CCTV 2012, Beijing, China
RECTILINEAR

Façade design

- Diagrid expressed behind continuous curtain wall
- Extra clear glazing chosen to allow AESS diagrid to show behind the glass
- Tapered building and triangulated plan required customization of glazing size at the ‘corners’
- Majority of glazing units are uniform in size and go ‘floor to floor’
- Expression of fire refuge floors



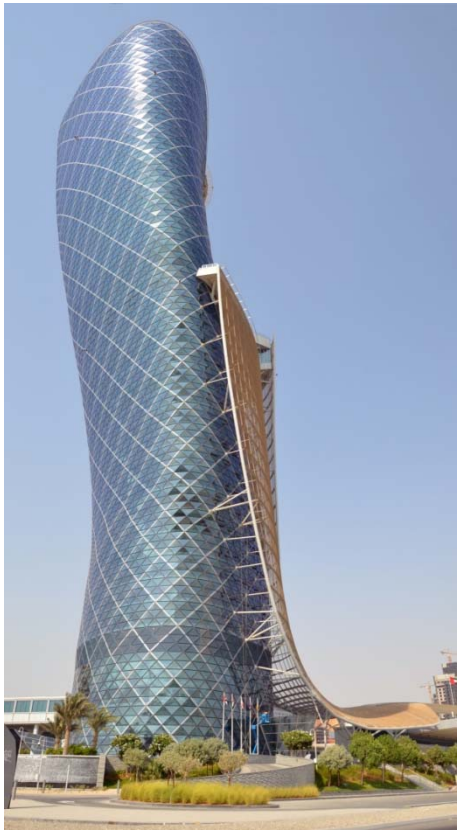
WILKINSON + EYRE w/ARUP
GUANGZHOU IFC 2010 - RECTILINEAR

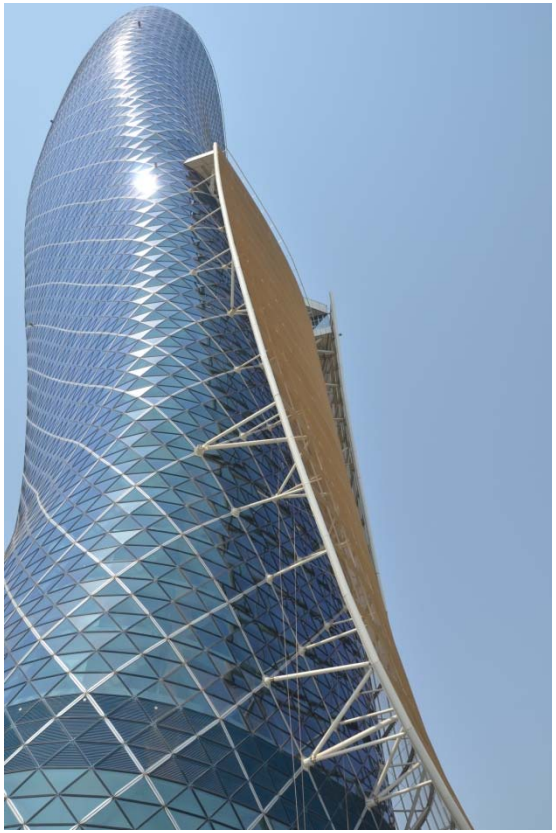
Façade design

- Curved shape
- Major expression of diagrid
- Non-rectilinear geometries
- Unique end condition

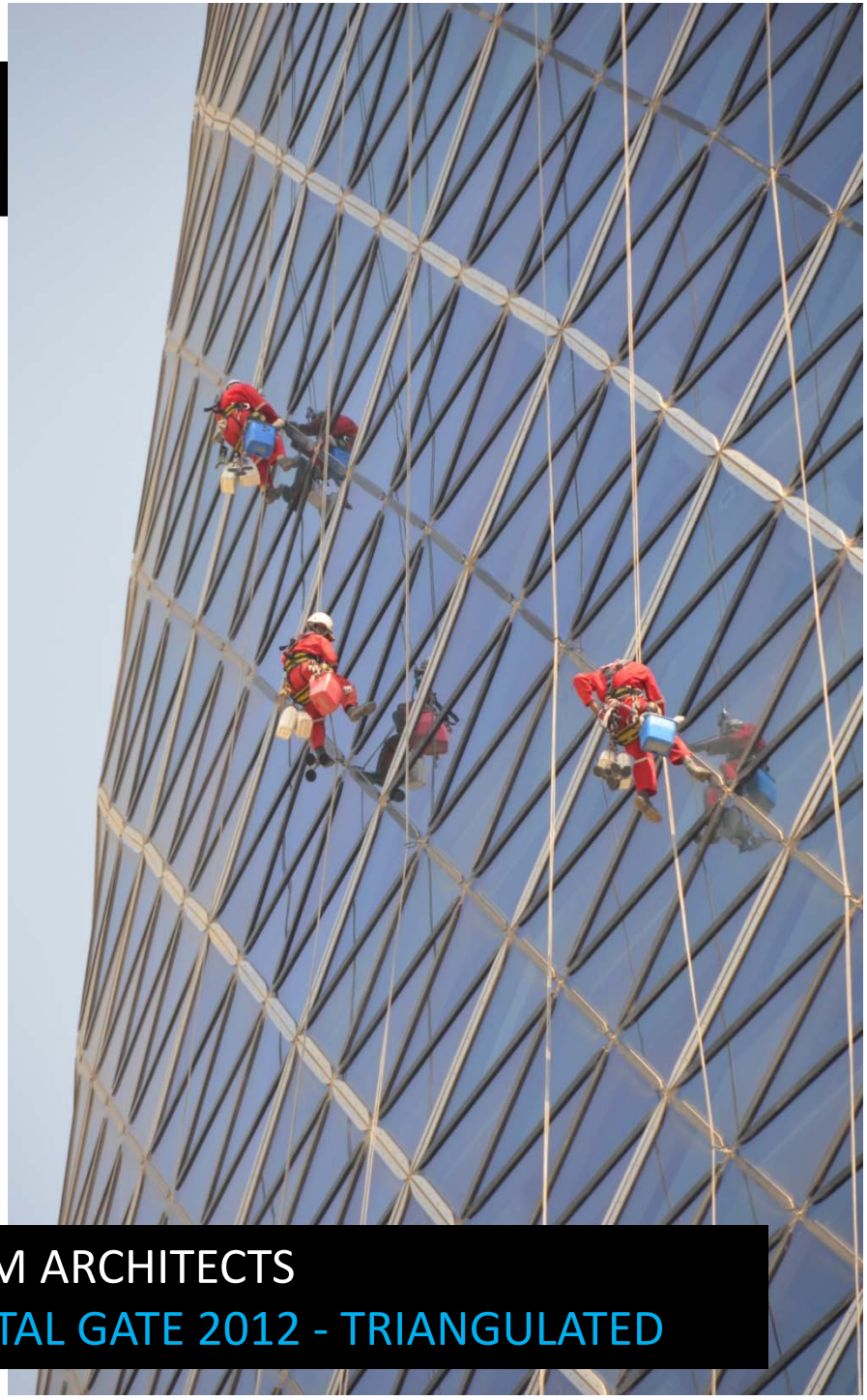
MZ ARCHITECTS w/ARUP
ALDAR HQ 2012 - TRIANGULATED

