DIAGRIDS

Prepared by Hatfield Group

Hatfield Group

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Covers: Hearst Tower, New York, NY. Foster + Partners, 2006.
Photograph © Tishman Speyer.
Opposite: Shabolovka Radio Tower, Moscow, Russia. Vladimir Shukhov, 1922.
Photograph © Richard Pare, 2007.

Introduction: What Are Diagrids

Diagrids combine lateral- and gravity-load bearing resistances into a single system that takes the form of a diagonal grid.

The system was first developed in 1896 by Vladimir Shukov, a Russian engineer and architect. In the 21st century, it became a popular approach to creating iconic buildings while maximizing structural efficiency. Using the system, the structural weight of a building can be reduced by as much as 15% to 25%.

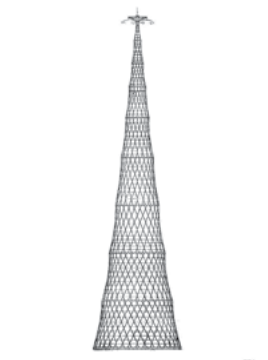
The following document, prepared by Hatfield Group, considers when, why, and how diagrid systems can be employed in the design of tall buildings.

Diagrid structure of The Bow, Calgary, AB. Foster + Partners, 2013.
Photograph © Brian Eirich, 2010.

A Brief History of Diagrid Structures

Diagrids were first put to use as a structural system by Vladimir Shukov in the design of a broadcasting tower in Moscow, Russia. Shukov began prototyping the structural system in 1896 and completed the broadcasting tower in 1919. It was only at the beginning of the 21st century, however, that the system gained widespread popularity. Today, it is used to create aesthetically distinctive and structurally efficient tall buildings.

1896-1919
Shukov Towers
Russia

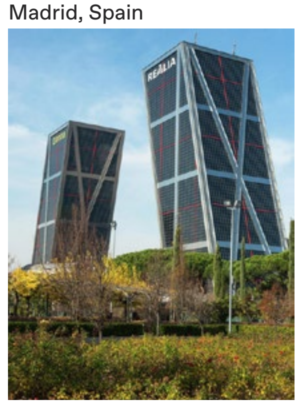


Building Height: up to 1,148 ft
Diagrid Type: Exposed Lattice
Designer: Vladimir Shukov
Drawing via Wikimedia Commons

1969
John Hancock Center
Chicago, IL

Building Height: 1,128 ft
Diagrid Type: Diagonalized Core
Architect: SOM
Engineer: SOM
Photograph © Chicago Architecture Foundation

1996
Puerta de Europa
Madrid, Spain



Building Height: 374 ft
Diagrid Type: Diagonalized Core
Architect: Johnson / Burgee
Engineer: Leslie E. Robertson Associates
Photograph © Andrew Michael, 2016

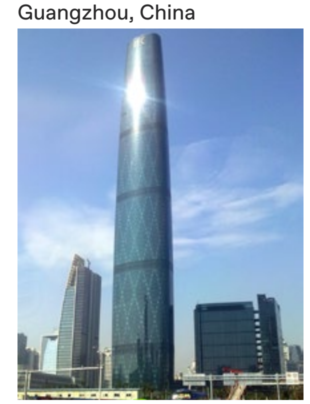
2004
Swiss RE (30 St. Mary Axe)
London, England

Building Height: 590 ft
Diagrid Type: Concealed
Architect: Foster + Partners
Engineer: Arup
Photograph © Swiss Re

2006
Royal Ontario Museum Addition
Toronto, ON, Canada

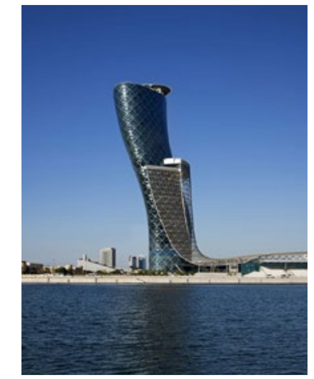
Building Height: 6 floors
Diagrid Type: Concealed
Architect: Libeskind w/ Bregmann and Hamman
Engineer: Arup
Photograph © Aviad2001 via Wikimedia Commons

2010
Guangzhou IFC
Guangzhou, China



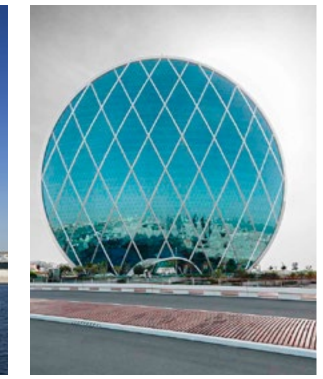
Building Height: 1,493 ft
Diagrid Type: AESS
Architect: Wilkinson Eyre
Engineer: Arup
Photograph © 慕尼黑啤酒 via Wikimedia Commons

2011
Capital Gate
Abu Dhabi, UAE



Building Height: 540 ft
Diagrid Type: AESS
Architect: RMJM
Engineer: RMJM
Photograph © Graitect

2011
Aldar Headquarters
Abu Dhabi, UAE



Building Height: 361 ft
Diagrid Type: Concealed
Architect: M.Z. Architects
Engineer: Arup
Photograph © Aldar Properties

2012
Doha Tower
Doha, Qatar

Building Height: 781 ft
Diagrid Type: AESS
Architect: Ateliers Jean Nouvel
Engineer: Terrell Group, China Construction Design International
Photograph © Ateliers Jean Nouvel

