WHEN AESTHETICS GOVERN: PEDESTRIAN BRIDGES AND ARCHITECTURALLY EXPOSED STRUCTURAL STEEL

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BIOGRAPHY

Terri Meyer Boake B.E.S., B.Arch., M.Arch., LEED AP is a Full Professor at the School of Architecture at the University of Waterloo in Canada. She has been teaching building construction, structures, environmental design and film since 1986. She works with CISC, ACSA and AISC developing teaching resources for Architectural education specializing in AESS. She worked with CISC on the development of the new AESS specification documents and published the CISC AESS Guide. This work was modified for use in Australia and New Zealand.

She has published three books on steel in architecture for Birkhäuser: "Understanding Steel Design: An Architectural Design Manual" (2012), “Diagrid Structures: Systems, Connections, Details” (2014) and “Architecturally Exposed Structural Steel: Specifications, Connections, Details” (2015). “Complex Steel Structures: Non Orthogonal Geometries in Building with Steel” will be published in 2018. She also works with the Council on Tall Buildings and Urban Habitat researching into composite materials and façade related fire issues. She is an avid photographer, documenting construction processes and completed buildings.

SUMMARY

Although highway and rail bridges have historically had aesthetics as a design criteria, resulting in some very pleasing and significant icons, more pragmatic safety-based and economic concerns have normally governed. More recently we have seen a surge in the construction of innovative looking pedestrian and cycle friendly footbridges, where aesthetics have played an increasingly important role in the decision-making process. Issues of stability and cost must now address significant aesthetic concerns. As a result, the design of the pedestrian bridge falls across the fields of engineering and architecture, having to answer to equally strong pulls between function and aesthetics. This aesthetic drive creates and must solve problems that are very different from the methods previously established for vehicular bridges. Architecturally Exposed Structural Steel (AESS) has become the structural material of choice for the majority of these recent footbridges. Structural steel is excellent in addressing many of the particular design and erection concerns of pedestrian bridges. The paper looks at communication, detailing and design issues as related to the 2016 AISC Code of Standard Practice, Section 10.

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Keywords

Pedestrian bridges, footbridges, AESS, Architecturally Exposed Structural Steel, steel detailing

Abstract

Although highway and rail bridges have historically had aesthetics as a design criteria, resulting in some very pleasing and significant icons, more pragmatic safety-based and economic concerns have normally governed. More recently we have seen a surge in the construction of innovative looking pedestrian and cycle friendly footbridges, where aesthetics have played an increasingly important role in the decision-making process. Issues of stability and cost must now address significant aesthetic concerns. As a result, the design of the pedestrian bridge falls across the fields of engineering and architecture, having to answer to equally strong pulls between function and aesthetics. This aesthetic drive creates and must solve problems that are very different from the methods previously established for vehicular bridges. Architecturally Exposed Structural Steel (AESS) has become the structural material of choice for the majority of these recent footbridges. Structural steel is excellent in addressing many of the particular design and erection concerns of pedestrian bridges. The paper looks at communication, detailing and design issues as related to the 2016 AISC Code of Standard Practice, Section 10.

INTRODUCTION

Recently we have seen a surge in the construction of innovative looking pedestrian and cycle friendly footbridges, where aesthetics have played an increasingly important role in the decision-making process. Issues of stability and cost must now address significant aesthetic concerns. This has resulted in some challenges to the bridge construction industry. Having an architect on the team can sometime bring real challenges to the process. As a result, the design of the pedestrian bridge falls across the fields of engineering and architecture, having to answer to equally strong pulls between function and aesthetics. This aesthetic drive creates and must solve problems that are very different from the methods previously established for vehicular bridges.

The marked decrease in live loading on pedestrian bridges has allowed for this increase in the expressive use of structure and created a paradigm shift in the standard design of the spanning typology normal to bridges. Pedestrian bridges are creating structurally and visually different ways to span, challenging and inspiring the design community with a multitude of one-of designs. Although many of the spanning methods have been derived from existing structural typologies for heavier bridge types, variations have arisen as a direct result of this unique marriage of structure, architecture and "art". Many of these new bridges are also being seen as urban public art elements, adding politics to the complexities of their design and fabrication.

Architecturally Exposed Structural Steel (AESS) has become the structural material of choice for the majority of these recent footbridges. Structural steel is excellent in addressing many of the particular design and erection concerns of pedestrian bridges. AESS is able to provide an excellent variety of aesthetic solutions for this new role of "pedestrian bridge as public art".

The unique properties of steel are also capable of addressing:

- Prefabrication of near complete elements prior to erection/installation
- Transportation to site of large bridge elements
- Minimization of disruption to normal traffic flows during erection
- Durability and ease of inspection for

maintenance

Figure 1 - The Kurilpa Bridge in Brisbane, Australia, by Cox Rayner Architects with Arup is a fine example of the exploitation of AESS to facilitate an exciting connection over the Brisbane River that separates the city. This tensegrity based structure makes a clear span across the river as no mid span supports were possible. Photo by author.

