

# Arch 570: Architectural Steel Design

Why I got interested in this subject  
A Course Intro

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tboake.com



**CISC**  
**Guide for Specifying**  
**Architecturally Exposed**  
**Structural Steel**



From Andreas Müller★

Reply Forward Archive Junk Delete

Subject **Contact about publication for Birkhäuser Publishers**

01/03/2009 11:37 PM

To Terri Boake★

Other Actions ▾

Dear Professor Boake,

Please allow me to introduce myself as editor in charge of the architectural program of Birkhäuser Publishers. I became aware of your activities for the SSEF. Students and young professionals constitute a large part of our readership. I wonder if the wealth of material, knowledge and connections that you have would make you consider a publication on this topic.

If so, there would be an occasion for a first meeting and exchange of ideas during my forthcoming visit to Toronto in early April, from Saturday April 4th to Tuesday April 7th.

I would be very pleased to hear from you.

With kind regards,

Andreas Müller  
Senior Commissioning Editor  
Birkhäuser

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# Understanding Steel Design

text and photos

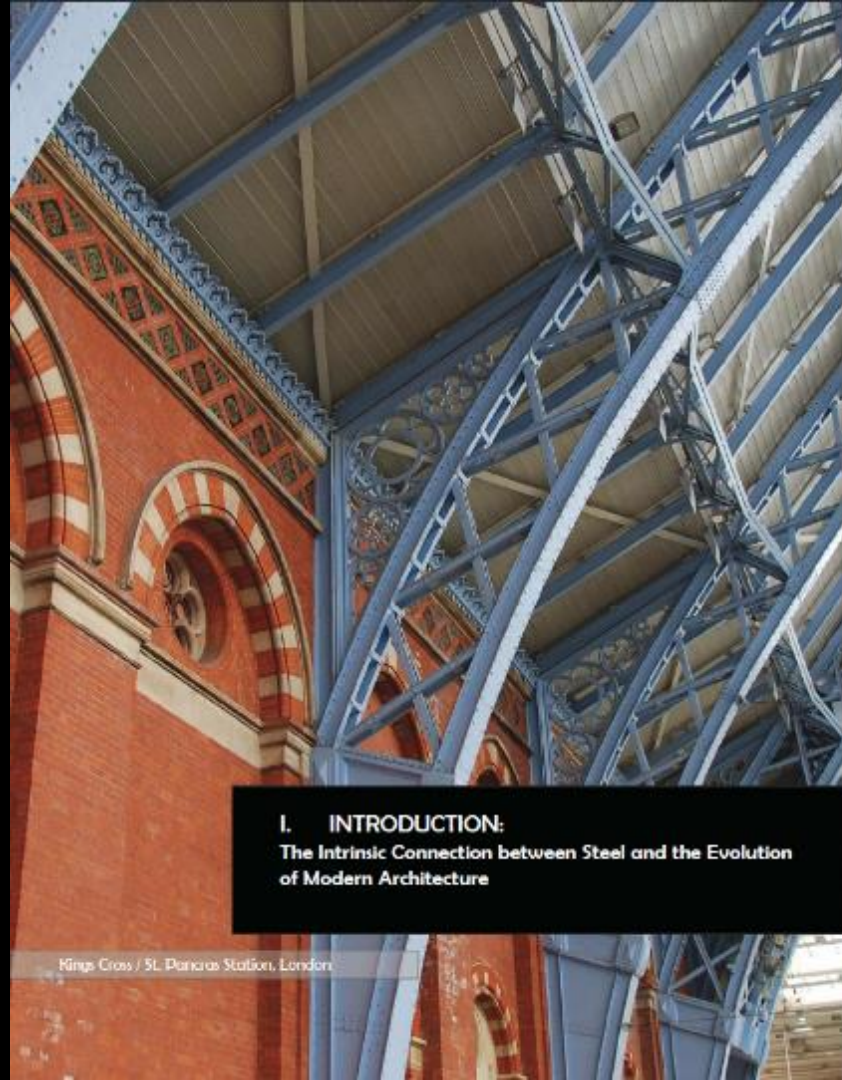
TERRI MEYER BOAKE

illustrations

VINCENT HUI

A book proposal  
required that I  
write an "expose"





**I. INTRODUCTION:**  
**The Intrinsic Connection between Steel and the Evolution of Modern Architecture**

Kings Cross / St. Pancras Station, London

**I. INTRODUCTION:**

*The Intrinsic Connection between Steel and the Evolution of Modern Architecture*

**TOPICS:**

- From Iron to Steel – From Technique to Technology
- Early Iron Developments of the 19th Century
- Multi-Story Building and the Development of the Skyscraper
- The Place of Steel in Contemporary Architectural Style of the 20th Century
- The High Tech Movement
- The Emergence of Architecturally Exposed Structural Steel
- Departing the Rectilinear:  
Introducing Diagrids and other non Regular Geometries in 21st Century Steel Construction

**BUILDINGS/IMAGES:**

Buildings in this section will be drawn from a wide variety of sources, ranging from early French and English iron and steel construction to examples of multi-rise buildings in North America. This section also introduces a range of early High Tech buildings and their evoked counterparts in the form of early AES structures.



Glass Atrium support system, Buffalo



Eiffel Tower, Gustave Eiffel



Reliance Building, Burnham and Root -  
early curtain wall framing



Bibliothèque Nationale, Henri Labrousse -  
early cast iron and modular construction



John Hancock Tower, Chicago - early  
diagrid!



O'Hare International Airport, Murphy /  
John - first AES airport





## II. The Materiality of Steel

Pritzker Pavilion, Frank O. Gehry

## II. The Materiality of Steel

### TOPICS:

- Types of Shapes: wide flange, angles, hollow structural steel, channels, plates, rods ...
- Selection of shapes for beams, columns, trusses.
- Deciding factors for system choice: aesthetics, shape, connections, cost, weight (cost factors will only be explored in general comparative terms as relates to weight, surface for painting and complexity of fabrication detailing required).

### BUILDINGS/IMAGES:

The buildings used in this section will be selected to highlight the rationale behind a particular choice in member type. Where do we use wide flange sections versus HSS, etc.



Pritzker Pavilion, Frank O. Gehry (wide variety of member types)



Canadian War Museum, Raymond Moriyama Architect (mostly square HSS)



Salvation Army Building (WF)



Palais des Congrès de Montreal (WF with cutouts)



Channel 4 News, Richard Rogers (specialty WF and stainless steel)



Millennium Dome, Richard Rogers (tube)

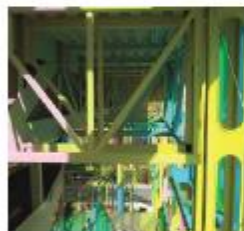
### III. Structural Steel Framing Systems vs. Architecturally Exposed Structural Steel: Differentiated Requirements

#### TOPICS:

- The Matter of Exposure
- Not all AESS Need Be Created Equal
- The Distance Factor
- Connection Types (a general introduction to connections – more detail later in the book)
- Member Selection
- Fire Protection
- The Finish Factor: Paint, Galvanizing and Intumescent Coatings

#### BUILDINGS/IMAGES:

A wide geographic range of AESS buildings will be worked into this section. Specific buildings will be chosen that best support the technical points being addressed – complexity of detail, degree of exposure, proximity to viewer, type of finish.



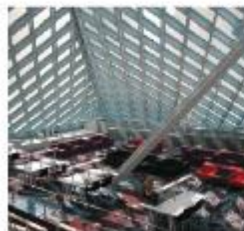
Palais des Congres de Montreal, Consortium of Architects



Ontario College of Art and Design, Will Altop



Case de Depots et Placements, Consortium of Architects



Seattle Public Library, Rem Koolhaas



BCE Place, Santiago Calatrava



Museum, Polish Partnership

### III. Structural Steel Framing Systems vs. Architecturally Exposed Structural Steel: Differentiated Requirements

Ontario College of Art and Design, Will Altop





#### IV. Steel Connections

Heathrow Terminal 5, Richard Rogers

#### IV. Steel Connections

##### TOPICS:

- Basic Connection Strategies (lap joints, butt joints – diagrams showing shear planes and where tensile failures would occur)
- Bolting versus Welding (some reference back to AESS but also issues of constructability, transportation size limits, erection size limits, quality control for site work, etc.)
- Basic Connection Types (column to base, column to column, beam to column, etc.)
- Hinge connections
- Specialty Connections: Moment, Castings, Tensile connectors
- Fabrication Issues

##### BUILDINGS/IMAGES:

The buildings used in this section will showcase a large variety of connections that will be developed with interpretive details to explain how they both reflect and have been derived from basic/standard steel detailing practices. The drawings will be developed as both line and 3D models. This section will see the majority of the development of purpose created illustrations. The discussion will center around times to bolt or weld. How this impacts design and construction. Level finish required depending on the concealment and distance to view (AESS considerations).



O'Hare International Airport, Murphy John



Peacock Pavilion Chicago, Frank Gehry



Salt Lake City Library, Moshe Safdie

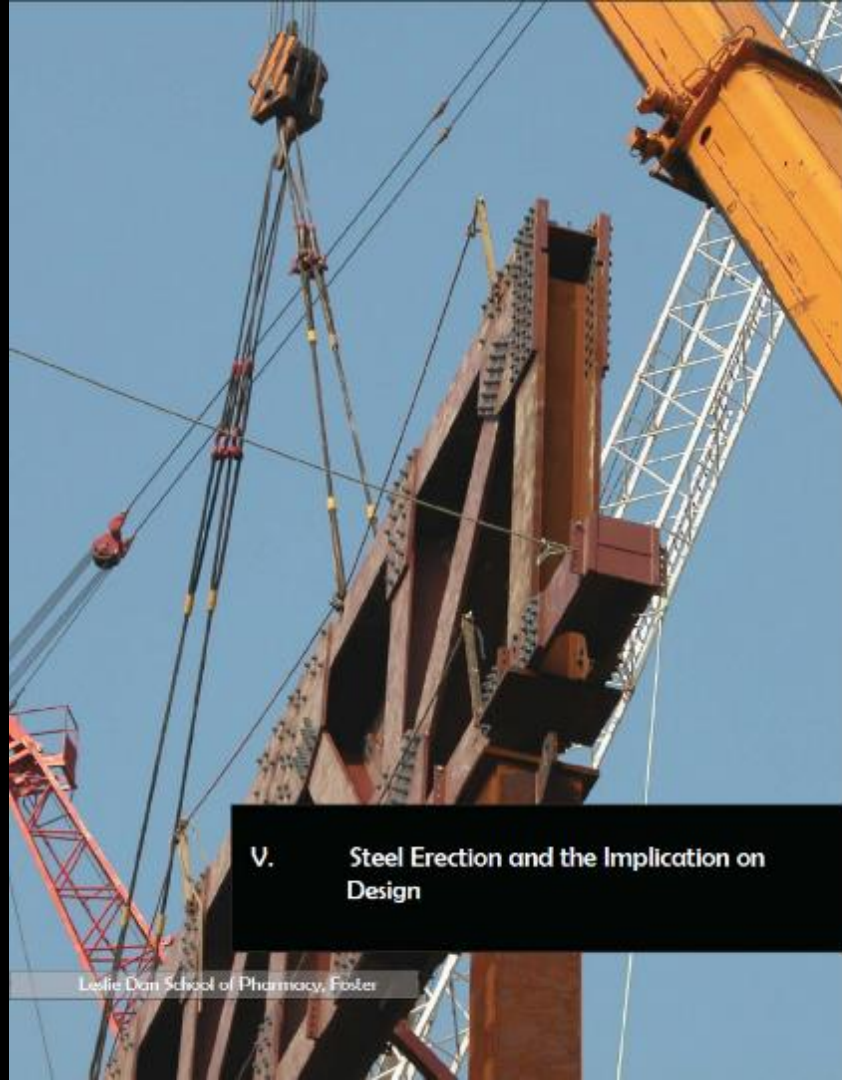


Guelph University Building, Young + Wright Pearson International Airport, SOM



Bird's Nest, Herzog and De Meuron





## V. Steel Erection and the Implication on Design

Leslie Dan School of Pharmacy, Foster

## V. Steel Erection and the Implications on Design

### TOPICS:

- Transforming an architectural design into a series of fabricated elements
- Transporting members to the site – limits on size – site access considerations
- Staging issues, just in time delivery, sequences, dealing with urban site constraints
- Handling the steel, erection procedures

### BUILDINGS/IMAGES:

The buildings used in this section will largely be derived from projects for which I have documented the construction of the building so that the relationships between the construction process and the implications of the design choices of various systems is clear.



Leslie Dan School of Pharmacy, Toronto, Foster Partnership



Royal Ontario Museum, Toronto, Studio Libeskind



Newseum, Washington, D.C., Polheh Partnership



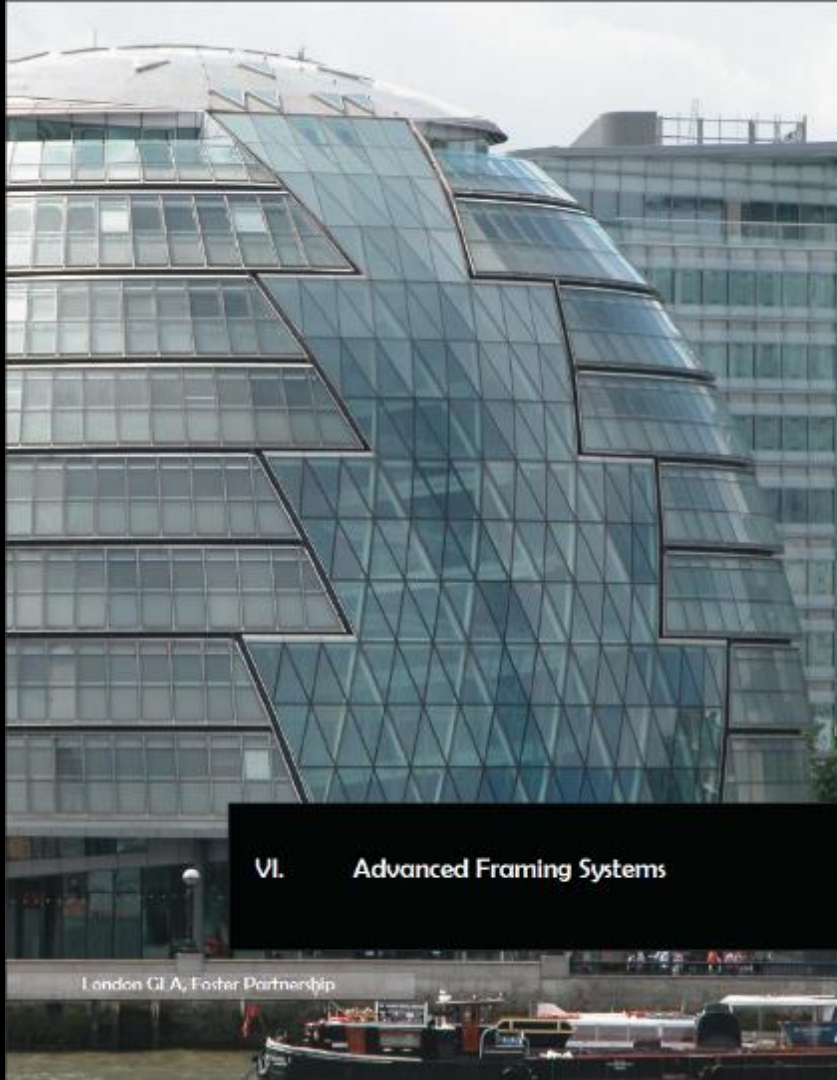
Denver Art Museum, Studio Libeskind



Ontario College of Art and Design, Will Alsop



Art Gallery of Ontario, Frank Gehry



## VI. Advanced Framing Systems

London G1 A, Foster Partnership

## VI. Advanced Framing Systems

### TOPICS:

- Traditionally Framed Steel Buildings
- Trusses and their Applications
- Diagrid Structures
- "Irregular" Shapes
- Architecturally Exposed Structural Steel Buildings
- Steel and Wood - Interrelationship issues that arise when designing with these two varied materials
- Steel and Concrete - Interrelationship issues that arise when designing with these two varied materials
- Example Projects

### BUILDINGS/IMAGES:

The buildings used in this section will draw from greatly varied sources as it is anticipated that this would be a major chapter for the book. This section will likely reference in excess of 20 significant projects. The images below only represent a small selection of potential works.



