Accelerated Steel

Achieving Speed in Steel Bridge Fabrication

NEED FOR SPEED

Smarter. Stronger. Steel.

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National Steel Bridge Alliance

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Foreword

Accelerated Steel: Achieving Speed in Steel Bridge Fabrication was initiated by an AISC/NSBA Need for Speed workshop in Fall 2019. The goal of the workshop was to find ways to speed projects using fabricated steel. The workshop participants recognized that there are significant fabrication time saving opportunities in the activities that support the shop floor, not just on the shop floor. These opportunities depend on the owner, the engineer, and the general contractor. This guide describes these opportunities and how the owner, engineer, and general contractor can act to achieve the best steel bridge project schedule.

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1.0 INTRODUCTION

How is speed achieved in steel bridge fabrication? What roles do the owner, engineer, and general contractor play?

Speed may be a matter of urgency: on some projects, the steel was needed yesterday. Most projects are less urgent, with the fabricated steel needed months or years out. Regardless, time always matters. On every project, the fabricator is working to a delivery commitment and associated schedule that is important. And accelerated or not, achieving the desired schedule depends on the same factors.

Achieving speed in fabrication is only partly associated with the time it takes for shop floor activities, like optimal cutting, fitting, welding, drilling, cleaning, and coating. Achieving speed is also about time related to shop support activities, like getting materials, shop drawings, procedures, and inspection on time. Further, these activities have significant time saving opportunities—and the possibilities of significant delays.

The point of this guide is that the owner, engineer, and contractor affect the shop support activities such as procuring materials, developing shop drawings and facilitating shop drawing approval, approving welding procedures, and schedule impacts due to shop inspection. The guide explains why this is and describes the best practices for achieving the best schedule, including how these issues relate to the use of design/build contracting, which is often chosen for speed. The guide is structured as follows:

- Chapter 2.0 describes fabrication practices on typical projects including the shop support activities
- Chapters 3.0 through 5.0 describe the responsibilities of the owner, engineer, and contractor as relates to the support activities, including recommended best practices
- Chapter 6.0 describes special practices as they relate to design/build contracting

Speed is important. Delivering projects on time is crucial and beating typical fabrication deliveries can significantly help many projects. Accelerating steel bridge fabrication is a very realistic possibility, not by processing the steel faster but by the fabricator getting excellent support from the fabricator's teammates: the owner, the engineer, and the contractor.

2.0 FABRICATION

The achievement of an effective steel bridge project depends on smooth, timely flow of project information in advance of actual fabrication and then depends on smooth, timely flow of the work in the shop. In both cases, this flow is facilitated when the owner, engineer, and contractor use best practices in support of the project. These best practices are defined below in conjunction with the basic steps of a steel bridge fabrication process.

The steps of a steel bridge fabrication project are presented below. The steps are sequential and are based on I-girder bridges. For other bridge types, such as tub girder bridges, arches, trusses, and cable stayed bridges, there are some differences, but the basic principles remain the same. The steps are categorized as follows:

1. Estimating
2. Bidding and Contracting
3. Scheduling
4. Planning
5. Shop drawing production
6. Shop drawing approval
7. Material procurement
8. Welding procedure development
9. Equipment programming
10. Fabrication
11. Assembly
12. Coating
13. Inspection
14. Shipping

The steps are also presented graphically on a hypothetical fabrication schedule in Figure 1. Further, where specific support is required on behalf of the owner, the engineer, or the contractor, this is included at the end of the step.

Throughout this discussion there are references to the standards of the AASHTO/NSBA Steel Bridge Collaboration. The mission of this Collaboration is to publish standards and guidelines that represent the best practices for steel bridge design and construction. The standards are developed by diverse groups of subject matter expert volunteers, and the standards and guidelines are approved by both the NSBA and AASHTO. Many of the best practices described herein are addressed by the Collaboration standards and guidelines, and so they are referenced where applicable.

2.1 Estimating

Fabricators compete for work and therefore must bring their best price to the market. The fabricator's estimate includes costs for shop and yard labor; inspection and testing; materials, including plate, shape, and smaller items like fasteners; shop drawings; CAD/CAM programs; consumables such as welding consumables and paint; shipping; margin; and overhead expenses for such items as tools and equipment, training, certifications, power, maintenance, and management. For the fabricator, an important key for achieving a good estimate is properly estimating the labor and documenting key assumptions for later reference by the project management team.