AISC Code of Standard Practice and AESS

The 2016 AISC Code of Standard Practice, Section 10 addresses important aspects of designing with Architecturally Exposed Structural Steel as would be applied to building elements *and pedestrian bridges*. Many of these bridges would typically need to be designed in accordance with the requirements of AESS Categories 3, 4 and Custom Elements, all of which permit all-welded connections and allow for (but do not require) the grinding of welds. The treatment decisions for welded connections must be carefully negotiated by the team as a welded and then ground choice can greatly increase the cost of the structure, but might not necessarily be required to achieve the desired aesthetic effect.

- AESS 3: Feature elements viewed at a distance less than 20 ft (6 m).
- AESS 4: Showcase elements with special surface and edge treatment beyond fabrication.
- AESS C: Custom elements

Spanning Characteristics

The spanning characteristics of these lighter bridges seem to have adopted three key "types". The primary influence on the generated typology seems to focus on the specific expression of the structure that is supporting the walking surface, in combination with the overall width of the span as a function of available support points. Support is often restricted in more congested urban locations.

- *Support from above:* The mast and cable system is designed as a variation of a suspension system. The location of the mast is often eccentric or sloped resulting in a very dynamic appearance to the structure. The structural deck that supports the walkway is quite light.
- *Support through the middle:* Tubular trusses have pedestrian walk through and experience the structure.
- *Support from below:* The structural support system for the deck is located beneath the walking surface, so is less apparent when the bridge is crossed, but very apparent when viewed from a distance.

CRITERIA FOR THE DESIGN OF PEDESTRIAN BRIDGES

When planning for the construction of a pedestrian bridge, the site conditions must be carefully considered as the site conditions for urban pedestrian bridges are often significantly constrained. Pedestrian bridges are frequently being constructed as improvements to existing severed urban conditions and as a result will have to negotiate between the footprints of existing buildings and respond to inflexible abutment conditions. Although some pedestrian bridges do make use of suspension systems, many have minimal access to their abutment or mid-span conditions and may not afford other than a simple span. Pedestrian bridges may have tighter budgets as many jurisdictions are only now seeing the need to encourage pedestrian access and flow and as such these bridges are often seen as extra to essential civic spending.

Artistic Potential

AESS, as will be seen through the pedestrian bridges profiled in this paper, has a very high potential for artistic expression. Pedestrian bridges are actively being designed as a combination of urban connection and "public art". This has enabled budgets that might be larger than for a simple service connection. It is encouraging that many municipalities are recognizing the value of design in the urban environment through pedestrian bridges. It is important to incorporate high quality fabrication and detailing in AESS bridges as the degree of visual and weather exposure of the elements is very high. Also the interactions with and impact by the public are more than would be expected in most public installations. Bridges must provide a safe environment that necessarily includes fall protection. This must be incorporated in such a way as not to appear overbearing or confining and maintain a positive sense of visual connectivity to the city either over or through the barriers.

Figure 2 - The Gateshead Millennium Bridge in Newcastle, England by Wilkinson Eyre Architects accommodates pedestrians and cyclists by creating a divide down the center of the curved bridge deck. The bridge rotates to allow for the passage of boats along the river. The elements were transported to site via barges to permit the prefabrication of maximum sized elements, ease of erection and difficult access via land. Photo by author.

Pre-fabrication

Architecturally Exposed Structural Steel can achieve high levels of quality in fabrication if much of the work is carried out in an environmentally controlled shop. In addition to the benefits of temperature stability, which serves to keep the steel dimensionally stable which ensures tighter tolerances and an improved fit (core to obtaining high quality AESS), better conditions are provided for the workers. This can increase the speed of production and eliminate delays that may arise from extremes of heat or cold as well as rain, snow or wind events. By their nature bridges are highly exposed work sites and it is normally impractical to provide much in the way of overall weather protection on the site.

The shop will have overhead cranes that can be used to manipulate and turn the steel, providing superior orientation for ironworkers to access the connections for welding. This also substantially decreases the amount of work that is done “at height”, making for a safer work environment and limiting accidents and deaths. Site work is particularly problematic for bridges given inherent issues with the placement of temporary shoring. Whether the bridge is being erected over a roadway, rail line or waterway, it will be physically difficult if not impossible to provide access across the span for erection, connections and even finishing operations.

Transportation

The natural width of most pedestrian bridges is restricted, which feeds well into being able to design for transport by truck trailer or barge. Although in some instances the widths may be greater than allowed on standard highways, a police escort can be used in combination with transport during off peak traffic hours to transport the bridge elements from the shop to the site.

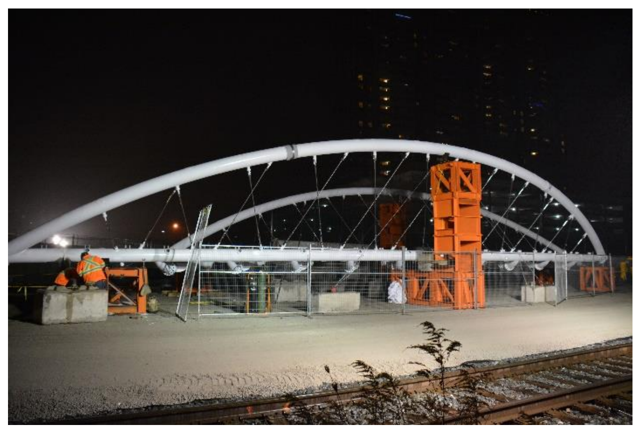

Figure 3 - The curved nature of the upper chord of the **John Street Pedestrian Bridge** in Toronto, Canada required that all welding be done in the shop and that each arched truss be shipped to the site preassembled. Temporary shoring (in orange) was set up at the site to allow for the bolted below deck connections between the trusses to be made after the two halves were delivered. The bridge could then be lifted as a whole, as laid out in Figure 4. Although the tonnage was not high, the assembled width exceeded widths of available access routes. The design uses a system of stainless steel cross bracing to create the web members of the truss. This use of force differentiation in the members creates a beautiful energy in the steel design. Photo by author.

