Arch 570: Architectural Steel Design

Why I got interested in this subject
A Course Intro

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CISC
Guide for Specifying Architecturally Exposed Structural Steel





Contact about publication for Birkhäuser Publishers • Andreas Müller • 01/03/2009 11:37 PM

Reply Forward Archive Junk Delete

From Andreas Müller

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 Birkh?user 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 M?ller
Senior Commissioning Editor
Birkh?user

www.birkhauser.ch


walters


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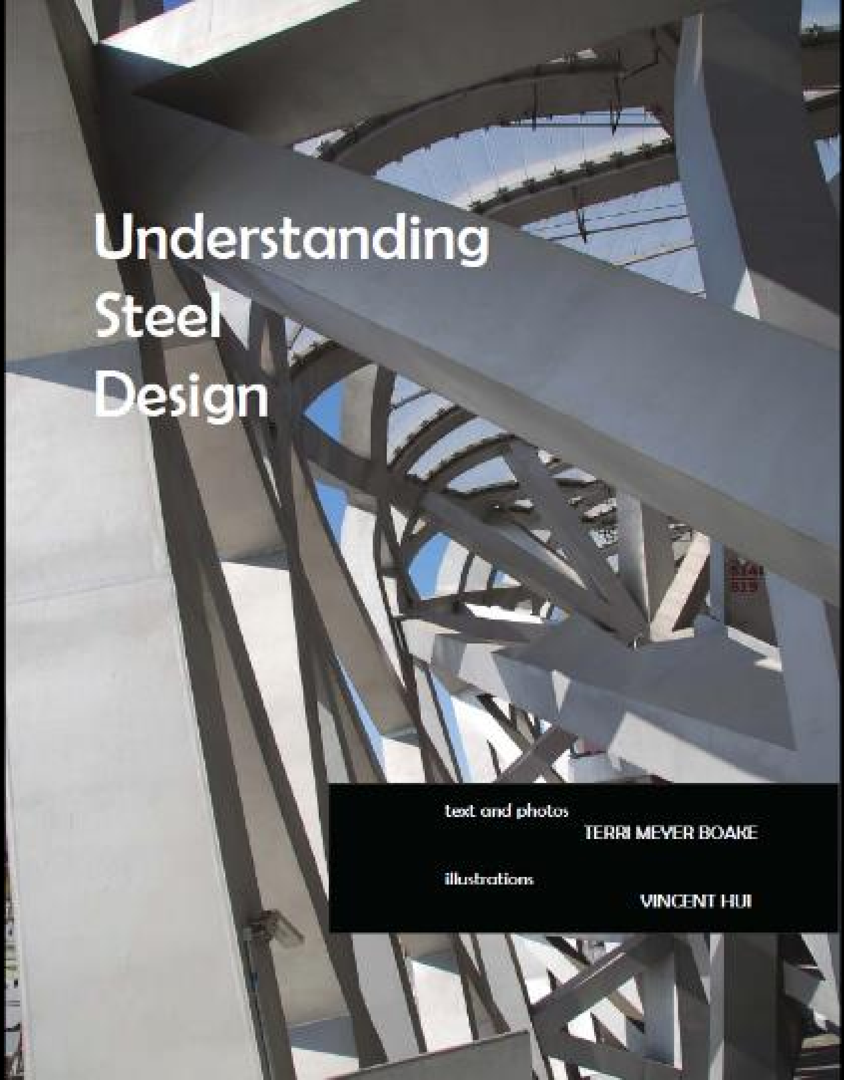
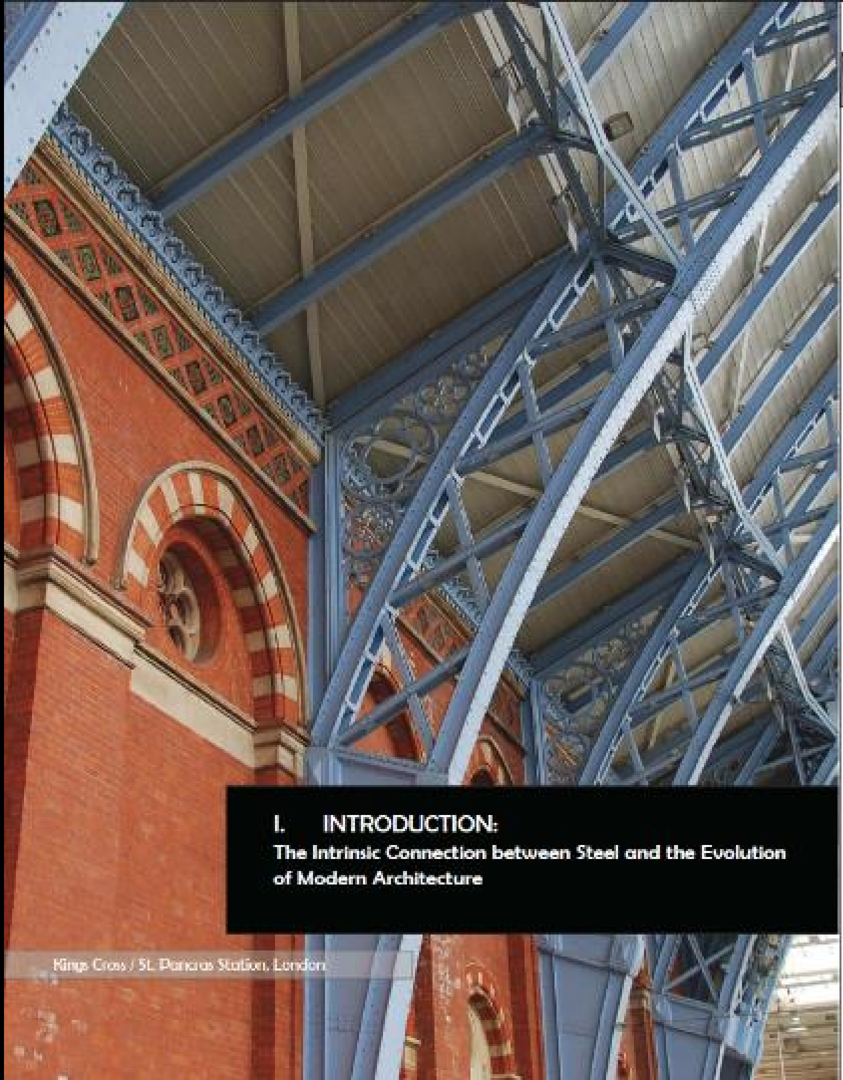


A book proposal required that I write an "expose"



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 evolved counterparts in the form of early AESS structures.

Glass Atrium support system, Buffalo

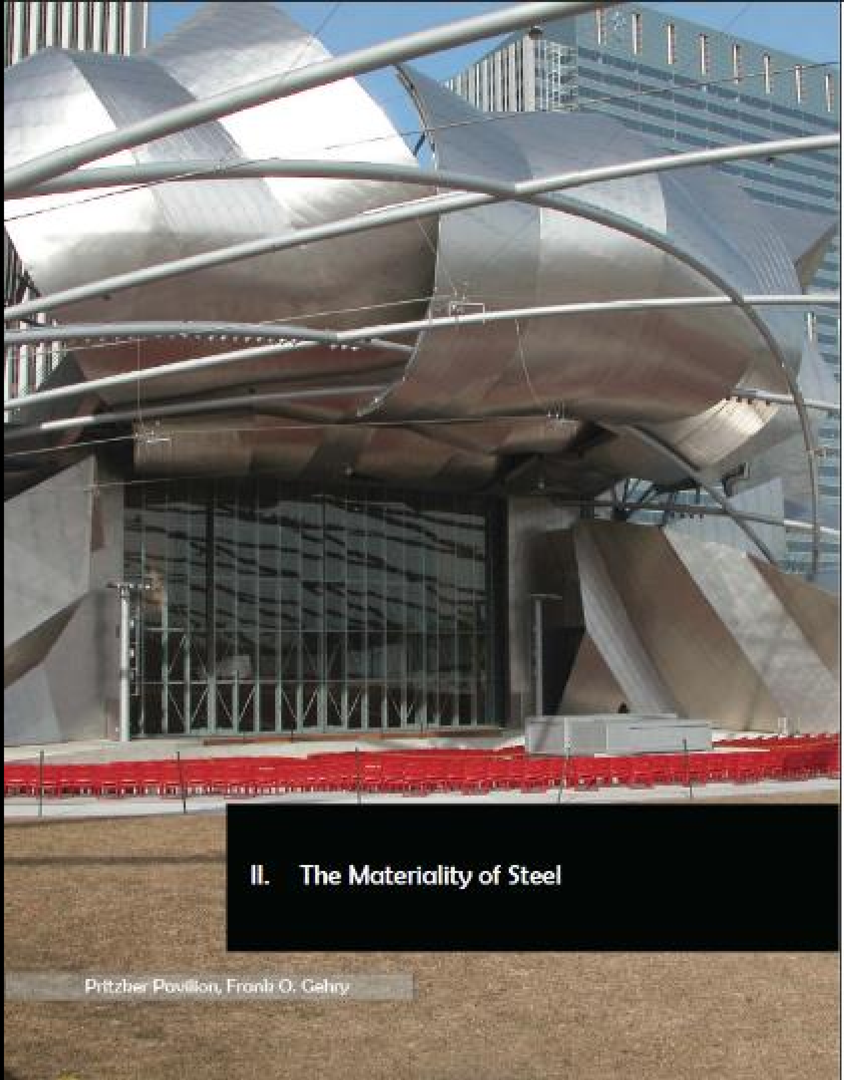
Eiffel Tower, Gustav Eiffel

Reliance Building, Burnham and Root – early curtain wall framing

Bibliotheque Nationale, Henri Labrouste – early cast iron and modular construction

John Hancock Tower, Chicago - early diagrid?

O'Hare International Airport, Murphy / Jahn – first AESS airport



II. The Materiality of Steel

Pritzker Pavilion, Frank O. Gehry

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)

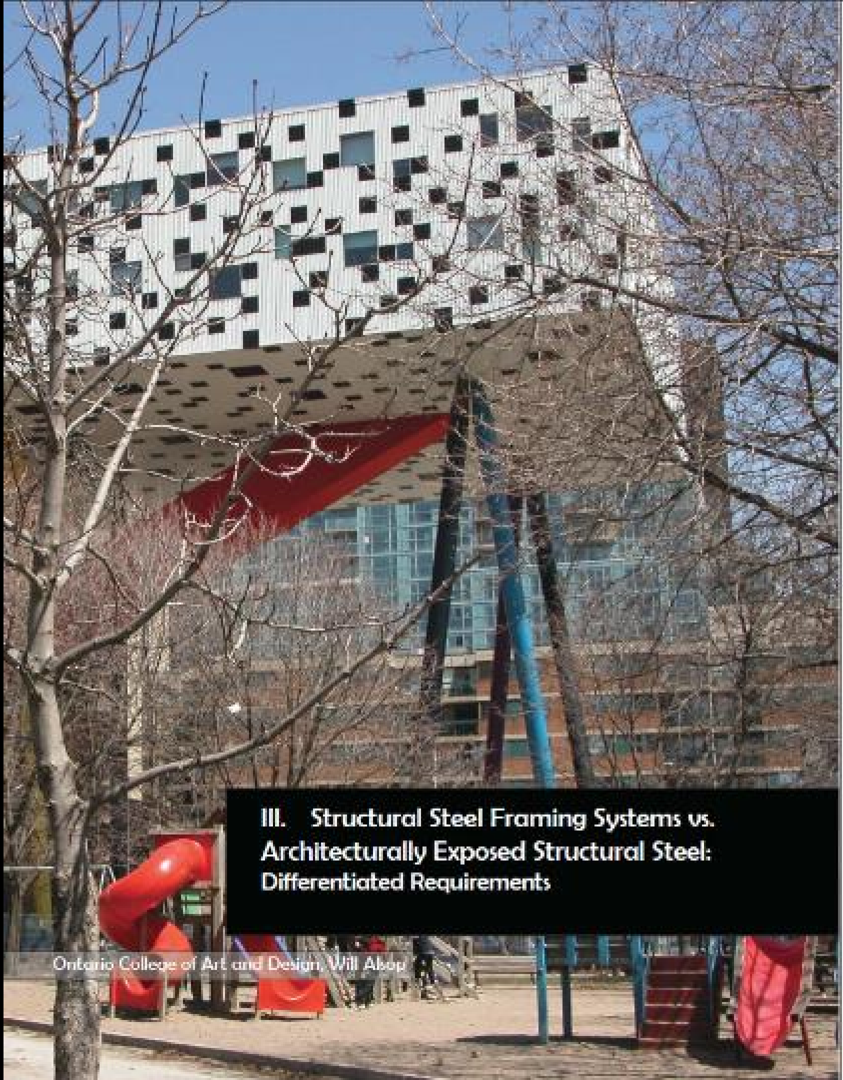
Canadian War Museum, Raymond Moriama Architect (mostly square HSS)

Salvation Army Building (WF)

Palais des Congres de Montreal (WF with cutouts)

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

Millennium Dome, Richard Rogers (tubes)



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

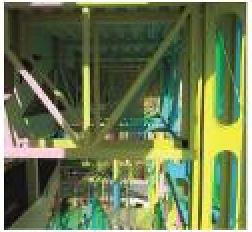
Ontario College of Art and Design, Will Alsop

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

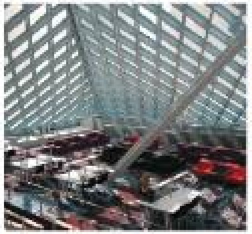
BUILDINGS/IMAGES:
A wide geographic range of AESS buildings will be worked into this section. Specific buildings will be chosen that best support the technical points being addressed - complexity of detail, degree of exposure, proximity to viewer, type of finish.