Labor is often thought of in terms of the common value-added operations associated with fabrication, such as cutting, drilling, fitting, welding, cleaning, and painting. These certainly apply, but there are also many others, including unloading and loading materials; moving materials and fabricated products; measuring and marking; and inspection, including visual inspection and non-destructive examination (NDE). Put another way, anything that a person can be seen doing in the shop or yard in association with the fabrication of a bridge is labor.

Having a clear understanding of the project expectations is paramount to producing an effective estimate of project costs. Every bridge is unique, and each project comes with its own design and specifications, both of which affect labor. As an example, consider if there are special and unclear requirements for shop assembly (see section 2.11) in the project specifications. Fabricators are the best judge of how much shop assembly is needed to ensure fit, and DOT standard specifications usually have language reflecting customary practice, but it is not uncommon for special fit checking requirements to be included in project specifications. Putting special assembly requirements into the project may mean adding movement and handling of fabricated products that are unnecessary. Workers are involved whenever fabricated product is moved, and this is especially so with the bulky and extraordinarily heavy materials and fabricated components used in steel bridges. Consider moving girders. Usually, two or three people are involved to safely operate equipment and position girders. Assembly requires moving and carefully positioning girders and any other members that are included. Thus, prescribing shop assembly that is not needed adds a significant amount of unnecessary time and cost to the project and including unclear assembly requirements in a project can put a fabricator's estimate in serious jeopardy.

Assembly prescriptions are a good example of why the best practice when writing project specifications is to use performance specifications which prescribe the desired outcome and to avoid using process specifications that prescribe practice requirements. Fabricators know how much assembly is needed based on their equipment, skill, and experience. Further, the fabricator is responsible for fit (notwithstanding field conditions that affect fit) regardless of specification requirements for assembly, so it is better not to include special assembly requirements in the project. Assembly is just one example of where prescribing methods may unnecessarily add time and cost to the project. Use of process specifications instead of performance specifications (i.e., specifications that require a process instead of specifications that require a desired outcome) can adversely affect any fabrication step, from cutting and drilling to welding, cleaning, or painting. In best practice, use performance specifications to the extent possible and only specify processes or process limitations when absolutely necessary.

Another key to facilitating a good estimate is clear, understandable presentation of design information. The key to achieving this is to use standard practices for design presentation and follow customary practices in design. Where unusual details or practices are necessary, it is a good idea to check with fabricators in advance of the project to ensure such items are presented in a way that will be clearly understood later. Detailed information about such design practices is presented in Chapter 4.0.

Summary

- Regarding specifications
  - Use specifications that are standard and customary wherever possible; in the case of local owners, reliance on state DOT specification is prudent.
  - Avoid process limitations in the project specifications, and where they are necessary, ensure use of standard and customary limitations.
  - Use specifications that reference national standards and are built on Collaboration recommendations and AASHTO Construction Specifications.

- Regarding designs
  - Use standard practices for design presentation, including recommendations of Collaboration Standard.
  - To the extent possible, avoid the use of nonredundant steel tension members (formerly referred to as fracture critical members).
  - Ensure design information is clear and easy to understand.
  - Specify expectations rather than prescribing processes.
  - When something new and innovative is used, check with industry in advance about how to present it best so that it is understood.

These practices are listed here because they first impact the estimate, but they also affect many other steps throughout the process.

2.2 Bidding and Contracting

Fabricators work as subcontractors to general contractors. Fabricators monitor owners' project advertisements and download plans when they see projects that have steel bridges they are interested in producing. Owners publicize the names of the parties who download plans; therefore, from this information, fabricators, and contractors each know who has interest in the project. Usually there is a month or longer between the project advertisement and the bid date; this interval provides time for fabricators to produce estimates and provide prices to general contractors.

After bids are open, the winning general contractor and fabricator will begin contract negotiations with each other. Although discussion of terms may begin, the general contractor will not sign contracts with fabricators and other suppliers until the general contractor has a contract with the owner, and this will not happen until after the owner has reviewed and approved the bid. Therefore, although the identity of the general contractor and fabricator on the project are known on the bid date, a contract between the general contractor and fabricator will not be in place for weeks or even months. Work done before contracts are in place is performed at risk.