Where bridge component lengths exceed the length of a standard flatbed, articulating trailers can be used. Here the cab and back wheels are detached, the bridge element being used to connect. The rear end of the truck is computer controlled remotely to negotiate turns.

The path from the fabrication shop to the site must be carefully mapped out, with all overhead bridge and roadway clearances accounted for as this will impact the maximum height to be transported. If using extra-long trucks it will also be necessary to map out the route to ensure that turns can be negotiated. Articulating trailers can assist. This information will be needed to inform the location of any joints or splices in the steel. The bridge in Figures 3 and 4 is a good example for best practices in maximizing the use of the shop fabrication required to keep the finish of the trusses to a high level, and using bolted connections below the deck to make site assembly more straightforward. The deck to be installed for the walkway will visually obscure the bolted connections, allowing for cost savings on the project as well.

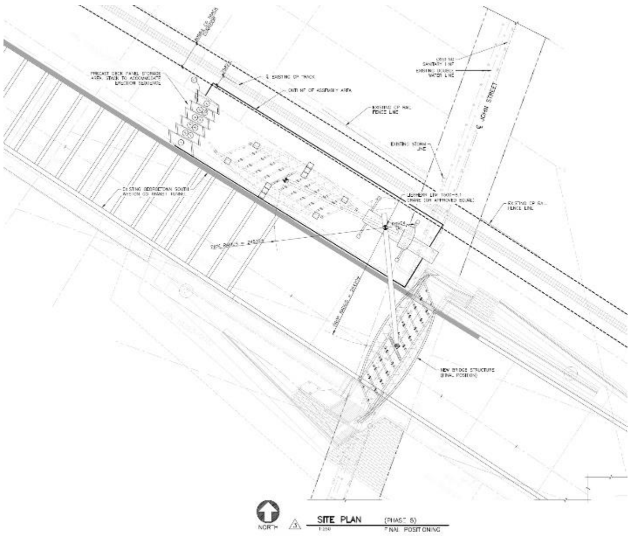

Figure 4 - The John Street Pedestrian Bridge in Toronto, Canada was shipped to site in a minimal number of pieces. There was adequate space adjacent to the railway cut for site assembly to take place. As it was to be erected over a rail corridor, the erection had to take place at night to accommodate a 4 hour stoppage of train traffic. The position of the crane was chosen to allow a clean swing lift from the staging area north of the tracks to the finished position. Drawing by Walters Inc. Steel Fabricators.

The determined maximum size of the transportable elements will inform the placement of splices that need to be done on site. It is preferable to have some lay-up area to complete the splicing prior to the lift as shoring towards the center of the span is usually difficult to arrange, if possible at all. Fabricators prefer quicker bolted splices to speed up erection, even if the major bridge components are fully welded.

Minimal Disruption to Traffic

Pedestrian bridges, particularly in cases where they are being constructed to rejoin existing severed urban neighborhoods, are often being used to span across "live" traffic. Particularly in busy urban centers it can be logistically impossible to close highways, ramps, streets and rail lines for extended periods of time to enable the construction of a bridge.

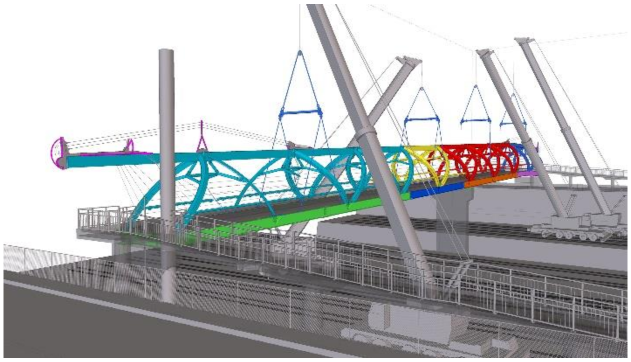

Figure 5 - The Puente de Luz Bridge in Toronto, Canada was erected over a large rail corridor. The fabricator was able to use a night closure of the tracks for the erection. Four cranes were positioned to lift the sections in place and hold until the bolted connections could be made. Tekla drawing by Walters Inc. Photo by author.

Pedestrian bridges are small and light enough if constructed out of steel to be lifted into place in a minimum number of pieces. Many bridges, if access between the shop and the site is minimally obstructed, can be transported and erected as a clear span.

Durability

Weathering is a critical aspect of the design of all bridges. It is of particular concern in the case of pedestrian bridges as these are much lighter in their construction method due to the decreased loading requirements in comparison to vehicular bridges. Where the structural steel members of large bridges are often made of substantial thicknesses of weathering steel, the artistic focus of pedestrian bridges more often makes use of colored coatings over standard hot rolled shapes, plates and tubes.