2015
Lotte Super Tower
Seoul, South Korea

Building Height: 1,819 ft
Diagrid Type: Vision (not built)
Architect: SOM
Engineer: SOM
Rendering © SOM

FIRST DIAGRID STRUCTURES BUILT — 1986

DIAGRIDS GAIN POPULARITY — 2000s

SWISS RE BECOMES TALLEST DIAGRID BUILDING W/O LATERALLY REINFORCING CORE — 2004

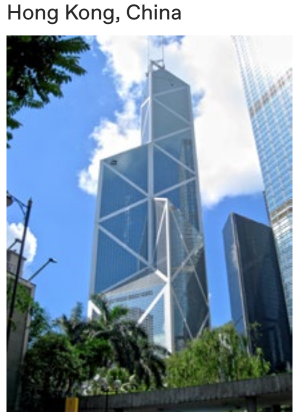
GUANGZHOU IFC BECOMES TALLEST BUILT DIAGRID STRUCTURE — 2010

LOTTE SUPER TOWER, SET TO BE TALLEST BUILDING IN ASIA, CONCEIVED AS DIAGRID STRUCTURE — 2015

1963
IBM Building
Pittsburgh, PA

Building Height: 13 floors
Diagrid Type: Concealed
Architect: Curtis and Davis
Engineer: Leslie E. Robertson Associates
Photograph via Pittsburgh-Post Gazette

1990
Bank of China Tower
Hong Kong, China



Building Height: 1,205 ft
Diagrid Type: Diagonalized Core
Architect: I. M. Pei
Engineer: Leslie E. Robertson Associates
Photograph © WiNG via Wikimedia Commons

2002
London City Hall
London, England

Building Height: 10 floors
Diagrid Type: AESS Diagrid to Support Glazing
Architect: Foster + Partners
Engineer: Arup
Photograph © MatthiasKabel via Wikimedia Commons

2006
Hearst Magazine Tower
New York, NY

Building Height: 597 ft
Diagrid Type: Concealed
Architect: Foster + Partners
Engineer: WSP Cantor Seinuk
Photograph © Alsandro via Wikimedia Commons

2008
Canton Tower
Guangzhou, China

Building Height: 1,969 ft
Diagrid Type: External AESS Diagrid
Architect: Mark Hemel / Barbara Kuit / IBA
Engineer: Arup
Photograph © Unsplash/Lycheeart

2010
0-14
Dubai, UAE

Building Height: 374 ft
Diagrid Type: Concrete Diagrid Variation
Architect: RUR Architecture
Engineer: Ysrael A. Seinuk
Photograph © Nelson Garrido

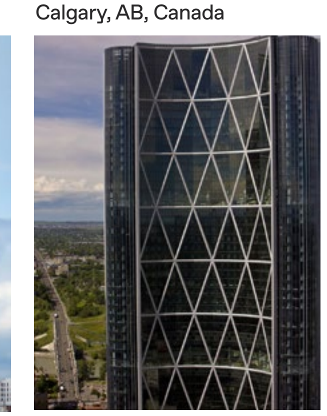
2011
KK100
Shenzhen, China

Building Height: 1,499 ft
Diagrid Type: Diagonalized Core
Architect: TFP Architects
Engineer: SOM
Photograph © Carsten Schael

2012
Arcelormittal Orbit Tower
London England

Building Height: 377 ft
Diagrid Type: AESS
Architect: Anish Kapoor, Cecil Balmond
Engineer: Arup
Photograph © Cmglee via Wikimedia Commons

2012
Bow Encana Tower
Calgary, AB, Canada



Building Height: 779 ft
Diagrid Type: AESS
Architect: Foster + Partners w/ Zeidler Partnership
Engineer: Yolles
Photograph © Getty Images / George Rose

2016
Zhounggou Zun Tower
Beijing, China

Building Height: 1,732 ft
Diagrid Type: Vision (not built)
Architect: TFP Architects
Engineer: Arup
Photograph © Milkomède via Wikimedia Commons

Why Employ a Diagrid System

Diagrids offer several advantages over conventional structural techniques, in terms of aesthetics, efficiency, and structural stability alike.

AESTHETICS

Diagrid structures can create visually distinctive, recognizable, and iconic buildings.

MATERIAL EFFICIENCY

By combining lateral and gravity structural systems, diagrids can save 15% to 25% of the total weight of the structure compared to conventional structural approaches.

SPATIAL EFFICIENCY

Diagrids reduce the size of the core by providing lateral bracing. Further, diagrids can eliminate the need for both shear walls and corner columns, resulting in open, flexible, and highly efficient floors.

