ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

SPECIFICATIONS / CONNECTIONS / DETAILS

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BIRKHÄUSER / BASEL

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CONTENTS

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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 Munich Airport Center in Munich, Germany, designed by Helmut Jahn and completed in 1999, showcases high-level detailing in Architecturally Exposed Structural Steel.

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This publication has been made possible through the generous support of worldsteel. Worldsteel was also the sponsor of *Diagrid Structures: Systems, Connections, Details*.

My early interest in steel must be credited to inspiration from the High Tech works of Foster, Rogers, Piano and Grimshaw as well as Santiago Calatrava. My appreciation of the importance of the details of these connections as elements of industrial design was inspired by my former colleague at the University of Waterloo School of Architecture, Ron Keenberg of IKOY Architects.

Much of my energy and understanding of Architecturally Exposed Structural Steel comes through my involvement with the Canadian Institute of Steel Construction in the development of the methodology that is expanded upon in this book. I owe so much to the large number of steel professionals involved in this development. Particular thanks go to Mike Gilmor, Rob Third and Suja John.

Also core to the CISC AESS committee work, my understanding and experience of steel would be nowhere without the assistance of Sylvie Boulanger, Walter Koppelaar and Tim Verhey. Sylvie is my engineering counterpart and has willingly shared so much knowledge and insight with me. Sylvie traveled with me to Australia and New Zealand in conjunction with expanding the Category System to Australasia. Walter has always encouraged me and allowed me into his fabrication shop, and provided access to numerous job sites and high-quality projects. Without these detailed first-hand experiences of construction in process, my expertise would not have progressed beyond that of a standard instructor and my image bank would be substantially poorer. Tim Verhey was always willing to provide me with very detailed technical clarifications, many of which are included in this book.

Thank you to Alistair Fussell of Steel Construction New Zealand and David Ryan of the Australian Steel Institute for hosting Sylvie and me and providing access to some excellent steel projects, many of which are included in this book.

Thanks as well to my editor Andreas Müller for his expertise, input and support and to Reinhard Steger and his team for their loving attention to the graphic layout of this book.

Lastly to my family for the continued support of and pride in my publication endeavors.

Ronald Reagan National Airport in Washington, DC, USA, designed by Pelli Clarke Pelli Architects, demonstrates the possibilities of AESS using a highly angular aesthetic. Here the curves are faceted. Much of the high-level steel makes use of simple structural shapes. A combination of remediated welded connections is mixed with exposed bolting. The extensive use of natural light successfully animates the technical appearance of the steel.

PREFACE

I have found great joy and inspiration in the detailed study of Architecturally Exposed Structural Steel (AESS) that has ensued from the research and writing I undertook for my first book *Understanding Steel Design: An Architectural Design Manual*, published by Birkhäuser in 2011. Where *Understanding Steel Design* looked more holistically at the potential in the informed use of steel in architectural projects, *Architecturally Exposed Structural Steel* looks more specifically at an approach to properly designing steel for exposure. Such exposure demands that architects become more engaged in the detailed design of steel systems, and with that, understand better the varying approaches to connection design, fabrication and finishing and how these impact the entire project in significant ways.

The category approach to specifying and detailing AESS that is presented in this book is derived from substantial work done in conjunction with the Canadian Institute of Steel Construction (CISC) between 2005 and 2011. The development of this system by CISC was intended to create better communications within projects in order to make the incorporation of AESS more straightforward by standardizing some of the core fabrication and detailing practices, thereby allowing the team to focus on the "real questions". The method has subsequently been adopted in New Zealand and Australia and I am working with a large team in association with the American Institute of Steel Construction (AISC) to create a unified approach to AESS practices additionally between the USA and Canada.

The photos included in this book were predominantly taken by myself during building visits. As the design of AESS strongly focuses on the details of finished steel, it was essential that the derivation of the Category System be done through first-hand experience, as it is the best means to validate the characteristics of projects. Certain project images taken during fabrication processes where I was unable to be present, have been sourced from the team members. These are credited at the back of this book.