Proper preparation of the steel, fabrication detailing and the use of a durable corrosion resistant system is critical to the success and longevity of the pedestrian bridge. Details must ensure that any accumulations of rain or snow can easily drain away and not accumulate. This will include the placement of vent holes in galvanized assemblies to ensure that moisture is not trapped inside causing unexpected corrosion. The basis of durability in any steel finishing system is surface preparation with commercial blast cleaning. In North America this is known as a SSPC SP-6 level of preparation.[7] Commercial blast cleaning ensures that all grease, rust, mill scale and paint are completely removed from the steel so that the coatings will properly adhere. This is a basic requirement of all AESS according to the AISC Code.

Figure 6 - The stairs on this pedestrian bridge in **Denver, Colorado, USA** have been improperly designed. The angle components are oriented to collect rather than drain water. The corrosion protection system is inadequate. The local use of de-icing agents was not considered when detailing and designing for corrosion resistance. Photo by author.

Best practices and proven durability have been achieved through the use of weathering steel, stainless steel, metallization and galvanization. There limitations with each choice.

Galvanization

Galvanization tends to result in a more technical or rugged appearance due to the natural finish of the galvanic coating and so tends to be chosen for exposed structures where the designed aesthetic is less finely detailed. As the thickness of the galvanic coating and its bond with the steel is directly impacted by the thickness of the steel, its use on thinner components has proved less durable. The size of assembled components will be limited by the size of the galvanizer's bath as it is a best practice to coat assemblies in a single dip. The size of the bath feeds directly into the design of the splice locations between the larger bridge elements. This can mean a greater number of site connections as compared to a fully shop welded assembly that is not galvanized but rather uses a different method of corrosion resistance. Vent holes must be included and arranged in such a way as to let gasses escape during the dipping process to prevent explosions. The vent holes must also be oriented in the finished bridge to permit drainage and to exclude water entry. The designer must be conscious of the location of these holes to prevent weathering failures. For tubular materials it is essential to make sure the surfaces are also coated on the inside to prevent unforeseen oxidation from trapped moisture. This expense must be noted.

Galvanizing is a hot process (the bath temperature is approximately 450°C) and can cause deformation of thinner steels or elements that are highly articulated. Therefore it is not appropriate for use with thinner structural members. If galvanization is absolutely desired, the thickness of the steel has been sometimes increased to prevent potential deformation from the heat of the dip process.

If a colored coating such as paint is desired as the finished coat, the galvanized surface must either age for around two years or be roughened to ensure adherence. Many failures can be seen if this is not done. The paint will peel rather immediately as it cannot adhere to the newly finished surface. It is considered the least expensive option for obtaining a reasonably durable exterior product.

Figure 7 - This simple pedestrian bridge in **Olympia, Greece** is fabricated from galvanized steel. The bridge was shipped in two pieces and is joined at the center of the arch and across the deck directly below. The corrosion protection system that also serves as the architectural finish suits the more rugged situation in the archeological site. Photo by author.

It is important to note that many failures have been observed in the bolted connections if the quality of the galvanizing on the bolts is not high or if excessive force was required in turning the bolts and resulted in damage to the coating. The durability of a bridge is only as good as its least durable element.

Figure 8 - The thickness of the metalized coating for a bridge in **Auckland, New Zealand** is being tested in this shop applied application. Metallization is commonly used in New Zealand due to its corrosive marine environment. Photo by author.

Metallization

Metallization is essentially a cold applied process that is normally shop applied as the material is sprayed into place and would obviously be badly affected by air movement such as wind. It is typically used as an under protection system, therefore naturally followed by a primer as well as a finished paint coating. Being a cold process it cannot deform the steel and so is quite suitable to highly articulated steel forms where thinner walled steels may be used.

Quality control is essential as the spray application needs to be carefully done and the applied thicknesses verified (Figure 8). There is increased cost over galvanization when you also consider the normal inclusion of additional finish coatings as this protection system is not normally intended to stand alone. One of the advantages of metallization is the unlimited size of the components as the limitations imposed by the galvanization bath do not exist. Metallization can then be applied to virtually any shape or size of steel, providing complete flexibility in design. This is of great benefit to aesthetically driven designs as there are essentially no limits placed on the shape or configuration of the steel or the choice of welded or bolted connections. As it is primarily these that drive the cost of the project, this zinc based method of corrosion protection is valid for application from the least to the most expensive bridges.

Weathering Steel

Weathering steel has a long history of use in vehicular bridges as it is very durable, although rugged in appearance. One of the limitations of the product is its availability. It is not readily available in all structural shapes. Plate is easily available. This means that the selection of weathering steel for the bridge can often requires fairly exclusive use of custom fabrication along with a high level of fully welded joints. These types of pedestrian bridges will incur much higher costs than any other corrosion resistant system as a direct result of the high level of custom fabrication. Weathering steel will fall into an AESS Custom category as it uses extensive custom fabrication with plate, usually all welded, but the welds are not normally ground smooth as the presence of the weld works with the rugged aesthetic of the product.