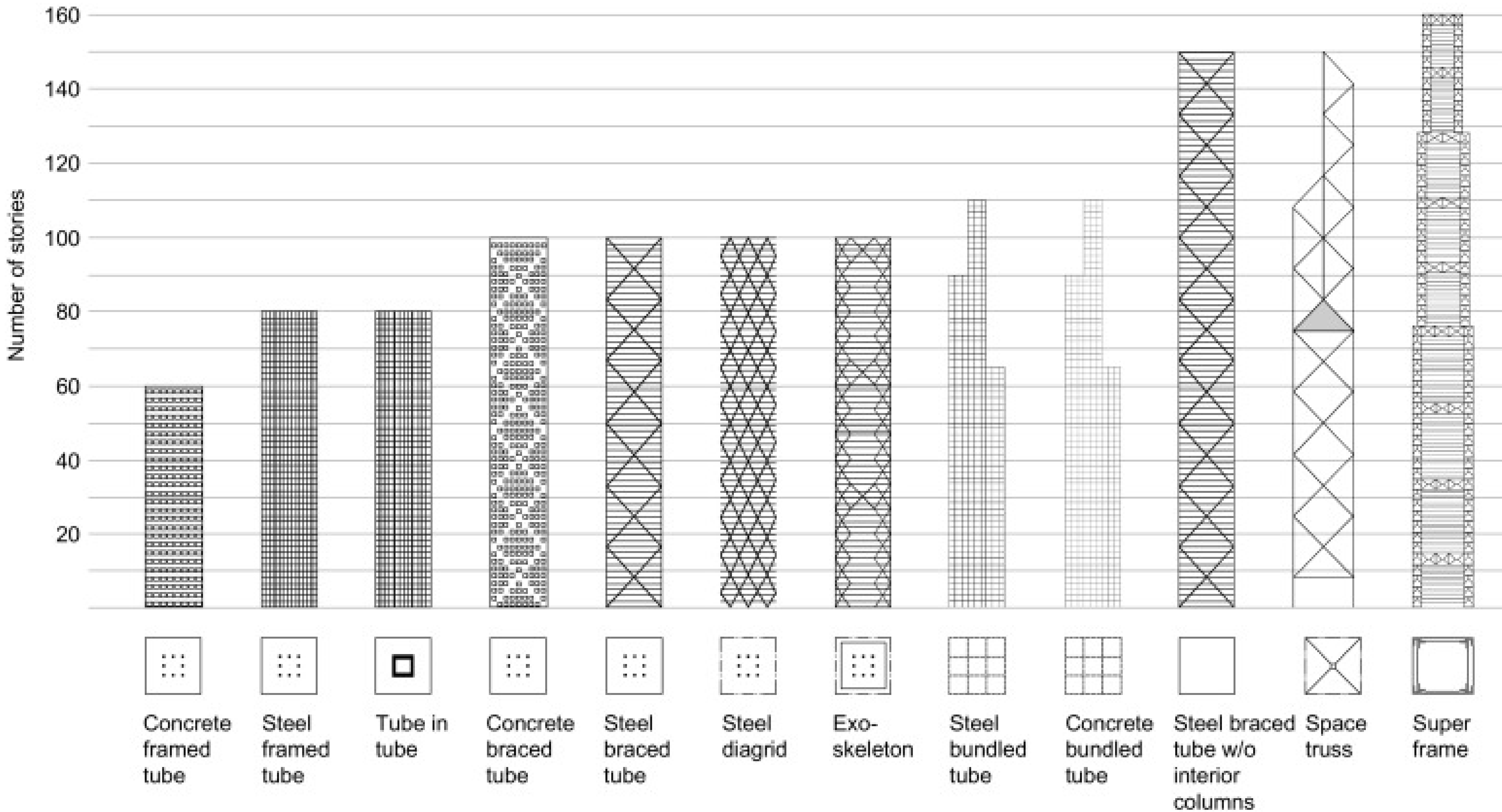
ROBUST STRUCTURES

A diagrid's diagonal members are redundant with one another, resulting in stronger, stiffer structures. Compromised portions of the structure transfer loads efficiently to intact portions.

Interior of Swiss RE Building (30 St. Mary Axe), London, UK. Foster + Partners, 2003.
Photograph © Hufton+Crow.

When To Employ a Diagrid System

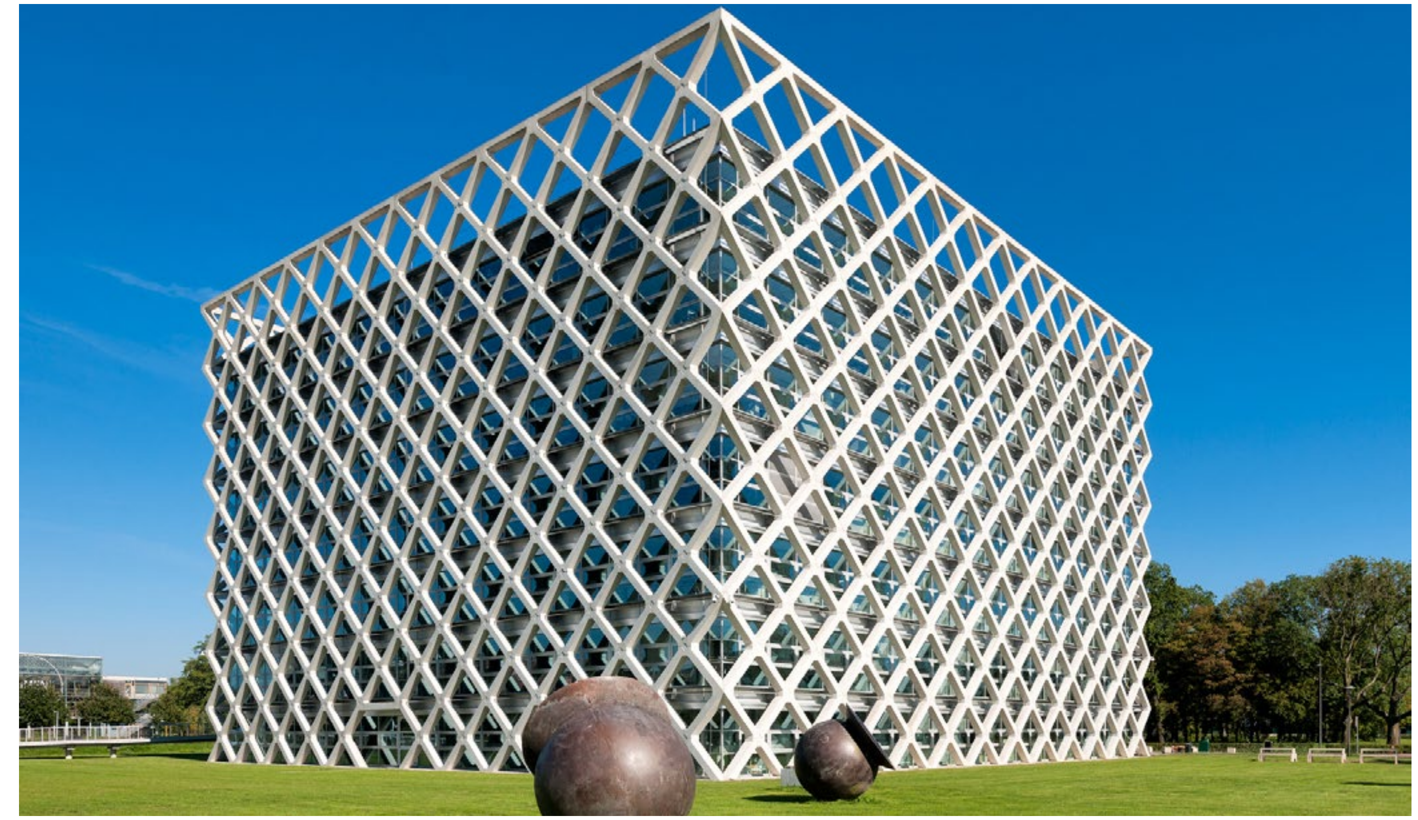
As the height of the building increases, the lateral resisting system becomes more important than the gravitational load-bearing system. Diagrid systems are optimal solutions for projects where wind or EQ starts to play a more important role than gravity in the design and economic feasibility of the structure. Below, a comparison of built projects using various lateral bracing systems.