Palais des Congres de Montreal, Consortium of Architects

Ontario College of Art and Design, Will Alsop

Caisse de Depots et Placements, Consortium of Architects



Seattle Public Library, Rem Koolhaas

BCE Place, Santiago Calatrava

Newseum, Polshek Partnership

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 Jahn

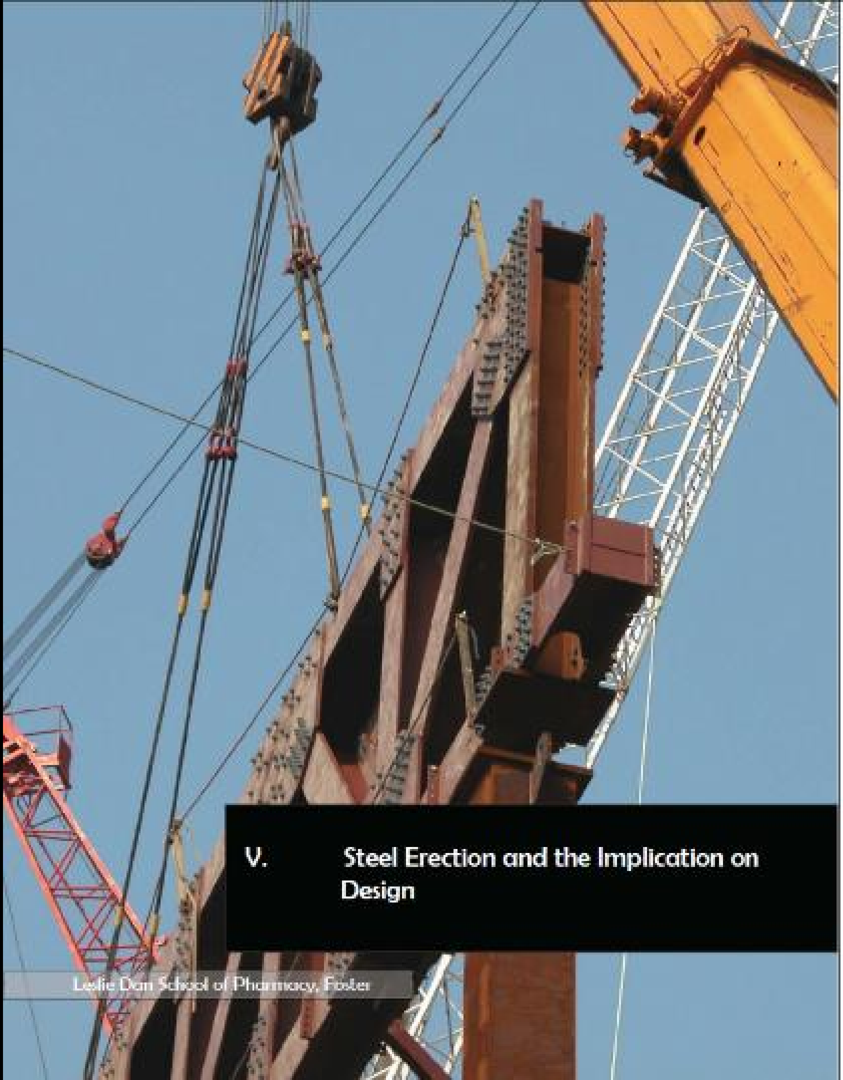
Pritzker Pavilion Chicago, Frank Gehry

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

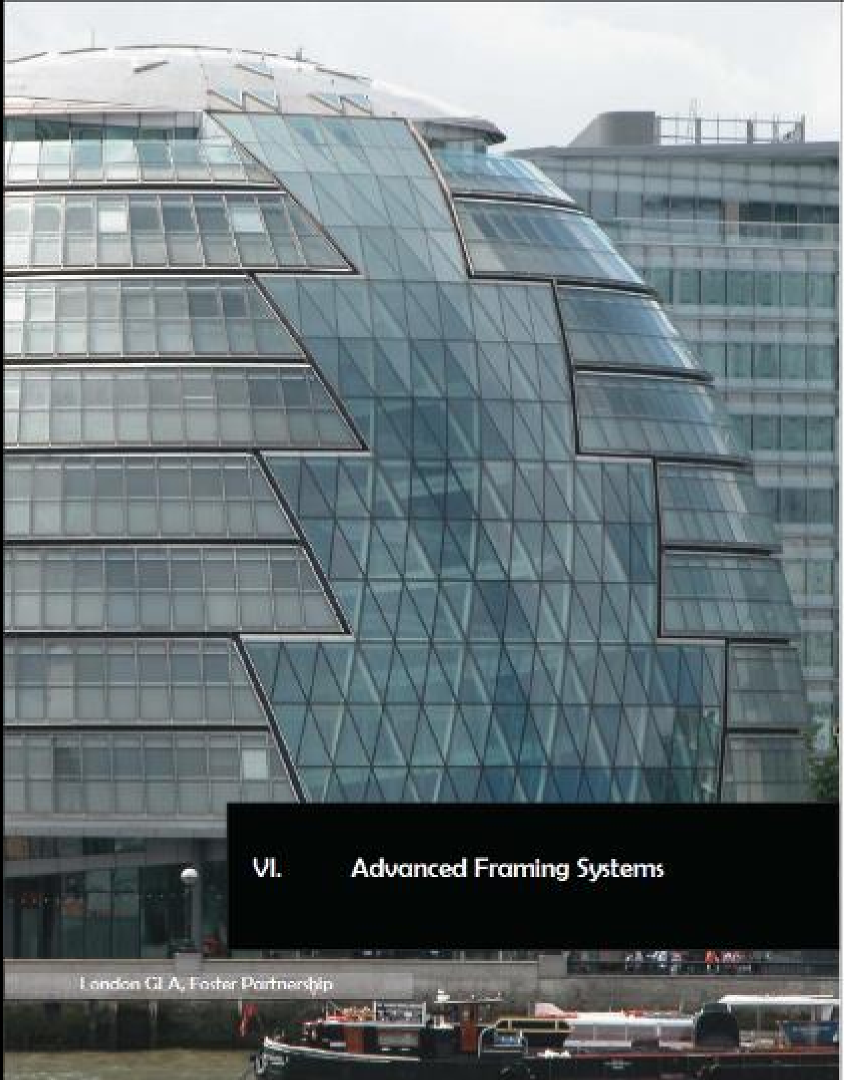
Royal Ontario Museum, Toronto, Studio Libeskind

Newseum, Washington, D.C., Polshek 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 GLA, 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 anctiapated 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)

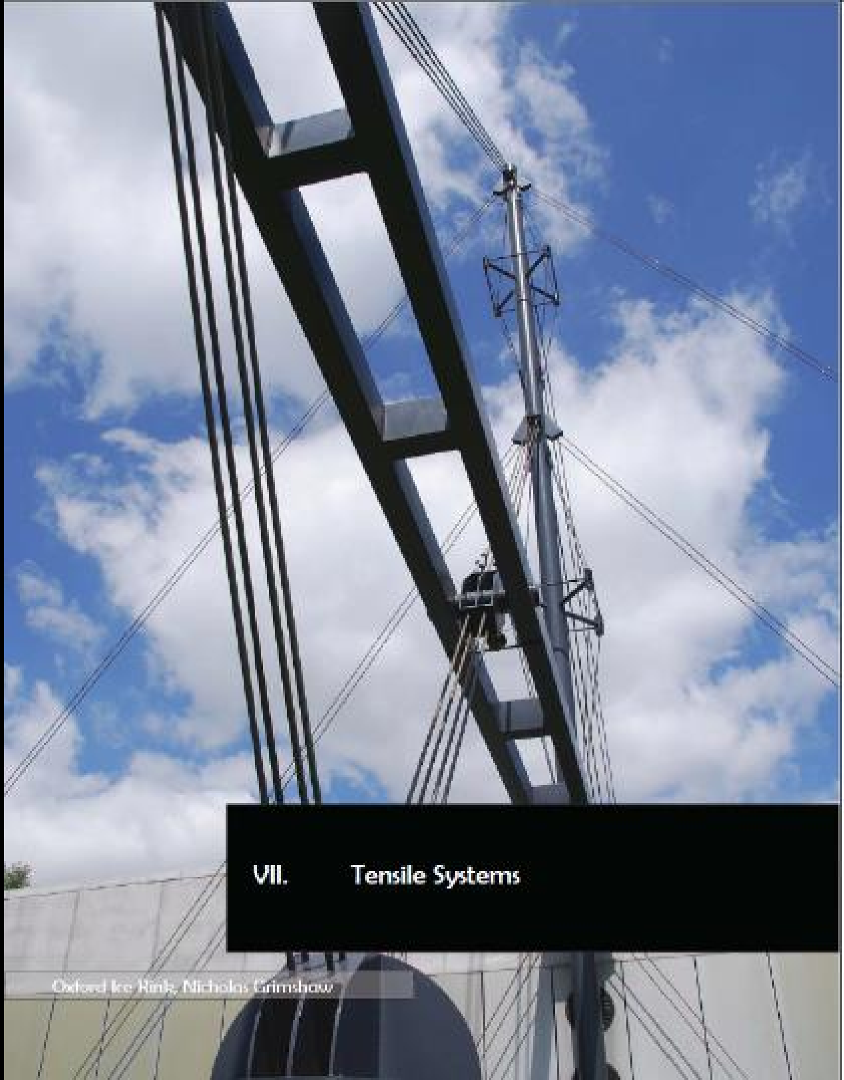
Swiss Re, Foster Partnership (diagrid)

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



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
- Specialty 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.


Jubilee Footbridge

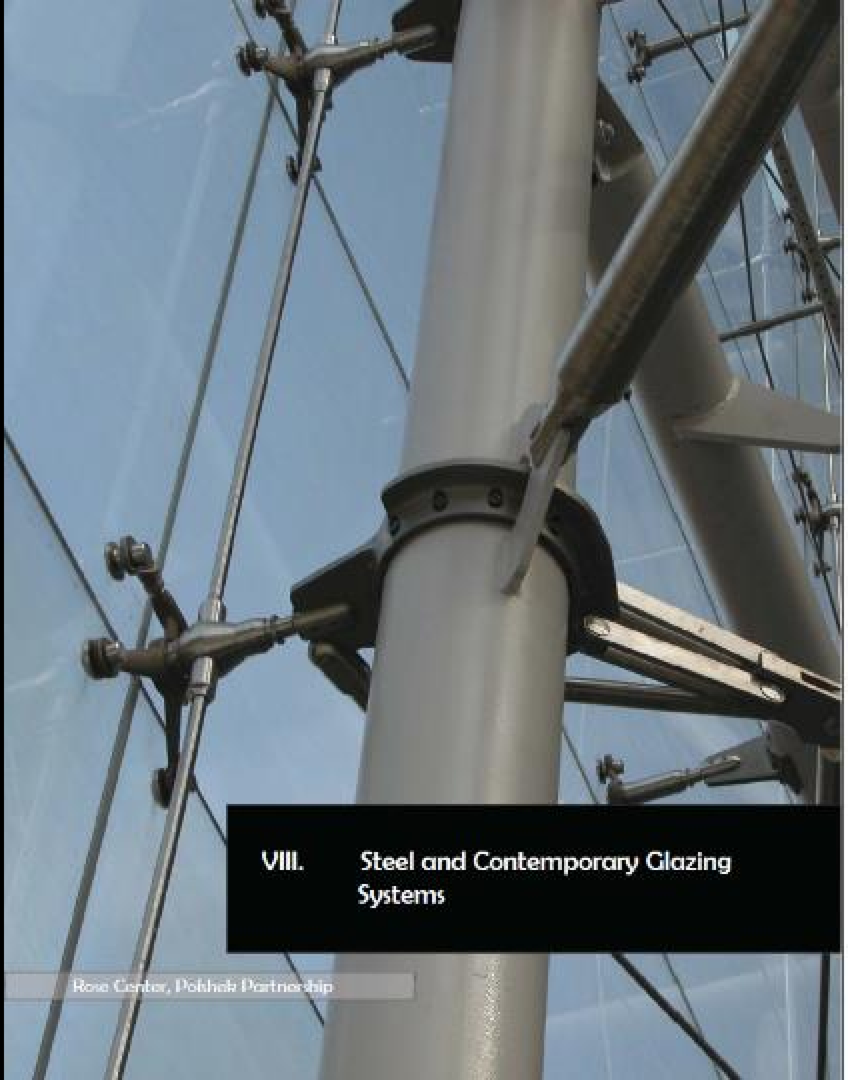

Denver International Airport, Fentress Bradburn


Water Cube, PTW Architects


Petal Structure, London Architecture Installation


Eden Project, Nicholas Grimshaw


Pedestrian Bridge, Salt Lake City



VIII. Steel and Contemporary Glazing Systems

Rose Center, Polshek Partnership

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

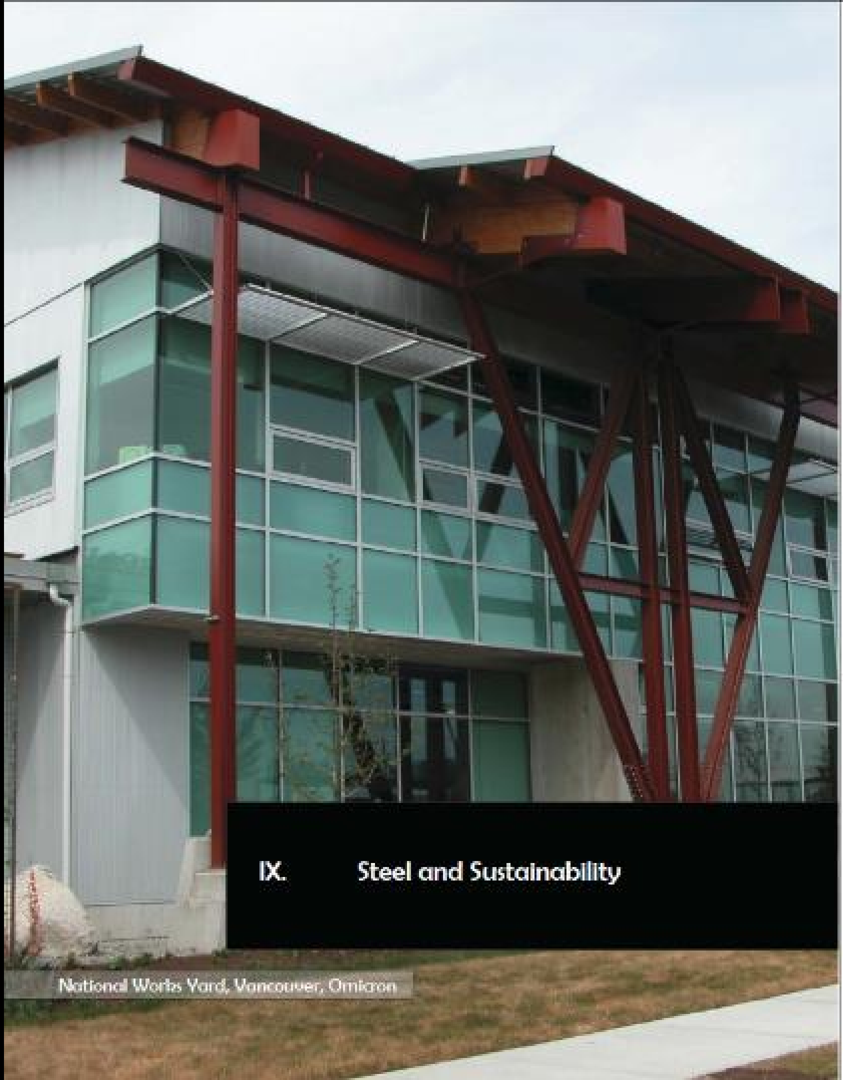
Denver International Airport, Fentress Bradburn

Tower Bridge House, Richard Rogers

Rose Center, Polshek Partnership

Brentwood Skytrain Station, Vancouver, Busby Perkins and Will

Salvation Army Building, Sheppard Robson



National Works Yard, Vancouver, Omicron

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

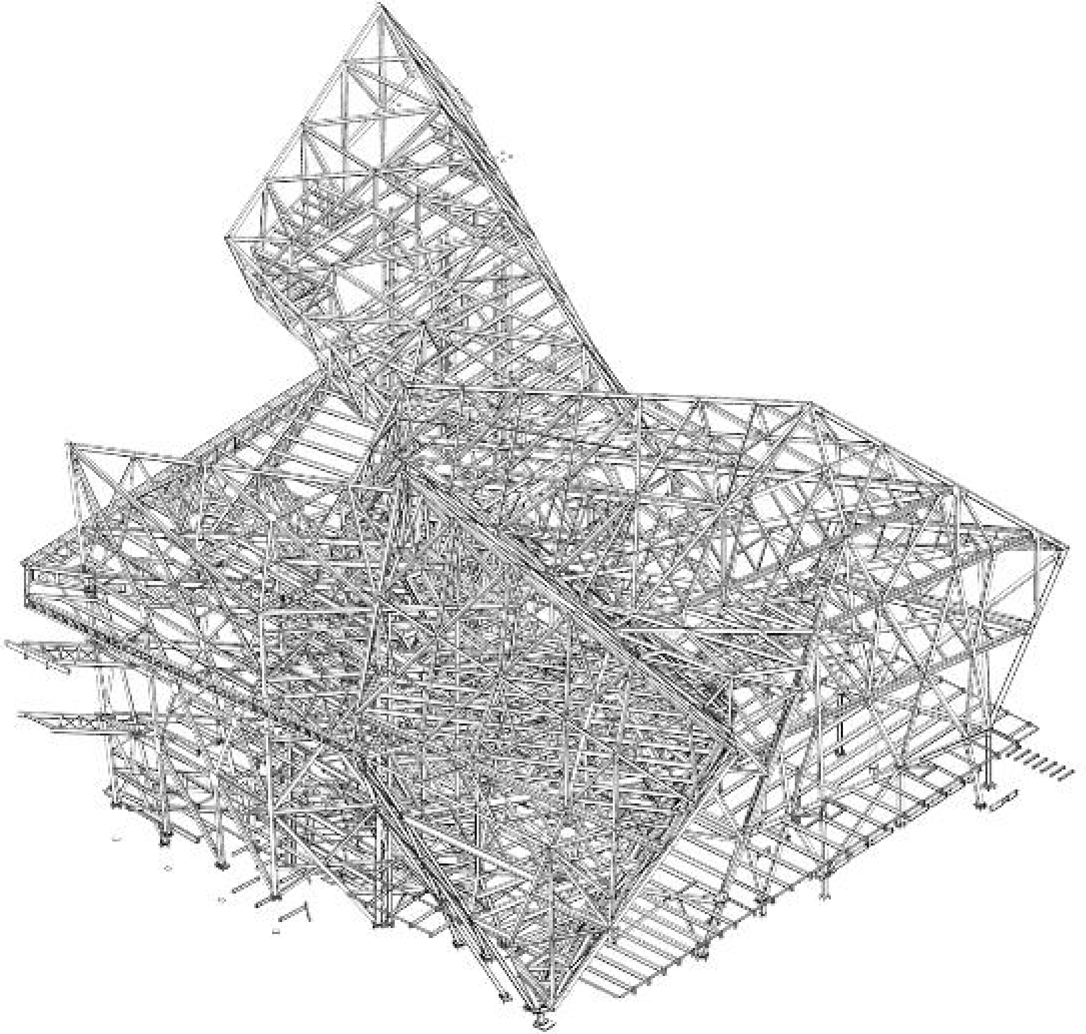
Lillis School of Business, University of Oregon, LEED Gold