Façade cleaning





- 18^{o} backwards lean
- Some external sun shading
- Triangulated glazing to fit form
- Abseiling as the method of cleaning

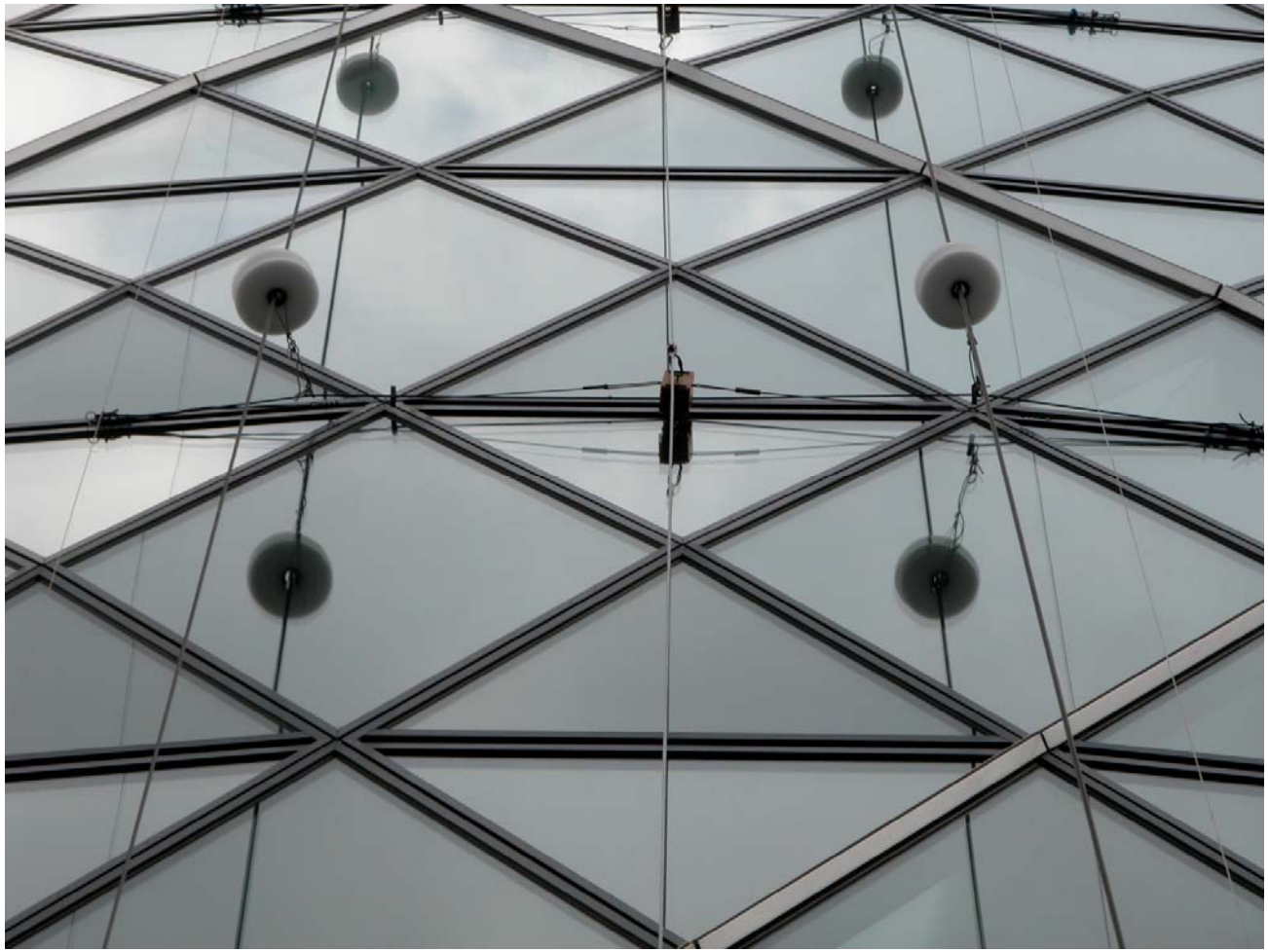


RMJM ARCHITECTS

CAPITAL GATE 2012 - TRIANGULATED

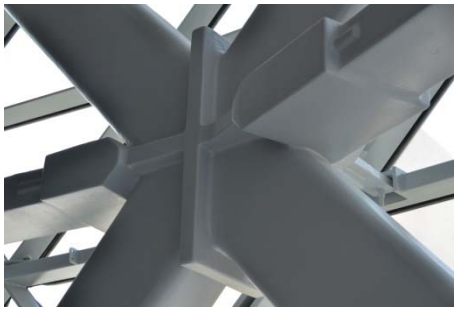
Façade cleaning

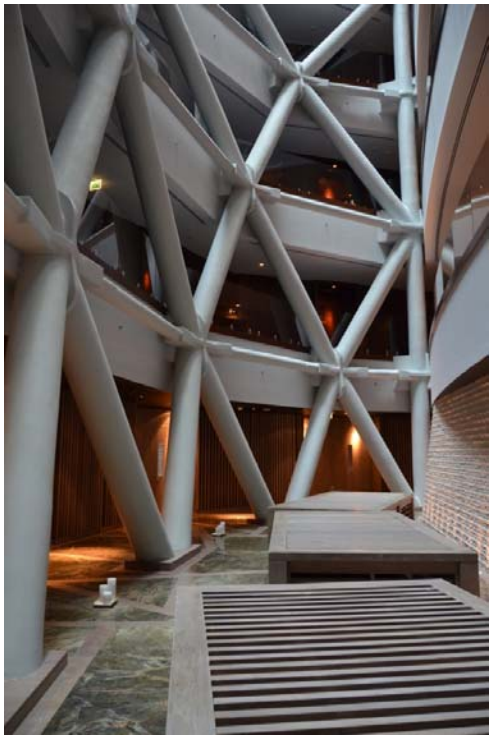
- Curved shape
- Triangulated glazing means no vertical track for equipment
- Need to prevent cables from hitting the façade