How to Employ a Diagrid System
Steel vs Concrete

Diagrid systems can be constructed out of both steel and concrete. Deciding which material to use depends on the specific requirements of the project. Steel is typically used for tall buildings rising 40 stories or more. Concrete can also be used for tall buildings, but is not as strong as a steel structure. Below, a comparison of the advantages and disadvantages of using steel and concrete for diagrid structures.

Swiss RE Building (30 St. Mary Axe), London, England. Foster + Partners, 2003.
Photograph © Adrian Pingstone via Wikimedia Commons, 2004.



WUR Atlas Building, Wageningen, Netherlands. Rafael Viñoly Architects, 2006.
Photograph © Dirk Verwoerd.

Steel Structures

ADVANTAGES

- Low self-weight
- High strength-to-weight ratio
- Stiffness
- Suitable for mass production
- Quick installation
- High ductility
- No formwork required
- Easy to transport and handle
- Easy to recycle
- Allows off-site fabrication and on-site construction

DISADVANTAGES

- Susceptible to corrosion
- High maintenance costs—requires frequent treatment with special paints
- High upfront cost
- Requires highly skilled labor
- Low fire resistance
- Susceptible to fatigue when exposed to constantly changing loads
- Susceptible to brittle fracture when ductility is lost

Concrete Structures

ADVANTAGES

- Moldable
- Uses low cost materials
- Can be manufactured to desired strength
- High compressive strength
- Reinforced concrete provides most durable building system
- Can be reinforced with steel bars for tensile strength
- Low labor cost, requires less specialized skill than does steel
- Low maintenance costs
- Pre-stressed concrete allows smaller cross-sections and lighter structures
- Fire and weather resistant

DISADVANTAGES

- Brittle when its strength is exceeded
- Requires formwork
- Long curing time—reaches maximum strength after 28 days
- Low tensile strength and toughness
- Requires a bulky structure
- Can crack due to drying shrinkage and moisture expansion (construction joints mitigate this issue)
- Structure with high self-weight, not recommended in regions with seismic activity
- Sustained loads can cause permanent deformation (creep)
- Demands strict quality control
- Salt deposits may form on surface (efflorescence)

How to Employ a Diagrid System
Optimal Diagrid Geometry

Diagrid structures are composed of repeated modules that usually span 2 to 6 floors, as measured from the apex of the diamond to the ring beam. The geometry of the module is critical to transferring the load to the ground efficiently. When deciding on the optimum module geometry for a specific building, consider the size of the diamonds and whether to use uniform or tapered angles.

DIAMOND SIZE

The size of the diamonds has implications on the total construction cost. Larger diamonds result in less nodes and more flexibility when it comes to installing the curtain wall, usually reducing costs.