Experience Music Project, Frank Gehry  
(curved steel)



Swiss Re, Foster Partnership (diagrid)



Royal Ontario Museum, Studio Libeskind  
(diagrid)



Milwaukee Art Museum, Santiago Calatrava  
(moving roof)

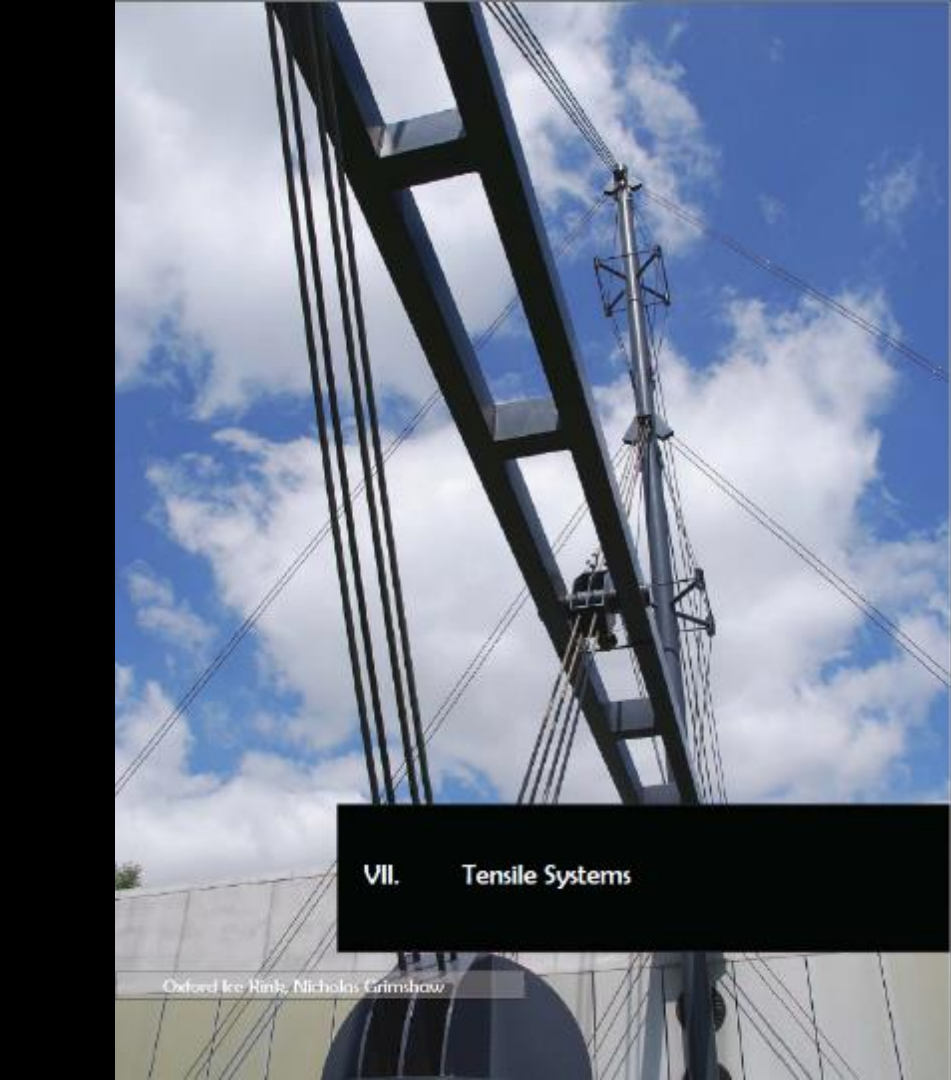


Art Gallery of Ontario, Frank Gehry (for  
steel and wood)



Seattle Public Library, Rem Koolhaas





## VII. Tensile Systems

Oxford Ice Rink, Nicholas Grimshaw

## VII. Tensile and Specialty Systems

### TOPICS:

- The Emergence of Tensile Systems in the High Tech movement
- Using Steel to its best Structural Advantage
- Speciality Connections
- Installing, Leveling and Alignment
- Fabric Applications
- Cast Steel Structures
- Curved Steel Structures
- Pedestrian bridges
- Example Projects

### BUILDINGS/IMAGES:

The buildings used in this section will showcase a range of steel applications that use highly specialized detailing and construction methods.



Iulius Footbridge



Denver International Airport, Pentris  
Broadbun



Water Cube, PTW Architects



Petal Structures, London Architecture  
Installation



Eden Project, Nicholas Grimshaw



Pedestrian Bridge, Salt Lake City



## VIII. Steel and Contemporary Glazing Systems

### TOPICS:

- Steel support systems for Structural Glass
- Spider Connections

### BUILDINGS/IMAGES:

The buildings used in this section will be derived from a wide range of projects that typically use specialized connection systems to support mullionless glazing systems on steel framed buildings. These accessory systems are typically comprised of stainless steel fittings.



Salt Lake City Library, Moshe Safdie

Denver International Airport, Fentres  
Bradburn

Tower Bridge House, Richard Rogers

## VIII. Steel and Contemporary Glazing Systems

Rose Center, Polhek Partnership



Rose Center, Polhek Partnership

Brentwood Skytrain Station, Vancouver,  
Busby Perkins and Will

Salvation Army Building, Sheppard Robson

## IX. Steel and Sustainability

### TOPICS:

- Steel as a recycled material
- Steel and reusability – Cradle to Cradle possibilities
- Steel and Net Zero Energy Design
- The benefits of using AESS as both structure and finish

### BUILDINGS/IMAGES:

The buildings used in this section will reflect aspects of the above criteria. In North American Sustainable Rating Systems terms, it is expected that all would have gained LEED points for their use of steel in terms under the Materials and Resources credits. The text will look at the advantages of steel in ways currently not accounted for in the various ratings systems. A bit more digging required for images and examples to support this section.



National Works Yard, Vancouver, LEED Gold



Lillis School of Business, University of Oregon, LEED Gold



Jackson Triggs Estate Winery, HPMB Architects (Canadian Entry for GB Awards)



Steel manufacturing process and use of recycling and how this feeds the base



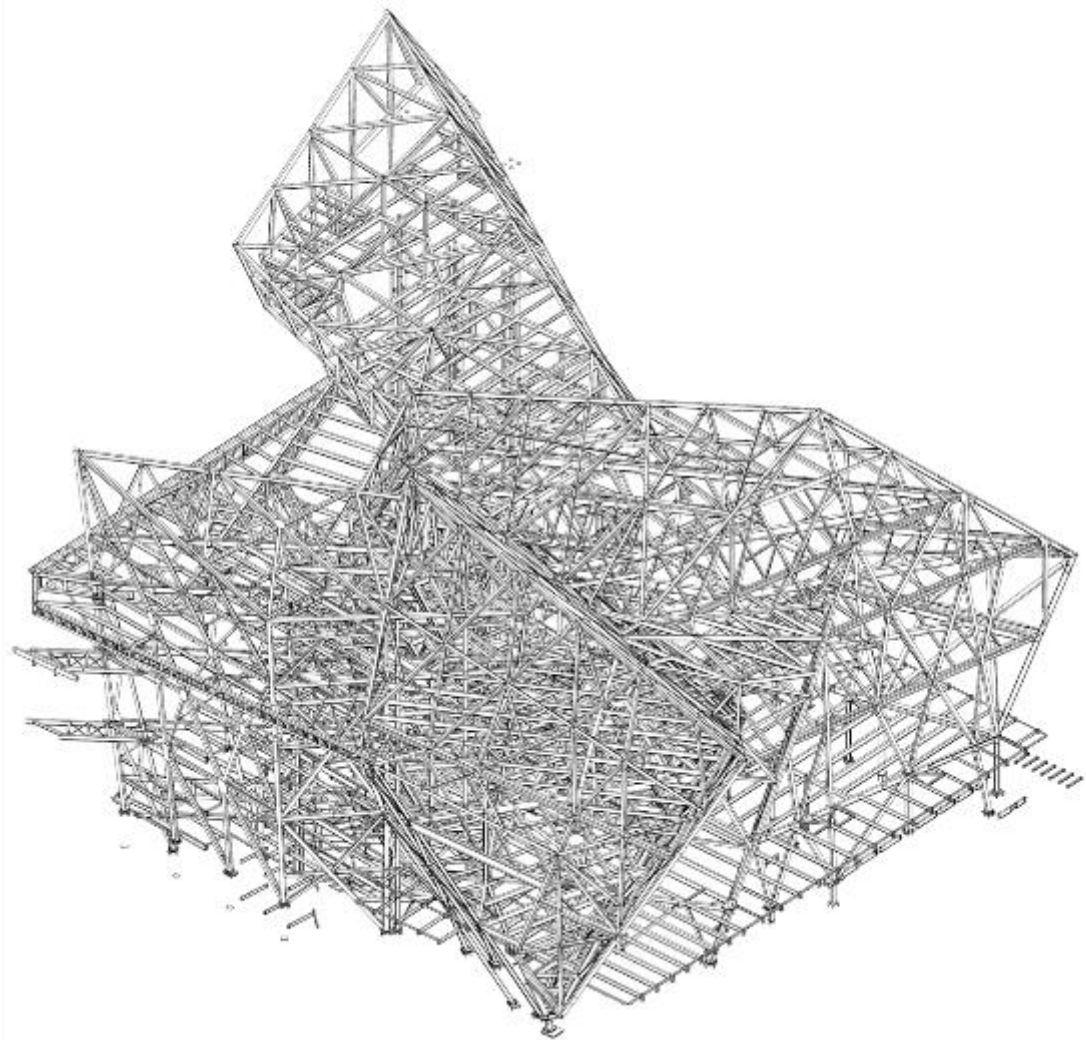
Semichanoo Library, Surrey, LEED Silver



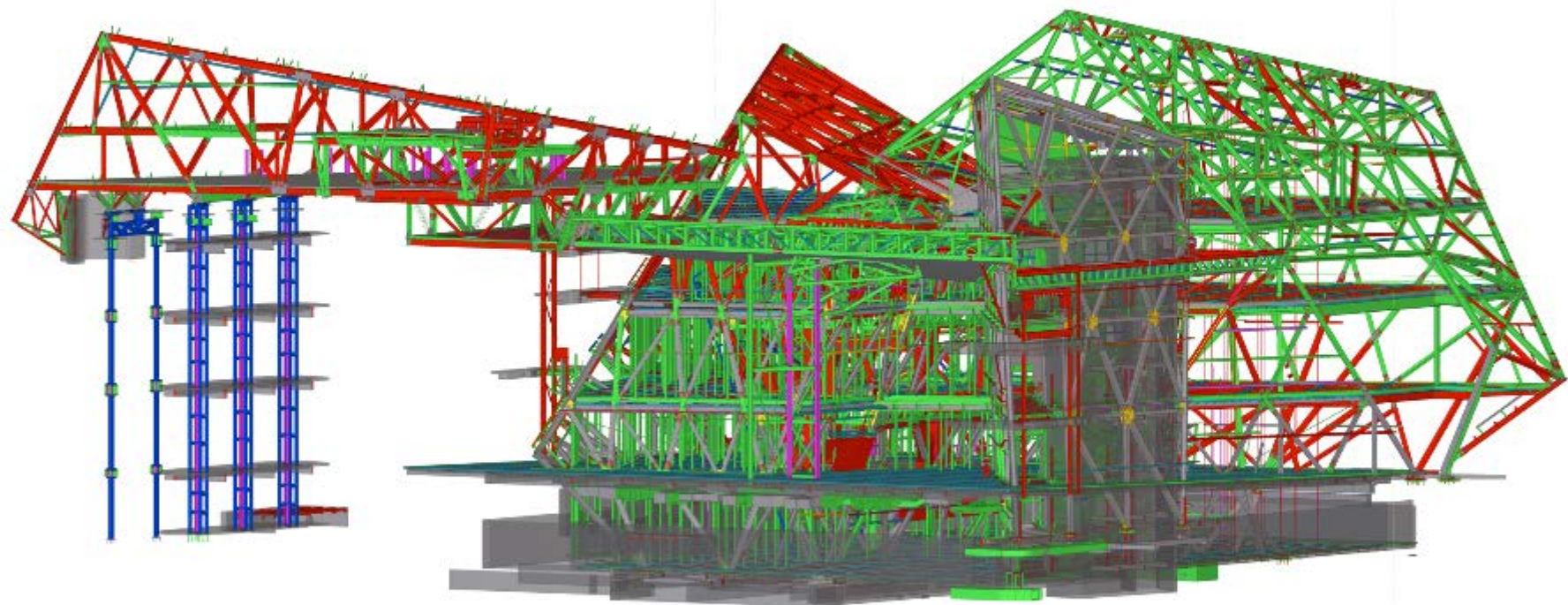
APECBC Headquarters, Richmond – steel structure and steel supported shading

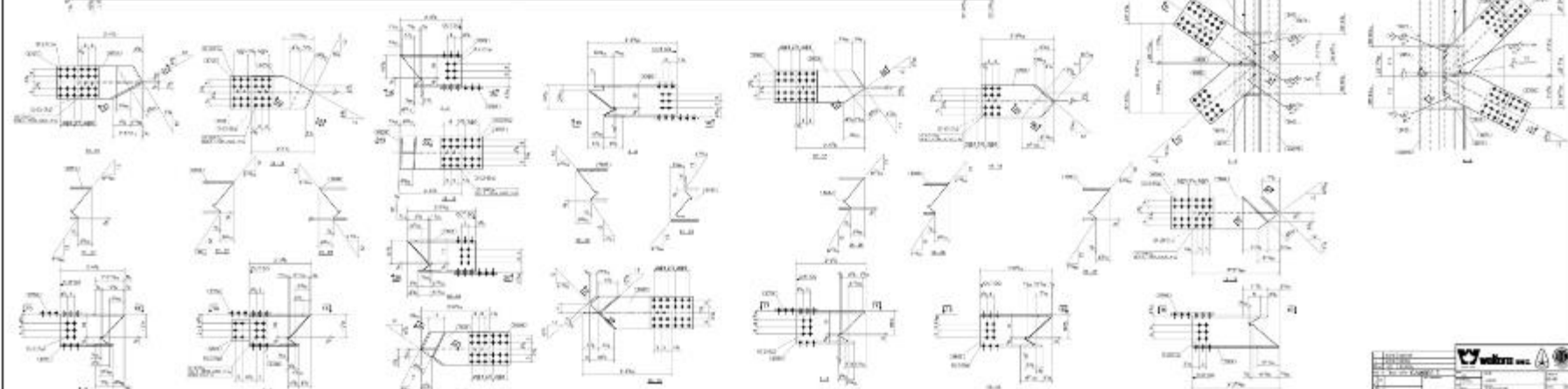
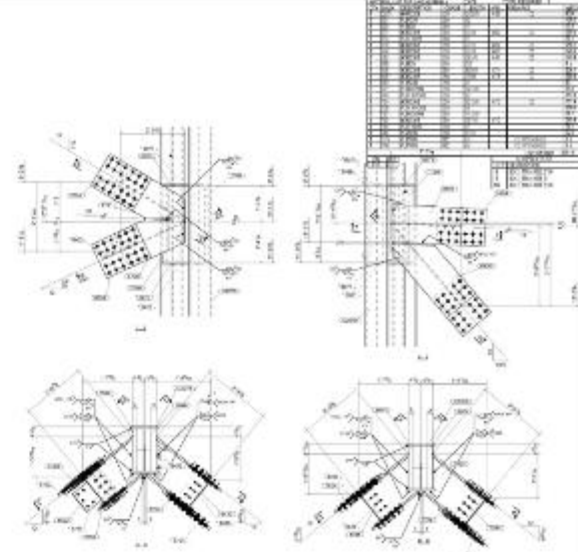
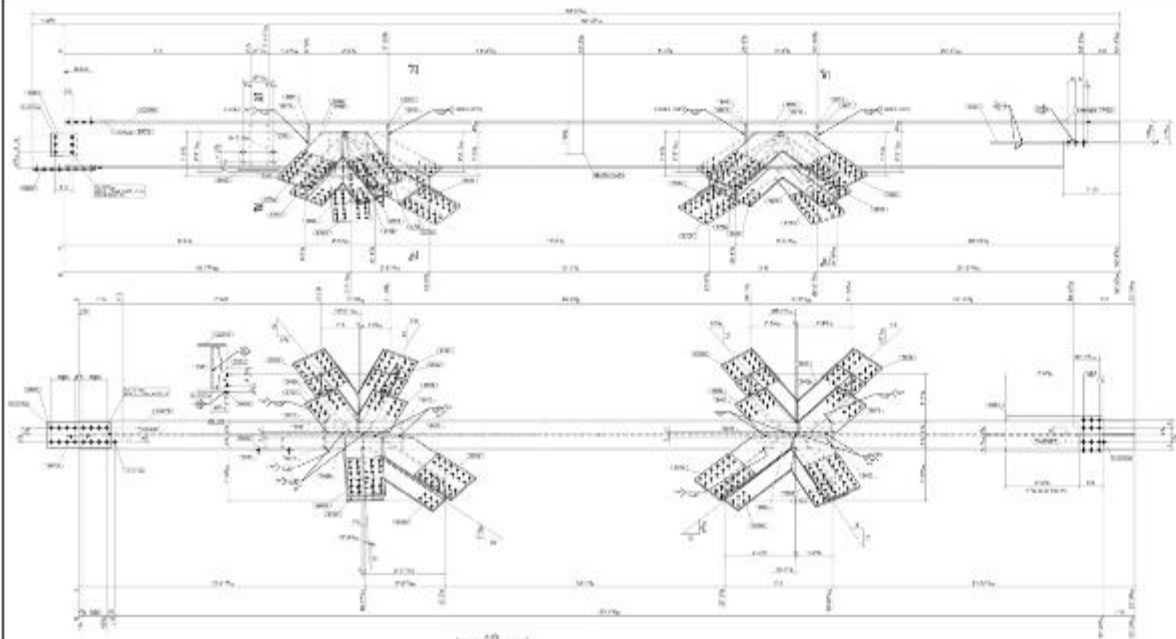
## IX. Steel and Sustainability