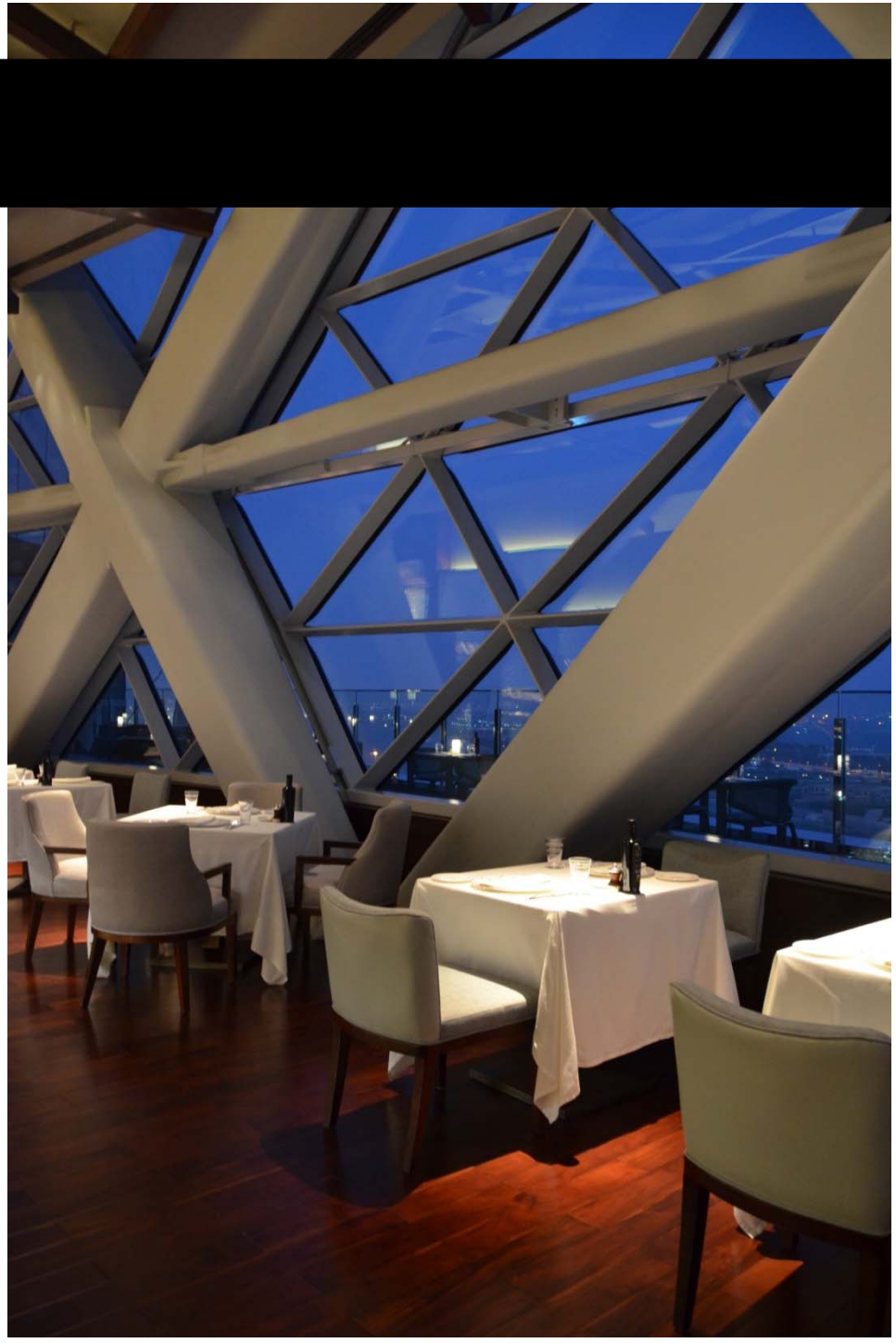


FOSTER+PARTNERS w/ARUP
SWISS RE 2004

Exposure



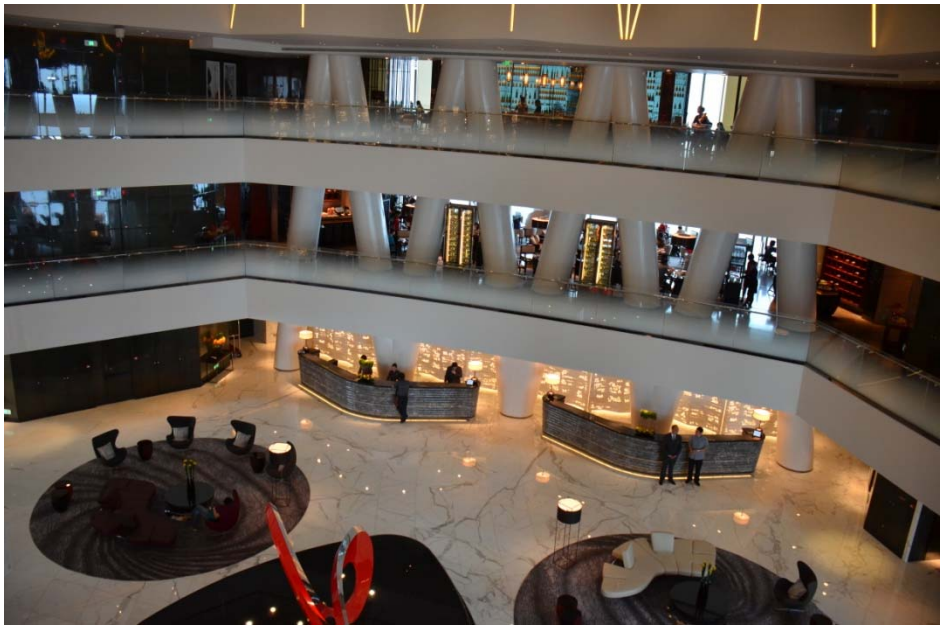


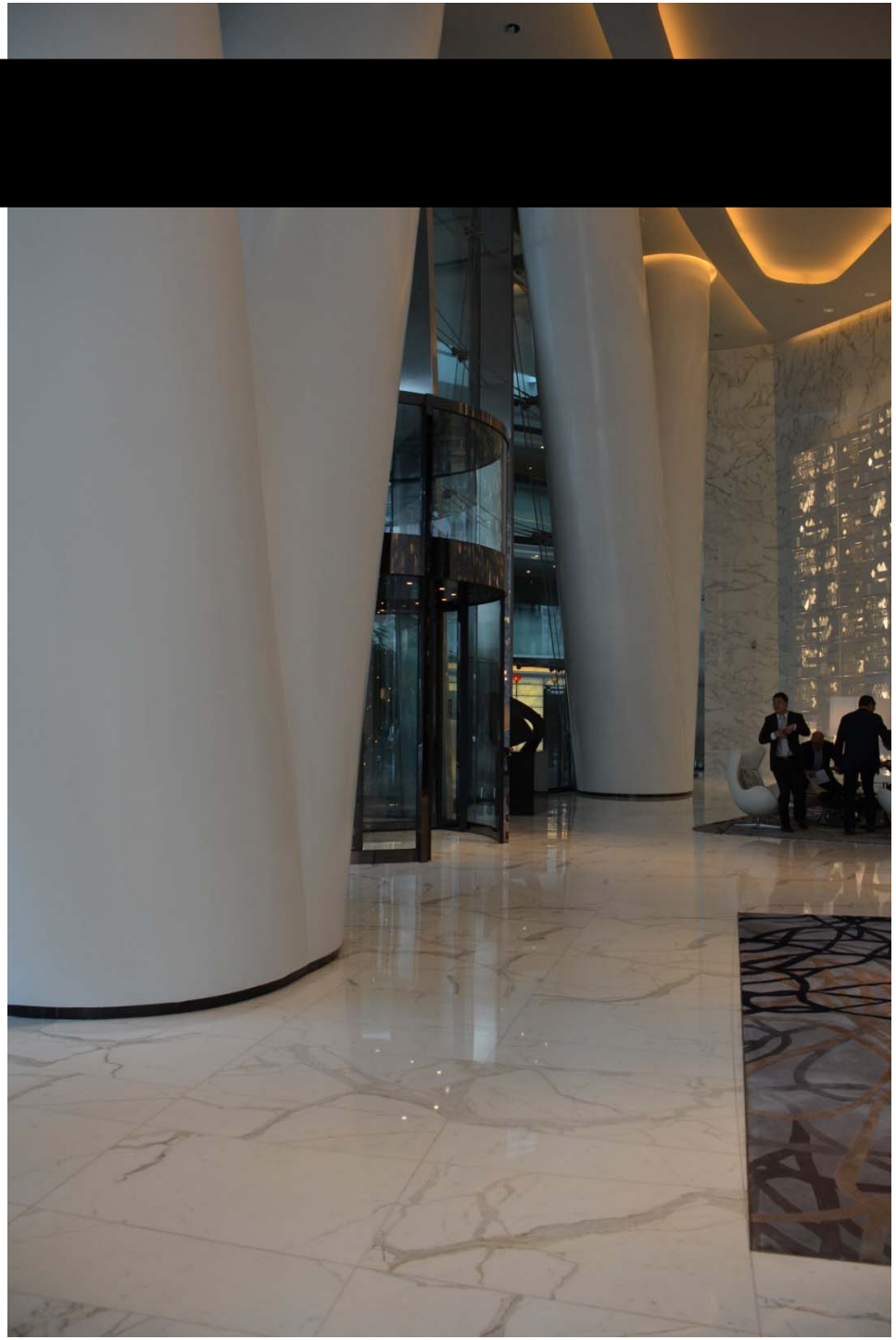


- Fire engineering a must (codes)
- Member selection criteria
- Function of space/aesthetic
- Impact of scale of members/nodes