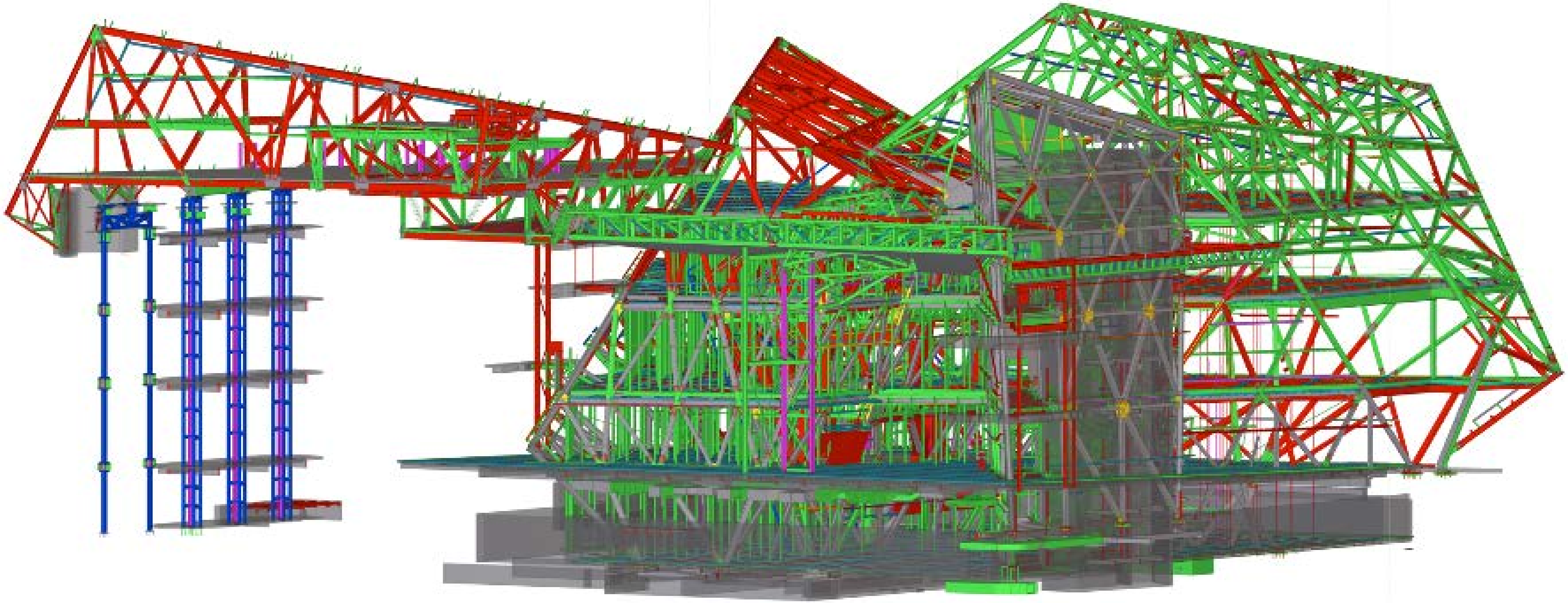
Jackson Triggs Estate Winery, KPMB Architects (Canadian Entry for GB Awards)

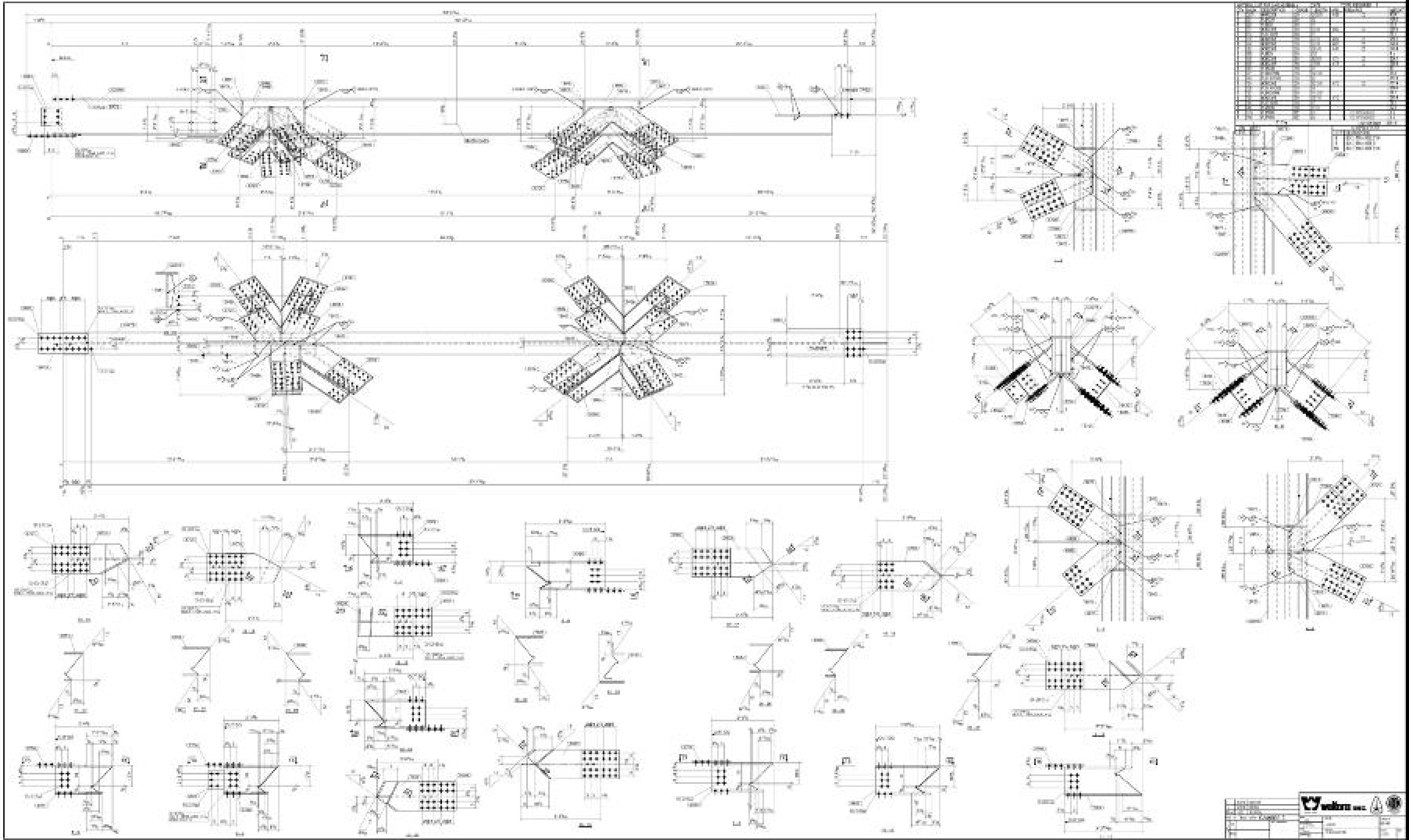
Steel manufacturing process and use of recycling and how this feeds the issue

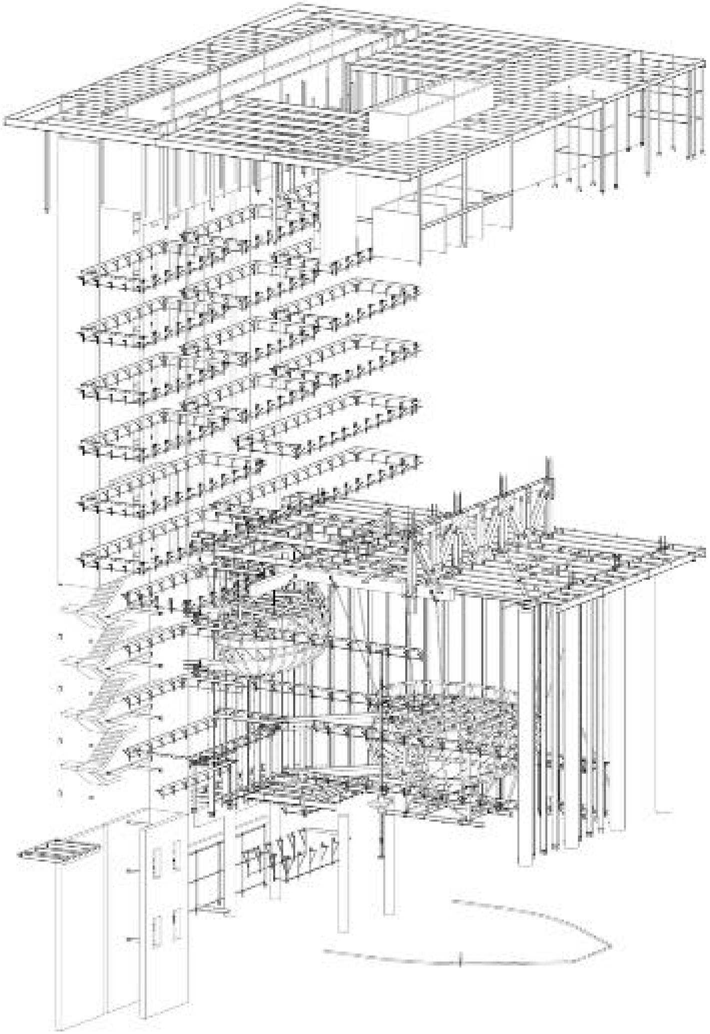
Semiahmoo Library, Surrey, LEED Silver

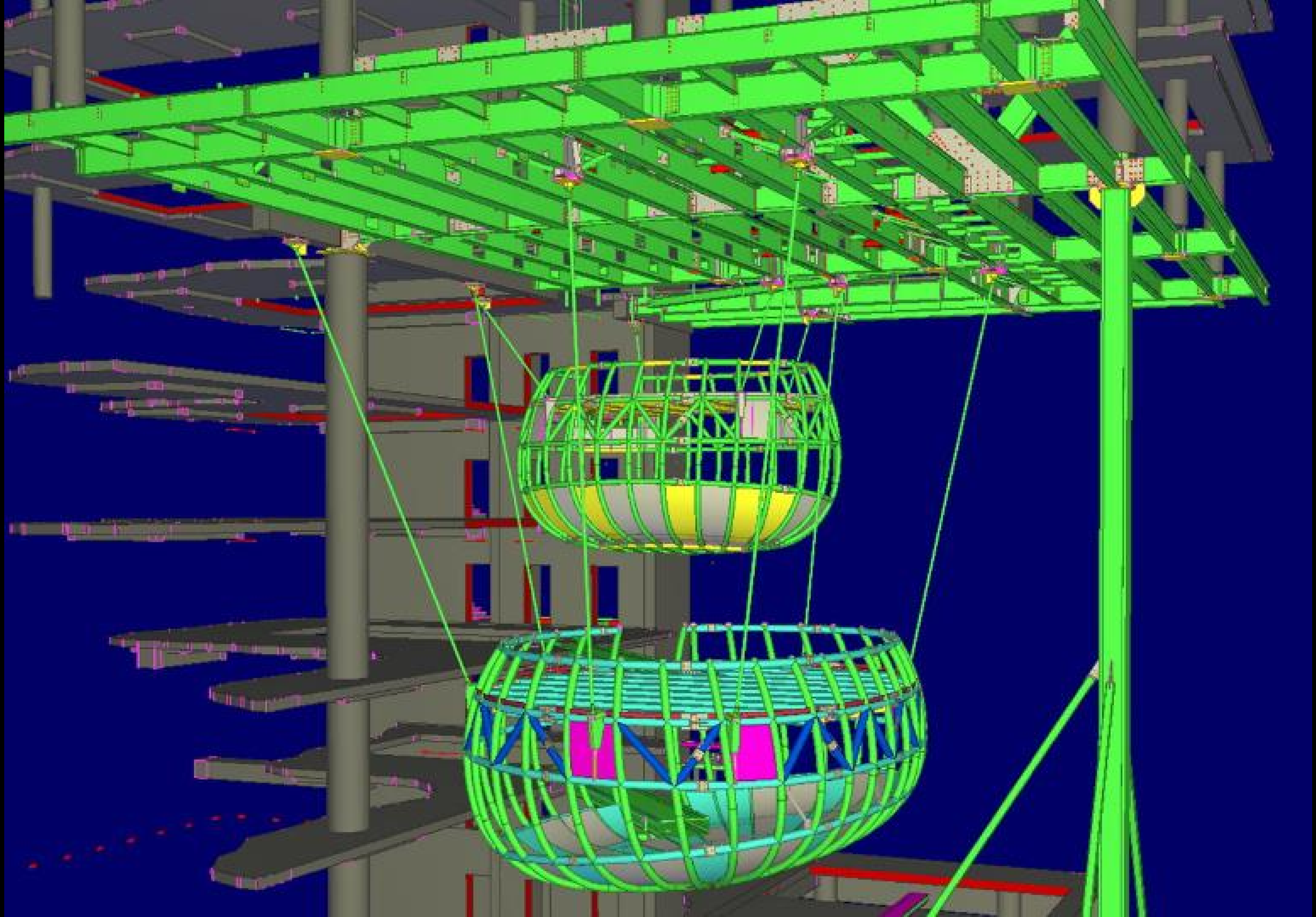
APEGBC Headquarters, Richmond - steel structure and steel supported shading