National Works Yard, Vancouver, Omicron

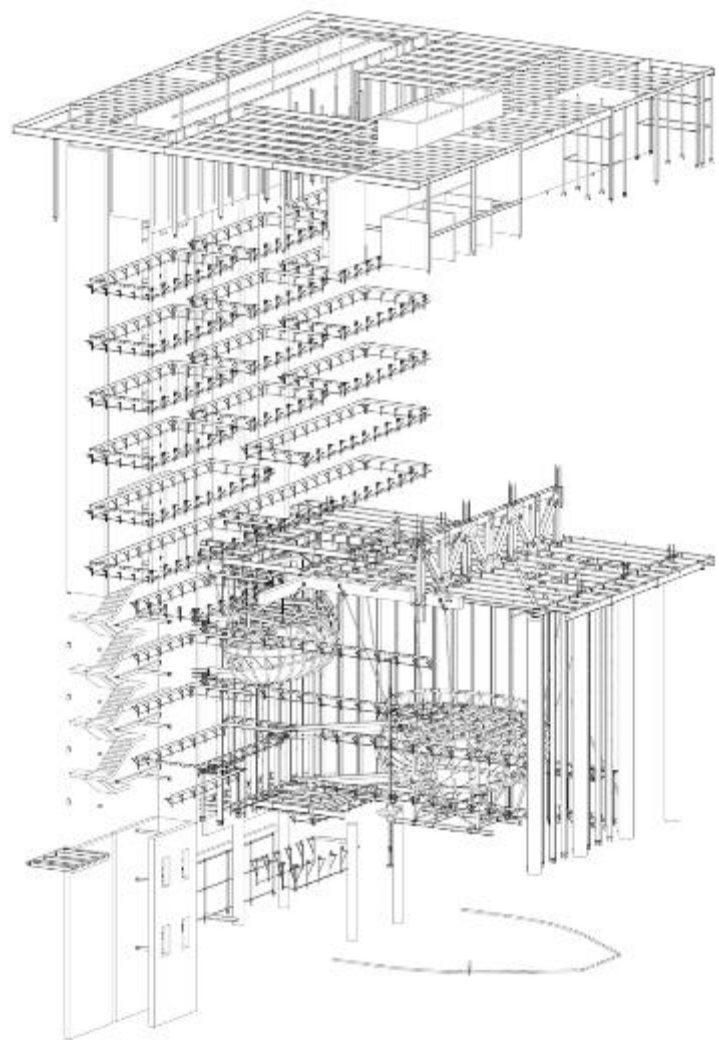




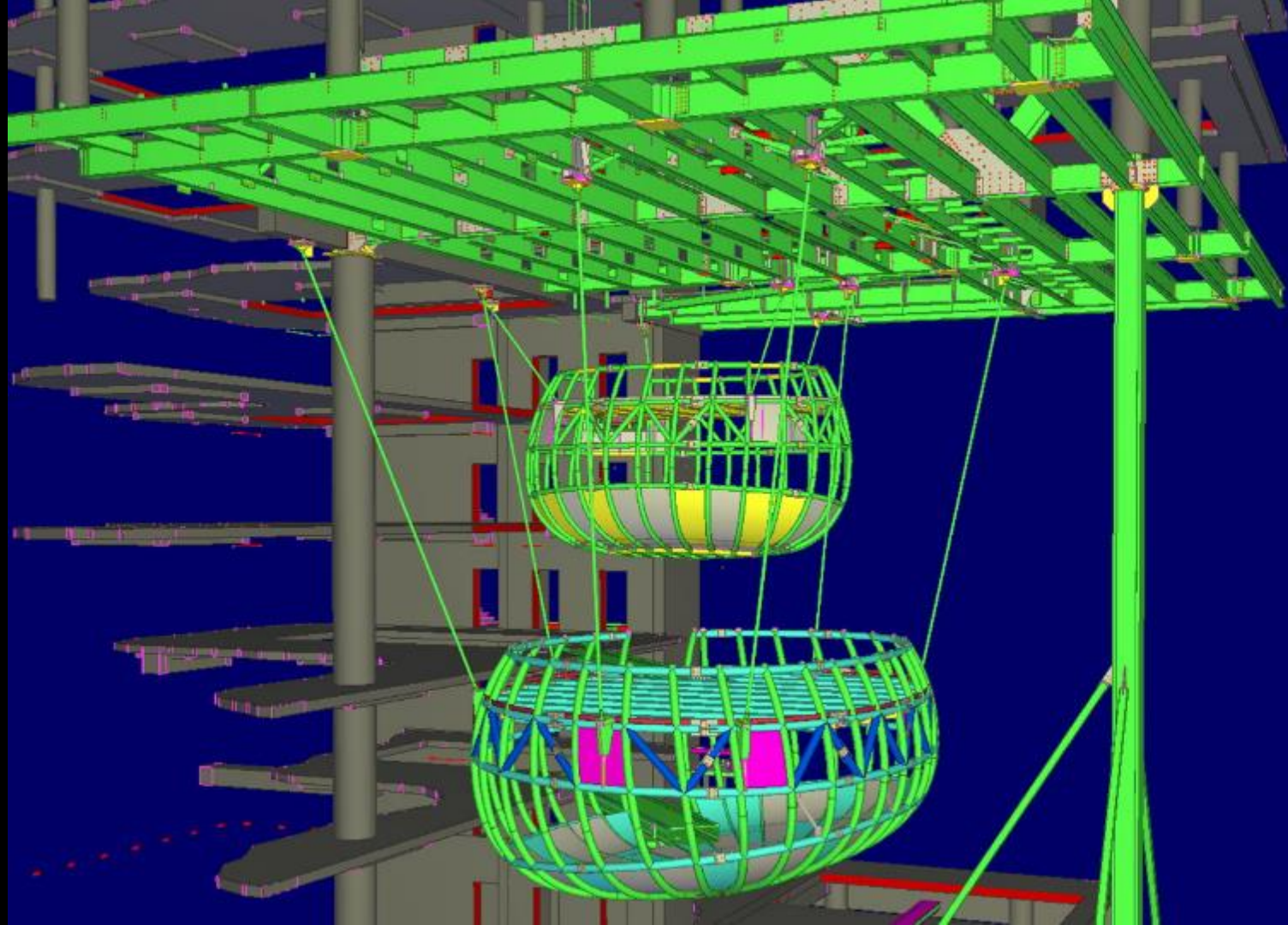


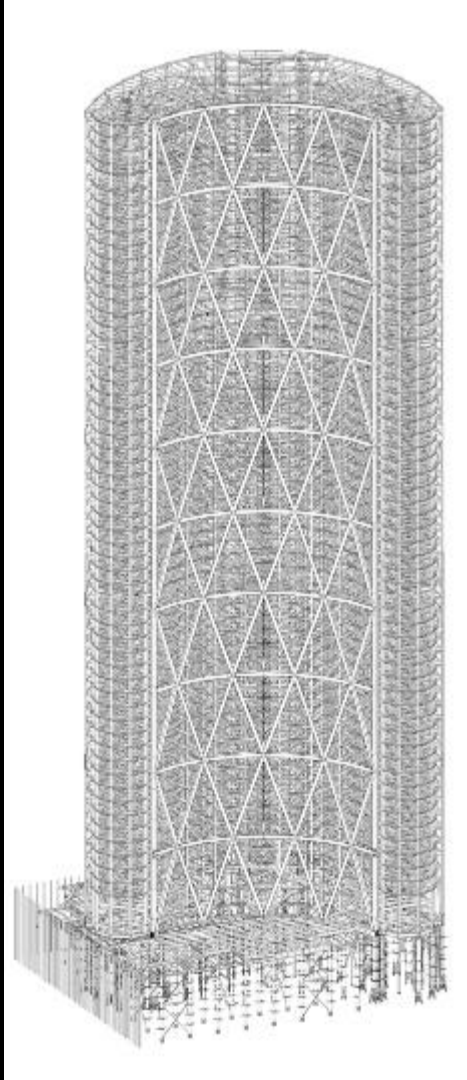


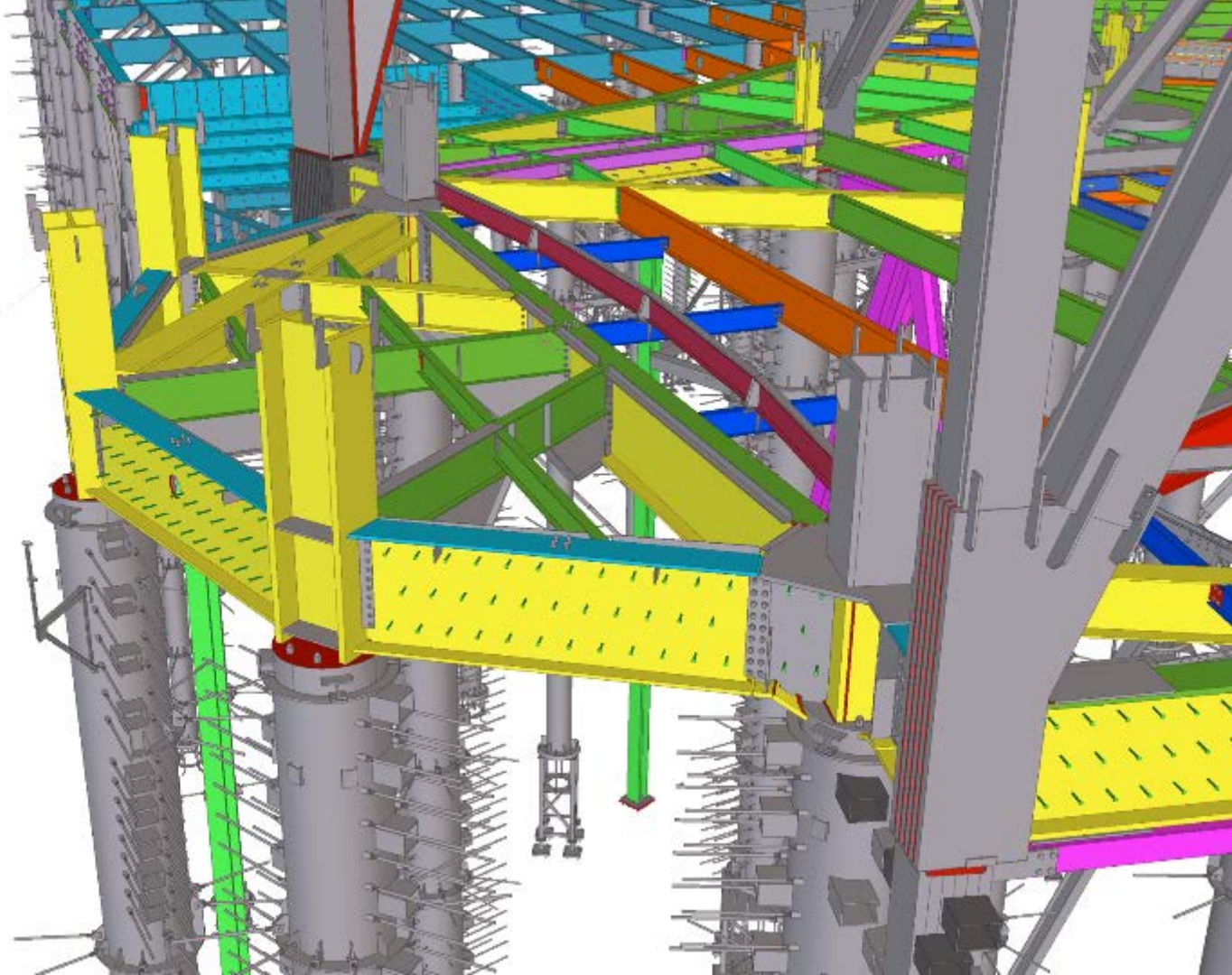
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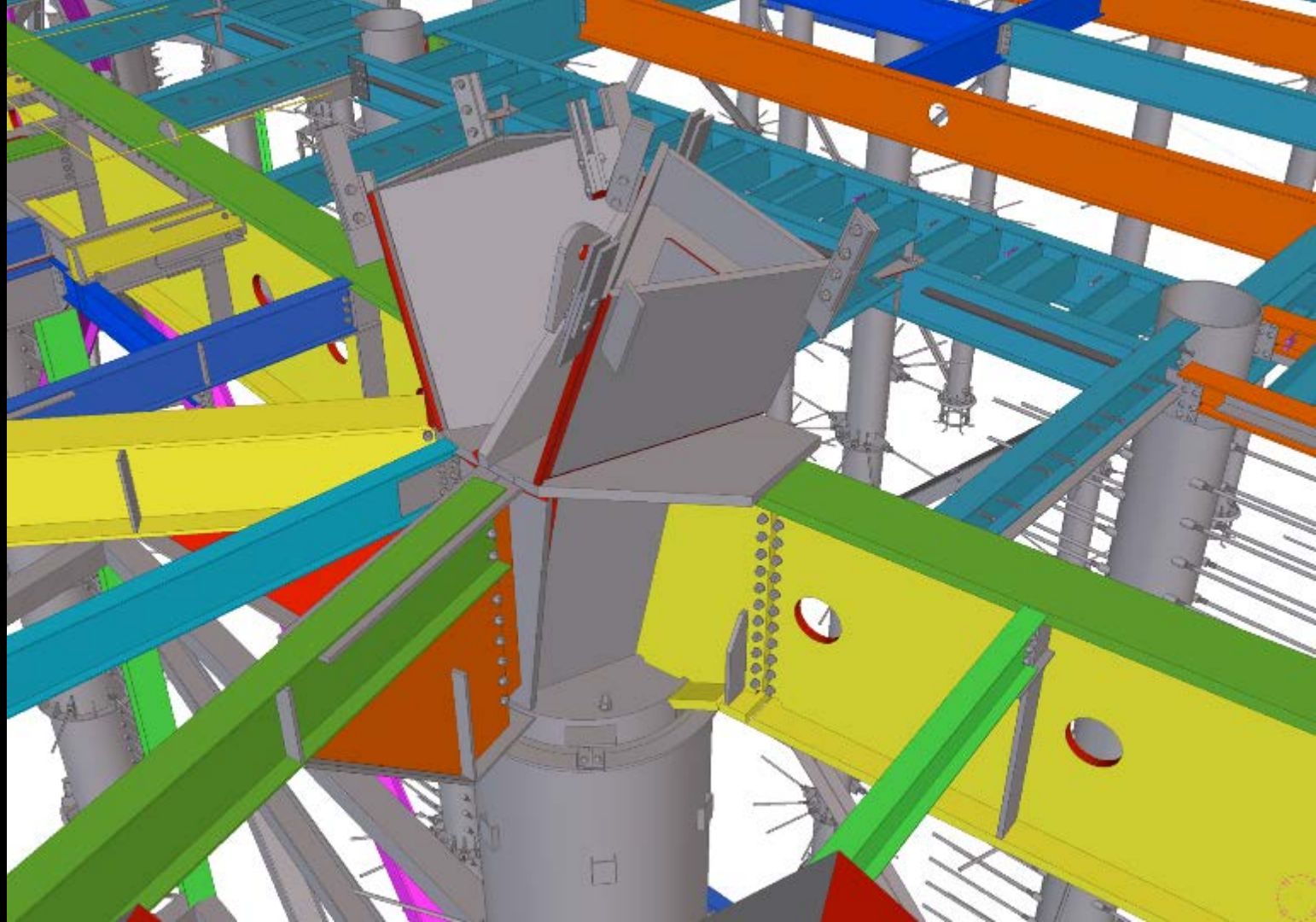


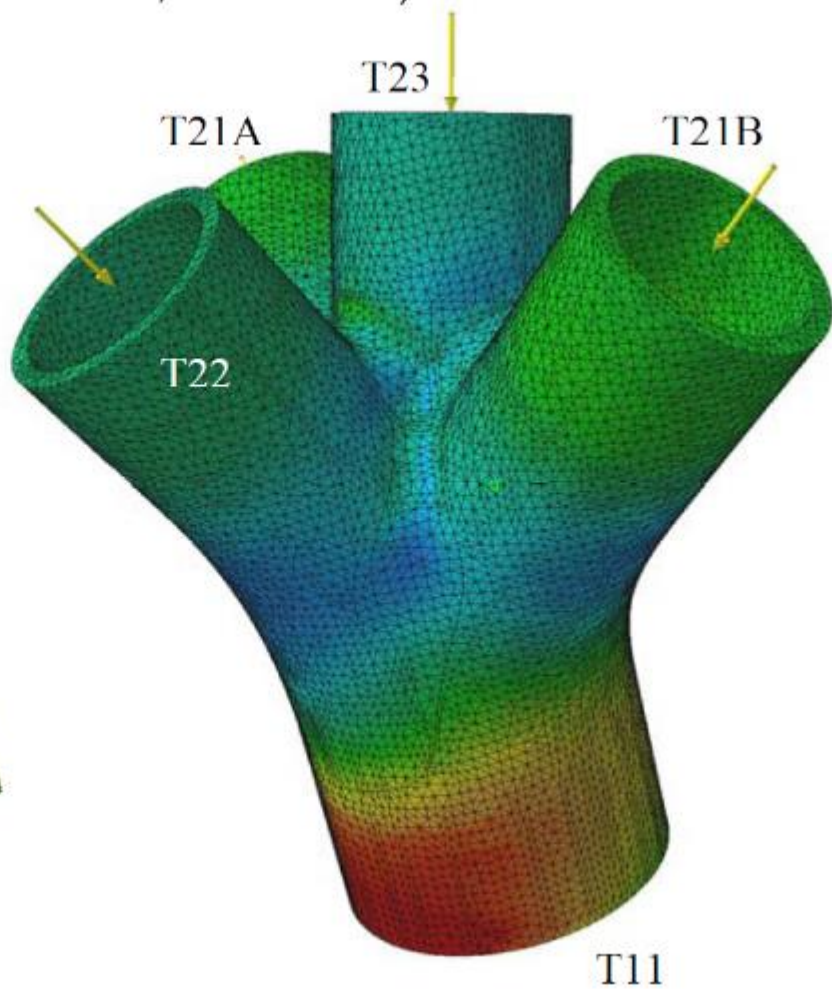
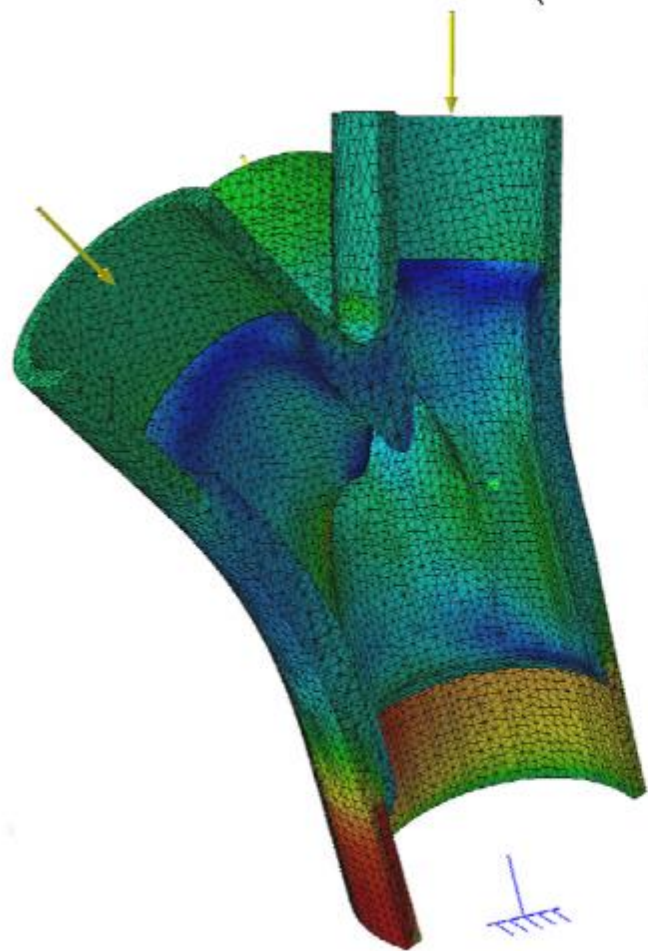