RMJM ARCHITECTS
CAPITAL GATE 2012

Exposure

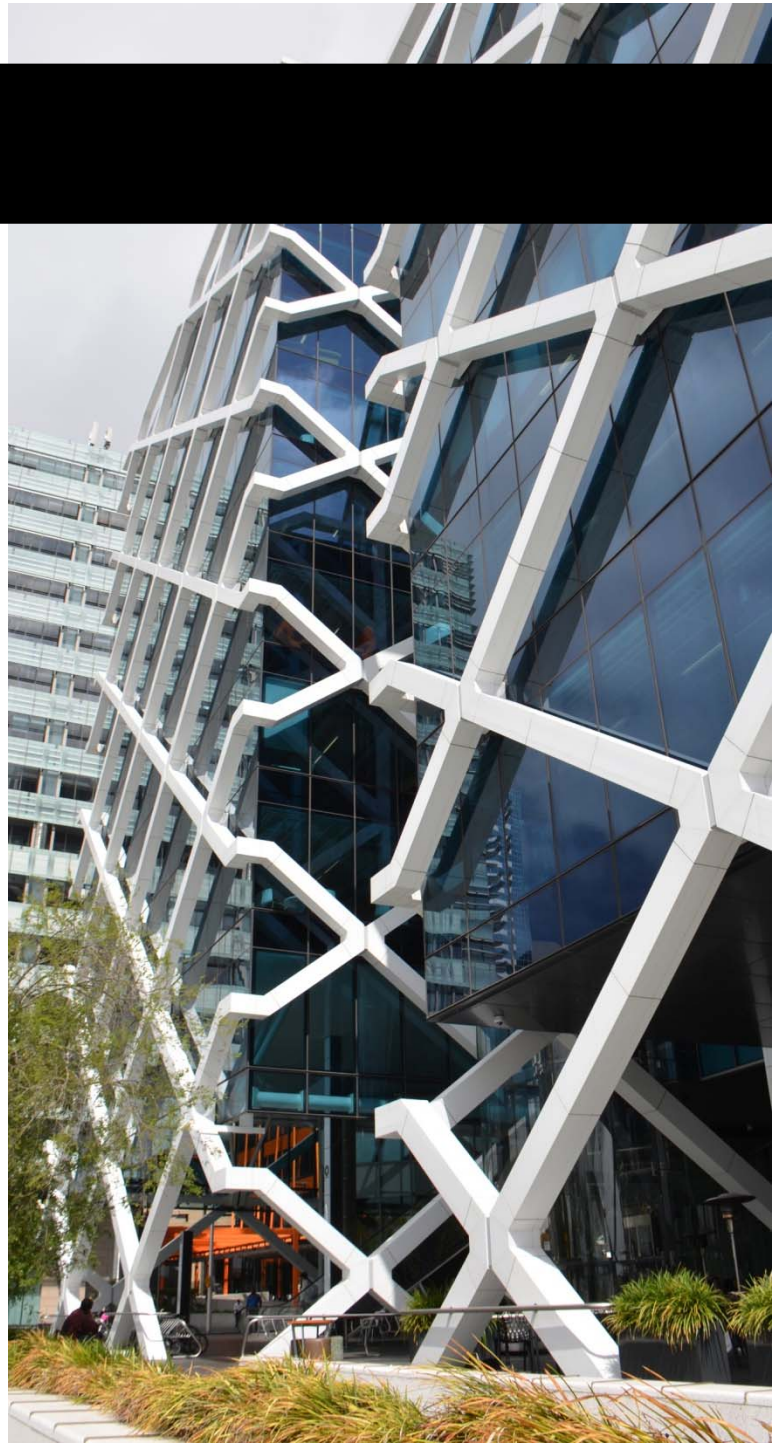




- Fire engineering a must (codes)
- Concrete-filled steel tubes + Intumescent
- Function of space/aesthetic
- Impact of scale of members/nodes

WILKINSON + EYRE w/ARUP
GUANGZHOU IFC 2010

Exterior structural



- Climate restricted (hot or temperate)
- Thermal bridging issues
- Corrosion protection

FITZPATRICK+PARTNERS w/ARUP
MCQUARIE BANK 2011
Sydney, Australia

Exterior structural

- Hot dip galvanized exterior structure
- standard structural steel interior
- bolted site connections

