Cast Steel Nodes for Bridge Structures Designed and Built with HSS

JENNIFER ANNA PAZDON, Cast Connex Corporation, New York, NY
and CARLOS DE OLIVEIRA, Cast Connex Corporation, Toronto, ON

IBC 23-01

KEYWORDS: bridge construction, Construction Engineering, ABC, AESS, fatigue, durability, tubular members

ABSTRACT: This paper will discuss the advantages tubular members offer in bridge design, will discuss some of the issues and challenges around connection design and performance in tubular connections in bridge structures, and will discuss how cast steel nodes can be used to address all of the challenges associated with connections between tubular members in bridges. Case studies of highway, rail, and pedestrian bridges incorporating tubular members and cast steel nodes from around the world and in the United States are presented.

INTRODUCTION

Bridge designers and stakeholders are increasingly taking advantage of the significant efficiency and serviceability benefits the use of tubular members (Hollow Structural Sections (HSS) and pipe) offer in the design and construction of truss bridges. The proposed addition of welded joint details for tubular members in the Bridge Welding Code (AASHTO/AWS D1.5) would further accelerate that trend. Globally, tubular members are very often leveraged in the design of highway, rail, and pedestrian bridges, and in most of these cases, cast steel nodes are leveraged at the key intersections of the tubular elements.

This paper will discuss the advantages tubular members offer in bridge design, will discuss some of the issues and challenges around connection design and performance in tubular connections in bridge structures, and will discuss how cast steel nodes can be used to address all of the challenges associated with connections between tubular members in bridges. Specific focus will be on how cast steel nodes enhance the stiffness, strength, and fatigue performance and simplify the fabrication of tubular connections, and thus it will be shown how the use of cast steel nodes improve the overall structural efficiency, reduce deflections, improve vibration performance, and improve coating system performance and longevity of bridge structures. Case studies of highway, rail, and pedestrian bridges incorporating tubular members and cast steel nodes from around the world and in the United States are presented.

ADVANTAGES OF TUBULAR MEMBERS FOR BRIDGE STRUCTURES

Tubular members are very often leveraged in the design of highway, rail, and pedestrian bridges to take advantage of the material and serviceability efficiencies. Tubular sections are often utilized in bridge structures where aesthetics are of concern.

STRUCTURAL PERFORMANCE - When properly selected, tubular sections offer the lightest sections to resist forces whereas open sections would have material inefficiencies due to their difference in section properties in the minor axis. For truss structures, round tubular sections are ideal for resisting compressive forces with minimal tonnage (Figure 1).

COATINGS – Coating system performance - Reducing maintenance costs by minimizing the number of repainting cycles can be an effective strategy to reduce the total life cycle cost of structures (Corus, 2005). This can be achieved by improving the performance of a structure’s paint/coating system.

In service, HSS members are more ideal for coating systems from a cost perspective compared to open-section members since the surface area per unit length is smaller with HSS. Sealed HSS members that are shop-welded and shop-coated are the best structural sections to use in a highly corrosive environment (Sebastian, 2015).

AESTHETICS – The clean lines of closed sections support aesthetic goals by reducing visual clutter, allowing the massing and form of the bridge structure to be expressed. Lightness in structure can be expressed as the efficiency of member utilization allows for smaller cross sections and more slender elements.

Figure 1: Use of round hollow sections and cast steel nodes enables the vehicular bridge (above) to achieve structural performance criteria with minimal tonnage and lightness in form. The custom cast steel node (directly above) sits at the bottom chord connection of the bridge. Cast nodes are also utilized at the connection to the concrete bridge deck and the top of the "trunk" of the bridge piers.

LEVERAGING CAST STEEL CONNECTIONS FOR TUBULAR BRIDGE STRUCTURES

Tubular connections present difficulties in design and construction that can be addressed by the use of cast steel nodes. In this section, the challenges in design and construction of tube-to-tube connections are described and the solutions offered by cast steel connections are detailed.

Casting manufacturing offers the ability to produce monolithic, high integrity structural steel components of virtually any geometry. Designers across the world over are leveraging cast steel components in innovative ways to economically address design challenges and to enable unparalleled architectural design opportunities – enhancing structural performance, improving quality, refining aesthetics, and saving money all at the same time.