Another issue with the use of weathering steel is the generation of a rusty drip below the bridge. If the bridge is situated above other lighter colored materials such as reinforced concrete, significant staining will occur. This will not be an issue where such bridges are located in a landscape or over a river.

Figure 9 - The Glass Bridge in Perth, Australia by Donaldson+Warn; Capital House Engineers; artists David Jones, Kevin Draper and Richard Walley; John Holland Constructions uses weathering steel without concern for the impact of runoff as a result of its park location. Here transparent glass guard rails provide fall protection as well as a purposeful contrast in material textures. Photo by author.

Figure 10 - Stratford Town Center Link, designed by Knight Architects with Buro Happold makes extensive use of custom bent and fabricated weathering steel plate. The bridge spans across a roadway as well as rail tracks. It is noted as the first launch of a bridge in the United Kingdom over live rail tracks.[5] Photo by author.

As mentioned the majority of internal connections for this custom fabricated material are made via welding. The weld material is also based in similar alloys and so results in a homogenous appearance. The welds are typically neatly done and not remediated by grinding. The naturally rugged appearance of the steel is complimented by the normal appearance of the multi-pass weld (Figure 11). Damage could be done with the grinder to the adjacent plate steel that would mar its appearance. Unlike carbon steels with a painted finish, it is not possible to remediate weathering steel surfaces via the use of any fill materials.

Figure 11 - A close view of one of the weathering steel welds on the **Stratford Town Center Link** showing the natural texture of the steel and the weld material. Photo by author.

It is to be noted that weathering steel is not to be used in marine environments as the salts present in sea water, mist or spray will cause accelerated corrosion, decreasing the lifespan of the material. It must also be maintained and kept free of a buildup of leaves, pine needles and other organic waste as these can also negatively impact the longevity of the material. Weathering steel requires wet/dry cycles to reach its full color potential in the rich dark red hue. The actual color will be dependent on the environment, so the color may be different from project to project and also between elements of a project as a function of exposure and wetting.

Stainless Steel

Stainless steel is simultaneously one of the most durable and most expensive structural options. It is available in tubular shapes, plates, rods and cables, in addition to having available a wide range of specialty fittings for rod and cable attachments, making it suitable for a very wide range of artistic applications that might exclude the need for high levels of custom plate work. The highly corrosion resistant nature of stainless steel makes it an excellent choice for bridges that are located in marine environments. It does require specialized engineering as its properties differ from regular carbon steel. It also must be fabricated in a shop with dedicated tools as any contact with carbon steel will embed rust prone materials within the stainless steel. It will be more common to use neatly done, un-remediated welds with stainless steel as grinding operations to hide the welds run the risk of damaging the naturally smooth and shiny surfaces of the structural elements.

Figure 12 - The Helix Bridge in Singapore by Cox Group with Arup showcases an exquisite application of stainless steel. The selection of the material creates a very durable structure for such a moisture exposed setting. The sleek nature of the steel works well with the aesthetic of the intricate double helix structure as well as the apparent curvature of the bridge. The member choices acknowledge their tensile versus compressive loading, adding textural interest in this force differentiated application. Photo by author.

Pedestrian bridges situated in marine environments will require a higher grade of stainless steel such as Duplex 2205 as lower grades will pit. All stainless steel requires periodic cleaning to prevent pitting.

Stainless steel is very often selected for railing and mesh components that will be required on pedestrian bridges as fall protective barriers. Meshes are often chosen as they resist climbing and the passage of smaller objects. In this way the highly durable nature of this more expensive product is selectively mixed with the other systems in a cost effective way. The finish of stainless steel is suited to the level of contact with users of the bridge, particularly for use as handrails. The maintenance costs can be quite low, particularly as compared to bridges with painted final coatings.

Staining, Weathering and Cleaning

These urban bridges must be designed to resist multiple environmental factors if they are to remain looking new, clean and vibrant. Figure 6 described degradation issues that resulted from the improper orientation of an angle section for drainage as well as the use of deicing agents as these can have disastrous effects on finishes.

Figure 13 -The drip marks on the underside of the white tubular frame of the AESS truss on this bridge in **Vancouver, BC, Canada** are the result of less than 2 years of use. The longer this is allowed to accumulate the more difficult it will be to clean. Paint will not adhere properly to the staining if refinishing is chosen in place of cleaning. Photo by author.

Figure 14 - The Webb Bridge in Melbourne, Australia is suffering from varying levels of deterioration on some of its components. The high level of articulation and the relative thinness of the steel is a challenge for its coating system. Some peeling is occurring. Some of the fasteners are corroding indicating a complete failure of their galvanic finish. The extreme amount of surface area that has resulted from the design, in the corrosive marine environment, makes this bridge difficult to maintain. Photo by author.

Bridges must be designed to be cleaned (within the frequency as determined by the budget) and so the overall design must accommodate physical access for periodic cleaning as well as structural inspection. Designers must acknowledge that the combination of air pollution and rain common in most urban areas will create significant staining on the underside of exposed members.