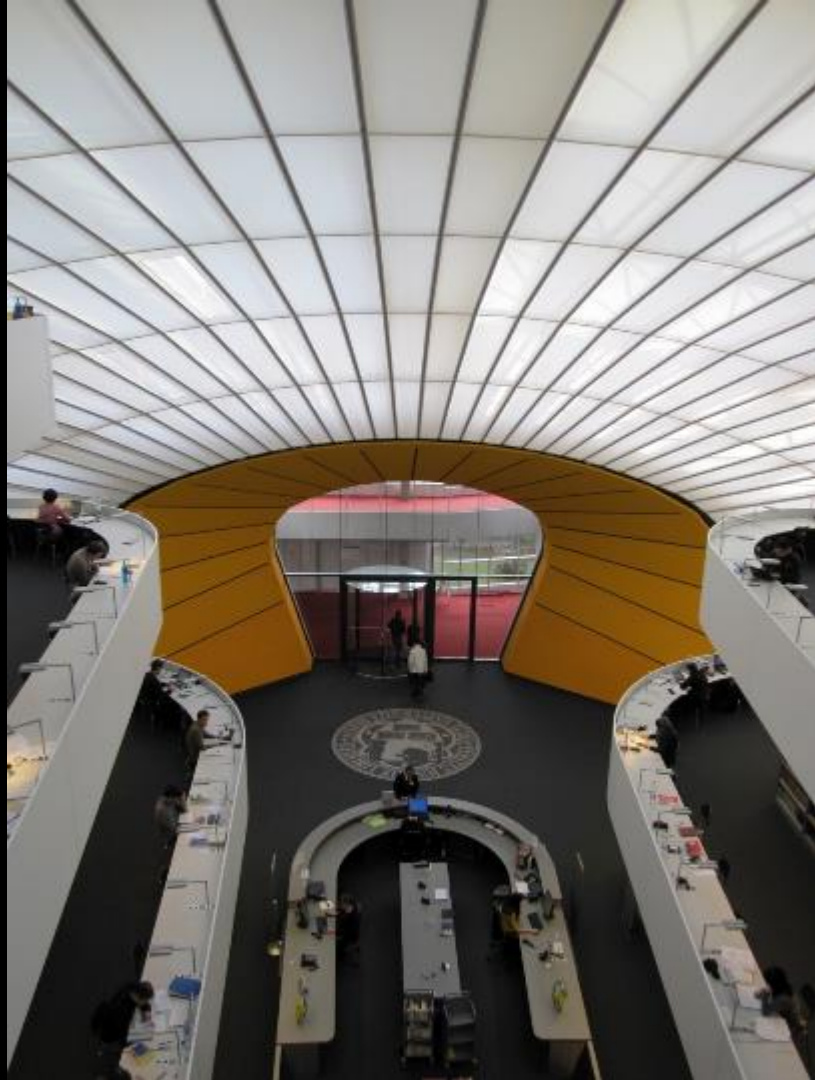


















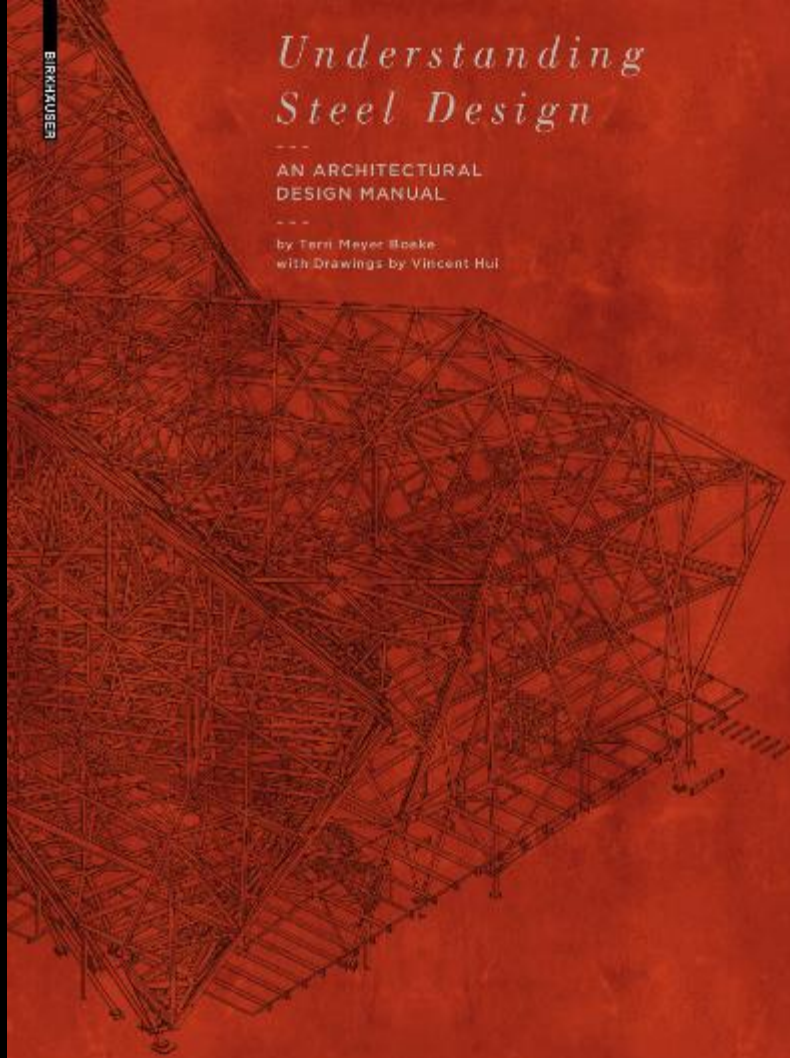


BRUNNEN

# *Understanding Steel Design*

---  
AN ARCHITECTURAL  
DESIGN MANUAL

---  
by Terri Meyer Boker  
with Drawings by Vincent Hul





Steel: A History of Strength. A Future of Possibilities.



**express it**  
use architecturally exposed structural steel categories



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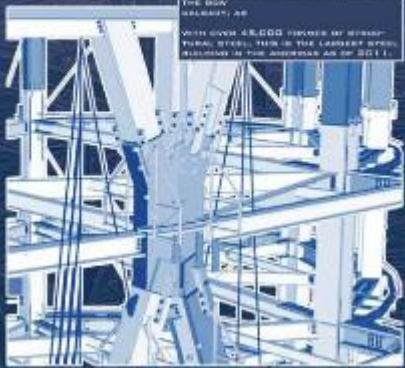
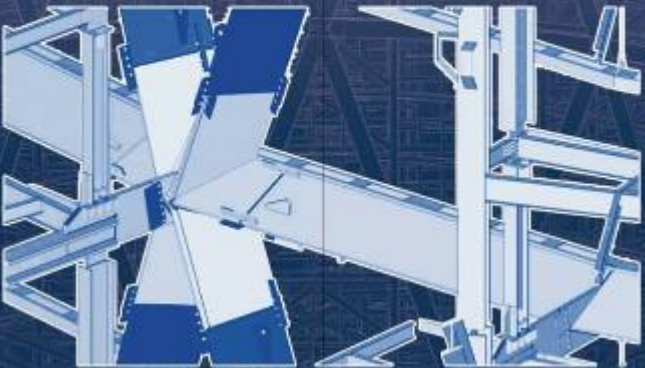
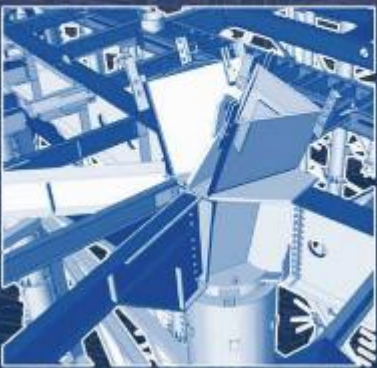
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CHAPTER 1

THE TRANSFORMATIVE  
NATURE OF IRON  
AND STEEL  
CONSTRUCTION

THE INTRINSIC CONNECTION BETWEEN  
HISTORIC DEVELOPMENTS IN STEEL  
AND MODERN ARCHITECTURE

STEEL IS ABOUT TENSION

STEEL IS ABOUT INDUSTRIALIZATION AND MASS FABRICATION

STANDARD STRUCTURAL STEEL VERSUS ARCHITECTURALLY EXPOSED STRUCTURAL STEEL (AESS)

FROM TECHNIQUE TO TECHNOLOGY

Oriental Pearl Tower. The  
Oriental Pearl Tower is an  
icon for the Hong Kong  
area. The design is distinctive,  
which is due to the impact  
of the postmodernist style,  
which emphasizes a skyline  
that breaks the hierarchy.  
What are these buildings?  
Structural steel skeletons,  
but concrete cores are used  
enhancing the potential of  
the materials and the struc-  
tural properties of steel have  
been used in architecture.





*CHAPTER 2*

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## *THE MATERIALITY OF STEEL*

---

*STRUCTURAL PROPERTIES OF STEEL*

*HOT-ROLLED STEEL SHAPES*

*HOLLOW STRUCTURAL SECTIONS*

*ECONOMIES IN DETAILING AND SPECIFYING  
STEEL (HSS)*

*DESIGN AND MODELING SOFTWARE*

There is a wide range of steel  
shapes in production. The  
availability of members varies  
by geographic location.



CHAPTER 3

STEEL CONNECTIONS  
AND  
FRAMING TECHNIQUES

THE IDEA BEHIND FRAMING

BASIC CONNECTION STRATEGIES

FRAMED CONNECTIONS

BEAM-TO-GIRDER CONNECTIONS

GIRDER OR BEAM-TO-COLUMN CONNECTIONS

COLUMN CONNECTIONS

PIN CONNECTIONS

FLOOR SYSTEMS

BRACED SYSTEMS, MMM

TRUSS SYSTEMS

PLANAR TRUSSES

THREE-DIMENSIONAL TRUSSES

The intricate steel structure of the Frank Gehry designed *Qatar Airways* shopping mall in Doha, Qatar, designed by Skidmore, OWINGS & Merrill, is a masterpiece of steel construction. The structure is a complex of interconnected steel members that form a series of overlapping, diamond-shaped trusses. The structure is a masterpiece of steel construction, and the image shows a close-up view of the steel members and their connections. The structure is a masterpiece of steel construction, and the image shows a close-up view of the steel members and their connections.





CHAPTER 4

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*FABRICATION,  
ERECTION AND  
THE IMPLICATIONS  
ON DESIGN*  
---

*TRANSFORMING ARCHITECTURAL DESIGN INTO  
FABRICATED ELEMENTS*

*PROCESS PROFILE: THE ADDITION TO THE ROYAL  
ONTARIO MUSEUM (ROM) – MICHAEL LEE-CHIN  
CRYSTAL / STUDIO DANIEL LIBESKIND*

THE ROLE OF PHYSICAL AND DIGITAL MODELS

APPRECIATING SCALE

TRANSPORTATION AND SITE ISSUES AND THE IMPACT ON DESIGN

ERECTING THE STEEL

THE EFFECTS OF WEATHER AND CLIMATE ON ERECTION

PROVIDING PERMANENT STABILITY FOR THE FRAME

COORDINATION WITH OTHER SYSTEMS

*PROCESS PROFILE: THE LESLIE DAN SCHOOL OF  
PHARMACY / FOSTER + PARTNERS*

SHOP FABRICATION

ASSEMBLING THE PODS

ERECTING A BEAM

ERECTING THE COLUMN

LIFTING THE 50-TONNE TRUSS

LIFTING THE PODS

Steel members to about 100,000 lbs. A large number of connections made in advance to that of the "spine" of the Leslie Dan School of Pharmacy in Toronto, Ontario designed by Foster + Partners. This is the first installation of its kind for the architect as well as the fabricator, Waters Inc. The entire structure is fabricated in steel to capture the look of the original structure and to check the fit for clearance.





CHAPTER 5

ARCHITECTURALLY  
EXPOSED STRUCTURAL  
STEEL (AESS): ITS HISTORY  
AND DEVELOPMENT

THE INVENTION OF HOLLOW STRUCTURAL  
SECTIONS (HSS)

THE EVOLUTION OF AESS THROUGH THE HIGH  
TECH MOVEMENT

THE TYPOLOGY OF EARLY HIGH TECH  
ARCHITECTURE

THE "EXTRUDED" TYPOLOGY

Sainsbury Centre for Visual Arts | Norman Foster

Centre Georges Pompidou | Renzo Piano and Richard Rogers

THE "GRID/BAY" TYPOLOGY

Renault Centre | Norman Foster

The Menil Collection | Renzo Piano

THE "TOWER-AND-TENSILE" TYPOLOGY

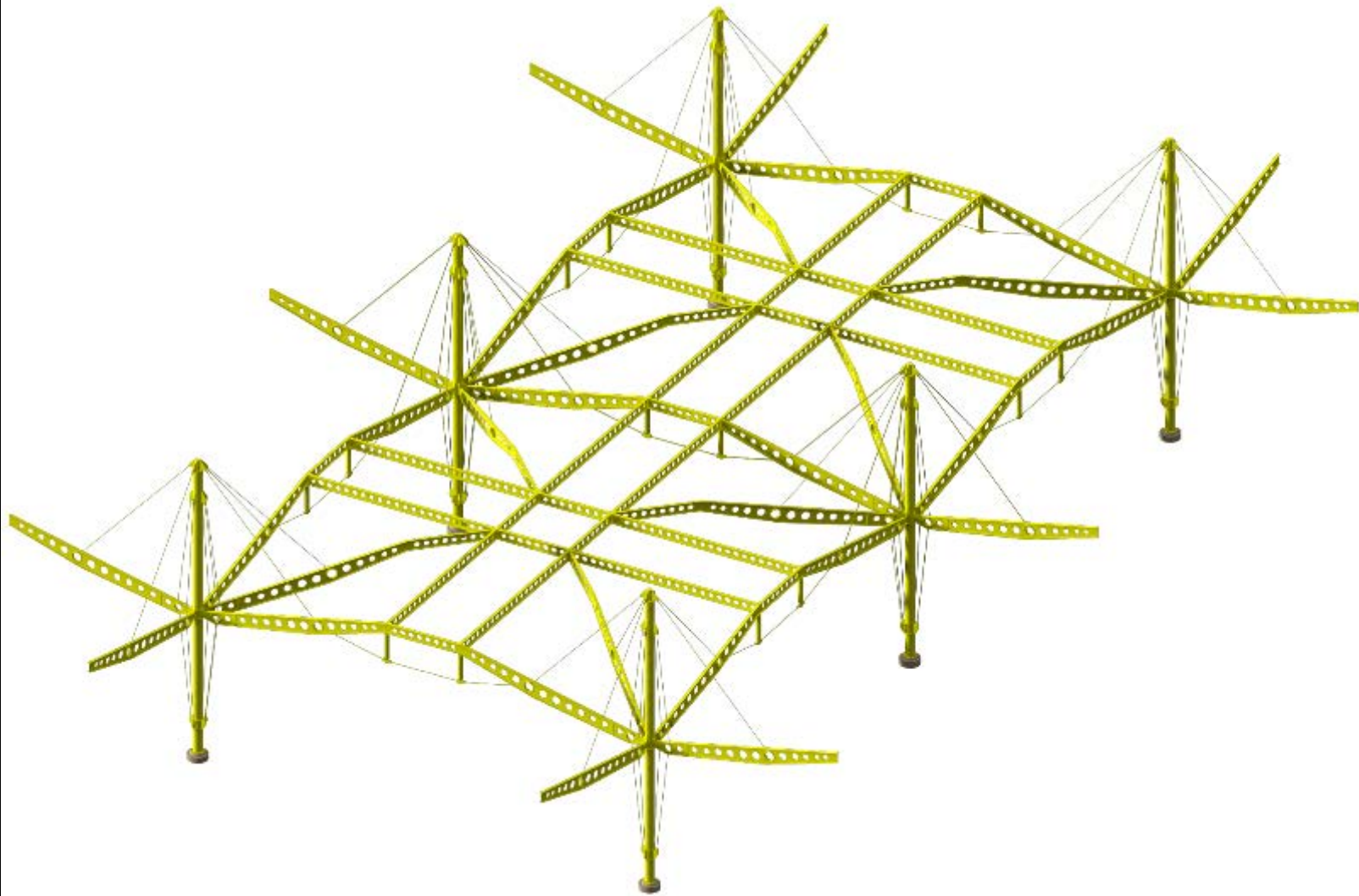
Oxford for Risk | Nicholas Grimshaw

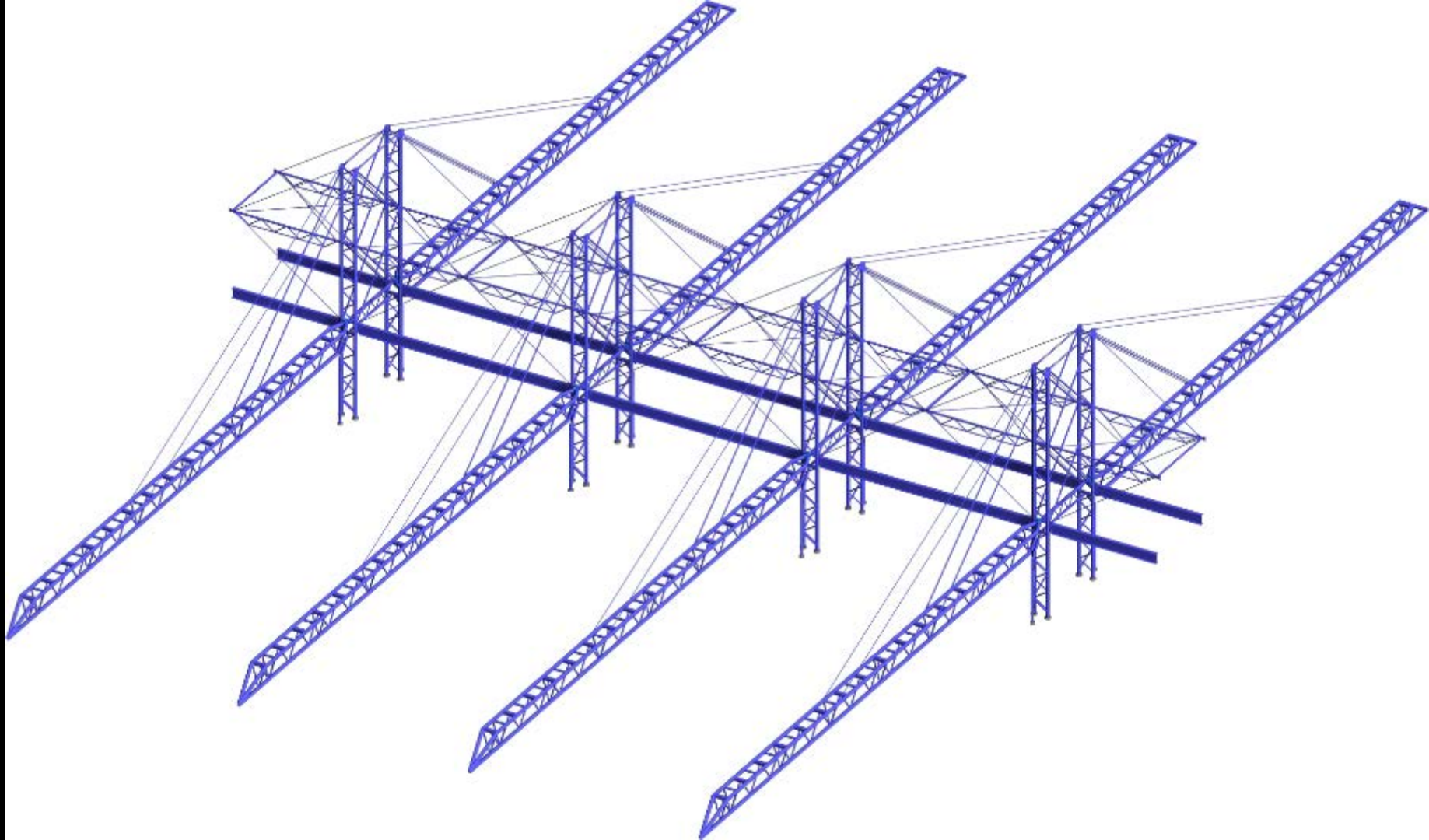
Inmos Microprocessor Factory | Richard Rogers