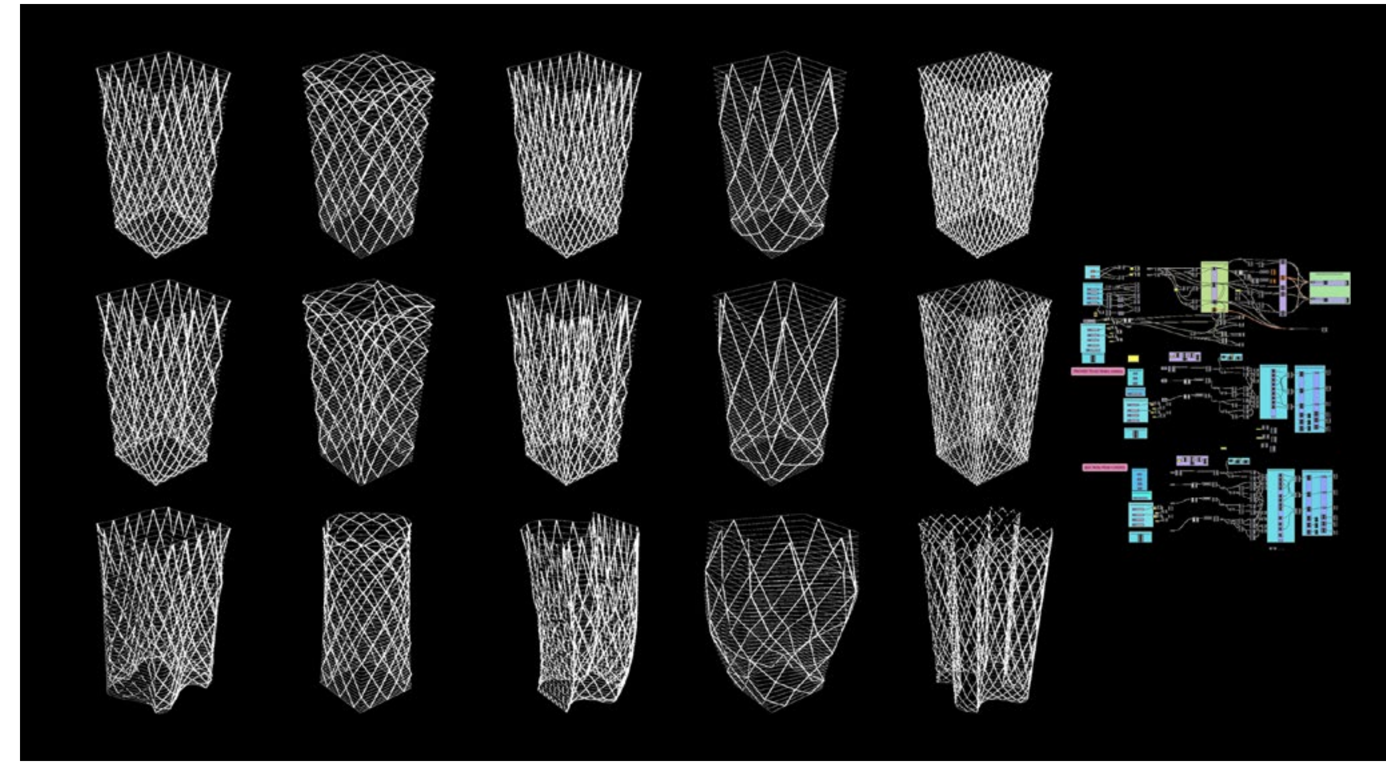
Running several stiffness-based optimizations and working with a construction manager to determine how each affects cost can help determine the best diamond size for a specific project.

ANGLE SIZE

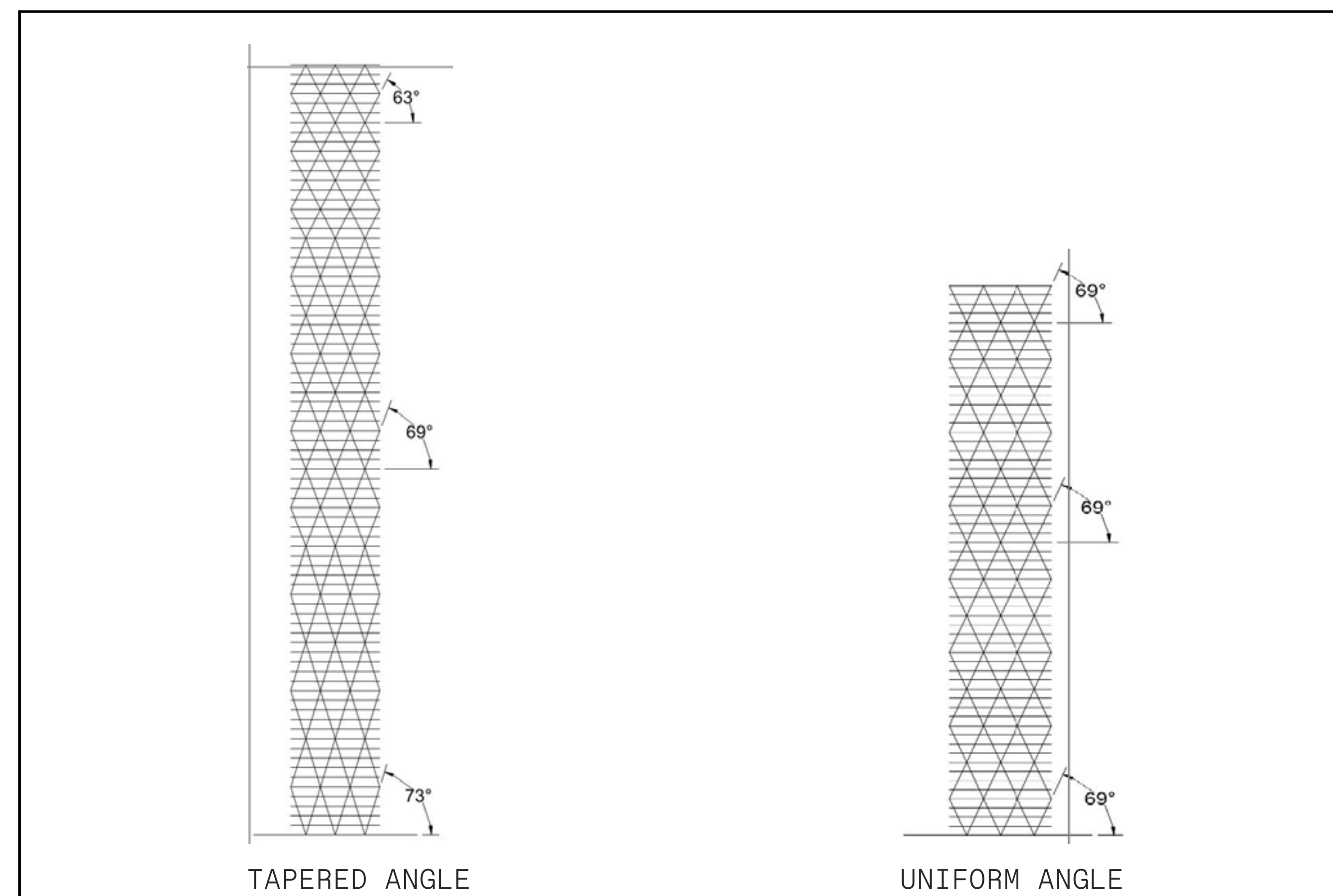
The optimum angle size depends largely on the building's height, but typically falls between 50 degrees and 75 degrees. Narrower angles have higher wind-load capacity but less gravity-load capacity.