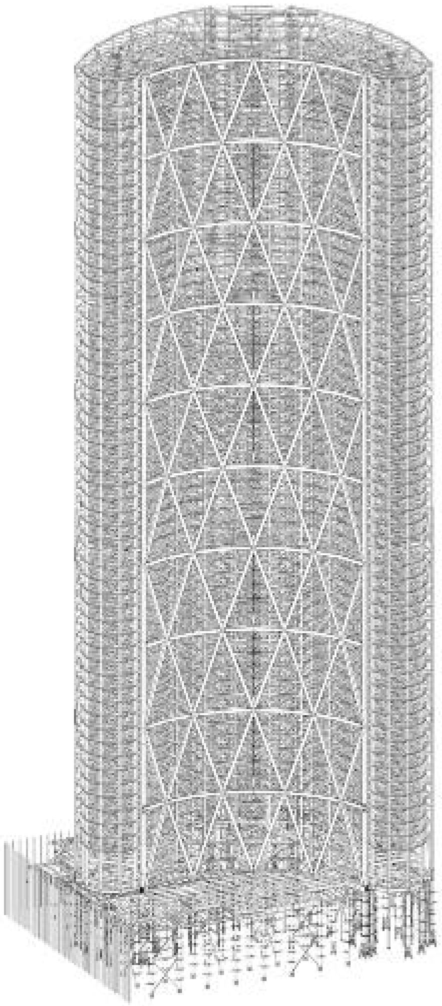


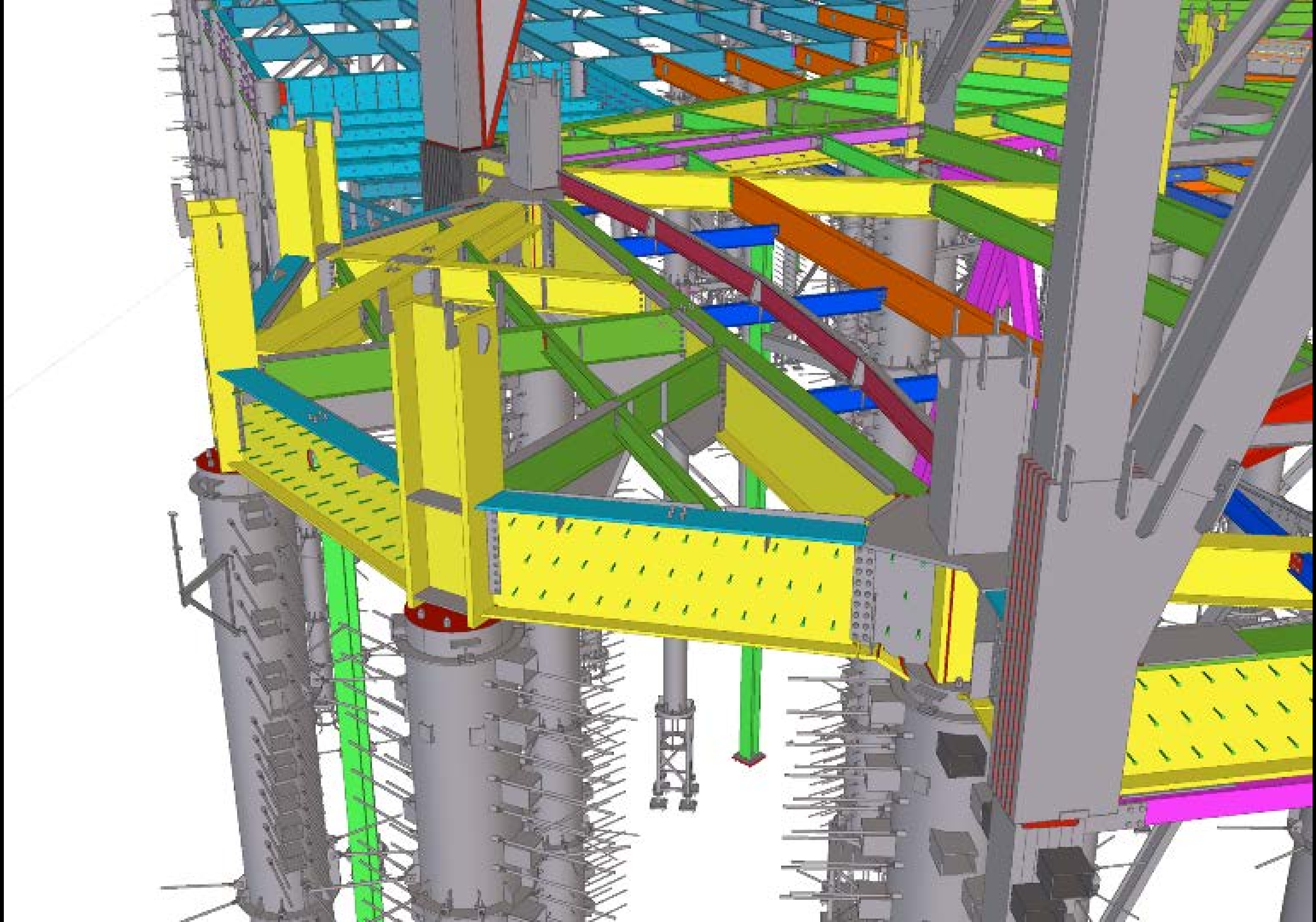


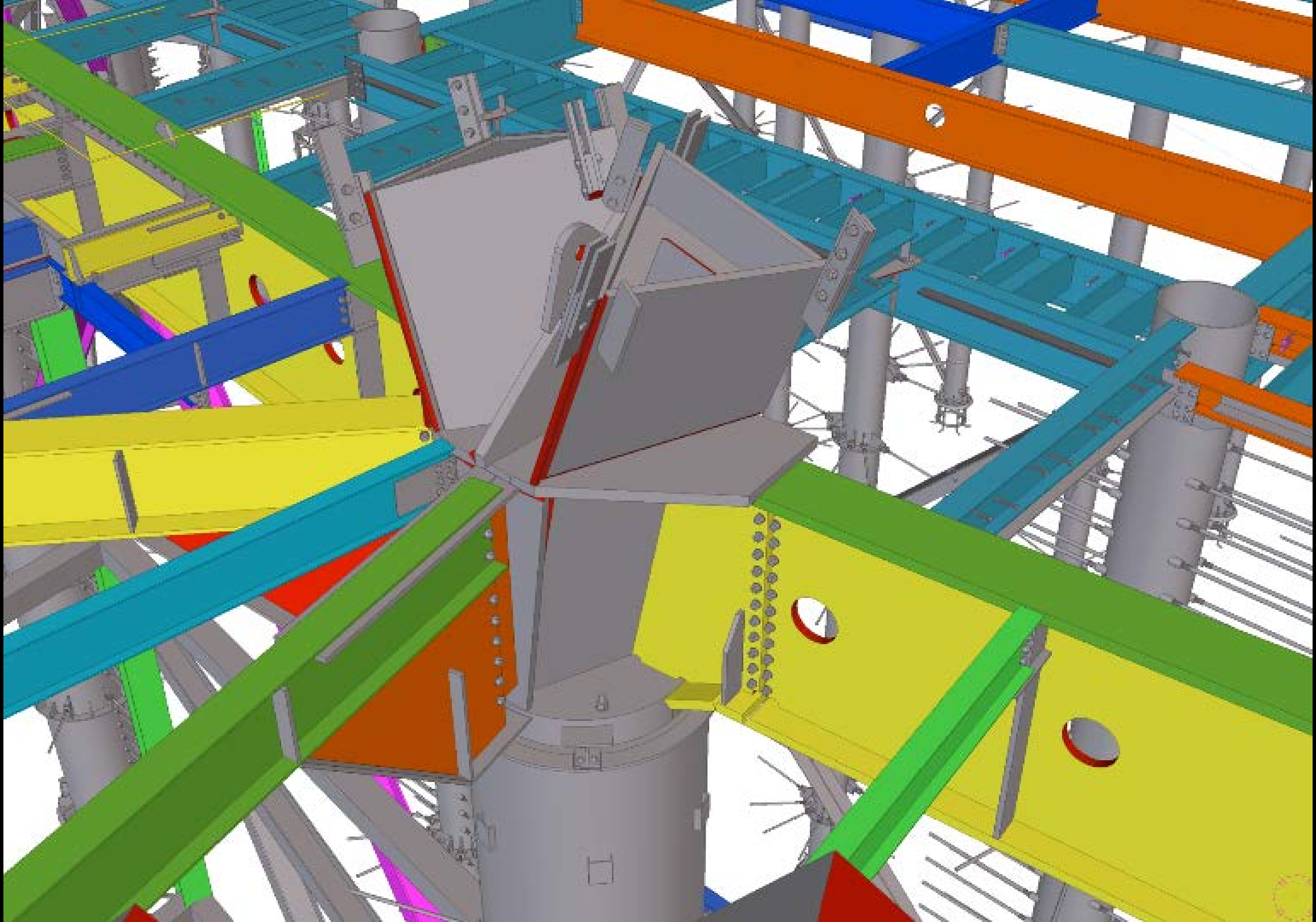

walters inc.