HIGH TECH BECOMES ARCHITECTURALLY  
EXPOSED STRUCTURAL STEEL (AESS)  
RESULTANT BUILDING SCIENCE PROBLEMS

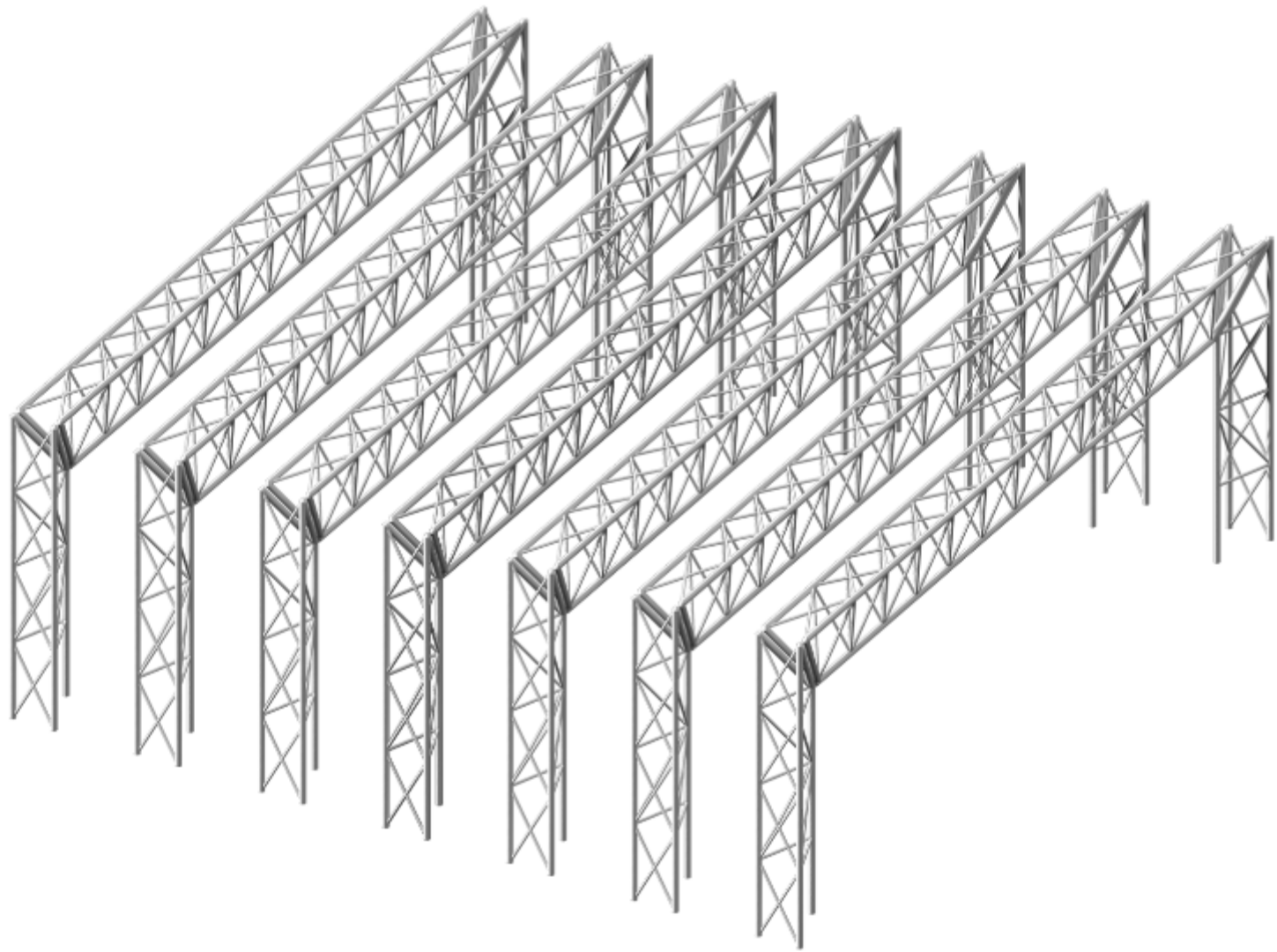
The Centre Georges Pompidou  
in Paris, France was constructed  
between 1971 and 1977. It was  
designed by the team of Renzo  
Piano and Richard Rogers and  
clearly exemplifies the early High  
Tech style of exposed and organized  
services.











CHAPTER 6

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*ARCHITECTURALLY  
EXPOSED STRUCTURAL  
STEEL (AESS):  
DESIGN AND DETAILING  
REQUIREMENTS*  
---

*STANDARD STRUCTURAL STEEL VERSUS AESS  
WHAT IS AESS?*

*PRIMARY FACTORS THAT DEFINE AESS*

*CATEGORIES OF AESS*

*DETAILING REQUIREMENTS*

CONNECTION MOCK-UPS

CUTTING STEEL

*CHOOSING CONNECTION TYPES*

BOLTED CONNECTIONS

WELDED CONNECTIONS

CAST CONNECTIONS

*CHOOSING MEMBER TYPES*

TUBULAR SECTIONS

STANDARD STRUCTURAL SHAPES

*CONSTRUCTION BEST PRACTICES*

CARE IN HANDLING

TRANSPORTATION ISSUES

SEQUENCING OF LIFTS

SITE CONSTRAINTS

ERECTION ISSUES

Architecturally Exposed Structural Steel, with its first case study for [Dome of the Holy Spirit, Bucharest, the Central Bank of the Republic of Moldova, Cluj-Napoca](#) (credited to James + Partners), has experienced a higher requirements for fabrication, erection and detailing than regular construction. These requirements result from the design from the outset of the project and from the constant collaboration of construction between the architect, engineer and fabricator.



CHAPTER 7

COATINGS,  
FINISHES AND FIRE  
PROTECTION

THE NEED FOR CORROSION PROTECTION  
THE NEED FOR FIRE PROTECTION  
PREPARING THE STEEL FOR COATINGS  
FINISH AND COATING SYSTEM SELECTION

PRIMERS

PAINT SYSTEMS FOR AESS

SHORTCOMINGS OF PAINTED FINISHES

SHOP VERSUS SITE PAINTING

CORROSION PROTECTION SYSTEMS

GALVANIZATION

METALLIZATION

WEATHERING STEEL

STAINLESS STEEL

FIRE PROTECTION SYSTEMS

FIRE SUPPRESSION SYSTEMS

SPRAY-APPLIED FIRE PROTECTION

CONCRETE

INTUMESCENT COATINGS

Material for construction of the Olympic Stadium in China in Beijing is shown here. The steelwork requires heavy and often white metalizing layers and surface treatments to create a protective barrier and to shield with a series of coatings of self-applied materials. The system that has been used, followed by two spray-applied coats of "Zing", a spray-applied intumescent layer of Epoxy Masticure (see Table 7.10), followed by two spray-applied coats of epoxy Emulsion finish.





*CHAPTER 8*

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*CURVED STEEL*

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*CREATING CURVES IN STEEL BUILDINGS*

*LIMITATIONS ON CURVING STEEL*

*THE CURVING PROCESS*

*CURVED STEEL APPLICATIONS*

*FACETING AS AN ALTERNATE  
METHOD TO BENDING*

*CREATING CURVES WITH PLATE MATERIAL*

The large curved steel IBS members of the pedestrian bridge at the Millstone building in Salt Lake City, UT, USA, designed by HKS Architects, provide a striking contrast with the glass facade they support as well as the tower behind. Highly specialized processes are essential to bend steel at this scale.



CHAPTER 9

ADVANCED FRAMING  
SYSTEMS: DIAGRIDS

TALL BUILDINGS

DIAGONALIZED CORE BUILDINGS

TRUSS BAND SYSTEMS

BUNDLED TUBE BUILDINGS

COMPOSITE CONSTRUCTION

WIND TESTING

DIAGRID SYSTEMS

THE ADVANTAGE OF A DIAGRID OVER A MOMENT FRAME

DIAGRID TOWERS

PROCESS PROFILE: BOW ENCANA, CALGARY | FOSTER + PARTNERS

CURVED DIAGRID-SUPPORTED SHAPES ON LOW TO MID-RISE BUILDINGS

CRYSTALLINE DIAGRID FORMS

HYBRID SHAPES

The Bow Encana Building in  
Calgary, AB, Canada, designed  
by Foster + Partners with Zaha  
Partnership and engineered by  
MBJ, uses an expression of a  
curved diaphragm system for the  
tower's building.



CHAPTER 10

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HISTORIC AND CONTEMPORARY CASTING

BASIC TYPES OF CAST CONNECTORS  
FOR STRUCTURAL STEEL

TENSILE CONNECTORS

BASE CONNECTIONS

BRANCH-TYPE CONNECTIONS

PROCESS PROFILE: UNIVERSITY OF  
GUELPH SCIENCE BUILDING / YOUNG + WRIGHT  
ARCHITECTS

Detailing Aspects in Shanghai  
China by Paul Anderson  
The University of Guelph Science Building is a  
prime example of a building where the  
structural design and the  
architectural design are  
integrated. The building  
is a prime example of the  
integration of the  
architectural and  
structural design.





CHAPTER 11

TENSION SYSTEMS AND  
SPACEFRAMES

TENSION SYSTEMS

TENSION CONNECTORS

CROSS BRACING

INNOVATIVE FORCE EXPRESSION IN TRUSSES

SIMPLE CANOPIES

CABLE-STAYED SYSTEMS

TENSORITY STRUCTURES

SPACEFRAME SYSTEMS

NON-PLANAR SPACEFRAMES

IRREGULAR MODULES

The cable fabric structure was able to resist strong winds of 140 km/h and temperatures that can only be found in a highly urbanised area, structures and connections. The glass fabric and steel roof of the Sony Centre at Newquay, Cornwall, UK, designed by Howard Jucker, is a landmark in modern public space.



*CHAPTER 12*

*STEEL AND  
CONTEMPORARY  
GLAZING SYSTEMS*

*EARLY STEEL AND GLASS BUILDINGS*

*TECHNICAL ASPECTS OF COMBINING STEEL  
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*CONTEMPORARY SUPPORT SYSTEMS FOR  
GLAZING*

*SELECTING THE APPROPRIATE SYSTEM*

*SIMPLE CURTAIN WALL SUPPORT SYSTEMS*

*SIMPLE WIND-BRACED SYSTEMS*

*CABLE-SUPPORTED STRUCTURAL GLASS  
ENVELOPES*

*CABLE NET WALLS*

*STAINLESS STEEL SPIDER CONNECTORS*

*CABLE TRUSS SYSTEMS*

*COMPLEX CABLE SYSTEMS*

*OPERABLE STEEL AND GLASS SYSTEMS*

*HANDLING CURVES*

*LATTICE SHELL CONSTRUCTION*

The highly innovative cable  
glazing system, the Tower  
at the Paris Expo,  
designed by U. K. Frey and  
Dier Sieb, characterizes the  
extensive studies between the  
functions of load-bearing,  
insulation and the possible form  
of steel glazing systems.



CHAPTER 13

\*\*\*

**ADVANCED  
FRAMING SYSTEMS: STEEL  
AND TIMBER**

---

*CHARACTERISTICS*

*DETAILING ISSUES*

*FABRICATION AND ERECTION ISSUES*

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*HIDDEN STEEL*

*PROCESS PROFILE: ADDITION TO ART GALLERY  
OF ONTARIO (ACO) / FRANK CEHRY*

*PROCESS PROFILE: THE RICHMOND SPEED  
SKATING OVAL / CANNON DESIGN*

The glass and timber facade of the Addition to the Art Gallery of Ontario, Toronto, ON, Canada, designed by Frank Gehry, relies on exposed steel framing to support and to the structural steel of the building. The design and construction of various steel details provide an integrated approach to connecting the structural steel and timber parts of the two materials.





CHAPTER 14

---  
**STEEL AND  
SUSTAINABILITY**  
---

**STEEL AS A SUSTAINABLE MATERIAL**

**THE LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN (LEED<sup>®</sup>) GREEN BUILDING RATING SYSTEM**

**RECYCLE VERSUS REUSE**

**RECYCLED CONTENT**

**COMPONENT REUSE**

**ADAPTIVE REUSE**

**SUSTAINABLE BENEFITS OF ARCHITECTURALLY EXPOSED STRUCTURAL STEEL (AESS)**

**LOW-CARBON DESIGN STRATEGIES IN STEEL CONSTRUCTION**

**REDUCE MATERIAL**

**REDUCE FINISHES**

**REDUCE LABOR**

**REDUCE TRANSPORTATION**

**DURABILITY**

The galvanneel trusses on the Lakeland Public Center, Lakeland, Florida, provide the exterior exposed steel with a durable and rugged appearance that contributes to the sustainable nature of the facility design. Steel is packaged and finished according to standard trade practices to meet the scheduling of construction. However, the material here is covered from high recycled content rather than virgin ore. The galvanneel finish means less waste by minimizing repainting for its service as an exterior finish. The exposed steel provides the most sustainable building materials, using recycled energy.



CHAPTER 15

---  
*STEEL IN TEMPORARY  
EXHIBITION BUILDINGS*  
---

The E.ON Energy Centre for the Stuttgart Expo 2009 (Image designed by SIA Architects) exploits the inherent potential of steel as its structural backbone of the steel lattice grid with a cantilevered perimeter plate using the proven manufacturing technique of rolling advanced engineering of Germany.



Patty Boske-Armour *Copy*  
16850 St. Andrews Road  
Caledon, ON L7C 2R9  
Tel: 905-584-6667 • Fax: 905-584-6668

*1/2/12*

*Dear Patty and Terri*

*How wonderful of you to send me  
Terri's ingenious book. I shall read it  
with great pleasure as I worked for 7  
decades at Algoma Steel from 1953-  
1966 and was always looking for more and  
better ways to use steel.*

January 3, 2012

His Excellency the Right Honourable David Johnston  
Governor General of Canada  
Rideau Hall  
1 Sussex Drive  
Ottawa, ON K1A 0A1

*Brave and long line work  
outstanding School of Architecture  
Unsung hero  
Jan 1/12*

Your Excellency,

On the occasion of your address to the University Club of Toronto in February, 2010, as President of the University of Waterloo, we had the pleasure of chatting with you before dinner, mentioning my daughter in law, Terri Boske, who was a member of your Faculty.

Terri has recently published the enclosed book "Understanding Steel Design" for use by students of architecture, and their teachers. Its creation took her to many parts of the world, and she is very happy that her child has now been safely delivered.

I feel that the book is a tribute, not only to Terri, but to the high standards of the University of Waterloo. Both Terri and I would like you to accept this copy.

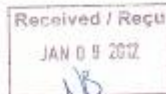
With kind regards,

*Patty Boske*

Patty Boske

PB/joc

Encl.