2.3 Scheduling

Scheduling is an essential fabrication function that begins even before bidding and continues through drawing preparation, planning and, to a lesser extent, fabrication.

The fabricator's scheduling is closely tied to the fabricator's capacity. Fabricators have finite production capacity that is dependent on the size of their workforce and physical plant. When projects are advertised, fabricators begin consideration of whether they have the capacity to produce the project on the anticipated schedule. This carries on in more detail when, in pre-bid discussions, general contractors convey their desired schedule and fabricators speak to their ability to deliver to this schedule.

Once the fabricator has the job, the fabricator balances several factors to manage the fabrication schedule:

- The general contractor's delivery schedule and sequence—during contract negotiations with the general contractor, both parties will arrive at mutually agreeable delivery terms. Often these are general terms because the general contractor may not have complete delivery information until erection plans are complete or site conditions have progressed
- Arrival of mandatory fabrication deliverables—to proceed with work, fabricators must have approved shop drawings, approved welding procedures, other procedures that require approval (if any), and materials
- Fit of the project in the schedule with other work—the fabricator must schedule the project among the other projects in the shop

2.4 Planning

Planning refers to the multitude of decisions the fabricator makes to execute a job. To some extent, planning begins pre bid, particularly for large and complex projects. Before bidding, the fabricator considers whether they have the capability to produce the project. Most especially, the fabricator must be able to handle the weight and the shipping length of the anticipated field pieces on the project.

Fabrication planning includes the following:

- If the fabricator has multiple facilities, which facility will be used
- Alignment of workforces, including any special skills training needed
- Identification and handling of any special material or processing needs, particularly processing that might require subcontracted work
- What equipment will be used for various operations like cutting, drilling
- In what sequence will plates and, if applicable, shapes be joined to produce the fabricated assemblies
- Regarding welding:
    - Which welding processes and equipment will be used for the various types of joints
    - What position the work will be placed in for welding
    - How the material will be prepared for welding, such as beveling for groove welds
- What level of assembly will be used, considering both what the fabricator determines is necessary and any requirements in the contract.

Even the simplest projects require some planning. More complex projects require more planning, particularly when components are large or complicated, or connections are complex. When projects have complex assemblies, the fabricator may use welding mock-ups to establish the best approach for welding process, preparation, sequence, and NDE of complex weldments, or the fabricator may use scaled cardboard or 3D-printed mock-ups to help establish the best fabrication sequence for the component. The results of the plan will be reflected in the fabricator's shop drawings, welding procedures, other shop instructions and schedule.

2.5 Shop Drawing Production

Complete and accurate shop drawings are essential to the effective execution of steel bridge fabrication projects. The shop drawings translate the design information in the bridge plans into the details needed to fabricate the bridge.

The primary purpose of shop drawings is to provide fabrication instructions to the shop, including:

- Dimensional information for cutting and preparing plates and shapes
- Joint details for welding and bolting
- Surface preparation instructions
- Welding information—this includes weld types and sizes but is separate from welding procedures
- Weld inspection information, including radiograph and ultrasonic testing requirements
- Processing requirements related to drilling and assembly
- Cleaning and painting requirements
- Supplemental holes for temporary attachments such as erection bracing and lifting devices
- Shop assembly information

Crucially, the designer must support shop drawing production by answering requests for information (RFIs) and cooperating with the contractor and fabricator in the resolving of any review comments in a timely manner. RFIs are generated by the fabricator or detailer when the design plans have errors or insufficient information to complete the shop drawings. They ask specific questions or request more details.

Shop drawings also play two other key roles: first, they confirm that the geometric information in the design is correct or, as needed, facilitating its correction, and second, they facilitate the production of bills of materials for ordering the steel.

Recognize that design drawings do not have the complete information that is needed on the shop floor to produce the steel for the bridge. In the shop, workers need explicit instructions about how to cut, fit, weld, and drill the steel, and these instructions are dependent upon the fabricator's equipment and preferred methods. While the design drawings must effectively define the bridge from the perspectives of engineering and final geometry, it is the shop drawings that present the fabrication geometry and fabrication instructions to the shop.

a. The Role of Shop Drawings as Shop Instructions

In the shop, work must move efficiently and at a steady pace. There is no time to make decisions about operations such as which processes and equipment should be used, which plate should be joined to which other plate first, or what sequence of weld passes will be best. Rather, the opposite is true. As the bridge parts progress through the shop, shop coworkers cut, fit, weld, drill, and coat the steel as the shop drawings show, with decisions having been made in advance, during planning.