TAPERED VS. UNIFORM ANGLES

Tapering the size of the angles over the length of the building can be an efficient solution, especially for buildings that rise above 60 stories. Using broader angles at the base of the building optimize gravity-load bearing capacity, while using narrower angles at the top optimizes wind-load bearing capacity.



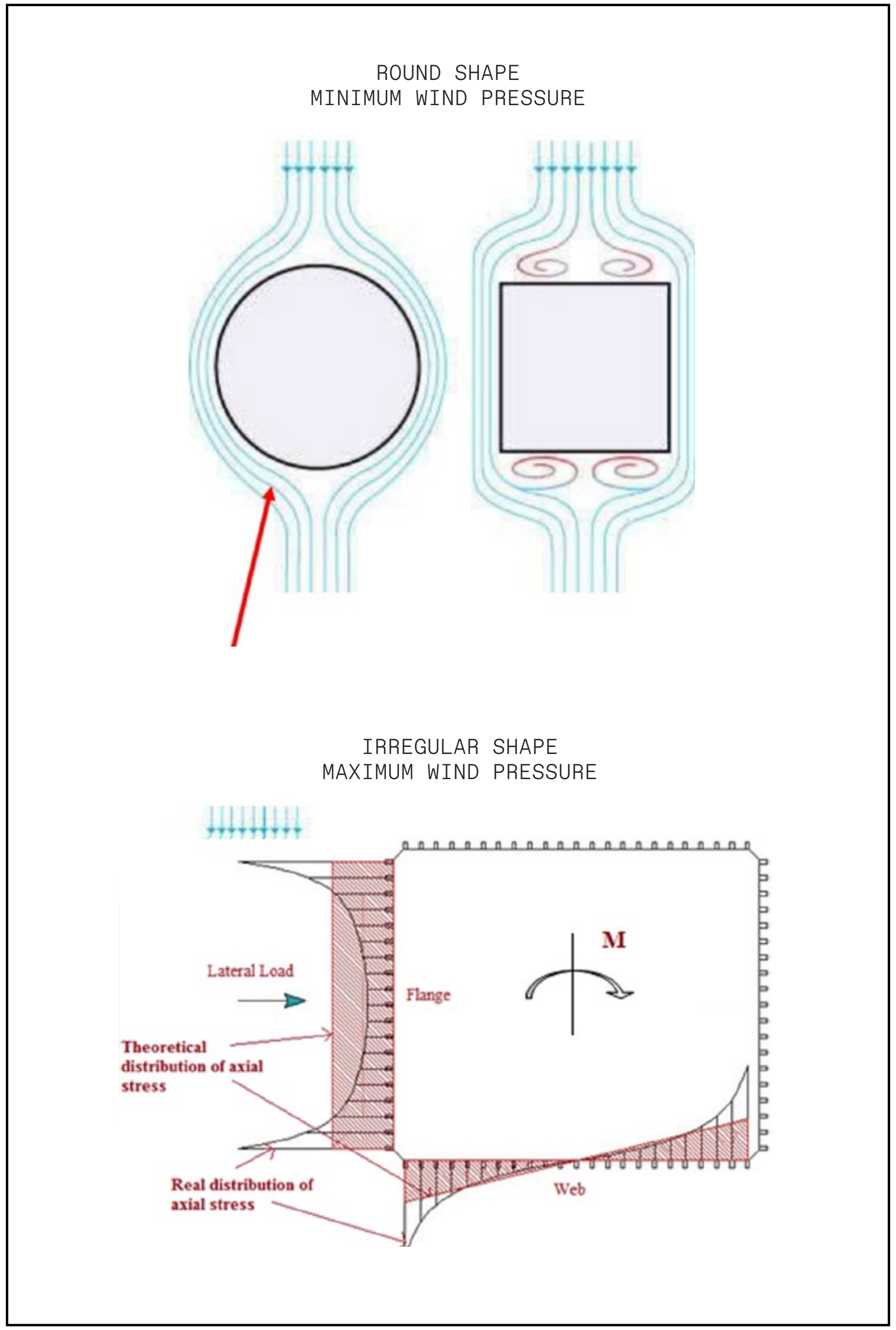
Parametric design processes allow several options for diagrid sizes to be tested efficiently.