Cast steel nodes have been used extensively in the design and construction of tubular bridge structures as they offer significant structural and architectural performance advantages in addition to practical advantages with respect to fabrication, field construction, and life cycle cost.

The following areas of performance and constructability are particularly improved through the use of cast steel nodes:

- Member utilization and structural efficiency
- Fatigue performance
- Deflection and vibration control
- Quality, fabrication, and field erection
- Coatings
- Aesthetics

MEMBER UTILIZATION AND STRUCTURAL EFFICIENCY - In HSS-to-HSS connections, local connection limit states often drive member section selection. That is to say, the wall thickness of the HSS member must typically be heavier than otherwise necessary simply to resist local connection failure modes (some local connection failure modes are shown in Figure 2). Additionally, shear lag effect at complex tubular connections can reduce available member strength and also drive section selection, reducing overall structural efficiency. Given their proportions (large width to thickness ratios, or "b/t"), Jumbo HSS connections in particular can be governed by local connection strengths.

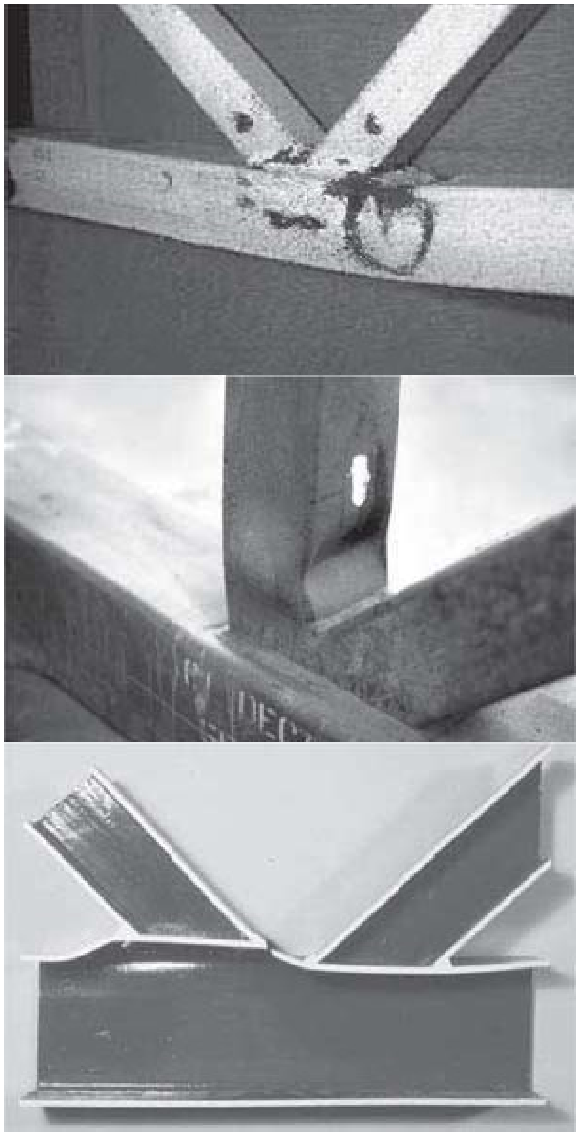

Figure 2: Various HSS connection failure modes

Conversely, HSS member selection is not dependent on local connection strength when designing tubular structures with cast nodes. This allows for every member in a complex framework to be optimized solely based on member forces (axial, shear, bending moments, and torsional forces).

As such, tubular bridge structures designed with cast nodes benefit from the ability to optimize HSS member sizes with no concern for connections, providing economies in overall tonnage.

Further, guidelines in the AISC Specification for the design of HSS connections are subject to ranges of validity based on member proportions and framing configuration. These would place limitations on the framing arrangements possible should the design of a tubular bridge proceed without cast nodes.

One example of such code provisions is the limitation of web to chord member size ratio, β, to less than or equal to 1. Whereas member forces or architectural requirements may call for β equal to or greater than 1, this configuration is not allowable using conventional HSS connection design (and would be challenging to fabricate even if it were allowable). However, accommodating such a configuration of member sizes is readily achievable with cast nodes. For example, Figure 3 shows a cast node at the Salesforce Transit Center where a similar condition existed in the building's 150-foot tall "Light Column" feature.