The complete instructions of the shop drawings bring together all details needed by various departments in the shop to keep the project moving. For example, when stiffeners are to be fit into a girder, the fabricator must decide how long to cut them. The space between the flanges is shown in the design, but the fabricator may cut stiffeners at slightly different lengths to facilitate fitting. If stiffeners are too long, they take more effort to fit; if stiffeners are too short, the gap between the flanges and the stiffener cannot be welded effectively. If the stiffener is angled or skewed, this must also be addressed. In planning, the fabricator will consider if any special considerations are needed given the size of the girders and the dimensions of the stiffener and then put these dimensions into the shop drawings. Later, in the shop, the person responsible for cutting the stiffener, or writing the program to cut the stiffener, will follow the print, keeping the work moving without needing to stop to make decisions about what dimensions to cut the stiffeners to and which equipment to use on the shop floor. As with the stiffener, the shop drawings reflect innumerable decisions made by the fabricator about how to dimension, cut, prep, fit, and join materials, providing clear and complete instructions to the shop.

b. Deflections, Camber, and Shop Drawing Geometry

Shop drawings translate the geometry of the final design into the geometry needed in the shop. These two geometries are not the same due to camber and the influence of deflections; the design geometry reflects the geometry of the steel in its final deflected condition, under its own weight and the weight of other dead loads. The geometry in the shop drawings is adjusted to reflect the fact that the steel is not yet deflected during fabrication because these weights are not yet present. Also, the geometry presented in the shop drawings is adjusted to reflect the fact that the geometry of the steel changes as it progresses through the shop due to the expansion, shrinkage, and residual stress changes associated with cutting and welding the steel.

The anticipated deflection of the bridge is communicated to the fabricator through the camber diagrams in the plans. During design, the engineer predicts how the bridge will deflect from the no-load, or fully cambered, condition through the steel dead load, or erected, condition, where the steel is under its own weight, to the fully loaded, or final, condition, with all dead loads present. These deflection predictions are reflected in the camber diagrams. The fabricator combines the deflection information with manufacturing behavior and allowable tolerances to arrive at the fabrication geometry reflected in the shop drawings.

In association with camber and deflections, the fabricator will detail the bridge in accordance with the fit condition indicated on the plans. The engineer chooses the desired fit condition based on the anticipated bridge deflection behavior. Deflection behavior of I-girder bridges is complicated. Designs present camber along girder lines, which is customary and logical, and these girder-line cambers suggest that the deflection of the bridge is simply the combined, simultaneous deflection of the girders. However, bridge deflections are more complicated than this because the girders are tied together by cross-frames and other diaphragms, and therefore the bridge deflects as a system. When bridges are skewed or curved, the amount of girder deflection on either side of each cross-frame is different; the greater the skew or curve, the greater the differential. At discrete cross-frame locations, the design camber diagrams may indicate that the cross-frame will deflect a different amount on either side, but this is not entirely possible on skewed and curved bridges. As dead loads are applied, the stiffness of the cross-frame resists this differential deflection, introducing twist into the girders. Due to this behavior, girders may twist out-of-plumb somewhat during erection, either being twisted during erection under force fitting such that they untwist under final dead loads (if detailed to full deadload fit), or, if erected plumb without force fitting, then twisting to an out-of-plumb condition under final dead loads (if detailed to steel deadload fit). Girders usually have enough torsional flexibility to facilitate either approach, but not always. Factors such as bridge curvature, girder spacing, and cross-frame spacing affect stiffness, as do the presence of elements like integral pier caps and lateral bracing. For stiffer bridges, it may not be possible to build the bridge detailing to full deadload fit, and in the case of very stiff systems, it may be necessary to detail the bridge to no-load fit and erect the steel on falsework in the no-load condition.