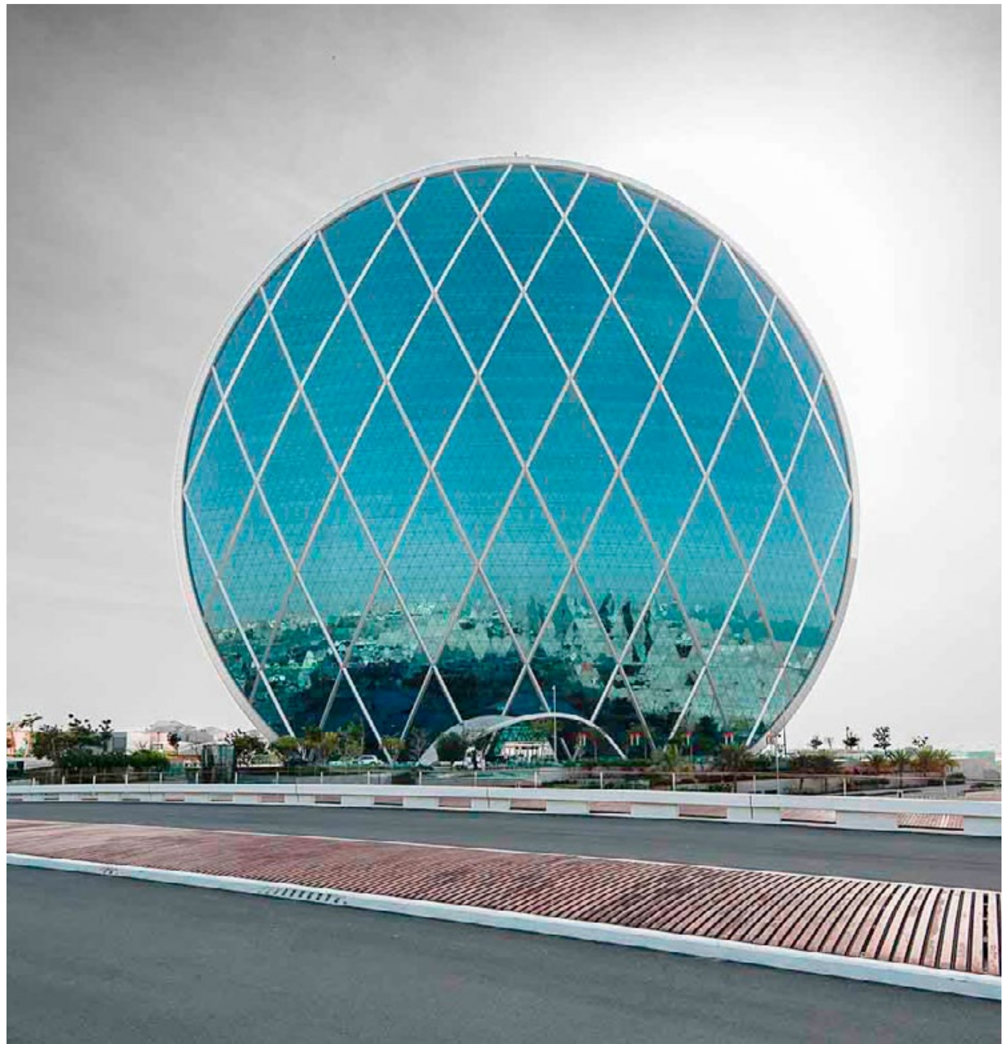


Tapering the angles is an efficient design solution for buildings greater than 60 stories tall.

How to Employ a Diagrid System
Optimal Plan Shape

Symmetrical plan shapes offer the most efficient load-bearing capacity for diagrid structures. Circular and elliptical footprints—as well as curved corners generally—further help to transfer loads efficiently and minimize wind pressure.





Clockwise from top left:
Swiss RE (30 St. Mary Axe), London, England. Foster + Partners, 2003. Photograph © Richard Bryant.
London City Hall, London, England. Foster + Partners, 2003. Photograph © MatthiasKabel via Wikimedia Commons, 2009.
Doha Tower, Doha, Qatar. Ateliers Jean Nouvel, 2012. Photograph © Ateliers Jean Nouvel.
Aldar Headquarters, Abu Dhabi, UAE. MZ Architects, 2010. Photograph © Aldar Properties.

How to Employ a Diagrid System
Curtain Wall Integration

Integrating the curtain wall into a diagrid structure requires planning and close coordination with the architect, the facade designer, and the structural engineer. It is essential to consider how the curtain wall will be fit to the facade—and any potential complications—early in the design process.

DIAGRID SIZE

Larger diagrid modules allow for more flexibility in curtain wall design and an easier fit.