THE BASIS OF ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

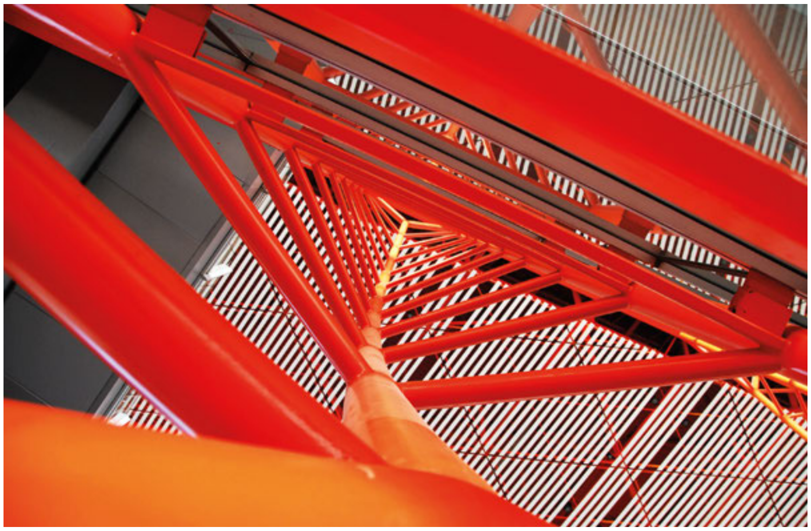
CHAPTER 1

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, 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 equal(ly 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.

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.



Heathrow Airport Terminal 5 in London, England, designed by Rogers Stirk Harbour + Partners, Arup and Watson Steel Structures limited (top left), is an example of very high-end custom fabrication and detailing. The connections make use of bolting and welding as appropriate to fabrication and erection and allow the process of the assembly to be seen.

The detailing of the Canadian Museum for Human Rights in Winnipeg, MN, Canada, designed by Antoine Predock (bottom left), makes use of a combination of custom-fabricated elements and more standard sections and detailing. Bolting is proactively used for its rugged aesthetic as part of the story told by the materiality of this museum.

Beijing Capital International Airport Terminal 3 in Beijing, China, designed by Foster + Partners, with Arup (top) is an example of high-end AESS that looks for a very smooth, all-welded solution. Connections that are more technical in character and might use bolting are hidden above the white slatted suspended ceiling.

The nature and level of fabrication detailing needs to address also the distance to view. It is unnecessary to detail connections and finishes located beyond normal view (approximately 6m/20ft) in the same way as steel located within range of view and sometimes touch.

The elaborate HSS truss system to support the pyramidal skylight over this city hall atrium in Edmonton, AB, Canada, designed by Dub Architects, is located well above view. It is therefore acceptable that the connections have not been fully remediated. This provided significant cost savings for the project.

Whereas designers tend not to be involved in connection issues for concealed structural systems, exposed systems tend to become the architectural trademark of the building, hence requiring the architects' involvement. Up to this point it has been difficult for designers to be adequately informed for choosing appropriate methods of AESS design and detailing or on the cost implications of their choices.

The surge in the use of AESS has created a paradigm shift in the sequential communication that usually takes place in projects where the steel structure is hidden. The paradigm shift centers on the simple fact that a "well-designed connection" or a "smooth surface" has very different meanings for an architect, an engineer or a fabricator. Such a situation can create a misalignment of communication, especially in terms of what can be accomplished within specific budget limitations.

In most countries, architectural and engineering contract documents do not contain much specification on the requirements for AESS. Exposed steel has normally been considered covered by the structural steel specification, with some additional notes and comments of clarification. As AESS applications become more complex and extensive, this rough method of communication has proven to be very ineffective.

It is the intention of this book to set out a very clear and systematic approach to designing, specifying and detailing AESS. The use of AESS on a project can be simplified by applying a standard, tiered, additive category approach. The requirements for the steel according to the categories are based primarily on the use of the building, the distance of view of the structural elements, aesthetic expectations and budget.