Deflections and the relative stiffness of a bridge system introduces restraint and associated loads into the members, and the designer may need to account for them. But most importantly for steel bridge projects, deflections and stiffness affect bridge erection, and this must be considered up front. On many bridges, differential deflections and twisting effects are small and not consequential, but on some bridges, they are significant and impact the ability of the bridge to be built. As mentioned previously, on curved or skewed bridges, girders twist during erection, and this affects how plumb they are when all dead loads are applied. It may seem desirable to build the bridge such that the girders will twist to a final plumb condition, but this is not always possible. In some cases, bridge members are so stiff that they must be erected such that there will be some out-of-plumbness or locked-in restraint in the final condition.

This phenomenon is complicated but normal. The designer anticipates this behavior and, as needed, accommodates it in the design. To address this behavior and associated loads and built-in restraint, the designer designates the fit condition for the bridge. The fit condition specifically refers to the way the connections between the girders and cross-frames are to be detailed in the shop drawings and built in the shop. Thus, the designated fit condition is manifested in the way bridges are detailed. On an effective bridge project, and as required by AASHTO, the designer must provide the desired fit condition up front so the detailing may progress, and the designer must choose an effective fit condition to facilitate the erection of the bridge. More information on this topic is available in the NSBA Technical Resource, "Skewed and Curved I-Girder Bridge Fit, Executive Summary," which provides recommended fit conditions for I-girder bridges, and the more complete "Skewed and Curved Steel I-Girder Bridge Fit" by the NSBA Technical Committee, which provides full details about fitting steel I-girder bridges and associated behavior during erection.

c. Shop Drawing Production

Shop drawings are produced by "detailers" on behalf of the fabricator. The detailer may be in-house at the fabricator or may be a subcontractor. There are only a handful of firms that provide third-party bridge detailing in North America. Especially due to the deflection behavior described above, bridge detailing is very different from detailing for other steel structures. Bridges are highly specialized, and not every structural steel detailer has the experience to provide bridge shop drawings. Because they turn bridge design into the instructions needed by the shop, bridge detailers are a good source of information about how to fabricate steel bridges.

The first step in producing shop drawings is checking and, as needed, correcting the bridge geometry. Geometry discrepancies in bridge plans are not uncommon. Most detailers use their own unique applications to produce the fabrication geometry from the design geometry. The bridge geometry is input into their application, and then the application runs a check. It is from the application output that most geometry discrepancies are discovered. Common discrepancies include items such as incorrect haunch depth, incorrect geometric camber, inaccurate bearing pad elevations, and incorrect vertical curve. The detailer will query the designer through a request for information (RFI) to reconcile the discrepancies in the geometry. At this point, the entire progress of the fabrication project hinges on the responses to such RFIs, so timely responses to these RFIs are crucial for the fabrication schedule.

Once the fabrication geometry is known to be correct, the detailer can proceed with working through the rest of the project details. Note the importance of this sequence—because the geometric information throughout the bridge is interrelated, work cannot proceed until the geometry is correct. Further, the geometry cannot be checked for correctness until it is all available. With respect to this, it is particularly important to note the influence of camber. Changes to camber basically change the entire geometry of the bridge. If for some reason the camber of a bridge does change after the geometry has been set, much of the detailing work performed up to that point may have to be redone.

A tremendous amount of information is compiled into the details needed to fabricate a bridge. Even a moderately sized steel girder bridge is made of hundreds of components, some large like webs and flanges, and others smaller, like stiffeners, cross-frame gusset plates and cross-frame members. The dimensions and grade of each unique part are identified and detailed in the shop drawings, as well as instructions for their cutting, beveling, and surface preparation. Other drawings show assemblies that indicate how the parts are to be arranged and welded into girders, cross-frames and other elements, and welding inspection instructions. Drawings include instructions for shop assembly, cleaning and painting, and any other special processes that are needed.

Also, once the geometry is set, the detailer will produce a bill of materials for advance material ordering. As discussed in the material procurement section of this document, fabricators usually procure material by custom order directly to the mill. Mill orders are often procured in advance, once the geometry is set but before shop drawings are complete. As with detailing, changes to camber after web and flange material has been ordered can be very disruptive; it may still be possible to use the ordered flanges, but if camber changes are significant, web material will probably have to be reordered, thereby adding cost and resetting the clock on the web material delivery schedule.