A certain level of environmental grime can be masked through the choice of color. The selection of a mid-range colors such as gray will facilitate the lengthening of the period between cleanings. White, which is a highly popular choice, will quickly show dirt as well as reveal any rusting that results from degradation of the corrosion protection system in the case of failures in galvanization, metallization and simple painted finishes. The degree of complexity of the structure overall will feed into issues with durability, cleaning and weathering. Particularly if an inherently durable material such as stainless steel is outside of the budget, painted finishes will require significantly more frequent attention. For less durable finishes that are often the result of "value engineering", detailing that limits the accumulation of puddling water is essential.

Color choice is also important when bright hues are selected. Fading is an issue with many brightly pigmented paint finishes such as red and yellow. Oxidation in general can dull the finish over time.

The Impact of Span Length

Generally the span lengths of discrete pedestrian and cycling bridges is not excessive as they tend to be used to link neighborhoods that have been segregated by roadways, rail lines and canals or other relatively narrow bodies of water. The site needs to be examined for the potential of intermediate support locations as these will directly structural span requirements as well as splice points along the structure. Clear spans are often desired as a means to allow for future modifications to lane widths and road patterns without the encumbrance of a pre-existing pier, however mid-span supports are often possible. The length of the resultant span(s) will impact transportation, delivery and erection.

It will also need to be understood whether or not shoring is possible to provide temporary support during the erection process. The ability to provide shoring (or not) must directly feed into the design and detailing of the elements as it will bear on the degree of span as well as the erection procedure. As illustrated in Figure 5, the Puenta de Luz Bridge required four cranes on site to lift and hold the bridge sections in place while temporary bolts were secured.

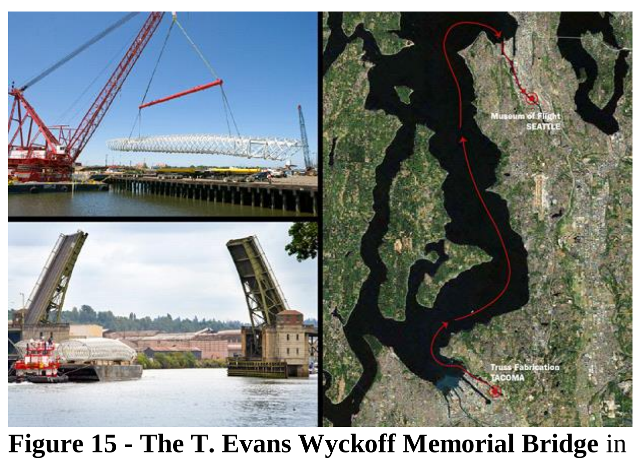

Figure 15 - The T. Evans Wyckoff Memorial Bridge in Seattle, WA, USA by Magnusson Klemencic and SRG Partnership makes a clear span across the 6 lane street in order to avoid the need for a central pier. Although the installation is over land, the route from the steel fabricator to the site required innovation in order to maximize the level of prefabrication of the curved tubular members.

The route from the fabrication plant to the site was carefully mapped. The prefabricated length was shipped by barge and then trucked the final distance to the site. The complex crisscrossed tubular truss was able to be completely welded at the shop. This was critical to keeping a high level of appearance. Photos courtesy SRG Partnership.[6]

Temporary shoring is more likely when erecting the bridge over land than over water. For bridge installations over water, barges have often been used to transport the nearly completely shop fabricated bridge to the site. The entire design of the bridge must understand this as a starting point for the design if it is not possible to transport via land.

Where more standard bridge types may use launching to assist with erection, the complicated nature of 'artistic' or 'sculptural' AESS bridges seems to work against this method due to concerns of potential distortion or damage to the surfaces of the AESS members. These lightweight structures tend to favor lifting into place via a crane. The span length and weight of the elements must work in conjunction with crane capacities. The limitations on the placement and tonnage of the crane, particularly in terms of reach, will inform the site logistics and in turn the size of the bridge elements, see Figure 4.

Figure 16 - The very slender profile of the **Simone de Beauvoir Footbridge** in Paris, France by RFR was the direct result of the requirement to transport the completed bridge to the site via barge. The clearances below the many existing bridges over the Seine required much innovation in creating a span that was extremely shallow. The bridge also had to permit adequate clearance below for the passage of vessels and was not permitted to employ an intermediate support to reduce the span. Photo by author.

The availability of interim support locations must also be known. These obviously decrease the effective length of the span and also provide locations for movement control and splices. Splices will be demonstrated to be of special concern in the design of pedestrian bridges that also have an artistic purpose as these are often required to be functional as well as discreet. Making splice connections less apparent will vary as a function of the member types being spliced as well as due to the location of the splice. Splices need to be located with erection and access for finishing operations in mind.

Member Shapes and Custom Fabrication

The budget of the project will have a direct impact on the design of the bridge, selection of members, details and the level of custom fabrication. Generally the more custom fabrication that is required, the higher the cost of the bridge. Much can be achieved in AESS bridges without requiring high levels of custom fabrication and expensive detailing.

Hollow Structural Sections

As the material surfaces of the bridge will come into close contact with the public, hollow structural sections are often chosen for their smooth nature and lack of sharp edges. This "softness" then becomes central to the aesthetic motivations of the bridge. In some instances tubes will be incorporated into large box or circular trusses where the pedestrian passage is through the middle of the truss. The bottom face of the truss will be structurally reinforced to assist with the support of the deck and structural span requirements. Often the underside of the bridge is less attractive as it is more difficult to view so need not be subject to the same high level design requirements as the upper portion of the bridge.