Another source of potential restriction on design efficiency and architectural design intent arises when considering multiplanar connections – that is, connections where multiple members frame into a chord member from more than a single plane. Multiplanar HSS connections are outside of the scope of AISC Specifications. For multiplanar connections, AISC Design Guide 24 points readers to Packer and Henderson (1997). The design provisions suggested in that text for multiplanar rectangular and square HSS connections are applicable only to axially-loaded members within specific ranges of validity, which again could limit possibilities in bridge design.

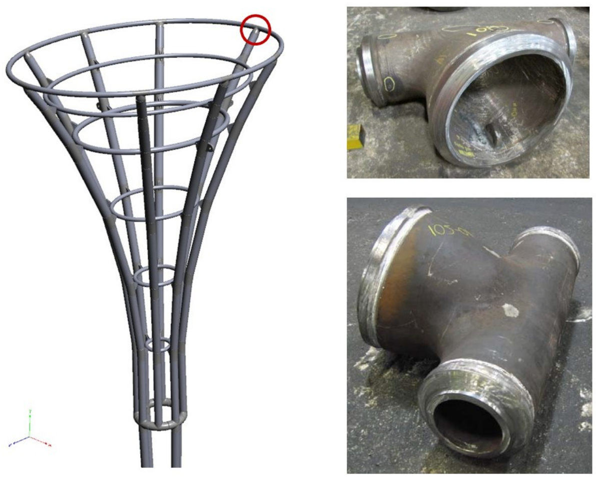

Figure 3 - Cast nodes are not subject to the same design limitations as are conventional HSS-to-HSS connections, as exemplified in this cast node which has web to chord dimension ratio, β, greater than 1, which would not be possible with conventionally fabricated HSS connections.

Designing a tubular bridge to use cast nodes eliminates the challenges of working within the confines and limitations of code-based HSS connection formulae. With cast nodes, the HSS members between the nodes can be treated as beam-column members subjected to biaxial bending and shear forces, torsion, and axial forces alone (which can be addressed with code-based member strength equations and computed with frame analysis software packages). Cast nodes can be addressed as "Disturbed Region" elements and analyzed using numerical analysis by a qualified casting engineer. Such an approach allows for maximum design flexibility, and as outlined below, casting may improve the structural and architectural performance of a tubular steel bridge in numerous other aspects.

FATIGUE PERFORMANCE - Casting manufacturing accommodates smooth transitions in thickness and geometry. With thoughtful casting design, smooth transitions can be made to coincide with the natural flow of forces within an element, and weld joint types can be selected to provide less stringent fatigue categories (Figure 4). This lowers geometric stress concentration factors and increases efficiency and fatigue life within cast elements (Schober, 2003).

Furthermore, fatigue life is particularly improved in applications where a casting replaces a welded connection at a member intersection. By introducing a cast node, weld locations are moved away from changes in geometry. This moves the residual stresses and weld toe notches that are inherent in welds (both of which cause stress concentrations) away from geometric stress concentrations. The separation of the two types of stress risers dramatically improves the fatigue resistance of the junction (Lomax, 1982). In the offshore energy industry (both in oil platform and wind tower basements), cast steel nodes provide fatigue resistances 4 to 18 times greater than fabricated connections (Breyaert, 1995). For this same reason, castings are often used in the design and construction of a variety of bridge types – from connectors, couplers, clamps, and rope heads in cabled bridges to cast nodes in steel truss and arch bridges.