Summary

- In design, be aware of the common pitfalls and errors and strive to avoid them.
- When answering RFIs during shop drawing development:
  - Provide expeditious responses; if possible, answer, or give an indication of an answer, within a day; and
  - If there is any confusion about the RFI, call the fabricator.

2.6 Shop Drawing Approval

Most owners require that shop drawings be reviewed and approved (or accepted) by the engineer before fabrication begins. Performing the correct level of review, without going into too much detail, is important for achieving a good project schedule.

The review provides the engineer with the opportunity to confirm that the shop drawings conform with the design intent. Therefore, the review is properly conducted at a high level, as needed for this confirmation. The review is not intended as a check of all the fabricator's dimensions and calculations. In fact, many of the details in the drawings are based on geometric calculations and geometric manufacturing assumptions that are not provided with the drawings. Further, the accuracy of the shop drawings is not the engineer's responsibility. Regardless of the shop drawing review, the fabricator is responsible for the conformance of the shop drawings and, ultimately, the fabricated bridge with the shop drawing. A timely review is crucial for effective steel bridge fabrication: due to the requirement for review and approval, the project cannot be kept on schedule if the drawings are not returned on time. Accepting partial submittals, providing partial approvals, and use of "approved as noted" for minor concerns are good strategies for helping the project schedule. More details regarding this review are provided in the owner's responsibility of this document and are also described in AASHTO/NSBA Standard G1.1, *Shop Drawing Review Guide*.

Summary

- In review, follow the practices of Collaboration standard G1.1.
- If there are questions during review, contact the fabricator for clarification (with concurrence of the owner and general contractor).
- Return reviewed drawings in a timely fashion.
- Allow partial submittals.
- Allow use of drawings that are "approved as noted."

2.7 Material Procurement

Steel plate is the primary material used in steel bridges. Plate girder webs, flanges, and stiffeners are all made from plate, as are splice plates and cross-frame and other diaphragm gusset plates. Angles, tees and sometimes W-shapes are common in cross-frames, and larger W-shapes are sometimes used as stringers in smaller bridges or as part of a floor system in large bridges like truss, cable stay, or arch spans. Fabricators do keep small quantities of commonly used plate thicknesses in the stock but procure most of the steel needed on a bridge project on a custom basis.

There are two choices when purchasing material: buy directly from a steel mill or buy the steel at a service center. Service centers purchase common sizes of plate and shapes from mills and keep them in stock. Unlike the plate purchased by fabricators, plate at service centers is usually delivered by coil. The coils are leveled and cut into standard lengths that the service centers keep in stock. Mills have minimum order requirements of 20 tons to 300 tons, depending upon the product and the mill, so purchasing from services centers is suitable for some fabricators in other industries who produce smaller projects, but quantities for bridge projects typically satisfy these minimum requirements. Further, the plates needed for girder webs and flanges will not be commonly found at service centers. Therefore, bridge fabricators purchase most girder material on a custom basis for each job directly from steel mills.

Material lead time is a key schedule driver on a steel bridge project. Lead time refers to how long the fabricator will wait to receive material once it is ordered. Lead times vary depending on demand and the type of material. Plates made of ASTM A709 grades 50 and 50W are usually available in eight to ten weeks. High performance steel (HPS) grades, which require special processing and are not as common, usually take longer, typically twelve to sixteen weeks. Most project schedules can accommodate typical lead times, but lead times are significant for projects on tight schedules. When speed is desired on a girder bridge, the key is to get flange and web material ordered as soon as possible.

For large W-shapes, such as those that might be use as bridge stringers, lead times can be much longer than those of plate. Such shapes are made on defined rolling schedules, usually a few times a year. When a fabricator orders these shapes, the delivery to the fabricator will be based on the next rolling. Thus, in some cases plate girders can be fabricated more quickly than rolled beams used as stringers. Therefore, when rolled beams are used in the design and the schedule is tight, it is a good practice to include an equivalent plate girder in the design as an option and be aware of the rolling schedule or be receptive to a substitution request from the fabricator.