*Book "Understanding  
Steel Design"*

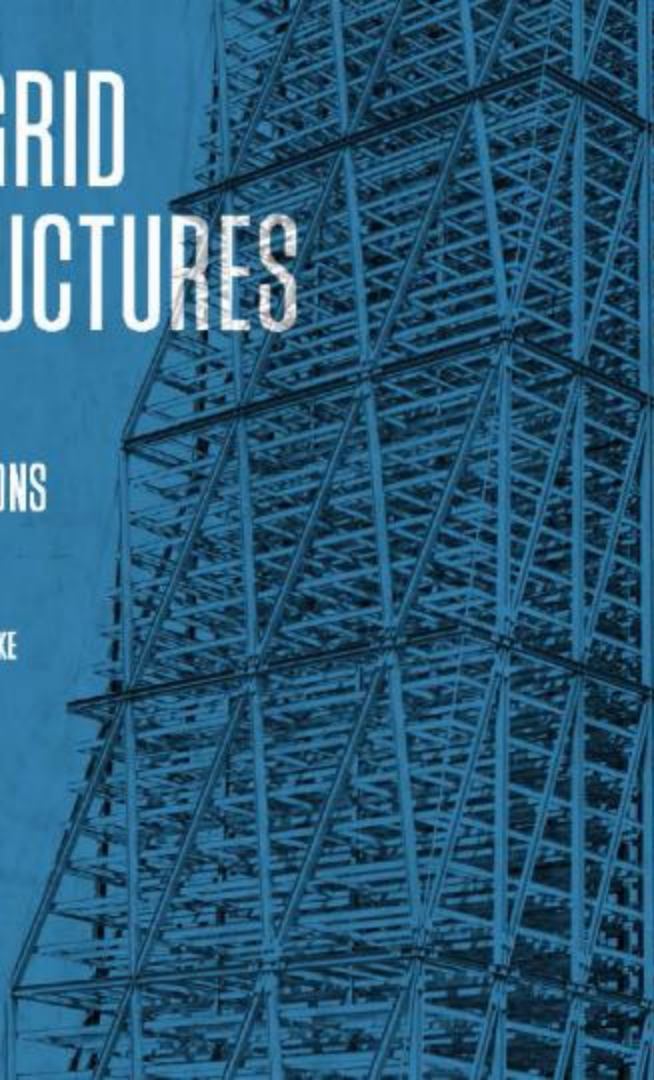


BIRKBECKER

# DIAGRID STRUCTURES

SYSTEMS  
CONNECTIONS  
DETAILS

TERRI MEYER DOAKE

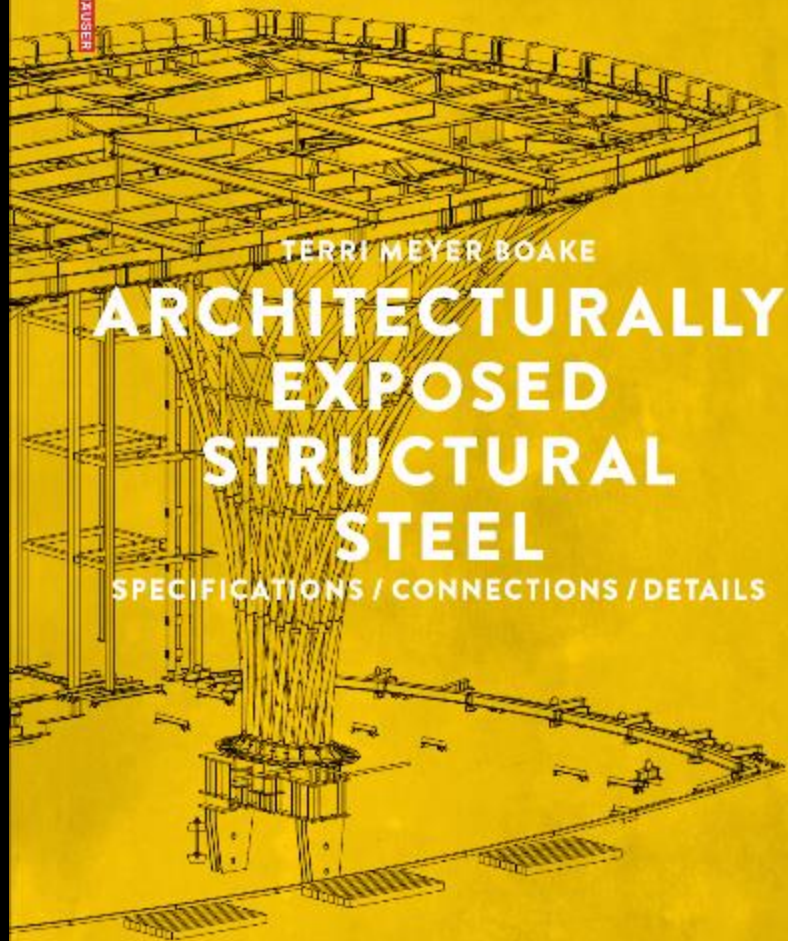


BIRKBECKER

TERRI MEYER BOAKE

# ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

SPECIFICATIONS / CONNECTIONS / DETAILS



AESS 1



AESS 2



AESS 3



AESS 4



## AESS Category Matrix

	AESS C	AESS 4	AESS 3	AESS 2	AESS 1	SSS
	Custom Elements	Showcase Elements	Feature Elements	Feature Elements	Basic Elements	Standard Structural Steel
<b>Characteristics</b>			viewed at a distance <math>< 20ft</math>	viewed at a distance <math>> 40ft</math>		
1.1 Surface preparation to SSPC or AS1627 Sa2/Class 2		x	x	x	x	
1.2 Sharp edges ground smooth		x	x	x	x	
1.3 Continuous weld appearance		x	x	x	x	
1.4 Ball head connections specified		x	x	x	x	
1.5 Weld spatters removed		x	x	x	x	
2.1 Visual Samples		OPTIMAL	OPTIMAL	OPTIMAL		
2.2 One half standard fabrication tolerances		x	x	x		
2.3 Fabrication marks not apparent		x	x	x		
2.4 Weld surface and finish		x	x	x		
3.1 All marks removed		x	x			
3.2 Bolt and plug welds ground smooth and filed		x	x			
3.3 GSA/SHOUST welds were oriented for enhanced stability		x	x			
3.4 Cross-sectional abutting surface aligned		x	x			
3.5 Joint gap tolerances minimized		x	x			
3.6 All-welded connections		OPTIMAL	OPTIMAL			
4.1 GSA/SHOUST welds were not apparent		x				
4.2 welds contoured and blended		x				
4.3 Surfaces filed and sanded		x				
4.4 weld thru-through shielded		x				
C1						
C2						
C3						
C4						
C5						
Sample use	Elements with special requirements	Showcase or dominant elements	Airports, shopping centers, hospitals, lobbies	Retail, and architectural elements viewed as a distance	Roof trusses for arenas, retail, warehouses, canopies	
Estimated cost premium	Low to high (20-250%)	High (100-250%)	Moderate (60-150%)	Low to moderate (40-100%)	Low (20-80%)	None or





The Munich Airport Terminal in Munich, Germany, designed by Helmut Jahn and completed in 1991, showcases high-level detailing in Architecturally Exposed Structural Steel.

## FOREWORD

The World Steel Association (worldsteel) is proud to be the exclusive sponsor of *Architecturally Exposed Structural Steel: Specifications, Connections, Details, Construction* is one of the most important steel-using industries, globally accounting for more than 50% of world steel use. Buildings – from houses to car parks to schools to skyscrapers – rely on steel for their strength and durability. In addition to structural frameworks, steel is also used on many other parts of buildings, including roofs and cladding for exterior walls.

Steel continues to be at the root of advances in architecture and construction. The use of exposed steel in buildings brings the design benefits and dynamic potential of steel to the public eye. Its stiffness allows steel to span greater distances and provides more design freedom than other materials. Steel's superior strength-to-weight ratio makes it possible for the structure to bear high loads using less material. Architecturally Exposed Structural Steel (AESS) plays a significant role also in the design of contemporary pedestrian bridges that elevate their role in the urban realm to that of art.

Sustainable steel is at the core of a green economy. Reusing or recycling building components is key to the sustainability of a structure's end-of-life as it is the most economic and ecological solution. The global recovery rates for steel construction applications stand at 85%, making it a good choice for building structures. The exposure of steel leads to a reduction of materials that would otherwise be used to conceal the structural systems, while at the same time creating stimulating architecture.

Steel is safe, innovative and progressive. Industry surveys consistently demonstrate that steel is the safest construction material. Steel offers the highest strength-to-weight ratio of any building material. Because of its strength and durability, steel structures are designed to withstand natural disasters. It is also impervious to attacks from termites or fungi, does not rot or split and is highly fire-resistant. The steel industry globally spends more than €12 billion annually on improving the manufacturing processes, new product developments and future breakthrough technologies.

Steel is a key driver of the world's economy. The industry directly employs more than two million people worldwide, with a further two million contractors and four million people in supporting industries. In 2013, the steel industry had a turnover of more than \$900 billion, yielding over \$100 billion in tax.

Steel plays a fundamental role in the development of modern societies and is an ideal material to help meet the societies' growing needs for buildings and infrastructures in a sustainable way. Its intrinsic properties such as its strength, versatility, durability and 100% recyclability allow improved environmental performance across the entire life cycle of buildings.

The AESS Category System of design presented in this book acknowledges the importance of the role of proper connection design and erection strategies, and communication between the fabricator, engineer and architect, as central to ensuring safety on the site.

Dr. Edwin Basson  
Director General, World Steel Association



# THE BASIS OF ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

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- 18 Initial Developments in High Tech Detailing
- 20 Primary Factors of Influence that Define AESS
- 22 Communication Issues between Architect, Engineer and Fabricator
- 25 The Role of BIM and Detailing Software

## WHAT IS AESS?

Architecturally Exposed Structural Steel (AESS) is steel that must meet two requirements: it must be designed to be structurally sufficient to support the primary needs of the structure of the building, canopy or ancillary structures, while at the same time being exposed to view and forming a significant part of the architectural language of the building. Any structural steel that is not concealed can therefore be considered architecturally exposed. The design, detailing and finish requirements of AESS will typically exceed that of standard structural steel, which is normally concealed by other materials or finishes. This naturally increases the time and cost to design, detail, fabricate, erect and finish AESS systems.

The categorisation of structural steel as architecturally exposed necessitates a new approach to its design and detailing, in particular as not all AESS need be designed to be equally expensive. Retail stores, arenas, museums and airports will each have very different expectations of the role of the steel in the aesthetics of the building. Even within building typologies, different approaches to steel design are valid.

Part of the book is part of the AESS Handbook by AIA Architecture and USA, also from which helps the steel to create a dynamic architectural structure for the steel structure. In 2017, the book is the first of the structure due to the construction of an AESS building.



## THE CATEGORY SYSTEM

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- 27 Standard Structural Steel
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The underlying principle in the design of AESS is the establishment of categories that are differentiated by their architectural requirements and consequently by the technical and cost requirements. The categorization is fine-tuned according to issues of distance to view, type or function of the building and the required budget. A tiered category approach to specifying AESS is essential for the design and decision-making process for a project. Not all projects will have the same requirements for the steel in terms of fabrication and finishing. It is therefore a waste of expense and time to create very high-quality steel for all projects. The selection of an appropriate category for the steel in the project provides the designer with a firm starting point for design detailing.

The AESS design system that supports the rest of the book is designed to be used in any location in the world. It is designed to meet the standards of AESS 4 design. Fabrication is required to be in accordance with the section of steel and the section of steel and the section of steel.

Although the categories of AESS 1 to AESS 4 have been developed specifically for the Canadian and Australian systems, the idea of differentiated categories of AESS is generally applicable as they reflect differences in finish and detailing that respect differences in viewing distance, function and cost. The projects in this book are examined according to their potential position in the Category System, regardless of whether the system was actually used in their detailing and fabrication, with the aim to build a visual language that corresponds to the types of details and the fabrication methods that can be used in each of the AESS categories. For more information and specifications of the specific national systems visit: <http://www.cisc-icca.ca/solutions-centre/ess>. This chapter builds on information first introduced in the chapter "Architecturally Exposed Structural Steel (AESS): Design and Detailing Requirements" in *Understanding Steel Design: An Architectural Design Manual*.





The Argemosa Bridge in Madrid, Spain, designed by Santiago Calatrava, uses a variety of custom fabrication services.

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# 3

A set of characteristics is associated with each category as outlined in the previous chapter. Higher-level categories include all of the characteristics of the preceding categories, plus a set of specific additional requirements.

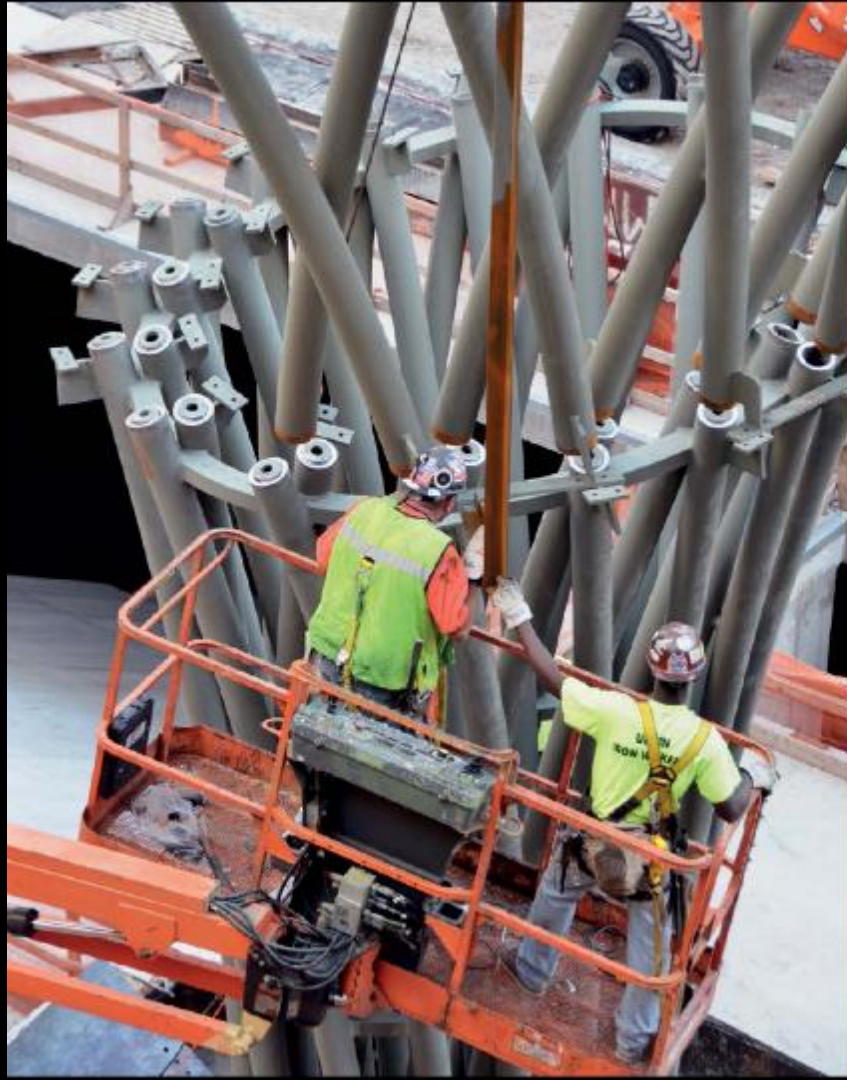
### AESS 1 – BASIC ELEMENTS

AESS 1 – Basic Elements is the first step above standard structural steel.

**1.1 The surface of the steel must be prepared using the standard of the Society for Protective Coatings for commercial blast cleaning (SSPC-SP6).<sup>1</sup> Prior to blast cleaning, any deposits of grease or oil are to be removed by solvent cleaning. Commercial blast cleaning is intended to remove all visible oil, grease, dirt, mill scale, rust, paint, oxides, corrosion products and other foreign matter, except for spots and discolorations that are part of the natural steel material. As a consequence, there should be no problems with the range of finishes that would be required for AESS 1 type applications.**



Steel prior to commercial blast cleaning carries various natural oxidation and may have other materials on the surface that would prevent proper adhesion of the paint. After commercial blast cleaning (SP6), the steel will contain mill scale. Grinding, such as is now more effective to remove problematic residues prior to painting and finishing.



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- 75 Combining AESS with Other Systems

CHAPTER

# 4

### TRANSFORMING AN ARCHITECTURAL IDEA INTO PREFABRICATED AESS ELEMENTS

There is significant work involved in transforming the architectural ideas of a steel-framed building into a series of prefabricated elements that can be readily erected on the building site. Even into the 21<sup>st</sup> century, and in spite of advances in technology, the design, fabrication and erection of steel buildings remains a hand-crafted process. This is even more true when using AESS due to the additional aesthetic requirements. There is human interaction, workmanship and decision-making during every step. The individual AESS project is quite unique so that the design, fabrication and construction must to a large extent be customized to suit the project. This might seem to run counter to the idea behind the early development of iron and steel as being suited to mass fabrication and assembly construction, while the industry still relies on these concepts as the basis for achievements in economy and speed of erection. Aspects of pure craft and pride in workmanship remain core to steel design.

Where the architect's proposal begins to stretch the limits of the use of successful precedents in detailing, fabrication and erection, fabricators are often brought into the discussion ahead of the finalization and tendering/bid phase of the project, to inform the detailing. At a later stage, the ironworkers who erect a project are critical to its proper completion. In all projects, but particularly when AESS is used, the problem-solving skills of the lead ironworker can make or break the pace, speed of erection and timely completion of the work. The ironworkers will have a sense or feel of

A single section is lifted into the base structure of the World Financial Center entry pavilion in New York City, NY, USA, designed by Peter Dinklage Park Architects, with fabrication and erection by the proprietary system. The transportation and care must be planned in the shop to ensure a good fit prior to transport. The connector at this structure and the design for a seamless AESS system requires special attention in the connections.



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The structure of the Beijing National Stadium ("Bird's Nest") in Beijing, China, designed by HOK & Arup (architect) Bakerly Inc., USA, was the largest paint project with weathering steel and surfaces that could not accommodate metallization, were treated with a series of coatings of 1100-40-9000 3000/1500. The surface was first roughened, followed by two coats of "Primer", a shop-applied metal treatment, before Epoxy Resincoat, from Delta 1950, followed by site-applied metal-topcoat, from Resincoat.

Coatings on AESS are critically important as they impact durability. SO<sub>x</sub> and NO<sub>x</sub>, by-products of high levels of traffic and certain industries and known in some regions as acid rain, can react with certain finishes causing accelerated degradation, as in the case of galvanization.

Surface preparation of the steel is the primary means to ensure proper adhesion and quality of varied finishes on all categories of AESS. This includes designing to shed water, prohibit corrosion and provide adequate layers of coatings to ensure that they last and do not wear thin in high-traffic areas.

The finish and the AESS itself must be designed to be maintained and cleaned. Choices in the color will impact cleaning frequency. The use or function of the building should inform the choice of color. Train stations, for instance, are more prone to degradation from airborne particulates. This holds for any exterior application of steel, including canopies, bridges and car park covers.





Member Section  
in Union, Portugal,  
designed by Santiago  
Calatrava, constructed  
for Expo '98, stands as  
a project that left a  
profound impression  
on AESS. The complexity  
of the fabrication  
was an important use  
of custom-fabricated  
members, a practice  
that has been included  
in reference to using  
a variety of types of steel  
and structural and  
fabrication details.

## MEMBER CHOICES

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### THE TEXTURE OF AN AESS PROJECT

The combination of the exposure of the steel, the selection of member types and exposed connection details creates the structural texture of an AESS project. This chapter examines the role that the basic choice of member types will have on the development of the aesthetic expression of a project, its relative cost as well as the type of connection detailing that will naturally ensue. There is a relationship between member types and connections that tends to drive the detailing in many projects. It is difficult to speak of one without the other and there are multiple ways to approach the selection of member types, connection types and AESS categories. Certain types of structural members tend to support the detailing choices aligned with the specific categories of AESS.