Figure 17 - The Skytrain Access Bridge, Vancouver, BC, Canada uses round HSS to create the trapezoidal, skewed, box truss that supports the deck of this lightweight bridge. Round HSS have also been used for the side rails and fall protection. Color is used to define the varying functions of the steel. Photo by author.

The choice of HSS tends to be accompanied by the desire for all welded connections to maintain the impression of smoothness. This infers that the majority of the fabrication is to take place in the shop and that site connections will be limited and span lengths maximized. If curvature is also included in the design, then shop welding is of increasing importance as a higher degree of control will be necessary to create neat and uniform welds.

The use of HSS weathering steel to create pedestrian bridges is quite common in the United States and Canada. Firms have been created that specialize in the creation of these bridges. They are often used in more rural locations due to their rugged appearance and are less likely to be used as an option in urban renewal projects for the same reason. The advantage of these bridges over galvanized bridges lies in their inherent durability and reduced need for maintenance.

Figure 18 - Simple un-remediated welds were used to connect the elliptical rings that comprise the **T. Evans Wyckoff Memorial Bridge**. To have ground these welds smooth would have drastically increased the fabrication costs. They are adequately removed from direct sight as to be unnoticeable. Photo by author.

Custom Box Sections

In designing AESS structures a very clear line is drawn between the acceptability of the soft or curved corners of square or rectangular HSS and the desire for sharp or crisp corners. Where round HSS are found more extensively in iconic bridge designs (as there is not much in the way of alternates to be custom fabricated), many high profile bridges that use square or rectangular cross sections will elect to use a shape that has been custom fabricated from plate material specifically to create precision in the design.

The choice to create custom structural shapes allows for a high degree of freedom in establishing the architectural and artistic character of the members. The decision making regarding the detailing will impact not only the expression but also the budget. The use of custom plate to create box type sections poses choices on the creation of the 'corners' of the box.

There are three basic ways to create the corner on the box:

- Use brake forming to bend the plate. It results in a rounded corner, the diameter as a function of the thickness of the plate material. The size of the member is not tied to the standard available HSS dimensions and can be irregular if desired. (see Figure 19)
- Use welding to have joining plates meet at a sharp corner. This is essentially done using a butt type weld even though the plates are meeting in a perpendicular fashion. If this weld is remediated by grinding, filling and contour blending it would be classed as AESS 4 in the AISC system of classification (very high).[1] If the welds are left 'as is' it would be classed as AESS 3 (medium to high finish and associated costs).(see Figure 20)
- The perpendicular meeting plates are offset so that the outer edge of the corner is created by one plate. The connection can be done using fillet welding whose dimension is less than the measurement of the inset plate. The weld does not require remediation affording savings in time and cost. (see Figure 21)

Specialized Detailing

The method of creating the span seems to generally be divided to bridges that use spanning systems such as box trusses that span unassisted and bridges that use a suspension system to support the spanning members and/or deck and railing system. Within these basic spanning types and the choice to use either standard or custom fabricated members, we also find a high degree of specialized AESS connection detailing that adds to the artistry of many urban bridges and assists in elevating their perceived importance in the urban landscape.

Figure 19 - The Peace Bridge in Calgary, AB, Canada designed by Santiago Calatrava uses brake forming to create the curved box sections. Photo by author.

Where the majority of tube to tube shop fabricated connections will be done using welding with the intention of downplaying the physical connection, connections that are done on site may use quicker bolted connections. Site bolted connections must be designed to follow the aesthetics of the overall design, while also answering to the more pragmatic problem of speed and ease of erection that accompanies the installation of bridges in more difficult to access locations.

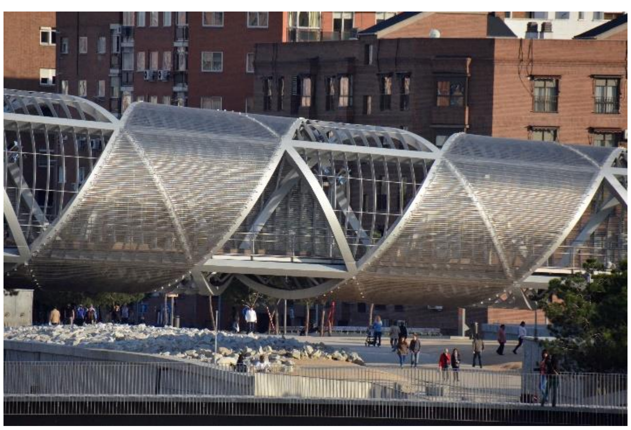

Figure 20 - The Arganzuela Footbridge in Madrid, Spain by Dominque Perrault uses un-remediated butt welds to create the corners on the custom box sections. The curved surfaces have been plate rolled. This bridge used extensive site welding to assemble the components and so the decision to leave the welds "as is" provided significant cost savings. The dappled light and texture of the screens worked well with the welding and overall aesthetic of the bridge. Photo by author.