Material is generally delivered to fabricators by rail car. Material can also be delivered by truck, but this is less practical and more costly. To keep material shipping cost effective, plates must fit on one rail car; if plates are longer than a rail car, then the railroad will use a triple-set, significantly increasing the cost of shipping. Rail cars are 85 feet long, and the usable shipping length of the cars is 83 feet. Fabricators use shop splices to help fit ordered plates to lengths that will fit on one rail car. In some cases, flange thickness transitions facilitate shipping: if flange thickness transitions are less than 83 feet apart, the fabricator will not need to add shop splices for shipping (but might need to add shop splices due to material availability—i.e., not all grades and thicknesses are available in lengths even up to the 83-foot rail car length). Adding shop splices for web material is very common: any field piece longer than 83 feet long is likely to have a welded shop splice.

Material cannot effectively be ordered directly from design plans. There are many fabrication factors that affect material dimensions. This is especially the case for web material regarding camber. Girders must be built in the no-load condition with consideration of camber tolerances. Camber curves and tolerances run from support to support, and except for shorter simple span bridges, girder field pieces do not directly align with camber curves. Thus, to properly order web material, the fabricator, through a shop drawing detailing process, must complete the processes of checking and correcting the bridge geometry and then incorporating camber, manufacturing, and tolerance information into the girders.

On a plate girder project, the webs and flanges are large and highly customized compared to the other components on the bridge, so ordering web and flange material is an important step in the project schedule. The order for these materials is commonly known as the "advanced bill of materials" or the "advanced bills."

In ordering material, fabricators optimize material usage through a process called "nesting." The fabricator groups components by thickness and lays out the components of each given thickness in such a way as to optimize plate ordering and usage. The layout of needed plate components on a given parent plate is called a "nest."

Summary

- In design, be aware of the common pitfalls and errors and strive to avoid them; this will speed ordering of material.
- Size webs and flanges so they are readily cut from commonly available slab lengths (not to exceed 83 ft) and widths (common slab widths range from 6 to 12 ft).
- Do not restrict the location or addition of shop butt splices.
- In design, follow practices of Collaboration Standard G12.1 to optimize material use and provide economical fabrication.
- Understand and expect shop splices to accommodate material availability.

2.8 Welding and Welding Procedures

Welding began to replace rivets for the fabrication of bridge parts in the 1950s, and the use of rivets died completely in the 1970s. Thus, welding has been an essential part of steel bridges for many decades. Modern steel bridge components are welded assemblies of plates and shapes.

Welding has evolved considerably over the past 100 years, originating with stick welding done by hand, and evolving to wire-fed, mechanized, and automated processes. Most welding in bridges is arc welding, and the following arc welding processes are used:

- Shielded metal arc (SMAW) welding—commonly referred to as "stick" welding is popular for small welds, tack welds, welds done "out of position" (vertical or overhead welding), and field welding.
- Flux-cored Arc Welding (FCAW) and Gas Metal Arc Welding (GMAW)—known as "flux-core" (FCAW) and "MIG" (GMAW; MIG is short for metal inert gas, and MAG is short for metal active gas, but "MIG" is often used to describe GMAW regardless of the gas type)—is commonly used for smaller welds and tacking; is usually hand-held, but can be mechanized; and is popular when automated (robotic) welding is used.
- Submerged Arc Welding (SAW)—known as "subarc," is usually mechanized and used for butt splicing and longer fillet welding.

SAW is the workhorse of the steel bridge fabrication industry. This is primarily because bridges are made of large structural members that have a lot of welding, and generally SAW is more productive than the other processes. SAW wires are much larger than other wires and run at a much higher amperage, thus providing much higher deposition, which is essential given the amount of welding and the size of welds used in bridges. Virtually all bridge web-to-flange welding and stiffener-to-web welding is done with mechanized SAW; most splicing is done with mechanized SAW as well although electro-slag welding (ESW), a type of resistance welding, is also sometimes used.

Fabricators make fundamental choices about how to go about welding and generally stay with the same processes and equipment for many years. Mechanization involves large, expensive equipment, and fabricators prefer to invest in this equipment, fine tune it, and then continuously rely upon it to produce the welds they need to fabricate bridges. Such mechanization and repetition are effective ways to both achieve productivity and weld quality. Therefore, when conducting welding oversight through welding procedure review and approval or in consideration of welding rules, the best practice is to facilitate the fabricator's continued use of the practices the fabricator has always used.