AESS structures, by their inherently exposed nature, put a greater than normal emphasis on connection design. The detailing language of the connections must feed into the overall aesthetic desired for the structure, as well as be constructable and within reason to erect. Although the details that are normally used for AESS structures include some fairly standard connection methods, these are mostly modified as a way of enhancing the architectural expression of the structure, and by their nature are likely to present challenges for both fabrication and erection as discussed in the previous chapters.

The proper application of the Category System approach to specifying and detailing an AESS project can assist in developing a layered or tiered approach to establishing the appearance of the steel, putting emphasis and budget towards elements that will have the most impact and allowing for simpler detailing on elements that are distant to view.



# CONNECTIONS

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- 120. Shop versus Site Fabrication
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- 126. Bolted Connections
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- 130. Pin Connections
- 134. BAHAMAS AIRPORT TERMINAL 4
- 137. RED BANKSIDE HOUSING

CHAPTER

# 7

The truss structure of the Los Angeles Bellows Hall in Pasadena, Spain, designed by Rogers Stirk Harbour + Partners, relies on a system of AESS tubular pin and moment connections to create its architectural statement. Color plays heavily into the expression of the AESS.

The basic issues and solution strategies for connecting steel, including lap joints, butt joints and methods of bolting and welding, are covered in detail in "Chapter 3: Connections and Framing Techniques" of *Understanding Steel Design: An Architectural Design Manual*. The intention of this chapter is to provide a coherent sampling of connection details that can provide the basis of and inspiration for project design and act as visual references. Contemporary connection design has borrowed significantly from the type of detailing characteristic of the High Tech movement. More information on these precedents can be found in "Chapter 5: AESS: Its History and Development" in *Understanding Steel Design: An Architectural Design Manual*.

## DEFINITIONS

**Member** refers to the discrete sections of steel, such as wide-flange (Universal) sections, hollow structural sections (HSS), angles, channels, rods or cables.

**Element** references the larger agglomerated pieces of a building. This includes trusses, beams and columns as they extend from one external connection point to the other. A small or uncomplicated element may be constituted simply by one steel member. In many AESS projects the additional complexity will require the assemblage of larger elements from a number of members.

**Connections** are of three basic types by virtue of their location and purpose: **Internal connections** are those by which the members are joined to create a larger element. These are most normally the result of shop fabrication.



# SPECIALIZED CONNECTIONS

CHAPTER

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- 153 RENOVATION OF OLYMPIA INDIEN BERLIN
- 154 REGENT PALACE HOTEL
- 155 DIALYTIC CENTRE FOR CONTEMPORARY ART

Special coatings have the ability to protect steel from the harmful effects of the weather. Photo by James Knapton, designed by Reinhold Brückner.

Beyond the adaptation of basic bolted and welded connections to suit AESS applications, there are other types of connections that respond to sophisticated expectations on the act of connecting, however without requiring completely customized fabrication as will be addressed in Chapter 9: Custom Fabrication. These special connection types are often used in conjunction with the range of bolted and welded connections described in the previous chapter. They address design and erection issues that include splicing and complex geometries arising from the convergence of multiple members.

## MAKING CONNECTIONS LESS VISIBLE

The majority of connections used in AESS structures tend to enhance, or make a design detail out of the act of connecting the steel. In certain instances, the design intention will be to hide connections or make them less visible. This is typically the case when splicing steel elements and it can also apply when trying to make connections between members appear more trim.

The limitations on the transportation size of elements will often require elements to be shipped as a number of smaller pieces, so that site connections have to be carried out. In AESS projects, particularly those designed with an all-welded aesthetic, this can present erection issues, as on-site welding can be problematic and bolted site connections are liable to disrupt the visual lines of the elements.





The Arpano Arch Pedestrian Bridge in Seattle, WA, USA, designed by Gehl Architects and AECOM Consulting Engineers, required significant customization due to its wide variety of geometries, deep steel floor level and form over the truss steel to a double deck that allows the pedestrian structure at one, through the truss, to allow an elevated walkway. The steel and wood arrangement vary, adding significantly to the fabrication and erection costs.

## CUSTOM FABRICATION

CHAPTER

# 9

Highly customized architecturally exposed structural steel served as the basis for the High Tech movement and continues to be a popular choice when designing contemporary AESS projects. The AESS System of Categories, Characteristics and Matrix was intended to identify highly customized fabrication of the kind that is addressed in this chapter. These projects represent the exception and not the rule. The fabrication requirements vary tremendously between projects. It will be noted, however, that many of the detailed aspects of design and fabrication use techniques, details and approaches that draw from established practices in AESS as described in previous chapters.

The complete custom fabrication of members tends to be reserved for AESS 4 categories and “above” due to the cost premiums required for more extensive remediation associated with higher levels of welding and increased aesthetic expectations. Plate steel is often selected when standard members do not fit with the desired aesthetic or the structural capacity cannot be met with standard section sizes as referenced in Chapter 6: Member Choice. Where plate material is fabricated into orthogonal shapes, it provides crisp corners that may be desired as part of the aesthetic or texture of the system. Plate material can be fabricated into a wide range of tapered or irregular shapes, including curved forms.

Highly eccentric or non-repetitive geometries can require significant customization even of standard section or tube types. This approach to design is often seen in AESS 3 projects if lower levels of remediation are acceptable.

Within this chapter, custom fabrication requirements and details will be presented on a project-by-project basis.



The Beijing National Stadium (“Bird’s Nest”) in Beijing, China, designed by Herzog & de Meuron and Arata Isozaki, represents the extreme high end of custom fabrication. The massive spawners and gusset bolts required the complete fabrication of all structural systems from plate material. The on-site connections were all welded, with the fabricator requiring significant grinding, fitting and reworkability to make the welds seamless.

The use of the primary AESS 1, 2, 3 and 4 categories leave the designation of Custom work to projects that truly warrant such detailing, thereby assisting in lowering the costs of AESS projects and increasing the viability of using AESS. The specific treatment of detailing with the type of workmanship associated with fabrication methods such as grinding and contour blending for categories AESS 4 and above can help prevent unnecessary over-specification of fabrication methods that are not warranted due to the use of the building, the distance to view and the type of finish required.

The application of Architecturally Exposed Structural Steel in a project can greatly benefit by the careful use of the system of categories and their associated characteristics. This system is able to create a much cleaner decision-making matrix and assist in creating better communication between the architect, engineer and fabricator regarding the expectations of the design of the exposed steel in the project.

The Phoenix International Media center in Beijing, China, designed by HOK Inc, showcases the use of AESS in conjunction with a high level of parametric design. It does so by engineering of the structural capabilities of steel, as well as efficient detailing and fabrication methods were essential for the success of this project.



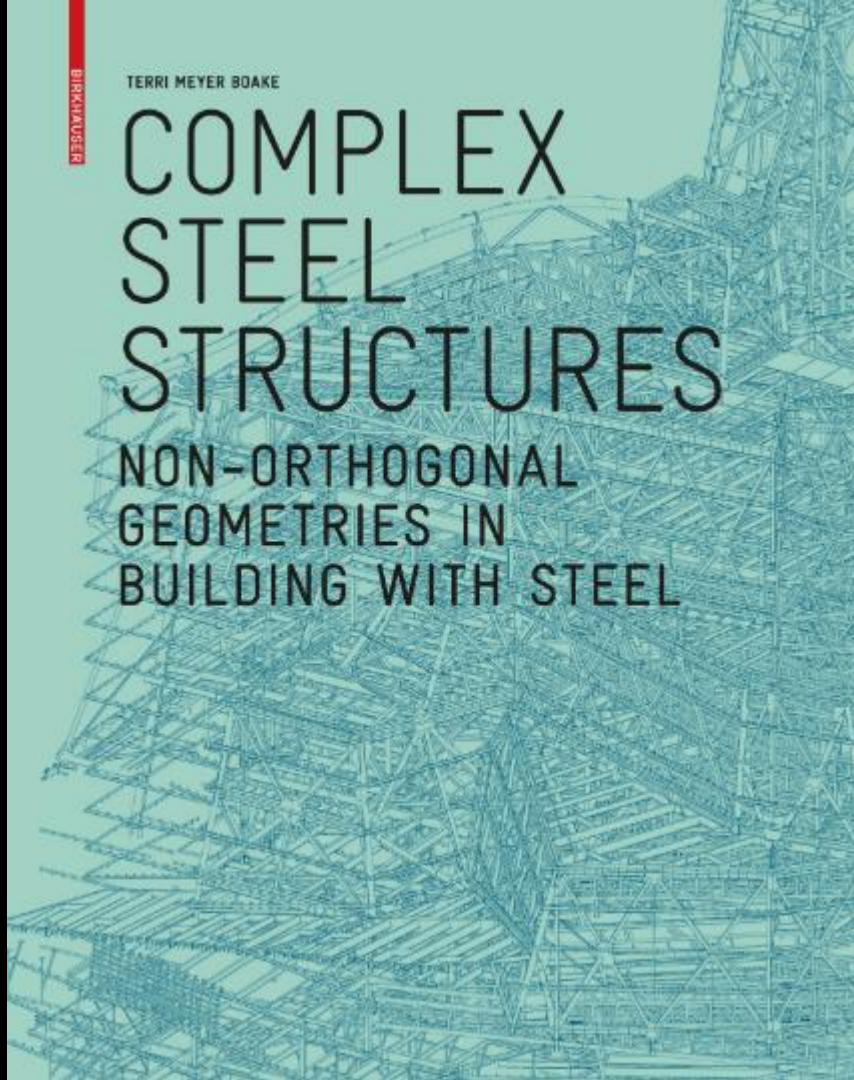


BIRKBECKER

TERRI MEYER BOAKE

# COMPLEX STEEL STRUCTURES

NON-ORTHOGONAL  
GEOMETRIES IN  
BUILDING WITH STEEL





# THE RISE OF COMPLEXITY



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In order to understand how we can best undertake steel design for complexity in the present Post-Modernist age of Parametricism, it is necessary to trace its evolution. Many of the current techniques for managing the design and fabrication of complex steel systems are closely based on practices that emerged from Modernism throughout the High Tech period. These strategies were subsequently modified and adapted over time. Current best practices still need to acknowledge the craft-based work of the fabricator that works in parallel to increasingly digitally driven practices in design and fabrication. Many present approaches to complex steel structures have been derived from these emerging trends.

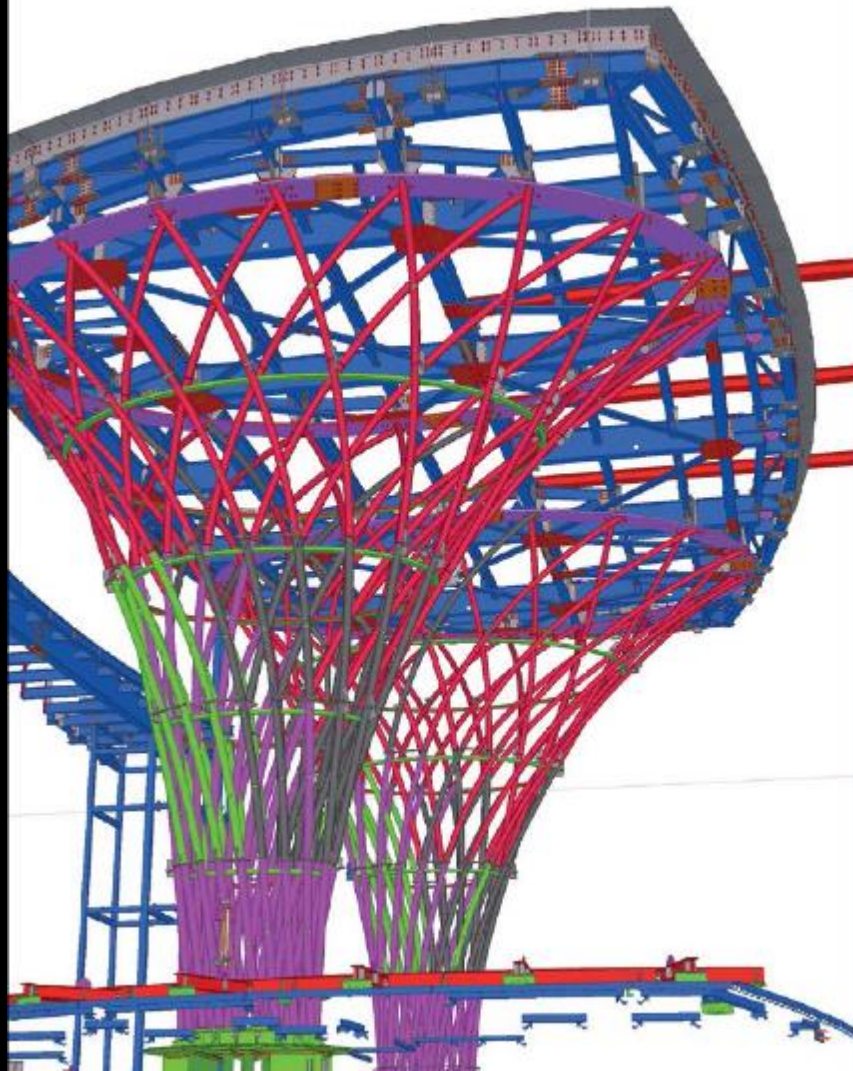
## 1. THE MODERN CONDITION: STARTING POINT

The Modern buildings that preceded the emergence of complex steel structures tended towards the use of a fairly regular column grid with a clear hierarchy of spanning systems exhibiting consistent characteristics: corrugated decking on joists or beams spaced at regular intervals, sitting on beams or girders. Larger spans were often accommodated with trusses, initially planar and eventually spatial to manage larger spans. This predisposition towards geometric simplicity aligned well with limitations on engineering practices of the period, practices that preferred to resolve structures into two-dimensional, determinate frame systems. This method worked with the dominance of pin and hinge type connections between members that could be resolved into simple vertical and horizontal force systems. Span and bight tables became the backbone of standard structural engineering. The majority of calculations were made using a slide rule until the advent of personal calculators in the early 1970s.

By default, the overall tendency during the Modern period was towards concealment of the structural steel system. The detailing was left to the discretion of the structural engineer to develop the most efficient solution. This led to concealment in design directed at minimizing the weight and thereby the cost of steel. Steel buildings were generally peiced by their bracing, so the complexity of the connection details was in the majority of cases not relevant. When the structure was expressed, the detailing and regularity tended to become cleaner, clearer and more regular. When exposed, connections tended to be welded so as to suppress the technical aspects of the joinery. This led well into the Modern aesthetic that was more formally driven and eschewed technical details.

The detailing of the steel in this car deck project by Gensert Torkler in Paris, France, 1997 reflects well the conditions of a free span truss structure in a clean, unobstructed environment. The beam-to-beam related sections exemplify a narrow concept of High Tech as structure is considered to establish a clear path of loading and resisting through of the assembly. The steel work is brought forward as a statement.





# THE DIGITAL REVOLUTION

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If the ultimate goal is to build, there needs to be a close alignment between the ability to imagine a structure, the ability to calculate the structure and the tools to fabricate and erect the structure. When digital capabilities step beyond techniques that remain predominantly craft-based, we need to come up with innovative approaches to overcome the mismatch.

## 1. THE LINK BETWEEN COMPUTING AND COMPLEXITY

There is an intricate connection between advances in computing technology and the evolution of complexity in architectural design. This includes all facets of design, drawing, calculation and production. It is logical, then, that the increase in complexity of steel structural systems has followed along quite tightly with the evolution of computing systems over the last five decades. Pre-computational methods of drawing and calculation typically required the simplification of structural systems to 2D scenarios, which tended to prefer orthogonal geometries, as they were easier to calculate, draw and construct. Architects, too, tended to eschew complex geometries in their designs, as they were difficult to draw.

There has not always been a precise match between what architects can conceive, create and draw, what engineers can reasonably calculate and what steel fabricators can economically and precisely fabricate and erect. There tend to be pushes and lags. And at present the fabrication and erection methods for steel tend to sit behind “the digital work done at the desk,” for very practical reasons related to tolerances, fabrication processes, irregularities of material and human error.

## 2. HIGH TECH ARCHITECTURE SETS THE STAGE

Some of the initial design changes that precede the widespread incorporation of computing in design began to generate a need for this assistance. Some of this need might be seen as subtle, thinking of the contrast in the nature of the steel structures of the Modern Movement (Mies) to those of the High Tech Period (Foster, Rogers, Pritz, Gehry, etc.). This increase in complexity was initially characterized by the introduction of force-differentiated structural systems – those making widespread use of the exposure of lightweight steel members to provide stability to the largely hinge-and-pin-connected pre-stabilized and other modular systems – as well as the fastening and exposure of the steel systems and connection details.

The Tokyo Skytree is an image of the Drexel Field Place Pavilion in New York City, NY, USA, designed by Paul Calter. In 2010, it was the first of a new era of building that is making complexity the norm. The building was designed by the Foster + Partners Group and is a prime example of the digital revolution in building processes.



# MANAGING COMPLEXITY

# 3

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This chapter looks to compare visual complexity to configurational complexity. When a designer seeks to create an aesthetic in exposed steel that embodies complexity, there are many ways and methods to achieve this. These methods will have a direct impact on the overall cost of the project due to associated challenges in fabrication and erection. This chapter sets up the third part of the book that examines projects on the basis of their complex typologies.

## 1. DEFINING COMPLEXITY

Complexity can be defined as the state or quality of being intricate or complicated. By applying this notion to steel structures we are referring to those systems that deviate from the oriented orthogonal structural systems that typified 20<sup>th</sup> century buildings. A general increase in the complexity of architecture and its structural systems has been the result of this marked shift away from the purity and simplicity of Modernism. Additionally, the perception and constitution of complexity has changed over the same time – from complex in appearance (High Tech) to complex in actual configuration (Deconstruction) – as has its relationship to structural steel design.

In order to advance our understanding and ability to better design complex steel towards buildability, there are key questions to be asked:

- What exactly constitutes complexity in steel design?
- Are all kinds of complexity the same?
- Are there different ways to achieve or respond to the desire to be complex?
- What does the increase in complexity mean for the design and practice of architecture with specific reference to structural steel design?
- What does the increase in complexity mean for the fabrication and constructability of steel?