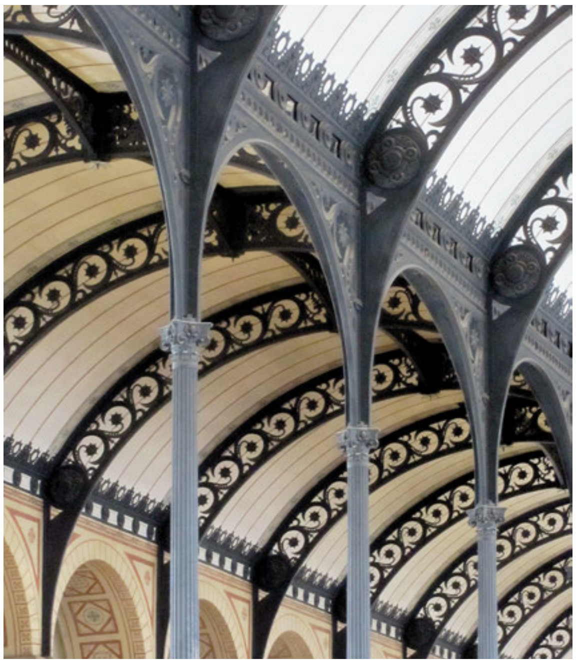
The AESS Specification Category System that forms the basis of the discussion in this book references a methodology that was developed by the Canadian Institute of Steel Construction, which has subsequently been adopted by Australia and New Zealand and is also being used in some projects in the USA. The origins of the tiered category approach go back to an initial document published by the American Institute of Steel Construction in *Modern Steel Construction* in May 2003. The AESS Specification Category System is the most detailed and comprehensive approach to AESS worldwide. This method was previously introduced in the chapter "Architecturally Exposed Structural Steel (AESS): Design and Detailing Requirements" in *Understanding Steel Design: An Architectural Design Manual*.

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.

THE EVOLUTION OF ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

The architecturally motivated exposure of the structural system has its roots in Gothic architecture. Here the stone structure, columns and buttress support systems were detailed expressively and effectively became the aesthetic of this style. Iron and steel systems as they were developed in the 1700s and 1800s continued in the spirit of this approach. A methodology of framed, elemental construction associated with a specific language of connections arose from the 19^{th}-century Structural Rationalist movement. The aesthetics were clearly driven and unfolded by the method of the manufacture of the iron. Cast iron lent itself to the development of more decorative, repetitive elements. Wrought iron elements tended to be more simple due to their manufacturing process. Both construction types used erection methods that centered on the use of physical connections for joining the structural elements into a stable system. As the brittle nature of the chemistry of cast iron negated the use of welding, joinery generally made predominant use of hot rivets, a method that fell out of favor with the invention of high-strength steel and the use of modern welding and bolting.

Steel detailing and connection design is intrinsically tied back to the types of profiles that are being connected. Early steel manufacturing processes in the 1800s were only able to fabricate angles, plates and later I-beam sections. The invention of processes that could hot-roll larger wide-flange or Universal column types generated the standard connection detailing typical in early Modern structures. Although round pipe had been technically available since the early part of the 20^{th} century, the material was cast by nature and predominantly intended for use in plumbing and services. It could not be welded and was not particularly friendly to work with in structural applications. Modern hollow structural sections (HSS) were not invented until the 1970s. These are fabricated from hot-rolled steel and therefore have the same chemical properties as regular sections.



The Bibliothèque Sainte-Geneviève in Paris, France, designed by Henri Labrouste, 1838, is a fine example of Structural Rationalist exposed cast iron detailing. The high level of ornate decoration was achievable by the casting process, which, however, also led to rigid repetition of identical elements and consequently a low level of variability in the design.

The iconic Farnsworth House in Plano, IL, USA, designed by Ludwig Mies van der Rohe, 1945–1951, makes use of simple hot-rolled shapes (channel, wide-flange and angle). The connections were welded to keep the detailing very clean and somewhat "mysterious".

The Sainsbury Centre for Visual Arts in Norwich, England, designed by Foster + Partners, 1977, demonstrates the very specific use of structural sections and connection detailing that distinguishes High Tech from the International Style. Hot-rolled tubular steel was quite new at the time of construction of this project, necessitating new approaches to fabrication and connection design.

The invention of HSS marked a major stylistic break in exposed steel expression. The range of available sizes increased slowly and eventually had an impact on the design of exposed steel structures. Very large diameters and elliptical sections only became available around 2005, closely followed by technical advancements in CAD and structural calculation programs. These assisted in an explosion of possibilities in the application of the materials to buildings with increasingly complex geometries.

FROM STRUCTURAL RATIONALISM TO HIGH TECH

Significant inventions in the recent history of steel construction have resulted in shifts in design and design theory. The geometric simplicity of International Style architecture aligned well with the limited palette of hot-rolled structural sections that were available through the beginning of the 1970s. Steel structures of this period were more often concealed than exposed, while exposed steel tended to be limited to quite standard welded or bolted connections that suited the available wide-flange (Universal) sections. The British High Tech movement was able to exploit the invention of tubular material, whose geometries challenged the articulation and expression of this new language of exposed steel connections. Tubular steel required the complete rethinking of connection design. Many of the designs of this period also incorporated tension and suspension systems. These too added design requirements to the exposure of connection detailing.