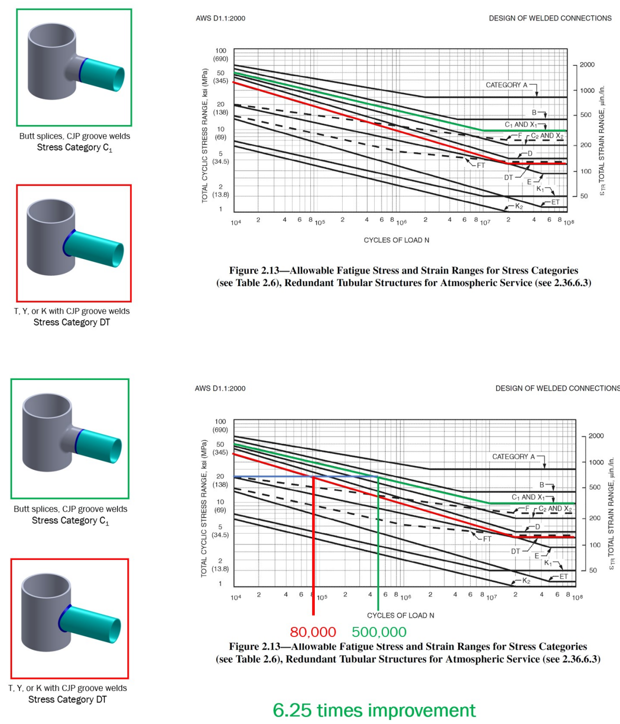

Figure 4: Fatigue reduction is achieved with the use of cast steel nodes when moving from TYK to Butt joint.

DEFLECTION AND VIBRATION CONTROL - Estimating service deflections in HSS bridges constructed with conventionally fabricated connections is challenging and imprecise. Tube-to-tube connections are flexible and depending upon the ratio of the web to chord member dimensions (chord with large d/t), HSS connections can be extremely flexible.

Research has shown that deflections estimated in tubular bridges without accounting for HSS connection flexibility can be underestimated by as much as 20-percent (Frater and Packer, 1992). As such, connection flexibility cannot be neglected in the computation of bridge deflections when using conventional tubular construction. The corollary of not being able to accurately compute deformation is that the estimation of the bridge's natural period will be inaccurate by the same degree.

The issue of imprecise estimation of deflection and fundamental period of tubular bridges can be precluded with the use of cast nodes (Figure 5). As previously discussed, castings can be shaped to accommodate the natural flow of forces though the junction, and increasing local wall thickness in heavily loaded regions or where additional stiffness is required is trivial with castings. This is in stark contrast to traditionally fabricated built-up connections which must either be locally reinforced to increase connection stiffness (with is costly in fabrication, increases coating surface area and presents greater sites for failure, and is often undesirable from an aesthetic standpoint); or where the wall thickness of the HSS member must be increased leading to global structural inefficiency, which is also costly, as discussed above.

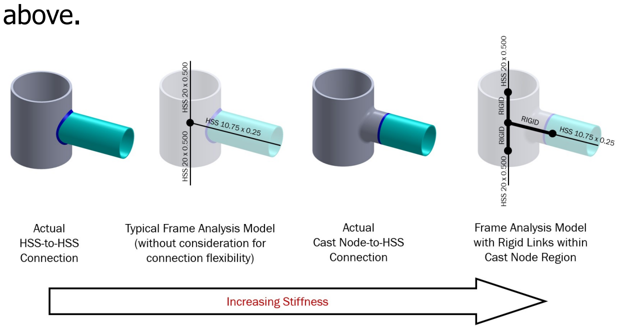

Figure 5: Bridge designers can model global behavior with more certainty in connection stiffnesses when utilizing cast steel nodes.

Further, because cast nodes can be designed to control connection flexibility, HSS bridges constructed using castings are stiffer than conventionally fabricated tubular bridges. In bridges where deflections or natural period considerations govern the design, the connection stiffness offered through the use of cast nodes translates directly to cost savings in reducing the tonnage of HSS necessary to meet flexibility criteria.

QUALITY, FABRICATION AND FIELD ERECTION - The casting manufacturing process produces high-integrity, monolithic structural steel geometries having isotropic mechanical properties, making castings ideal for multi-axis, arduously loaded joints (Figure 6).
Casting designers have the freedom to specify chemistry and heat treatment to achieve a wide range of mechanical properties – notch toughness being one of particular importance in the design of bridge connection nodes. In contrast, manufacturing of HSS involves cold forming that consumes part of the material's available ductility and imparts residual stresses into the product; the resulting product displays material anisotropy. Thus, cast nodes provide vastly superior quality and robustness than junctions that are comprised of built-up, weld fabricated connections between cold formed steel sections with welds located in regions of geometric complexity.