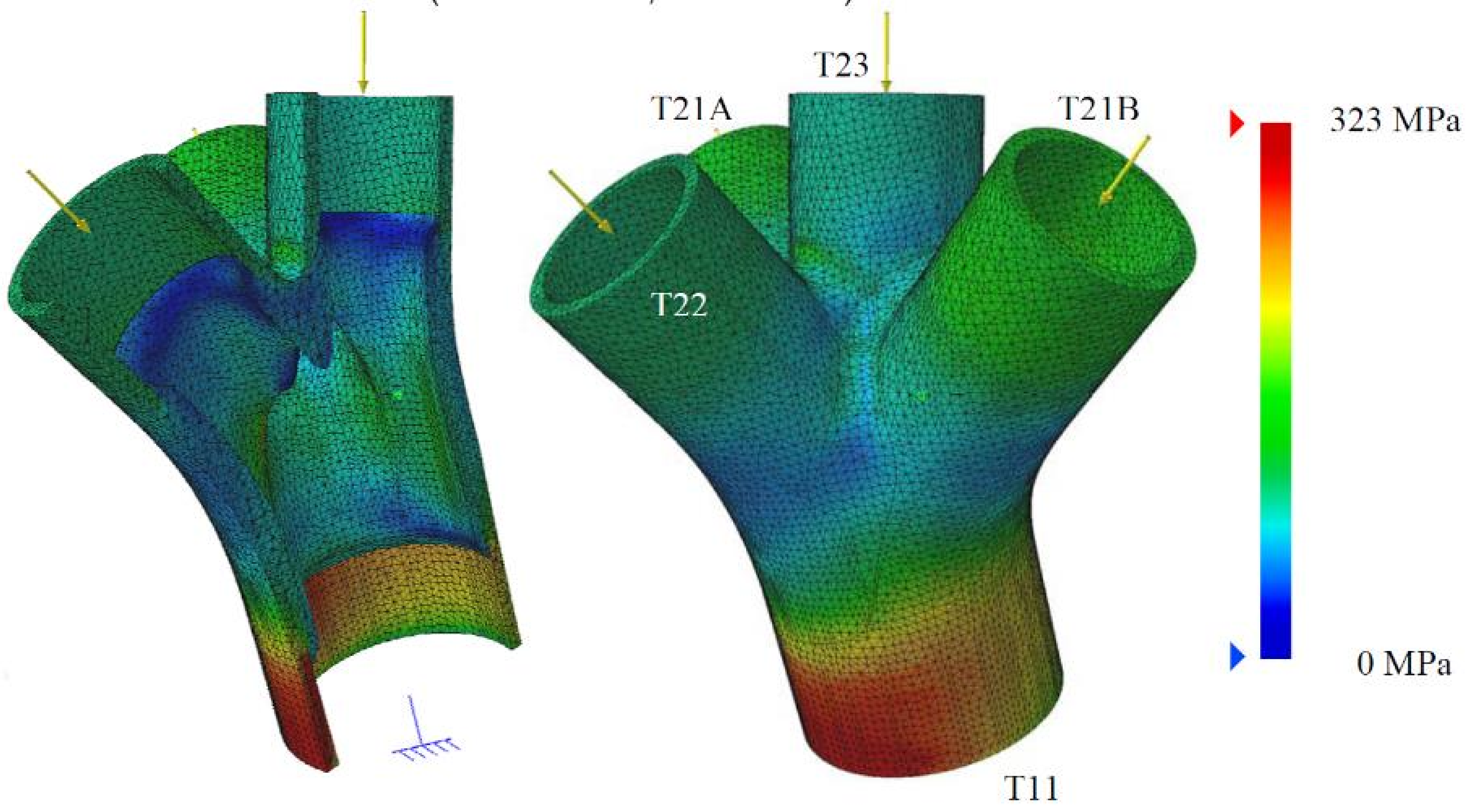






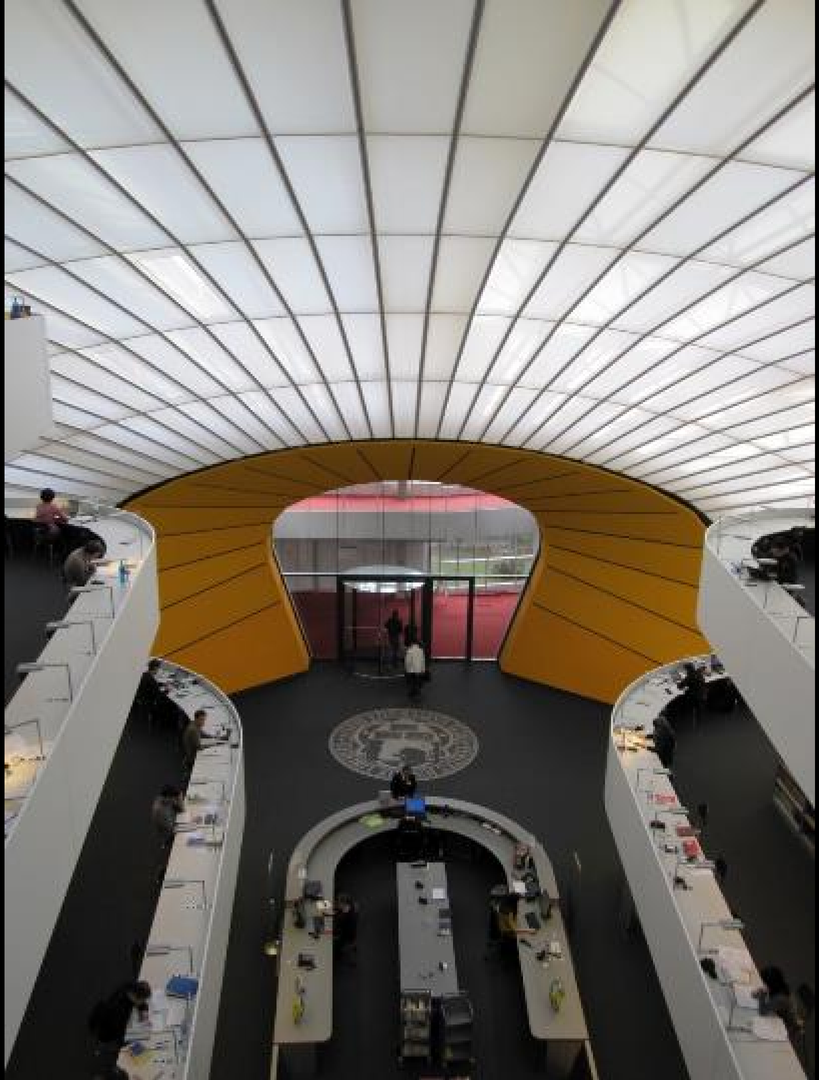






T23
T21A
T21B
T22
T11
323 MPa
0 MPa


Snorkel

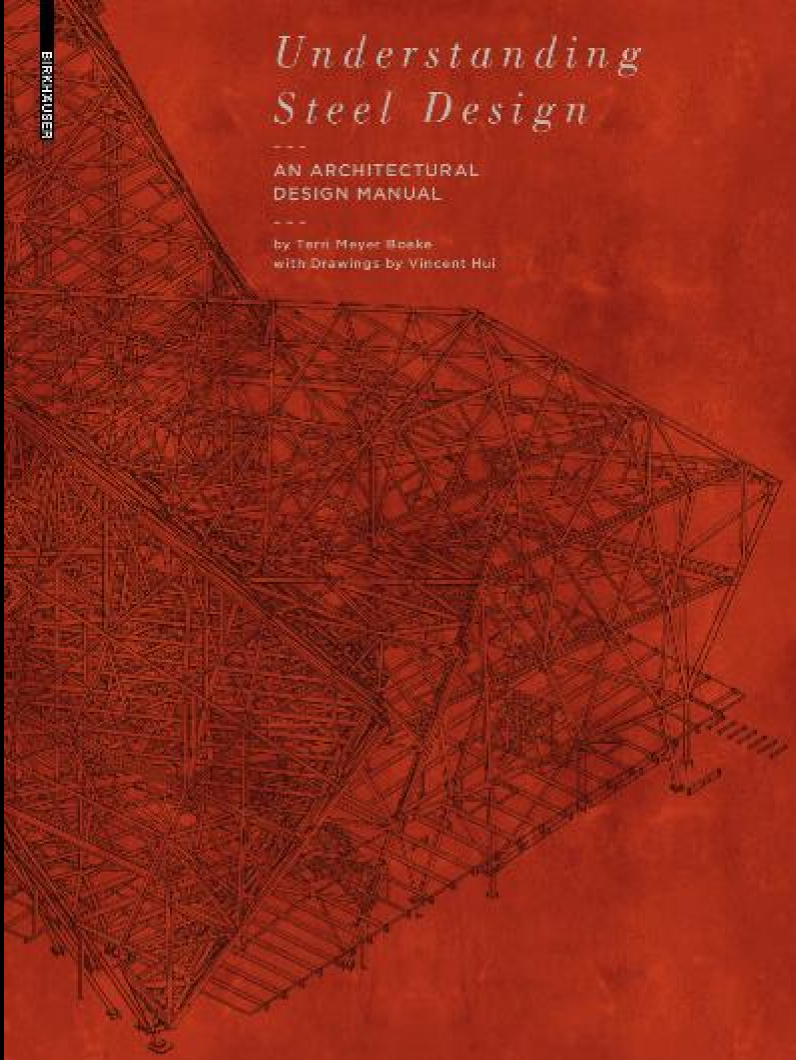

Huttenstraße
Berlichingenstraße
30
ZONE

BIRKHÄUSER

Understanding Steel Design

AN ARCHITECTURAL DESIGN MANUAL

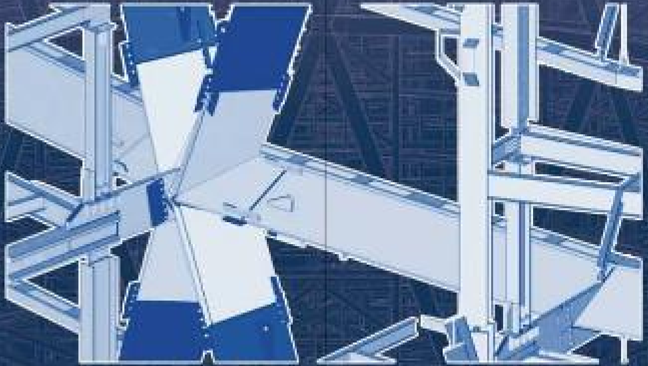
by Terri Meyer Boake
with Drawings by Vincent Hui

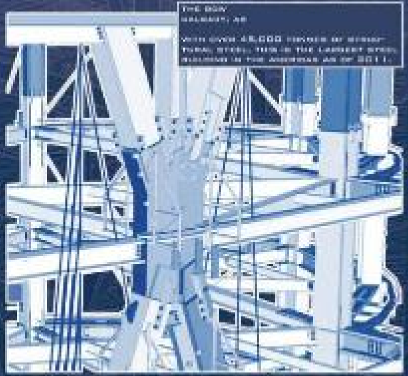



RAMS HORN SCULPTURE
CALGARY, AB


ROYAL ONTARIO MUSEUM
TORONTO, ON


ONTARIO COLLEGE OF ART AND DESIGN
TORONTO, ON




THE BOW
CALGARY, AB

WITH OVER 45,000 PIECES OF STRUCTURAL STEEL, THIS IS THE LARGEST STEEL BUILDING IN THE AMERICAS AS OF 2011.

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 skyline of Shanghai, China as seen from the Huangpu River. The change in architecture, which is due to the impact of the potential of steel, is clearly evident in a skyline that borders on the futuristic. Whether these buildings have structural steel skeletons, or have concrete cores or steel reinforcing, the potential of the materiality and the structural properties of steel are at the root of the architecture.

CHAPTER 2

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.

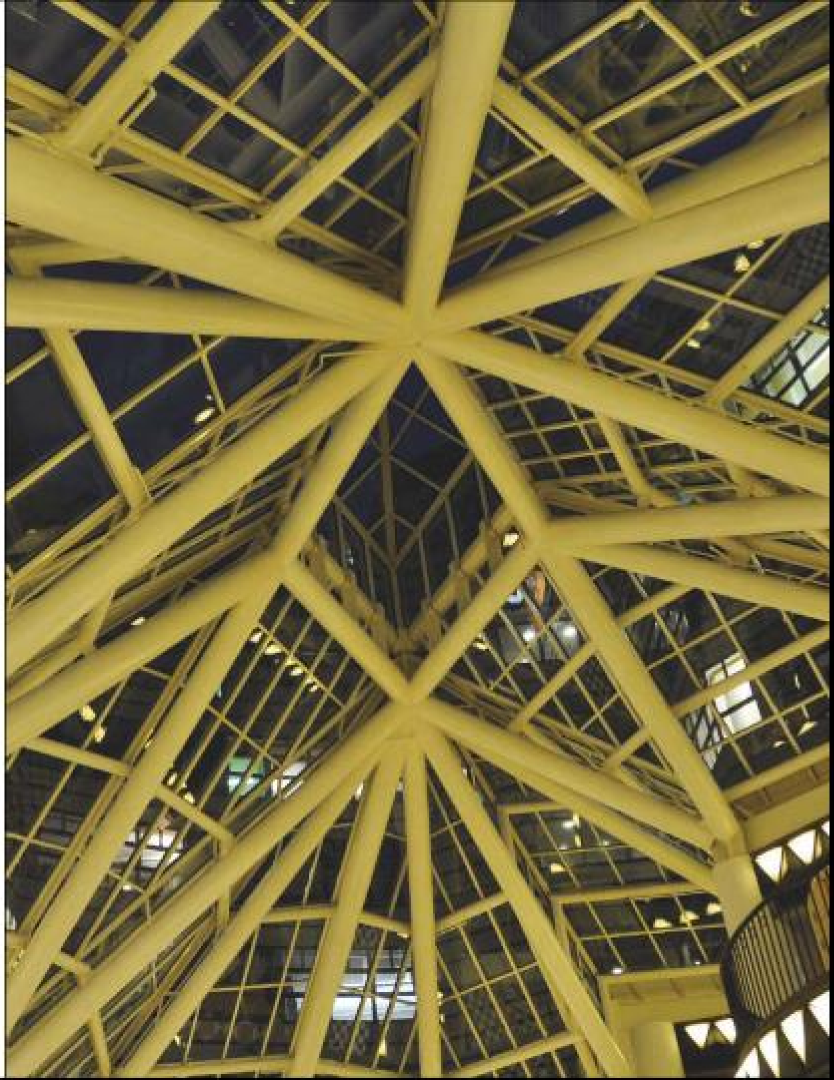
CHAPTER 3

- - -

STEEL CONNECTIONS AND FRAMING TECHNIQUES

- - -

The tubular steel structure at the Friedrichstadtpassagen Quartier 206 Shopping Mall in Berlin, designed by Pei Cobb Freed and Partners, makes predominant use of welded connections to achieve a clean appearance in resolving the intersection of the large round members. The smaller members that support the skylight are a combination of welded and bolted connections, as these are clearly less dominant. The framing is highlighted against the dark night sky, making its joinery more dramatic at night than during the day.



CHAPTER 4

FABRICATION, ERECTION AND THE IMPLICATIONS ON DESIGN

Steel erection is about teamwork. A large number of personnel are on site to oversee the lift of the "pod" at the Leslie Dan School of Pharmacy in Toronto, ON, Canada designed by Foster + Partners. This is the first installation of its kind for the architect as well as the fabricator, Walters Inc. The bright orange dots on the chains allow the rigging at levels during erection and to check the lift for alignment.

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

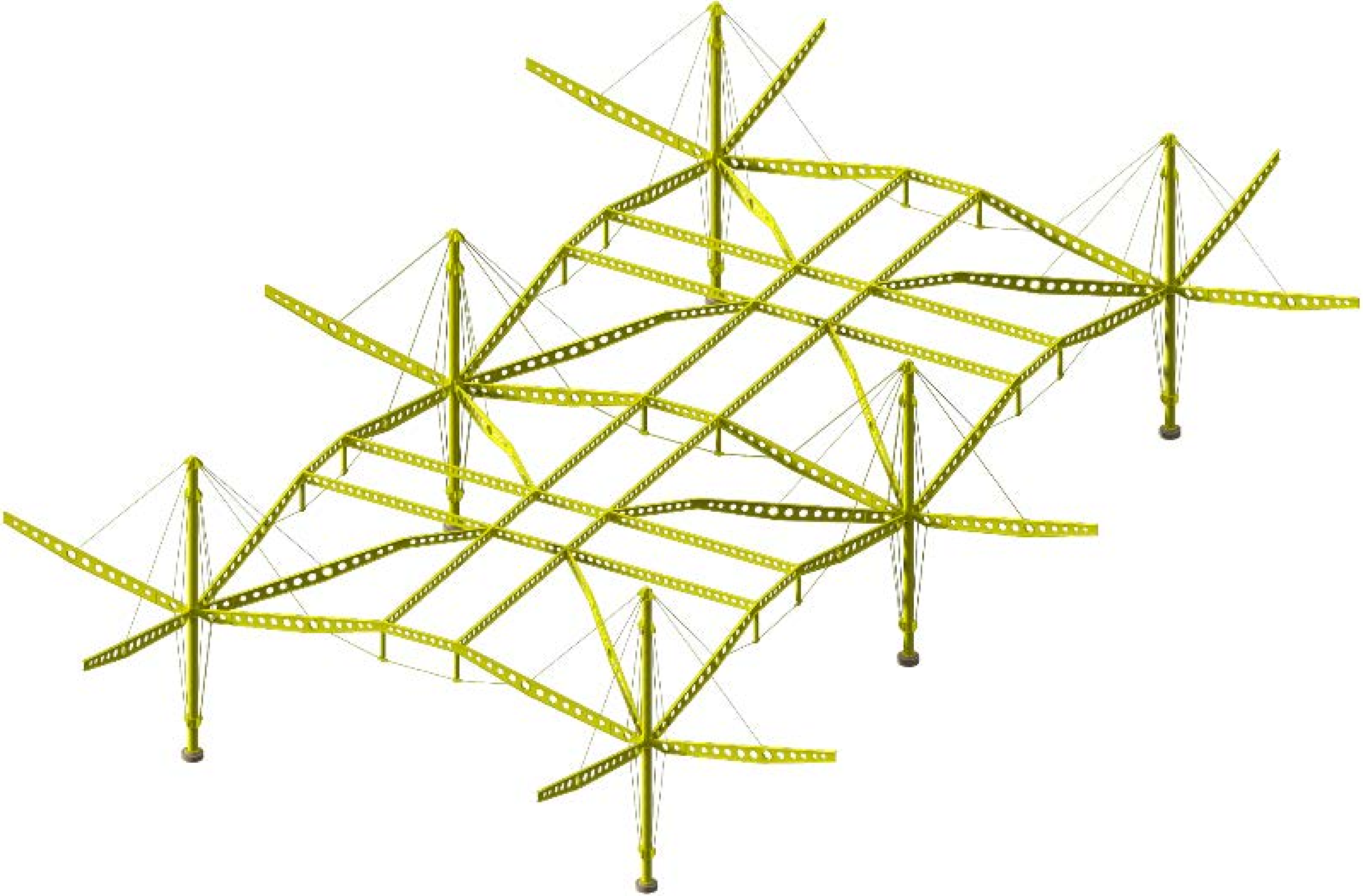
Oxford Ice Rink | Nicholas Grimshaw

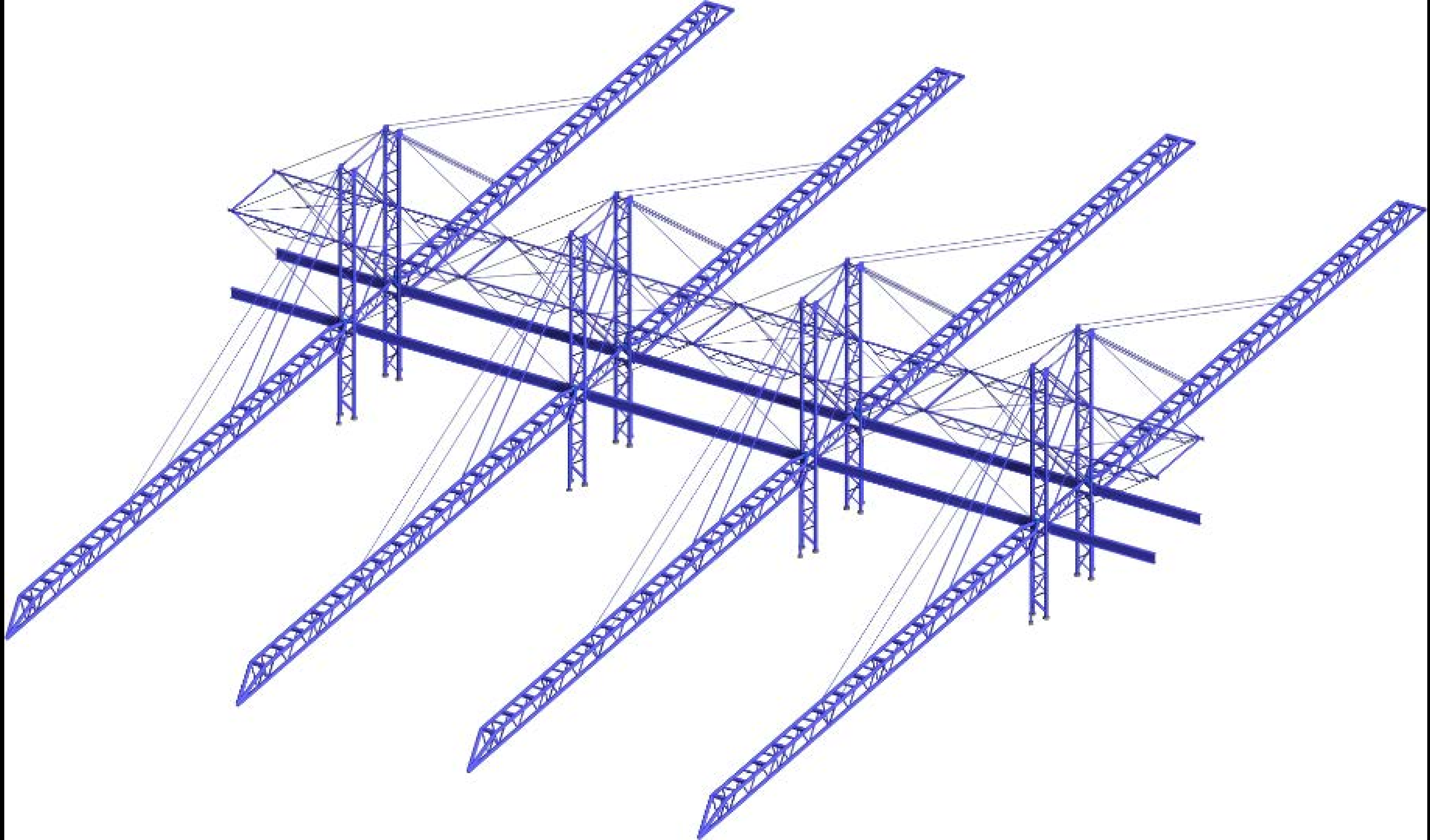
Inmos Microprocessor Factory | Richard Rogers