We could likely add in here, “and why should architects be concerned about any of this?” As will be demonstrated by the constructed examples in the book, knowledge is empowerment. Better outcomes are possible if a more complete understanding of the interrelationships between complex steel structures and fabrication, detailing and erection issues are incorporated into the overall design detailing and strategies. The basic knowledge pertaining to general issues was addressed in *Understanding Steel Design: An Architectural Design Manual*. A detailed exploration of the requirements associated with exposed steel were expanded in *Architecturally Exposed Structural Steel, Specifications, Connections, Details*. There are additional issues that continue to play in conjunction with the complexity associated with non-orthogonal geometries that will be addressed in this book. There are different strategies that can be adopted when approaching the detailing of a complex steel structure – differing paths that can be taken towards approximately the same end result that can incur differing costs and demands of time. Some of these reflect back on the strategic detailing approach addressed in *Architecturally Exposed Structural Steel, Specifications, Connections, Details*, which outlined a matrix of categories and characteristics that reflected ascending levels of fit and finish expectations in AESS as a function of distance to view and the program of the architecture.

Fabrication Spreads in Melbourne, Australia designed by LAO Architects and Network, 2007, www.laoarch.com. From a structural configurator composed of galvanneel square steel tubes defining the presence of the architect's view in the interior of the project.



# FABRICATING THE STEEL

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On complex steel projects it is essential that the steel fabricators be included in the project development, as they may have critical suggestions regarding innovative approaches to designing for best fabrication and erection. This is particularly true for connection design, especially the splice connections completed on site, as these must reflect logistical restrictions of which the architect may be unaware.

### 1. COMMUNICATION AND THE TEAM

Different jurisdictions have varying approaches to handling teaming rules and communication. Regardless of the geographic location, complex steel projects require a higher than normal level of understanding among the players. On traditional concrete/steel projects it is normal for the architect to be distanced from the selection of the steel fabricator and erector. These decisions will normally be made during the bid or pre-bid process after the drawing set is complete. On complex steel projects, whether concrete or using AISC, the involvement of the fabricator for advice early on during the design phase can contribute to a more successful project. This does not necessarily infer a pre-selection of the fabricator. Fabricators can be retained to assist in this process and later provide bids alongside their competitors.

In some jurisdictions and for some clients it is normal to divide a larger steel contract into subcontracts, with several separate entities to handle the fabrication and erection. In other places, several fabricators might be awarded portions of the overall contract because of the sheer tonnage of steel required. On very large projects, the production capacity is often beyond the plant capacities of a single fabricator. A tight tolerance on absolutely essential when working with complex angular geometries and curves, great care must be taken when subdividing the work. A fabricator may desire to pre-check the fit of the pieces in the shop, and this is more easily accomplished if they have either fabricated or have easy access to all of the adjacent pieces and have them in the shop for fast assembly.

Verifying the working method and communication capabilities of the team in terms of software will be critical for coordination. This is a fluid aspect, as software is constantly improved. The requirement of interoperability extends also to associated consultants such as mechanical and electrical, as clash detection is essential when dealing with geometries that are difficult to comprehend and require 3D visualization. Accurate dimensional coordination with cladding suppliers is also essential, as the complexity of forms is transferred to the envelope design.

The slight curvature for the Occidental Place Pavilion in New York City, NY, USA, designed by Paul Chase Park Architects, 2013, was fabricated in Merrill, OH. Curved and tapered over hundreds of elements to the site. A strategy for locating the ribs along the ribs has been possible elements was critical to the success of the project and greatly reduced the number of re-works.

# CORROSION PROTECTION & FINISHES

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To act responsibly in the design of steel structures exposed to weathering means understanding the limitations of coating systems and altering the design accordingly to ensure minimal environmental degradation and reasonable maintenance requirements.

## 1. AESS AND ITS IMPACT ON FINISH SELECTION, CORROSION PROTECTION AND MAINTENANCE

Although complex geometries necessitate much tighter tolerances than standard structural steel that is precoated in order to ensure the proper fit between members for structural integrity, complex Architecturally Exposed Structural Steel will have even tighter tolerances than complex steel that is to be concealed either entirely or partially. The accuracy of fit between adjoining members and the ability of the fabricated connection to fit precisely match the digitally produced drawings is critical to ensure not only a good looking final product but also to not slow down the erection process due to fitting issues.

AESS also requires much more careful handling than standard structural steel. This care in handling begins in the fabrication shop and the preparation for shipping. In some cases, the elements may come prefinished, ranging from a simple primer coat, to galvanizing to a final maintenance coating. Even if shipped with only a protective primer coat, care needs to be taken not to damage the surfaces, as any elements will require remediation on site. Large elements will require additional temporary supports in transit in order to prevent deformation. While the designer is not involved in the design of the implements used to assist shipping, it is important to understand that this handling will impact the overall cost of the project. More delicate elements will need to be shipped separately, meaning increased transport costs over standard steel.

When dealing with AESS it will be important to discuss the nature of the final finish and where this is applied (shop versus site). In some cases this will impact the size of the elements and impose specific connections on the design. It will be important for the ultimate usability of the project to ensure that coatings are applied in optimal conditions.

AESS should always start with a professional blast cleaning to remove any mill scale, grease, or oxides that will prevent the proper adherence of the finish. This is a cost above the cleaning prepared for standard precoated steel.

If not galvanized for a permanent exposure to weathering, AESS is normally primed to prevent excessive oxidation on site and preserve the integrity of the steel given during shop fabrication. The primer will be held back from areas that are adjacent to future welded connections. These will be cleaned up immediately before the weld operations take place. The primer must be coordinated with the final finish to ensure compatibility.

The Helix Bridge in Singapore, designed by Cox Architecture and Arup, 2010. It is the world's first to be made of stainless steel. For this reason it was deemed to be the highest grade of stainless steel, as lower grades would not have been suitable. This also means that it requires no further welding or welding in the future to complete the structure.





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There is little that is straightforward when it comes to the erection of complex steel structures. Be the elements angular or curved, there will be a constant fight with gravity due to essential loads. The team working on the site needs to be highly skilled, as the problem-solving skills and experience required to ensure success are extremely high. It is imperative that designers appreciate the difficulties that must be overcome when erecting these heroic structures.

## 1. FIGHTING GRAVITY

There is little about complex steel projects, due to their non-orthogonal geometries, that does not impact every stage of the design, fabrication and erection processes. However, when it comes to the erect on processes, many of the variables from the installation of conventional steel present extreme challenges to the project schedule and the skills of the ironworkers on site. Conventional steel projects are largely comprised of symmetrical or balanced elements. In the case of columns, the crane lowers the piece into position and the largest challenge is the alignment of the plate holes to the receiving bolts. Eccentric items will have odd requirements for lifting. Even having the crane attachment points slightly out of position can make for a tied struggle and impact time. This will obviously increase the time needed to properly install the element. Although in an ideal world, particularly one that is now so augmented with digital computation, one would imagine all of the lifting points would come pre-calculated, this is not always possible in practice. This is where experience comes into play, and it is a study the lead ironworker on the project who is doing the extraction for the lift points.

Where projects exhibit a greater degree of geometric regularity, it is possible to pre-plan the crane attachment points and the geometries of the chain arrangements to facilitate predictable and accurate lifting. This becomes more critical on AESS projects. If the elements do not align it becomes difficult to manipulate them into position without damaging the materials. When lifting and providing shoring or temporary supports for AESS it is necessary to also provide added slings and pads for any supports that come into contact with the steel to prevent damage to the surfaces.

Although angle is a concept and a principle of geometry, it is often forgotten as the design process moves forward. In Toronto, ON, Canada, engineering company GCS Architects, S.E.I.C., was not only the lead engineer for a complex steel structure but also the lead ironworker on the project. The team was able to coordinate with the design team to ensure proper fit.



# ECONOMICALLY DRIVEN STRATEGIES

# 7

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As discussed in Chapter 3: Managing Complexity, there are many different ways in which the presentation of complexity in steel design can be pursued, some costlier than others. This chapter will look at a number of strategies that can soften the fabrication requirements for the steel to some extent, while still arriving at an aesthetically high level final state.

## 1. THE DISTANCE FACTOR

The overall strategy behind the category system for specifying Architecturally Exposed Structural Steel is to allow the distance to view to offset the fabrication requirements for the steel. If a surface or element is viewed further than 6m/20ft from view it is unlikely that the viewer will either be able to see or appreciate tedious detailing. This is considered a 360° distance, and this would hold also for multi-storey atrium spaces, for instance.

The distance factor is of significance in particular when it comes to weld remediation. Although AESS 8 projects are permitted to ask for all-welded structures – including connections between the smaller transported elements as well as internal splice connections – it is permitted to use hidden or discreet connections if deemed appropriate based on viewing distance. Hidden or discreet connections may also come in handy where it is physically difficult to provide proper access to complete site welds, including remediation tasks.

In larger projects, such as airports, where the number of connections is extremely high, the multiplication factor can be considered when contemplating the relative importance of weld remediation to the project. It may be deemed not worth the expense in terms of an aesthetic benefit to cost ratio to perform the remediation.

TRANSPOSED structure of Tokyo Station, Japan, by SOM and Nikken Sekkei, 2007, is a great example of the effective application of the distance factor. Different approaches to detailing and systems are used in various situations, depending on the viewing distance. The lower level structure, for example, is more aesthetically high level due to the high level of detailing and the use of high level detailing. The upper level is more aesthetically high level due to the high level of detailing and the use of high level detailing.

# CURVED GEOMETRIES



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The Qube A Gateway Arch, designed by Cesar Pelli, 2004. The highly sculptural entry portico is fabricated from stainless steel. This material required the installation of a permanent, hidden scaffolding to support its construction work, and a high level of steel workmanship to achieve the highly regular curvature.

The incorporation of curvature into steel design is the area with the greatest gap between what can be digitally designed and what can be reasonably fabricated. It requires of the designer a high level of understanding as to limitations on accuracy and how to best work with steel fabricators and a subset specialty fabricator, the roller bender, to realize a curved aesthetic.

Methods of curving steel are covered in detail in *Understanding Steel Design*, Chapter 8: Curved Steel.

One of the most striking disparities in the last 20 years of steel design is the widespread incorporation of curvature. As discussed in Chapter 3: The Digital Revolution, the ability of design software to produce smooth curves has fueled the desire for this aesthetic. Prior to the prevailing advances in design, calculation and fabrication techniques, curvature, to a large extent, had been limited to and characterized by monolithic reinforced concrete construction. The invention of the geodesic dome by Richard Buckminster Fuller, and experimentation with the application of bubble geometries in steel structures by Frei Otto, were long considered unusual and their extraordinary nature prevented them from being incorporated into mainstream architectural design. Yet even the majority of these structures "hold the curve" as they were comprised of straight members connected via nodes. Their scale allowed the fixation of curvature. These early experiments tended to be based on highly regular and repetitive geometries. This method of creating curvature is still quite valid today and leads to more economical solutions, as referenced in Chapter 7: Economically Driven Strategies.



While the stainless steel members of the Qube Arch are fabricated from stainless steel, which requires field site care in creating and finishing, the stainless steel entry portal, a directly supporting structural member, has been fabricated from mild H100 steel. This member had to also support the loads with the portal appearance. This allowed some savings to the project.



# ANGULAR GEOMETRIES



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The most direct result of the impact in advances in digital technologies that followed the shift in design towards Deconstructivism and then Parametricism has been the widespread incorporation of angular geometries in steel structures. Whether architecturally exposed or concealed, they define the overall building shape. Their implementation has had a great impact on the fabrication and erection process, as the steel industry has been able to respond to this development due to the interoperability of software, directly to inform fabrication processes and also to assist with erection sequencing logistics.

## 1. DECONSTRUCTIVIST BEGINNINGS

Unlike the projects addressed in Chapter 7: *Economically Driven Strategies*, many complex steel projects that use angular geometries push them to the forefront of the aesthetic. The fabrication of steel has been able to match the more geometrically challenging expectations of Deconstructivist and parametrically influenced designs. These form-driven designs are distinct from digital structures, which are based on a recognized and systematic design process that entails the use of nodes as connecting mechanisms. This will be addressed in Chapter 10: *Nodes*; details are investigated in great detail in *Digital Structures: Systems, Connections, Details*. The angular geometries investigated in this chapter consist of less system-driven and more chaotic or *ad hoc* assemblies of angular steel.

Highly irregular angular geometries require extreme precision in their fabrication, with maximum work done in the shop, where purpose-built jigs can ensure that the steel exactly matches the digital model. Early angular projects had to rely on hand-measured members to translate dimensions to the steel. CNC processes are essential to creating accuracy and efficiency in the translation of digital dimensions to the cutting of the steel. Tolerances must be held extremely tight, in particular for AISC projects with preferences for an all-welded look, as dimensional inaccuracies are difficult to correct. Extremely large structures do not have the benefit of pre-fit testing and will be forced to resolve fit issues on site. Some workarounds and strategies include positioning potentially problematic on-site-welded connections so that view to them is distanced or obscured.

The City of Doha  
Richard Aronin  
Designed by Coe Rapier  
Architects Inc.  
© 2018. The University  
of Texas at Austin  
wrote the remaining  
structures in this  
chapter as well as the  
structures in the  
chapter on  
the member sizes  
many members  
are pre-fabricated  
and pre-fabricated  
designations. For more  
information, see p. 118.

# NODES

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The steel structures that defined the Modern era were characterized by fairly standard "framed" connection details. Standardized ways of connecting beams to columns were possible due to the orthogonal nature of the structures. Even the engineering of many structures was able to be simplified into a two-dimensional system of forces. The advent of complex structures introduced a high level of difficulty both in the calculation of force systems as well as the means to resolve their transfer through connection points. This was due to the more three dimensional nature of the overall form as well as the absence of right angles of intersection. Complex geometries require a more responsive approach, and nodal connections have been developed to satisfy this role. Nodes play a critical role in the design of spaceframes, diagrid structures and lattice/gridshell systems.

## 1. THE EMERGENCE OF THE NODE: SPACEFRAMES

### node /noʊ/

*Noun.* A point at which lines or pathways intersect or branch; a central or connecting point.<sup>1</sup>

Reflected on the introduction to the term "node" in the history of structural steel design. Although in a looser sense the terms "joint" or "connector" might be considered synonymous, the term "node" conveys a very different visual idea of the aesthetics and functional requirements of a three-dimensional connection. Nodes as structural and functional terms first appeared in conjunction with geodesic domes and spaceframe technology. Nodes were critical in the creation of a heavily prefabricated system that could permit easy assembly on site. The members were fairly light and the geometries, though relatively regular, required the resolution of a high number of angled components at a point. The size of the node also directly related to the number of connecting members and the ability to transfer their summative cross-sectional areas. Traditional steel fabrication methods using standard bolted or welding methods were incapable of addressing this type of connection. They were too bulky.

Spaceframes were designed as prefabricated systems subjected to fairly consistent loading that encouraged significant uniformity in their design. Although some pre-assembly of larger spaceframe assemblies can be done prior to lifting, many of the connections are done on site. Spaceframe nodes were quite unlike the angled connections in 2D or 3D trusses which were normally shop-fabricated and could afford some structural continuity of the chord members through the joint, providing stiffness. In theory, moment resistance at panel points is not required, as truss members are typically designed only for axial loading. Nodes, on the other hand, tend (although not exclusively) to be fabricated as discrete elements to which other members connect, so there is a level of discontinuity at this point, shifting certain responsibility to the physical connection between the node and the adjoining members.

<sup>1</sup> Definition of Node by Collins Dictionary as used herein, a common definition relating to structural systems.

The incorporation of cast steel nodes at the intersections of the 3D space frame steel structure for the Queen Elizabeth Centre in Toronto, ON, Canada, 2016 by Skidmore, Archiplex and a critical assembly of other contractors related to this project has resulted. This project required a high level of fabrication coordination between the building contractor, Steel Connect and the steel fabrication contractor, Wabara Group.



# LATTICE/ GRIDSHELL STRUCTURES

11  
LATTICE/  
GRIDSHELL  
STRUCTURES

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## 1. BASIC DESIGN PARAMETERS

Lattice structures, also called gridsells, are specialized steel framing systems developed to facilitate the creation of complex, curved glass roofs and facades. Lattice structures work well as a composite system, as their geometry and strength make them ideal for modulating between odd-looking geometries, and they can also exhibit complexity in form in their own right. They are different from typical skylight systems that frame the glazed panels in a more traditional aluminum frame supported on a system of purlins, beams or trusses. The steel lattice provides the opening and support for the glazing normally without need for a heavier support structure for the lattice itself. The lattice is designed to be sufficient in strength to achieve the structural spans while maintaining a light and modular feel. The structural requirements for the lattice vary due to span, geometry or support characteristics. The strength of the steel is modified by subtle changes in the section properties of the elements rather than by significant changes in the module size that would interrupt the aesthetic. In some instances, slim vertical members are used to provide additional lateral bracing where required. If required, the steel lattice can be fire-protected with an intumescent coating system.

The module for the glazing normally coincides with the module for the steel structure. Therefore, there is direct support for the aluminum framing system of the glazing, which in this way needs not be steel for major span requirements and can be very shallow and visually unobtrusive.

The lattice-supported skylight Gateway Bridge in Beijing, China, designed by Zaha Hadid, 2012, was an ideal choice for providing a single steel structure that could be used to fabricate a uniquely designed project. The steel lattice center is easily modified towards the edges to meet modular requirements of the geometry of the glazing system.

The majority of lattice grids use all-welded connections, as their appearance is much cleaner and the relatively small member sizes may not easily accommodate bolted connections. Generally speaking, as with all complex steel structures, the aim is to fabricate large panels at the shop to minimize on-site welding. As lattice grids are not self-supporting until the system is complete, temporary support for the installation must be provided. When scaffolding is used, no work can proceed under the lattice until it is structurally complete. This has a great impact on the construction schedule.

The major design choices will depend greatly on the desired non-orthogonal geometry of the lattice, the overall span distances and the geometry of the forms between which the lattice resides. Smaller spans can use more slender members. Tight curvatures require triangulated geometry and also leads to smaller module sizes, to keep the appearance of curvature smoother. Larger module sizes lead to a more faceted appearance to the curved surfaces.