FITZPATRICK+PARTNERS w/ARUP
MCQUARIE BANK 2011
Sydney, Australia

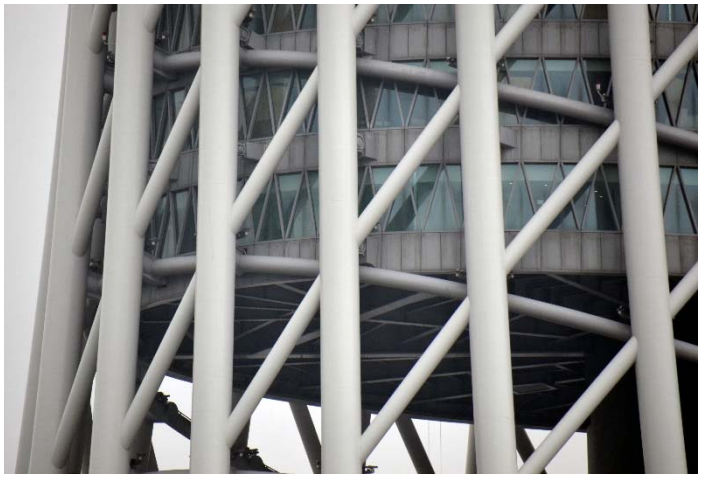
Exterior structural

- Climate restricted
- Thermal bridging
- Corrosion protection

WARREN + MAHONEY ARCHITECTS
w/MJH ENGINEERING
Manukau Institute of Technology
Auckland, New Zealand

- Module 5 storeys
- Middle node at mid floor height
- Use of steel cable to tie mid height nodes together