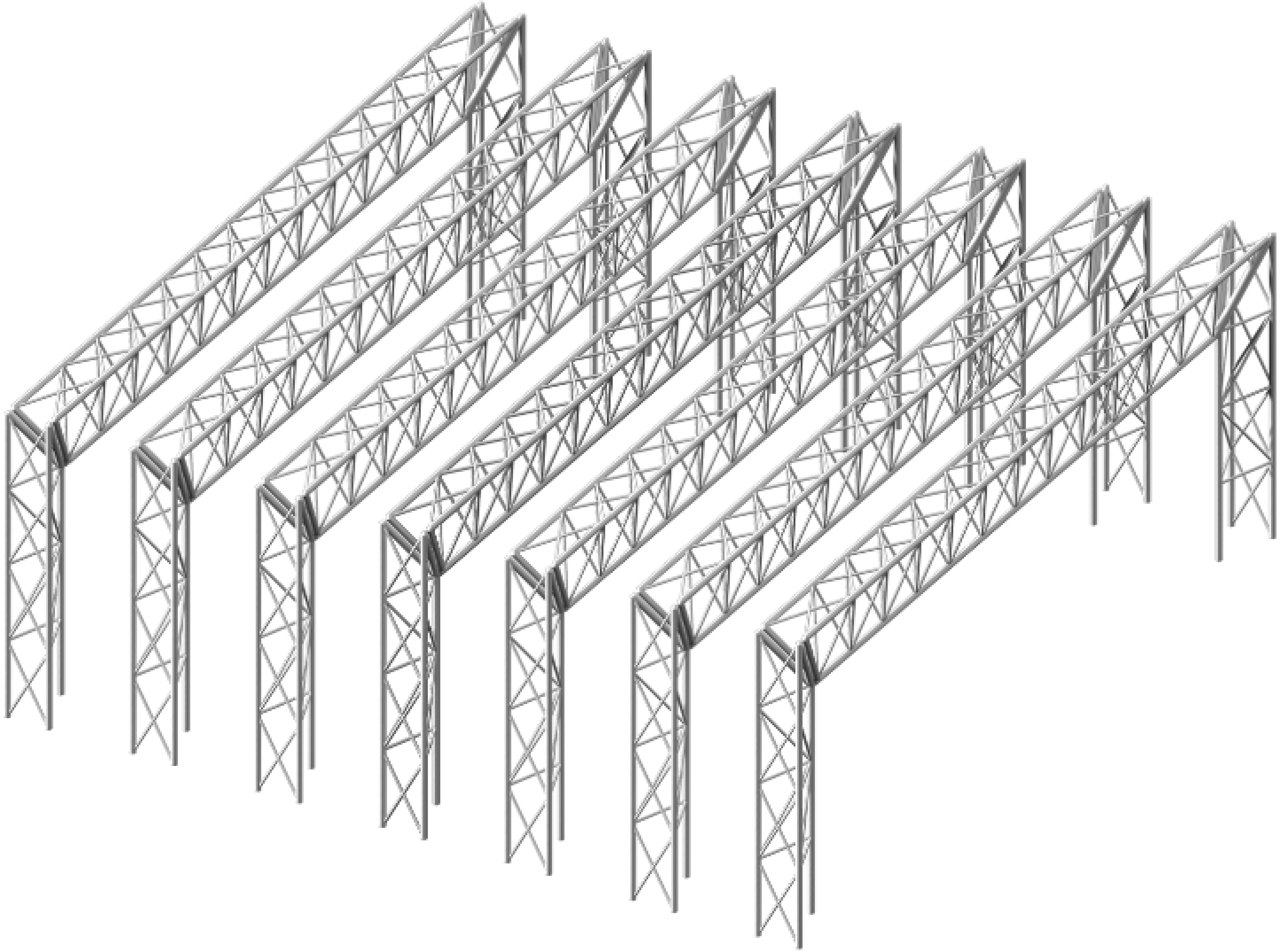
HIGH TECH BECOMES ARCHITECTURALLY EXPOSED STRUCTURAL STEEL (AESS)

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 use of expressed and exposed steel systems.



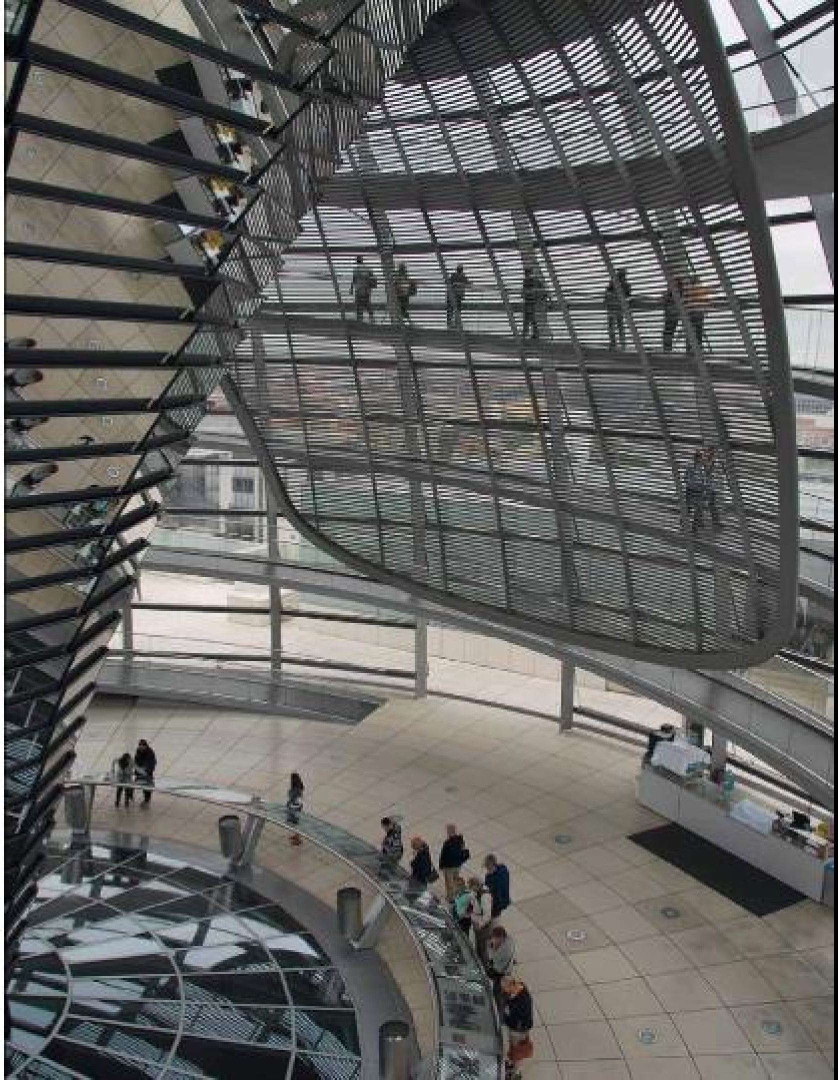




CHAPTER 6

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

Architecturally Exposed Structural Steel, such as that used in the Dome of the Reichstag Building of the German Bundestag in Berlin, Germany designed by Foster + Partners, has significantly higher requirements for fabrication, erection and finishing than regular structural steel. These requirements must inform the design from the outset of the project and form the central element of communication 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

Much of the structure of the Beijing National Stadium in China by Herzog & de Meuron was finished with matching [illegible] after welding. Complex joints and surfaces that could not [illegible] were finished with a series of coatings of field-applied materials. The surface was first roughened, followed by two spray-applied coats of "Zinga", a spray-applied intermediate layer of Epoxy Micaceous Iron Oxide (MIO), followed by a spray-applied final metallic grey fluorocarbon finish.

CHAPTER 8

CURVED STEEL

CREATING CURVES IN STEEL BUILDINGS

LIMITATIONS ON CURVING STEEL

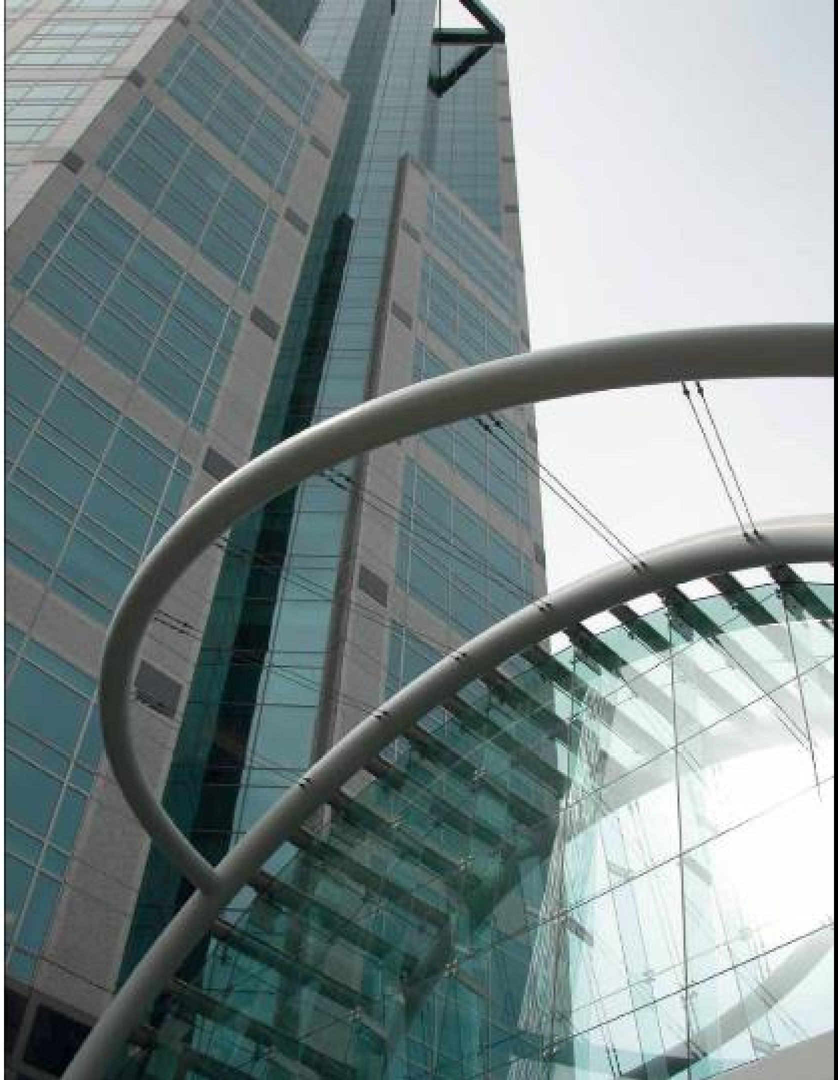
THE CURVING PROCESS

CURVED STEEL APPLICATIONS

FACETING AS AN ALTERNATE METHOD TO BENDING

CREATING CURVES WITH PLATE MATERIAL

The large round curved HSS members of the pedestrian bridge at the Wells Fargo Building in Salt Lake City, UT, USA, designed by HKS Architects, provide a striking contrast with the glass box they support as well as the tower behind. Highly specialized processes are required to bend steel of this diameter.



CHAPTER 9

ADVANCED FRAMING SYSTEMS: DIAGRIDS

The Bow Encana Building in Calgary, AB, Canada, designed by Foster + Partners with Zeidler Partnership and engineered by SMHP, uses an expressed diagrid structural system for this double façade building.

CHAPTER 10

CASTINGS

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

Pudong Airport in Shanghai, China by Paul Andreu uses a variety of steel shapes to create the undulating curved roof over the terminal. Custom castings are used to transition the differing geometries of the roof beams and of the angled supports of the tree-like columns.

CHAPTER 11

TENSION SYSTEMS AND SPACEFRAMES

Tensile fabric structures are able to exhibit amazing feats of architecture and engineering that are only possible using highly articulated steel structures and connections. The glass, fabric and steel roof of the Sony Center at Potsdamer Platz in Berlin, Germany by Helmut Jahn creates a functional semi-enclosed public space.

CHAPTER 12

STEEL AND CONTEMPORARY GLAZING SYSTEMS

The highly technical tensile glazing system at the Louvre pyramid in Paris, France, designed by I. M. Pei and Peter Rice, characterizes the extreme contrast between the limitations of load-bearing masonry and the possibilities of steel glazing systems.

CHAPTER 13

- - -

ADVANCED FRAMING SYSTEMS: STEEL AND TIMBER

- - -

CHARACTERISTICS

DETAILING ISSUES

FABRICATION AND ERECTION ISSUES

FINISH ISSUES

HIDDEN STEEL

PROCESS PROFILE: ADDITION TO ART GALLERY OF ONTARIO (AGO) / FRANK GEHRY

PROCESS PROFILE: THE RICHMOND SPEED SKATING OVAL / CANNON DESIGN

The glass-and-timber façade of the Addition to the Art Gallery of Ontario, Toronto, ON, Canada, designed by Frank Gehry, relies on exposed steel framing to support and tie the sculptural element back to the building. The design and erection of such an articulated piece requires an integrated approach to coordinating the structural benefits and limitations of the two materials.

CHAPTER 14

STEEL AND SUSTAINABILITY

STEEL AS A SUSTAINABLE MATERIAL

THE LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN (LEED™) 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

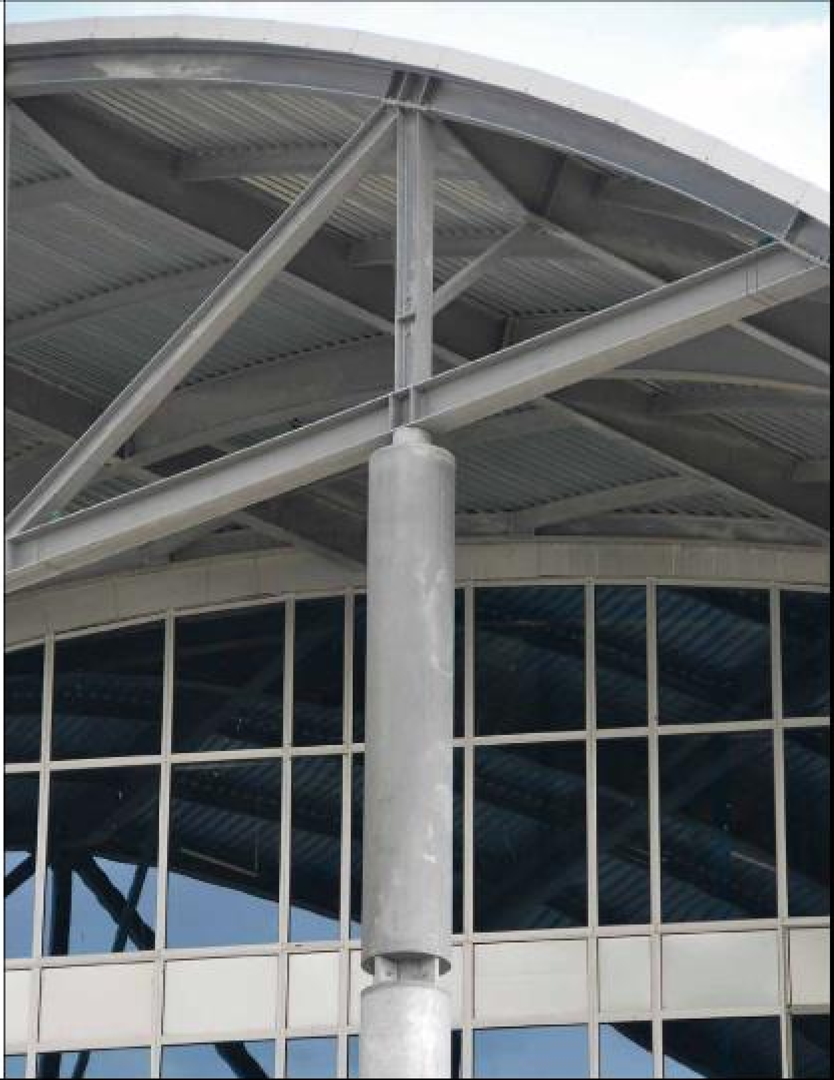
REDUCE MATERIAL

REDUCE FINISHES

REDUCE LABOR

REDUCE TRANSPORTATION

DURABILITY



The galvanized finishes on the Calgary Water Centre, AB, Canada provide the exterior exposed steel with a durable and rugged appearance that speaks to the sustainable nature of the facility design. Steel is perhaps not the first structural material that springs to mind when thinking of sustainability. However, the material here is sourced from high recycled content rather than virgin ore. The galvanized finish means less waste by avoiding repainting the structure on an ongoing basis. The exposed steel precludes the need for other cladding materials, saving embodied energy.