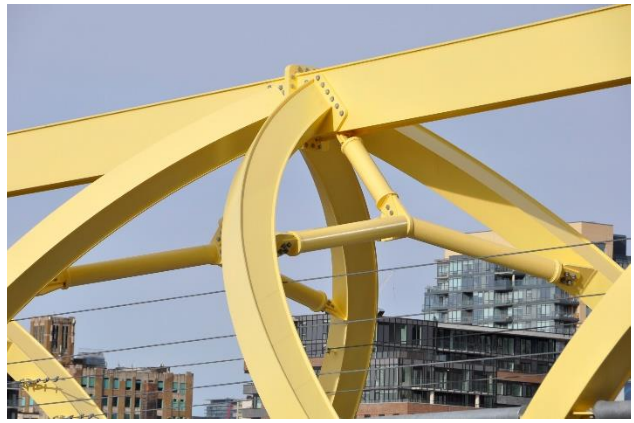

Figure 21 - The Puente de Luz Bridge uses the inset method to create its sharp corners. The sides of the box ribs have been plate rolled to set their curvature prior to being fillet welded. Photo by author.

Site bolted detailing is evident in Figure 21 on the Puente de Luz Bridge. Fairly simple hinge connections have been created by welding plates to the ends of the tubular or square sections. Here galvanized bolts have been used, for durability as well as to allow them to contrast with the yellow painted finish of the bridge.

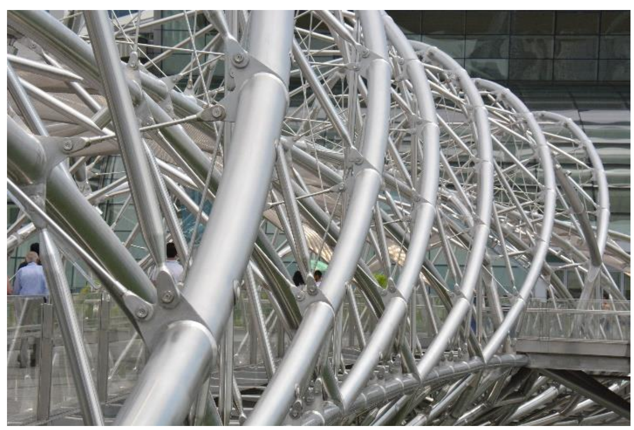

Figure 22 - The Helix Bridge in Singapore is an excellent example of a force differentiated design that makes widespread use of pin connections. The round HSS curved tubes that create the primary form of the outer portion of the double helix are attached via straight tubular compression members that are fitted with tapered conical ends and clevis attachments. The compressive forces use slender rods with clevis ends, these pins also allowing for site adjustments. Photo by author.

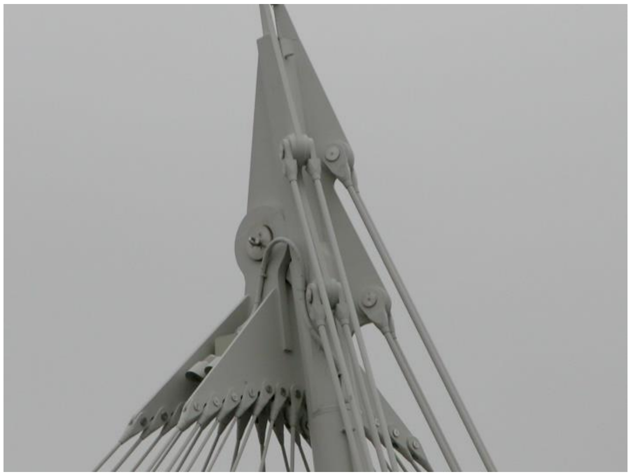

Figure 23 - The connection at the top of one of the masts of the **Jubilee Bridge** in London, England must accommodate the fan like attachment of multiple tensile members that are used to suspend the deck. The lower edge of the plate is serrated to gracefully allow for the splayed geometry of the members and their clevises. Photo by author.

Pin connections are often used in force differentiated structures in conjunction with the use of very slender elements that may require clevis type attachments. Pins allow for quick assembly on site of components that are not necessarily attached at the shop prior to transportation. Pins also accommodate rotation, allowing for adjustment and fitting on site. Suspension systems will also require the use of specialized end connectors, usually clevis type attachments, to accommodate the slenderness of the members. Pedestrian bridges are seen to use both solid rods as well as cables for these tensile members. Solid rods may be fabricated from stainless steel to resist corrosion. If galvanized rope is used it is sometimes left exposed or wrapped in UV resistant vinyl coverings to better protect from the elements.

CONCLUSIONS

Pedestrian and cycling bridges that are being used more extensively to relink urban centers that have suffered division due to the impact of vehicular systems are making good use of Architecturally Exposed Structural Steel to create vital, often iconic structures that combine aesthetics and functionality. This has raised the level of collaboration required from the design team – architect, engineer and fabricator – to achieve success. This paper has outlined a set of primary design criteria that need to be addressed to enable a better, more thoughtfully detailed and more durable use of AESS to this end. The new Categories of the AISC Code of Practice can be seen as the essential point of departure for all design and detailing discussions.

Many of the mentioned best practices required to ensure the longevity of the project are based in the creation of durability in terms of corrosion protection and detailing. Although the paper cannot be exhaustive, more detailed information on best practices in design with AESS can be found in the primary references listed below, also by the author.

References

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