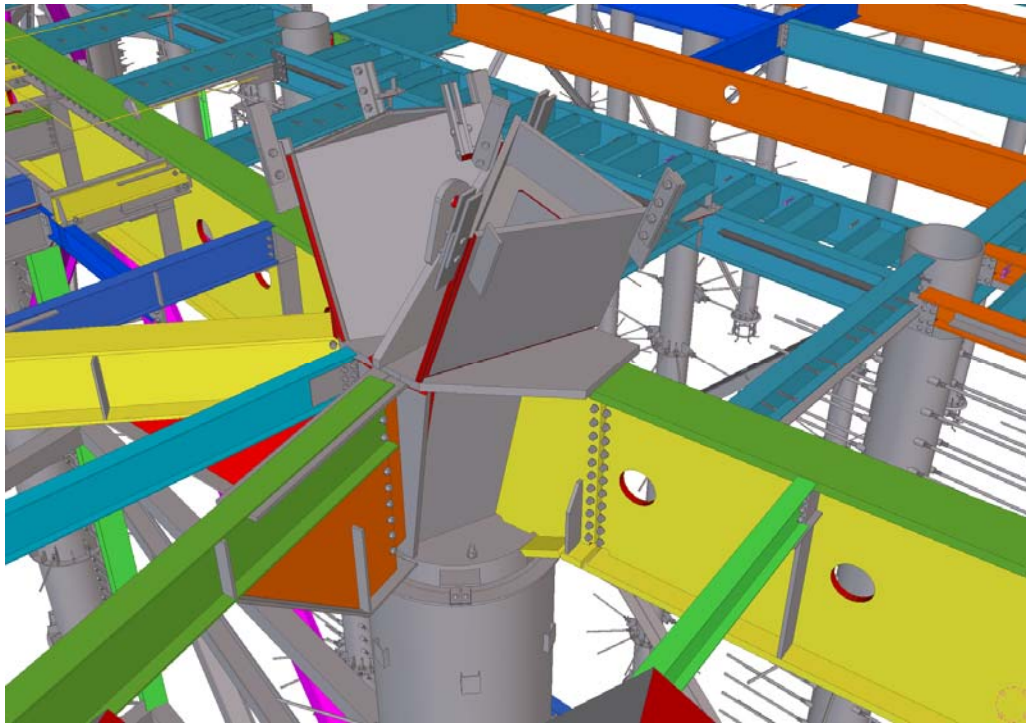
Exterior structural

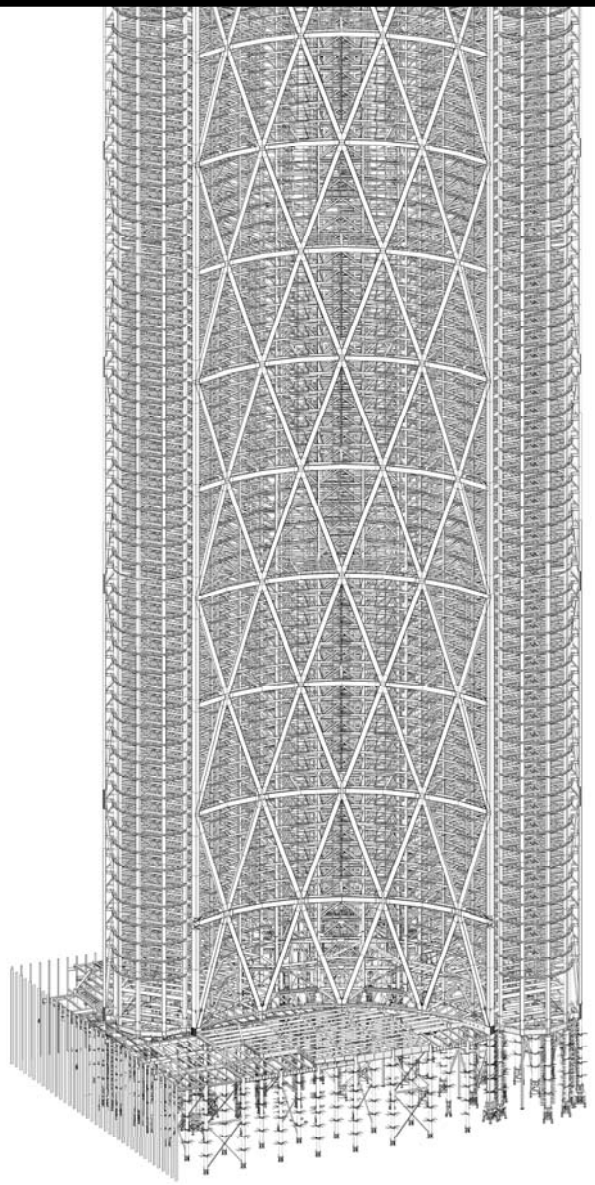


- Climate restricted
- Thermal bridging

CANTON TOWER
IBA ARCHITECTURE w/ARUP
Guangzhou, China

Communication



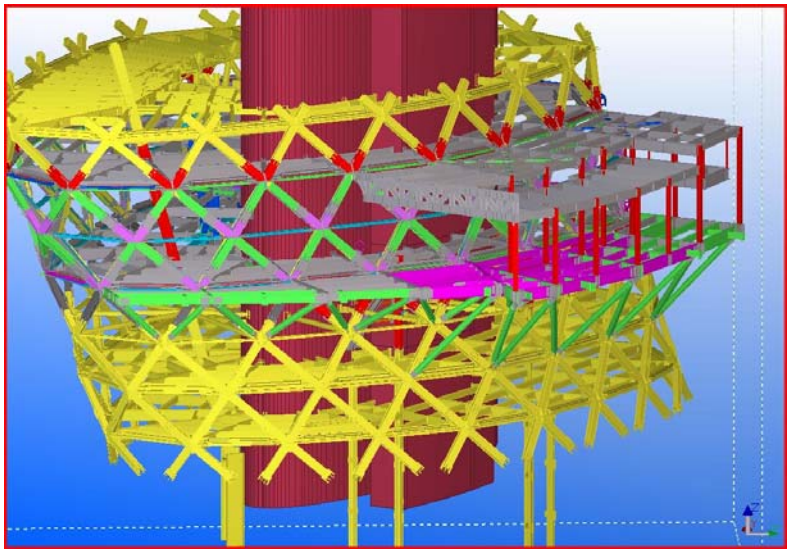