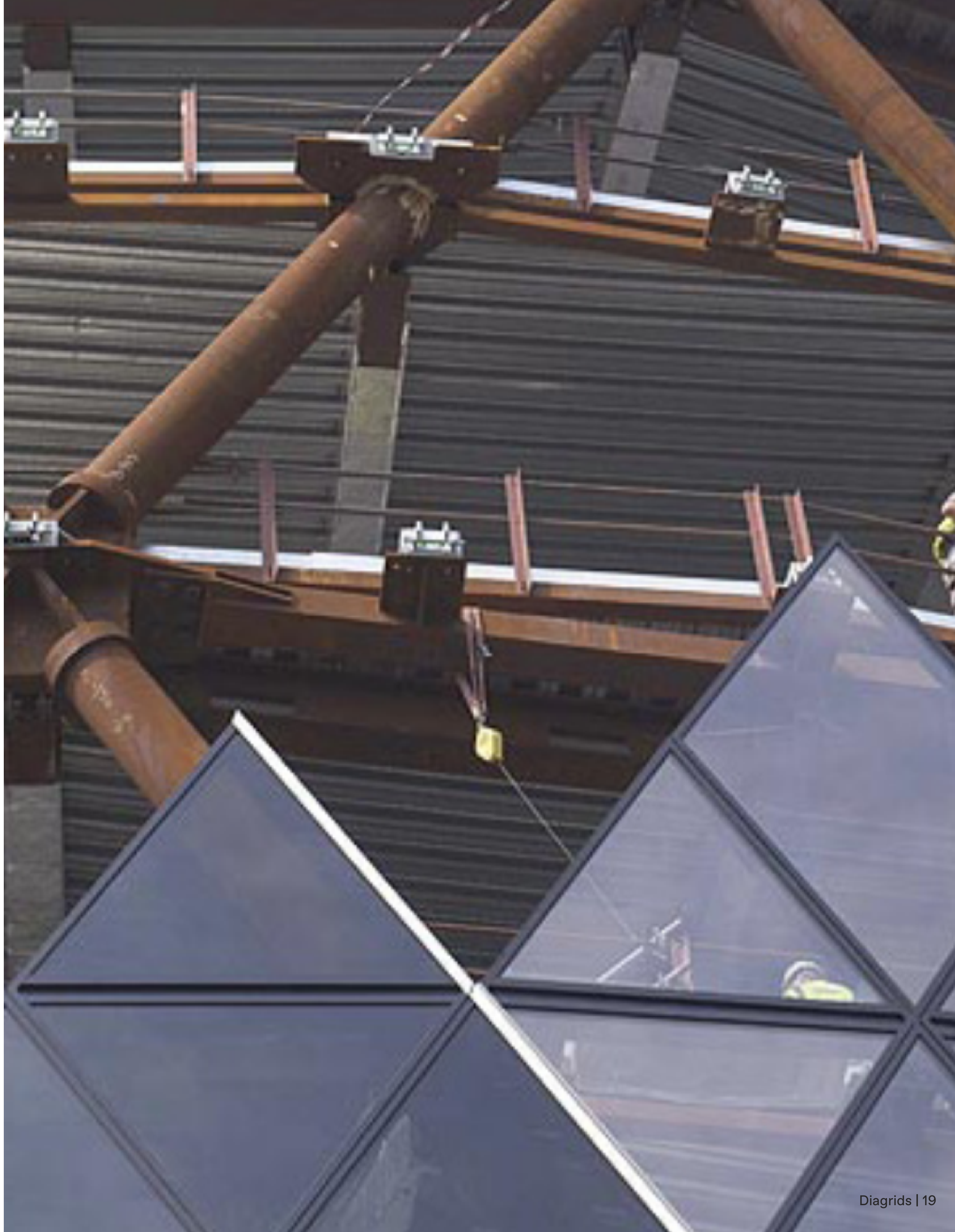
Smaller diagrid modules, on the other hand, necessitate more complex curtain walls. A smaller diagrid module will restrict curtain wall design.

WINDOW WASHING DETAILS

When using a diagrid system, it is essential to resolve window washing details early in the design.

TOLERANCE

Attachments between the structure and the curtain wall need a greater tolerance when using a diagrid system compared to a conventional structural system.



Swiss RE (30 St. Mary Axe), London, England. Foster + Partners, 2003.
Photograph © Getty Images/Universal Images Group Editorial.

Common Pitfalls

Despite their advantages over conventional structural methods, diagrid systems also have their own set of pitfalls that can complicate the design and construction process. Below, some of the most common challenges encountered when using diagrid systems and solutions to overcoming these challenges.

CONSTRUCTION COMPLEXITIES

Challenge: Complex nodes can be expensive and slow to erect

Solution: Prefabricate nodes off-site

Include repetition for economy

ENGINEERING INEFFICIENCIES

Challenge: Inefficient diagrid angles can be difficult to engineer and construct

Solution: Solicit the input of the engineer at the concept stage to ensure seamless design and engineering process

PERIMETER FOUNDATIONS

Challenge: When using a diagrid system, the foundations move to the perimeter

Solution: Solicit the input of the engineer at the concept stage to ensure seamless design and engineering process

HIGH STRENGTH STEEL

Challenge: Diagrids require high-strength steel (A913 Grade 65 or higher)

Solution: Budget for high-strength steel and coordinate with the engineer and contractor to avoid welding incompatibilities

National September 11th Museum Pavilion, New York, NY. Snøhetta, 2014.
Photograph © Snøhetta/Esto Photographers/Jeff Goldberg, 2014.

About Hatfield Group

Inventive engineering rooted in architectural thinking

Hatfield Group is a New York-based, globally-minded team of designers, engineers, and thinkers dedicated to bringing architectural thinking to the field of engineering. Founded by engineer Erleen Hatfield and architect Martin Finio, we think and work like architects to better engineer distinctive and enduring buildings.

Where other engineers see risks, we see opportunities to innovate. We partner with our clients from concept through delivery, treating inventive engineering as an integral part of design. We make the architect's priorities and working methods our own, approaching engineering an iterative, creative process to realize complex buildings with a meticulous attention to aesthetic intent.

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Yale School of Management, New Haven, CT. Foster + Partners, 2014.
Photograph © Chuck Choi, 2014.

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