The very basis of High Tech design lies in its roots as an "assembled" and largely prefabricated methodology putting unparalleled emphasis on the design of connections. It is about taking "rationalized industrial technology into building construction" (Peter Buchanan).[1] The High Tech movement in England incorporated this focus into architectural manifestation through a transformed reinvention of earlier Structural Rationalist methodology. This industrialized construction system is also responsible for providing steel with a competitive edge over site-cast systems by preferencing shop fabrication that tends to be faster and more economical than site fabrication. The shop environment is safe from the negative impacts of climate and normally able to use less expensive labor.

High Tech design also included the exposure of mechanical services and systems. The associated exposure of the interior applications of steel adds to the coordination requirements as mechanical systems elements are also exposed to view and thereby become a critical part of the architectural aesthetic. The choice must be made to highlight or minimize their influence on the space. This concern has carried directly into considerations in AESS applications.

The mechanical systems on the interior and exterior of the Centre Pompidou in Paris, France, designed by Renzo Piano and Richard Rogers, 1972–1976, required increased coordination, also because the appearance of these systems fed into the expression of the project.

The louver system on the ceiling of the Sainsbury Centre for Visual Arts allows partial exposure of the mechanical systems above and increased the coordination requirements with the exposed steel systems.

Even though High Tech is similar to Structural Rationalism in its exposure of the structural framework and embellishment of the connection details, it more clearly differentiates the members by their tensile or compressive load capabilities. The high tensile capabilities of modern steel enables this force-varied expression. This was not possible in the age of wrought or cast iron as the tensile capabilities were much smaller and engineering science not adequately developed. Common to most High Tech buildings is an expanded use of lightweight tension systems. Many of these projects are about "doing more with more" and created elaborate structural systems to solve problems that could arguably have been constructed more simply. The High Tech buildings do serve to explore the architectural potential of steel and steel connections as expressive devices. They bear revisiting as precedents for contemporary detailing in AESS structures.

INITIAL DEVELOPMENTS IN HIGH TECH DETAILING

The British High Tech movement did much to establish the basis for the detailing of expressed steel connections. As presented in the chapter "AESS: Its History and Development" in *Understanding Steel Design: An Architectural Design Manual*, the High Tech style was rooted in the regularity of the systems and the ease of repetition of the primary elements. Further to this we see buildings that:

– make fairly exclusive use of purpose-fabricated components
– make predominant use of standard, off-the-shelf components
– buildings that use an even mix of specialty and off-the-shelf components
– buildings that place a high level of attention on connection detailing

Early High Tech buildings created a clear distinction between the fabrication processes that were best handled in the shop – welding – and the erection processes that were most efficient on the site – bolting. This holds true both for projects that were making use of entirely custom components and those that incorporated more standard sections; prefabrication was consistently applied in all projects. This critical recognition of process has been carried over into contemporary methods for AESS. The early High Tech projects developed approaches to connection design that continue to influence the way that AESS detailing is approached.

The connection language that characterized 19th-century Structural Rationalist buildings, and subsequently High Tech architecture, continues to be developed, perfected and exploited as one of the desirable aesthetic features of Architecturally Exposed Structural Steel. This type of structural expression demands that architects become increasingly engaged in understanding the design, detailing and construction of steel structures, not only as a function of the engineering of such forms, but also with regard to the realities and promises to be found in their fabrication.

The moment of transition from High Tech to AESS happened around the time of the design of Chicago O'Hare International Airport United Airlines Terminal by Helmut Jahn from 1985 to 1988. Up to that point, the exploration of High Tech had been contained within a small number of predominantly British or other European practices and few of the projects had been constructed outside of the European mainland and the United Kingdom. O'Hare was a remarkable deviation from the established tradition of reinforced concrete use in airport design, represented by Eero Saarinen's Dulles Airport in Washington, DC, and the TWA Terminal at John F. Kennedy Airport in New York City.

High Tech detailing such as explored in the Centre Pompidou needed to address the use of force-differentiated systems. The use of exposed tension systems had to that point not formed a dominant theme in architecture. The geometric resolution of multiple forces through a point, as explored in the Centre Pompidou, was to become an important design focus in the development of AESS systems.

The interior of the United Airlines Terminal at Chicago O'Hare International Airport in Illinois, USA, designed by Helmut Jahn, makes critical use of the expression of the steel detailing as the primary aesthetic of the architecture.