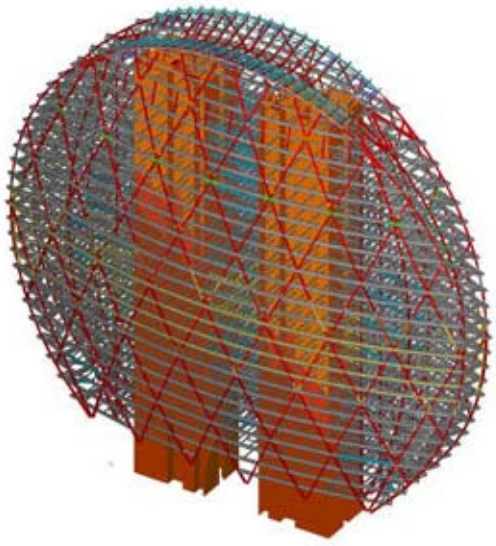
- Specialty steel modeling software is essential
- Fabricator more involved in detailing and construction sequencing decisions

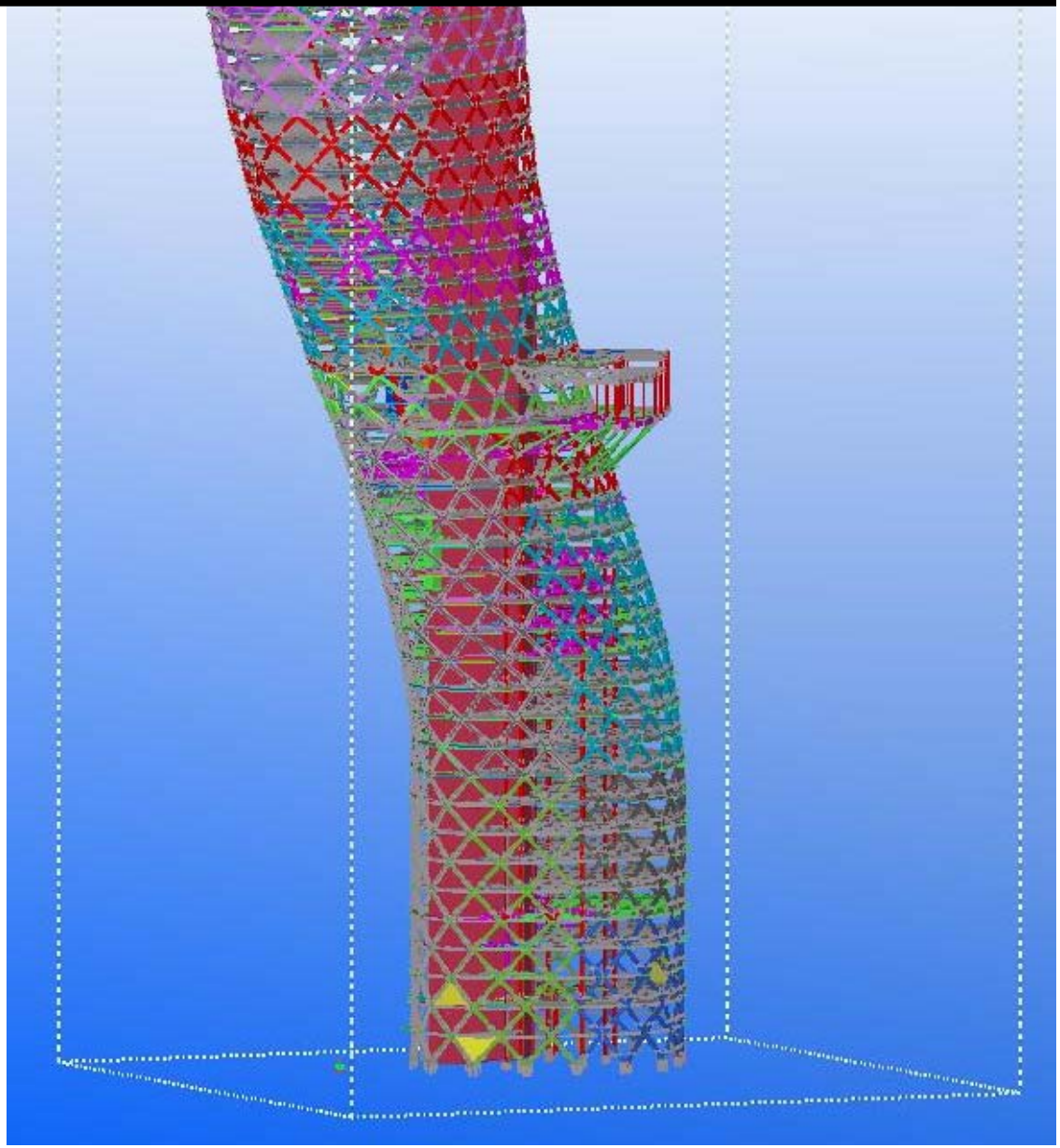
FOSTER+PARTNERS w/ ZEIDLER
HALCROW YOLLES
BOW ENCANA 2012