CHAPTER 15

STEEL IN TEMPORARY EXHIBITION BUILDINGS

The Entry Pavilion for the Shanghai Expo 2010, China, designed by SBA Architects, exploits the innovative potential of steel in its three-dimensional modulation of the steel lattice grid with a membrane-supported fabric canopy. The project was constructed by Knippers Helbig Advanced Engineering of Germany.

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Copy

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Dear Patty and Terri

How wonderful of you to send me Terri's impressive book. I shall read it with great pleasure as I worked for 7 summers at Algoma Steel from 1959-1966 and was always looking for more and better ways to use steel.

Bravo and long live UW's outstanding School of Architecture

Warmest regards

David Johnston

January 3, 2012

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

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 Boake, 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 Boake

Patty Boake

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Book "Understanding Steel Design"

DIAGRID STRUCTURES

SYSTEMS
CONNECTIONS
DETAILS

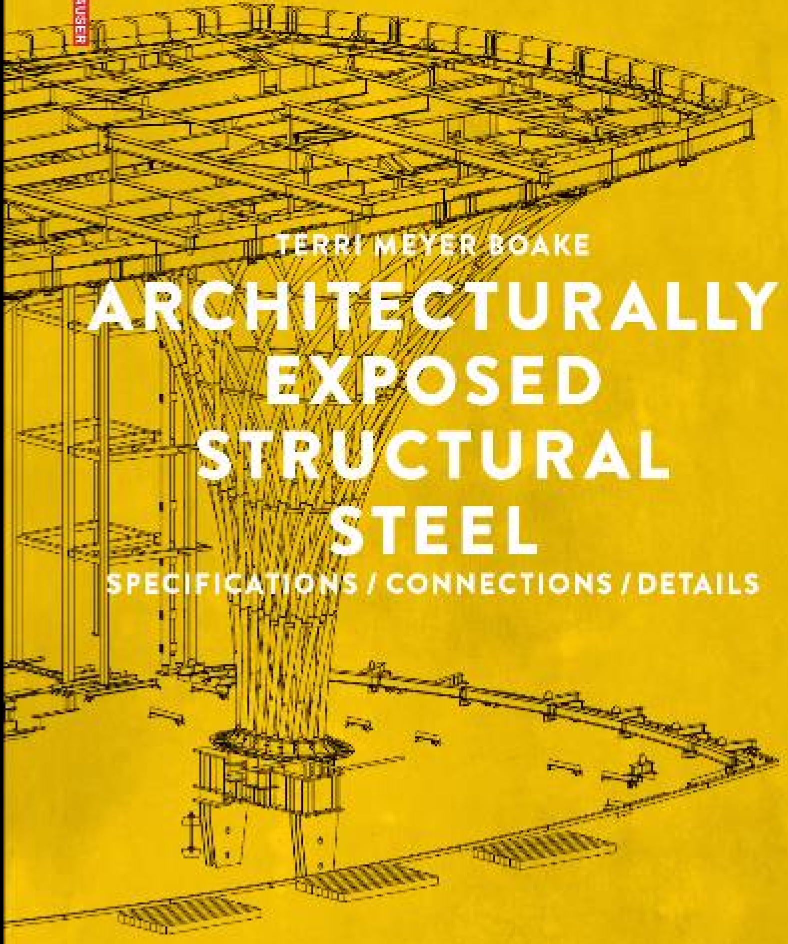
TERRI MEYER BOAKE

BIRKHÄUSER

TERRI MEYER BOAKE

ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

SPECIFICATIONS / CONNECTIONS / DETAILS



AESS 1

AESS 2

AESS 3

AESS 4

AESS Category Matrix

	Characteristics	AESS C Custom Elements	AESS 4 Showcase Elements	AESS 3 Feature Elements	AESS 2 Feature Elements	AESS 1 Basic Elements	SSS Standard Structural Steel
				Viewed at a Distance ≤6m/20ft	Viewed at a Distance >6m/20ft		
1.1	Surface preparation to SSP6 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	Bolt head orientation specified		x	x	x	x	
1.5	Weld spatters removed		x	x	x	x	
2.1	Visual Samples		OPTIONAL	OPTIONAL	OPTIONAL		
2.2	One-half standard fabrication tolerances		x	x	x		
2.3	Fabrication marks not apparent		x	x	x		
2.4	Welds uniform and smooth		x	x	x		
3.1	Mill marks removed						
3.2	Butt and plug welds ground smooth and filled		x	x			
3.3	HSS/RHS/CHS weld seam oriented for reduced visibility		x	x			
3.4	Cross-sectional abutting surface aligned		x	x			
3.5	Joint gap tolerances minimized		x	x			
3.6	All-welded connections		OPTIONAL	OPTIONAL			
4.1	HSS/RHS/CHS weld seam not apparent		x				
4.2	Welds contoured and blended		x				
4.3	Surfaces filled and sanded		x				
4.4	Weld show-through minimized		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 at 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 (20–60%)	None 0%

The Munich Airport Center in Munich, Germany, designed by Helmut Jahn and completed in 1999, 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 elevates 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

CHAPTER **1**

WHAT IS AESS?

Perth Arena in Perth, Australia, designed by ARM Architecture and CCN, uses finely welded round HSS tubes to create a dynamic entrance structure for this arena completed in 2012. The complex angles that challenge the fabrication of the structure push this construction to an AESS 4 category.

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, canopies 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 categorization 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.

THE CATEGORY SYSTEM

CHAPTER 2

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 diagrid columns that support the roof of the World Financial Center entry pavilion in New York City, NY, USA, designed by Pelli Clarke Pelli Architects, meet the highest standards of AESS 4 design. Fabrication by Walters Inc. and erection by Metropolitan Walters.

Although the categories of AESS 1 to AESS 4 have been developed specifically for the Canadian and Australasian 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/aess. 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.*

CHARACTERISTICS

CHAPTER 3

The Arganzuela Bridge in Madrid, Spain, designed by Dominique Perrault, uses a variety of custom fabrication methods.

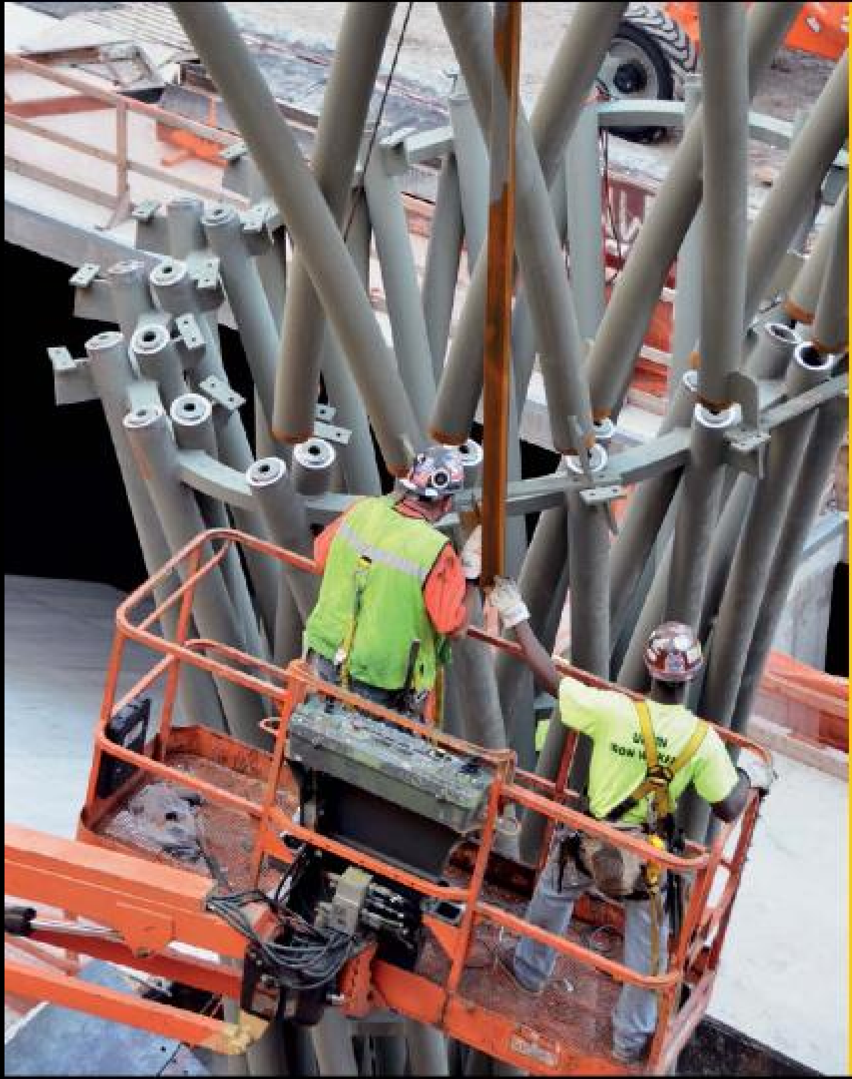
A set of characteristics is associated with each category as outlined in the previous chapter. Higher-level categories include all of the characteristics of the preceding categories, plus a set of specific additional requirements.

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).[1] 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, dust, 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 (left) exhibits natural oxidation and may have other materials on the surface that would prohibit proper adhesion of finishes. After commercial blast cleaning (right), the steel will oxidize prior to final finishing, but it is now more effective to remove problematic residues prior to painting and finishing.



ERECTION CONSIDERATIONS

CHAPTER **4**

TRANSFORMING AN ARCHITECTURAL IDEA INTO PREFABRICATED AESS ELEMENTS

A diagrid section is lifted onto the base structure of the World Financial Center entry pavilion in New York City, NY, USA, designed by Pelli Clarke Pelli Architects, with fabrication by Walters Inc. and erection by Metropolitan Walters. The components had been test-erected in the shop to ensure a good fit prior to transport. The complexity of this structure and the desire for a seamless AESS 4 finish required special precision to the connections.

There is significant work involved in transforming the architectural idea of a steel-framed building into a series of prefabricated elements that can be readily erected on the building site. Even into the 21st 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 assemblage construction, while the industry still relies on these precepts 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

COATINGS & PROTECTION

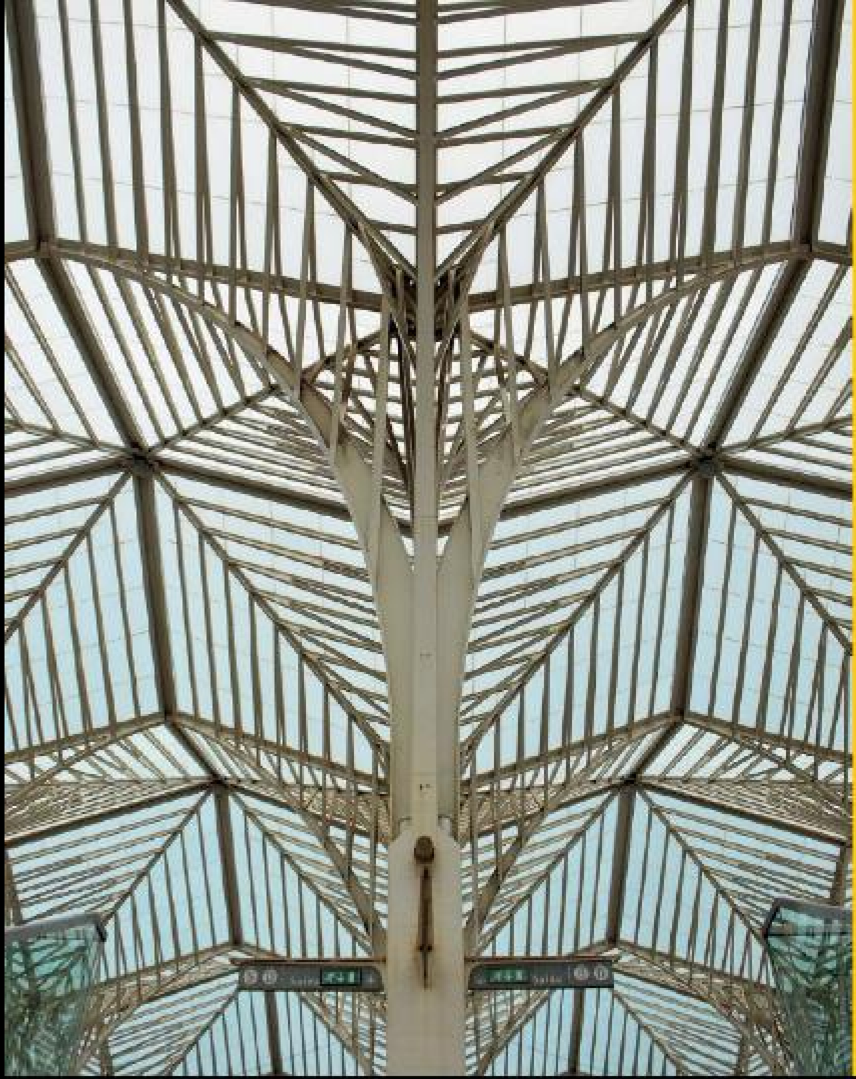
CHAPTER 5

The structure of the Beijing National Stadium ("Bird's Nest") in Beijing, China, designed by Herzog & de Meuron/[illegible] Arup, 2008, was for a large part finished with metallizing after welding. Complex joints and surfaces that could not accommodate metallization were finished with a series of coatings of field-applied materials. The surface was first roughened, followed by two coats of "Zinga", a spray-applied intermediate layer of Epoxy Micaceous Iron Oxide (MIO), followed by also spray-applied metal, fluorocarbon finish.

Coatings on AESS are critically important as they impact durability. SO_2 and NO_x, 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.



Oriente Station in Lisbon, Portugal, designed by Santiago Calatrava, constructed for Expo '98, stands as a project that influenced the development of AESS. The detailing of the fabrication made predominant use of custom-fabricated sections, a practice that has been reduced in deference to using a wider range of stock and structural and hollow shapes.

MEMBER CHOICES

CHAPTER 6

THE TEXTURE OF AN AESS PROJECT

The combination of the exposure of the steel, the selection of member types and expressed 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

CHAPTER 7

The transformation of the Las Arenas Bullring Mall in Barcelona, Spain, designed by Rogers Stirk Harbour + Partners, relies on a system of AESS tubes, pin and tension 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

8

Special castings form the pin connections for the tapered columns at the expansion to Zurich airport, designed by Grimshaw Architects.

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 [illegible] Pedestrian Bridge in Seattle, WA, USA, designed by Johnson Architecture and KPFF Consulting Engineers, required significant customization due to the widely varying geometries. Huge steel tubes twist and turn over the railroad tracks in a double helix that recalls the ladder-like structure of DNA. Although the individual members are similarly fabricated, the sizes and actual 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 noticed, 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 Choices*. 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.