Furthermore, as machining is a standard part of casting production, cast nodes are produced with machine-level dimensional precision at locations where other structural elements are to mate with the casting (whether through chemical or mechanical means). As such, cast nodes can be used as "jigs" in shop layout of complex steel assemblies, simplifying and speeding fit-up and improving tolerances in shop constructed assemblies. When these assemblies arrive in the field, machine-level nodal tolerances again improve fit-up which aids and speeds field assembly. Time savings in the field offered by cast joints can translate to achievement of ABC goals, of a project, risk reduction and significant overall project cost savings to Owners and the public.

Figure 6: The Sankt Kilian Viaduct, completed in 2006, utilizes cast steel nodes at the locations identified to address multiplanar tubular connections.

COATINGS – As discussed above, improvement of coating system longevity will reduce life cycle cost of bridge structures. This can be achieved through reduction in sharp edges, corners and crevices, particularly at weld sites. While tubular structures offer immediate savings over open sections for their reduced surface area per unit length, additional advantage can be found with the use of cast steel nodes for tube to tube connections.

The performance of the paint/coating system is not solely based on the type of coating selected, but also on the geometry and connections selected for the structural steel system. Sharp edges, outside corners, crevices, and welds are often sites where coating failures occur and corrosion begins due to the reduced coating barrier protection (Kogler, 2011). Research shows that the anti-corrosive performance of paint coating systems is negatively affected by corner geometries (Itoh et al., 2008).

Steel castings inherently replace corners, crevices, and narrow gaps with generous radii and gentle geometric transitions. Clearance between connecting members at junctions is increased by pulling welded connections away from the central workpoint. Concealed bolted connections may be utilized in the field and if field welding of connections is performed, the weld type and position will be greatly simplified as compared to overlapping welded HSS connections – which are susceptible to cracking due to shrinkage constraints and which are thus hotspots for coating system failure and corrosion problems (Sebastian, 2015). Cast nodes pull the welded regions away from one other and allow for simple girth welds, which are far easier to weld, inspect, and coat. Regions that require "stripe coatings" are thus dramatically improved from an access perspective a hence also from a performance and maintenance perspective.

AESTHETICS – Where aesthetics are important to the realization of the design of the bridge project, whether in projects with architecturally exposed structural steel (AESS) requirements or with exposed standard structural steel, the architectural performance advantage, and potential economy offered by cast steel connections is substantial.

Craftsmanship requirements when utilizing cast steel connections are vastly decreased in order to achieve high quality AESS (Category 3 and beyond per AISC 303).
The reduction in fabrication labor results in cost savings which should be recognized when considering the value of cast connections to the overall project.

The award-winning Frances Appleton Pedestrian Bridge serves as an example of reduction in AESS welding requirements and achievement of geometries that would not be possible with traditional fabrication methods. As conceived by the architects, the bridge piers, given a tree-like shape meant to complement the natural trees on the bridge site, called for complex fabrication and in effect a geometry that would not be possible to achieve with traditional fabrication methods. Instead, cast steel nodes were leveraged to vastly simplify fabrication labor and scope of AESS weld remediation, resulting in savings in fabrication (Figure 7 and 8).

Figure 7: The Frances Appleton Pedestrian Bridge, completed in 2019, features cast steel nodes at the intersections of the HSS-12.75 branch members and the built-up trunk of bridge piers.

Figure 8: Cast steel nodes for the Frances Appleton Pedestrian Bridge awaiting incorporation into the bridge pier assembly at the fabrication shop. Machined weld preps support shop assembly and improved tolerances. AESS weld remediation is limited to three, simple girth, shop-welds. The recessed detail was precision machined to meet the architectural requirements.

CONCLUSION

While tubular members are very often leveraged in the design of highway, rail, and pedestrian bridges, challenges in the design and construction of tubular connections can be improved upon with the use of cast steel nodes.

Bridge designers can leverage cast steel connections in tubular bridge structure to enhance the stiffness, strength, and fatigue performance and simplify the fabrication of tubular connections, leading to improvements in overall structural efficiency, deflection control, vibration performance, coating system performance and longevity of bridge structures.

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