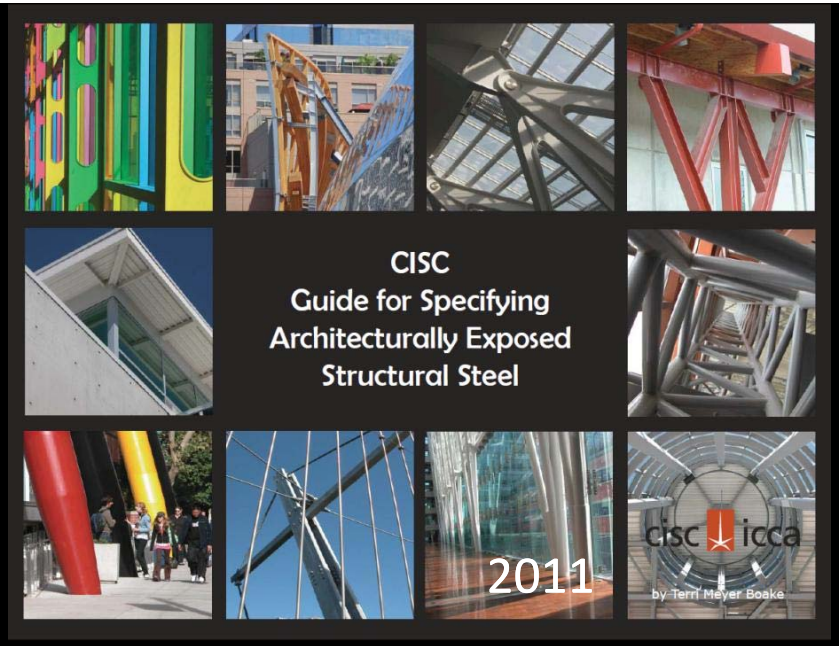
Images: Walters Inc.

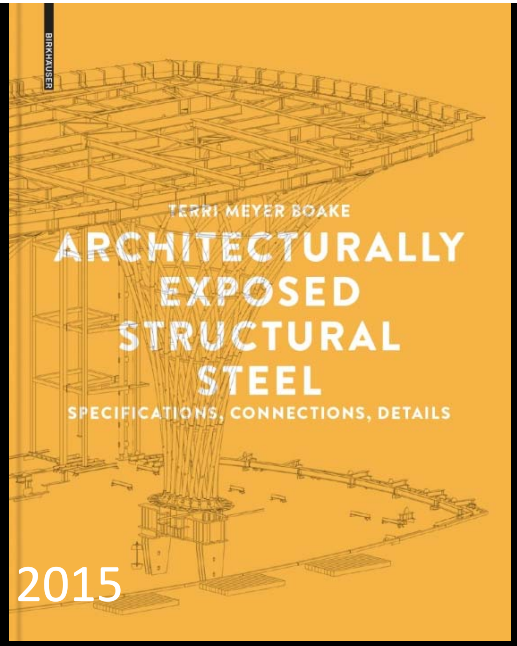
Communication

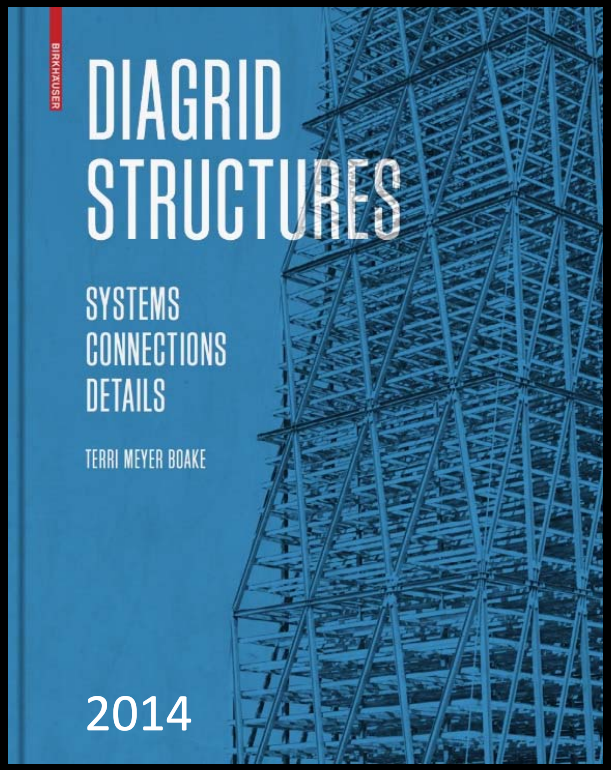












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