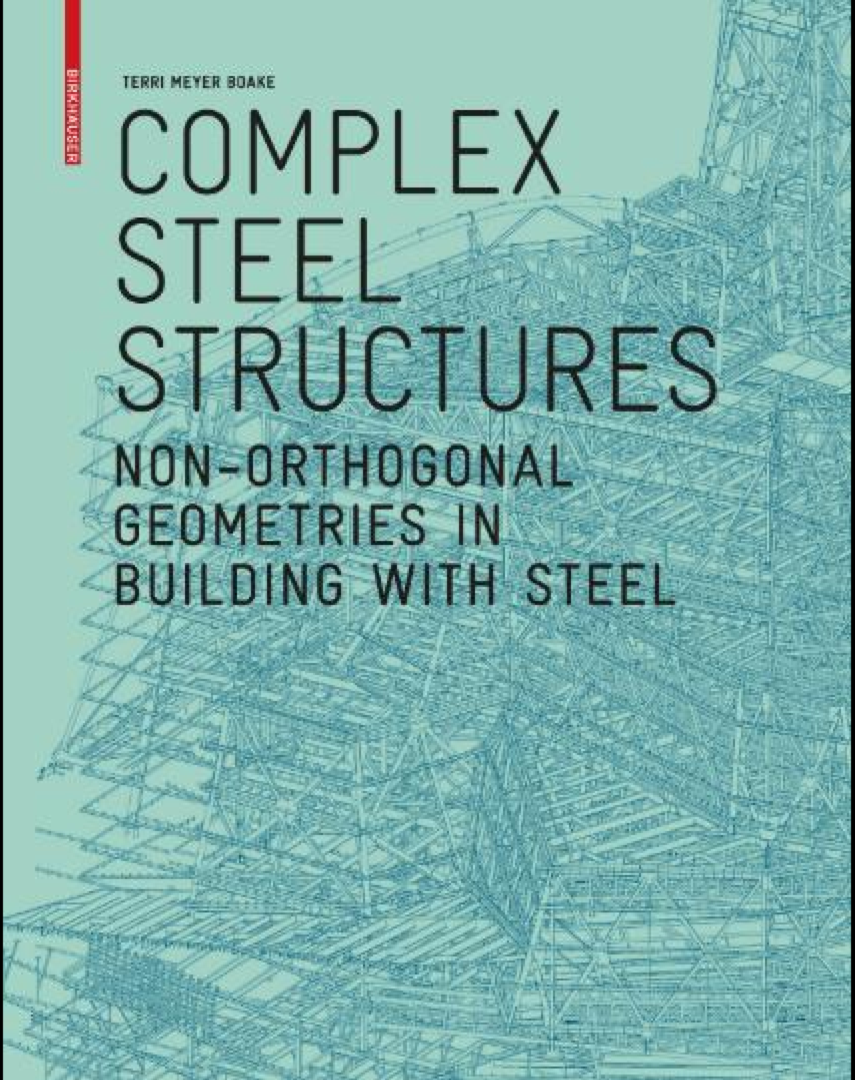
Within this chapter, custom fabrication requirements and details will be presented on a project-by-project basis.

The Beijing National Stadium ("Bird's Nest") in Beijing, China, designed by Herzog & de Meuron/[illegible], represents the extreme high end of custom fabrication. The complex geometry and overall form required the custom fabrication of all structural elements from plate material. The on-site connections were as exposed, with the majority requiring significant grinding, filling and remediation to make them appear 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 BIAD UFo, showcases the use of AESS in conjunction with a high level of parametric design. A deep understanding of the structural capabilities of steel as well as effective detailing and fabrication methods were essential for the success of this project.



BIRKHÄUSER

TERRI MEYER BOAKE

COMPLEX STEEL STRUCTURES

NON-ORTHOGONAL GEOMETRIES IN BUILDING WITH STEEL

THE RISE OF COMPLEXITY

CHAPTER 1

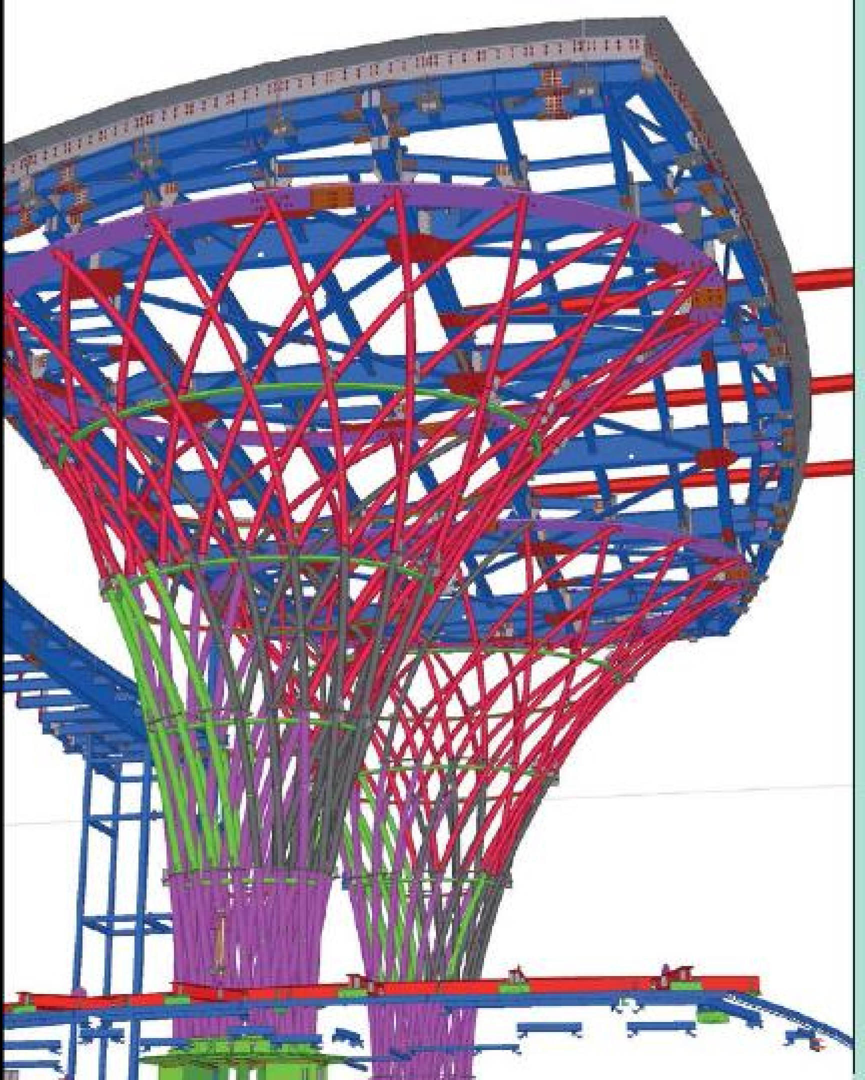
In order to understand how we can best undertake steel design for complexity in the present Post-Fordist age of Parametricism, it is necessary to trace its evolution. Many of the current techniques for managing the design and fabrication of complex steel systems are closely based on practices that emerged 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 ironworker 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.

The detailing of the steel in the La Villette project by Bernard Tschumi in Paris, France, 1987, reflects well the transition to a new type of steel detailing in Deconstructivism. The forms differ from related structural systems that had been developed in High Tech architecture, transformed to stabilise the eccentric loading and twisting shapes of the new style. The work includes angled as well as curved elements.

1. THE MODERN CONDITION: STARTING POINT

The Modern buildings that predated 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 force 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 sizing 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.

Stylistically 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 conservative detailing directed at minimizing the weight and thereby the cost of steel. Steel buildings were generally priced by their tonnage, 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 clearer, cleaner and more regular. When exposed, connections tended to be welded so as to suppress the technical aspects of the joinery. This fed well into the Modern aesthetic that was more formally driven and eschewed technical details.



THE DIGITAL REVOLUTION

2

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 intrinsic 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, desire 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 tolerance, fabrication processes, irregularities of material and human error.

The Tekla Structures image of the Brookfield Place Pavilion in New York City, NY, USA, designed by Pelli Clarke Pelli 2013, shows the level of drawing and detailing complexity that the steel fabricator Walters Group used to guide the fabrication and erection processes.

2. HIGH TECH ARCHITECTURE SETS THE STAGE

Some of the initial design changes that predate the widespread incorporation of computing in design began to generate a need for that 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, Piano, Grimshaw). This increase in complexity was initially characterized by the introduction of force-differentiated structural systems – those making widespread use of the exposure of lightweight tensile members to provide stability to the largely hinge-and-pin-connected prefabricated and often modular systems – as well as the forefronting and exposure of the steel systems and connection details.

MANAGING COMPLEXITY 3

This chapter looks to compare visual complexity to configurational complexity. When a designer seeks to create an aesthetic in expressed 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 standard orthogonal structural systems that typified 20th 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 (Deconstructivism) – 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 this 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 base 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 come into 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 amounts 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 programme of the architecture.

Federation Square in Melbourne, Australia, designed by LAB Architecture and Bates Smart, 2002, uses a chaotic three-dimensional configuration comprised of galvanized square steel tubes to define the expression of the architecture in this important civic project.

FABRICATING THE STEEL

4

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 team logistics and communication. Regardless of the geographic location, complex steel projects require a higher than normal level of understanding among the players. On traditional concealed 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 tender process after the drawing set is complete. On complex steel projects, whether concealed or using AESS, the involvement of the fabricator for advice early on during the design phase can facilitate 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. As tight tolerances are 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 test assembling.

The eight baskets for the Brookfield Place Pavilion in New York City, NY, USA, designed by Pelli Clarke Pelli Architects, 2013, were fabricated in Hamilton, ON, Canada and transported hundreds of kilometres to the site. A strategy for breaking the large baskets into transportable elements was critical to the success of the project and greatly influenced the connection strategies.

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 translated to the envelope design.

The Helix Bridge in Singapore, designed by Cox Architecture and Arup, 2010, is fully exposed to a harsh marine climate. For this reason it was decided to fabricate the bridge from Duplex 2205 stainless steel, the highest grade of stainless material, as lower grades would not have been as durable. This choice of material required extensive welding and weld remediation to complete the aesthetic.

CORROSION PROTECTION & FINISHES

5

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 concealed 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 identically 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 intumescent coating. Even if shipped with only a protective primer coat, care needs to be taken not to damage the surfaces, as any abrasions will require remediation on site. Large elements will require additional temporary support in transport 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 designing 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 splice connections on the design. It will be important for the ultimate durability of the project to ensure that coatings are applied in optimal conditions.

AESS should always start out with a professional blast cleaning to remove any mill scale, grease, or others that will prevent the proper adherence of the finish. This is a cost above the cleaning required for standard concealed 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 care 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.

ERECTION LOGISTICS

6

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 eccentric 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

Although simple in concept and symmetrical in geometry, the delta trusses on the Queen Richmond Centre in Toronto, ON, Canada, designed by Sweeny&Co Architects, 2015, showcase the challenges during erection. Fit tolerances between the concrete work and the sloped tubular steel segments were very tight, as a seamless welded connection between the members was the aesthetic goal. The casting design was executed by CastConnex and the steel by Walters Group, a division of labor that required close coordination to ensure proper fit.

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 erection processes, many of the variations 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 forms will have odd requirements for lifting. Even having the crane attachment points slightly out of position can make for failed attempts and repeat tries. This will obviously increase the time needed to properly install the element. Although in an ideal world, particularly one that is now so engrained 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 usually the lead ironworker on the project who is doing the estimation 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 padded slings and pads for any supports that come into contact with the steel to prevent damage to the surfaces.

ECONOMICALLY DRIVEN STRATEGIES

7

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 AESS structure of Tokyo Midtown, Tokyo, 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 selection have been strategically applied to the lower level structure, the spanning system and the extreme high level structure for the canopy. Layering effectively obscures the view to the most distant steel.

The overall strategy behind the category system for specifying Architecturally Exposed Structural Steel is to allow the distance to view to soften the fabrication requirements for the steel. If a surface or element is situated further than 6m/20ft from view it is unlikely that the viewer will either be able to see or appreciate fastidious 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 3 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 into play 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.

CURVED GEOMETRIES

8

The Osaka Art Gallery, Japan, designed by Cesar Pelli, 2004. The highly sculptural entry portion is fabricated from stainless steel. This material required full consideration of symmetries, fastidious workmanship to support its aesthetic demands, and a high level of craft and expertise to achieve the slightly irregular 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 departures 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 pertaining advances in design, calculation and fabrication techniques, curvature, to a large extent, had been limited to and characteristic of monolithic reinforced concrete construction. The invention of the geodesic dome by Richard Buckminster Fuller, and experimentation with the application of bubble geometries to 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 "faked the curve," as they were comprised of straight members connected via nodes. Their scale allowed the illusion 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 sculptural superstructure of the Osaka Art Gallery has been fabricated from stainless steel, which requires fastidious care in detailing and fabrication, the structure immediately behind it, directly supporting the glazed enclosure, has been fabricated from round HSS sections that have had a finish applied that blends with the overall appearance. This affords some savings to the project.

ANGULAR GEOMETRIES

9

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 diagrid 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*; diagrids are investigated in great detail in *Diagrid Structures: Systems, Connections, Details*. The angular geometries investigated in this chapter consist of less systems-driven and more chaotic or varying 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 measurements 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 AESS projects with preferences for an all-welded look, as dimensional mismatches are difficult to conceal. Extremely large structures do not have the benefit of pre-fit testing and will be forced to resolve fit issues on site. Some workaround strategies include positioning potentially problematic on-site-welded connections so that view to them is distanced or obscured.

The Kurilpa Bridge, Brisbane, Australia, designed by Cox Rayner Architects with Arup, 2009. This tensegrity-based structural system was the first spanning structure of its kind. There is an underlying order behind the apparent and intended chaos of the structure. The member sizes clearly indicate their compressive or tensile designations. For more on this project see p. 1[illegible].

NODES

CHAPTER 10

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 structure. 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 connections 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 /nōd/

*Noun. A point at which lines or pathways intersect or branch; a central or connecting point.**

* Definition of Node by Oxford Dictionary on [illegible].com, a common definition referring to structural systems.

Reflect on the introduction to the term "node" in the history of structural steel design. Although in a looser sense the terms "joint" or "connection" might be considered synonymous, the term "node" conjures 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 was directly related to the number of connecting members and the ability to nimbly accept 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.

The incorporation of cast steel nodes at the intersection of the 8 concrete-filled steel tubes that form the delta frame supports at the Queen Richmond Centre in Toronto, ON, Canada, 2015 by Sweeny&Co Architects was a critical aesthetically driven choice that has resulted in the numerous design awards that this project has received. The project required a high level of fabrication coordination between the casting designers Cast Connex and the steel fabricator/erector Walters Group.

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 incoming members.

LATTICE/ GRIDSHELL STRUCTURES

CHAPTER 11

1. BASIC DESIGN PARAMETERS

Lattice structures, also called gridshells, are specialized steel framing systems developed to facilitate the creation of complex, curved glazed roofs and façades. Lattice structures work well as a complex system, as their geometry and strength make them ideal for mediating between odd enclosing 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 spanning 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 span 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 tensile 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 sized for major span requirements and can be very shallow and visually unobtrusive.

The lattice-supported skylight at Galaxy Soho in Beijing, China, designed by Zaha Hadid, 2012, was a natural choice for providing a simple and clean system that could work with the parametrically designed project. The triangular pattern is easily modified towards the edges to accommodate the tightening of the geometric requirements of the oval shape.

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 distance and the geometry of the forms between which the lattice mediates. Smaller spans can use more slender members. Tight curvature requires 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.