Since the earliest days of structural welding, owners have prescribed the use of welding standards to facilitate control and quality of welding. Rules have evolved over time, and for a period, there were a variety of requirements among state bridge owners, with some owners having their own rules and others using American Welding Society (AWS) standards. Then, in the 1980s, the American Association of State Highway Transportation Officials (AASHTO) formed a partnership with the AWS to establish AASHTO/AWS D1.5, The Bridge Welding Code (the Code), with the goal of standardizing requirements throughout the country. First published in 1988, the Code has evolved through eight editions, changing over time to keep up with technology advancements and practice improvements in the industry. The Code is maintained by a joint AASHTO/AWS committee, and changes are approved both through all levels of the AWS and up through the AASHTO Committee on Bridges and Structures.

The Code covers every aspect of welding needed to fabricate highway and railroad bridges, including requirements for

- Welding procedures and testing to support welding procedures
- Welder qualifications
- Suitable welding joints
- Welding process and associated consumables to be used with bridge steels
- Welding practices for hydrogen control, such as preheat and consumables controls
- Weld quality, including visual weld quality and non-destructive (NDE) testing requirements
- Weld repairs
- Special practices for nonredundant steel tension member welding (formerly referred to as fracture critical members)

Given its breadth, completeness, and history, the best practice in welding is to prescribe use of the

Code. It covers all aspects of welding that need to be covered, it is generally up to date with the latest technologies and materials, and it reflects standard practices. Fabricators are intimately familiar with the Code requirements, their personnel and procedures are qualified accordingly, and thereby use of the Code consistently leads to high-quality fabrication.

A key aspect of the Code is that it prescribes which welding consumables (electrodes and, for SAW, fluxes) to use with various steels. If typical materials are to be used in the bridge, such as ASTM A709 grades 50 and 50W, then use of the Code is suitable. However, if an unusual material is used in the bridge, i.e., a material that is not found in the Code, then special language is needed in the contract documents to address welding requirements for the material.

The Code states that all welding must be "performed in conformance with the provisions of an approved Welding Procedure Specification, which is based upon successful test results as recorded in a Procedure Qualification Record (PQR)…" (clause 1.9, 2020 edition). The key word in this provision is *approved*: if the Code is specified on the project, then the welding procedures must be approved in accordance with the requirements of the Code. This includes procedures for all types of welding, including tack welding, production welding, and repair welding. Thus, welding procedures and their approval are on the fabricator's critical path.

When reviewing procedures for approval, the procedures can be reviewed in and of themselves. It is not necessary to match the procedures to specific applications on the bridge; rather, the procedures are defined for specific scopes, and then may be used for any application suitable to this scope. For example, an SAW procedure developed for single-pass 5/16-in. fillet welds (a very common procedure) can be used for welding stiffeners to webs, webs to flanges, angles to gussets, or any other place that the drawings call out a 5/16-in. fillet weld.

Further to this point, welding procedures do not need to be approved for particular jobs or, for that matter, for particular owners. Most bridge owners allow the same procedure to be used time and again, without resubmittal on each job, provided it has been properly, originally approved, and local owners often allow use of procedures approved by the state DOT without additional review and approval. These practices are logical considering that most welding procedure rarely change. As discussed above, fabricators generally prefer to stay with the same equipment, processes, and consumables, continuously over time. Further, at any given time, there may be projects from multiple owners in the same shop—in large shops this could be a dozen owners or more Standardization under the Bridge Welding Code facilitates reciprocity of welding procedure approval among owners and associated standardization in the shop, which in turn facilitates quality and efficiency, helping achieve project schedules.

Summary

- Specify use of the Bridge Welding Code.
- Allow use of procedures that are already approved without requiring resubmittal on a project basis.

- If a local owner, allow use of welding procedures approved by the state DOT without resubmittal and approval.
- If procedures must be submitted for approval, then approve and return them expeditiously; a two-week turn-around is reasonable.
- If questions or concerns come up during review, call the fabricator to discuss them in-process.
- In design, when a partial or complete joint penetration weld is required, allow the fabricator to choose the specific weld detail from the collection of prequalified weld details in the Code.

2.9 Equipment Programming

Use of computer numerically controlled (CNC) equipment is common in bridge fabrication. Applications include cutting, marking, drilling, and hole punching. In all cases, programs are required to operate the equipment. Once shop drawings are ready, programmers, often known as CAD/CAM programmers, produce these programs based on the information shown in the drawings. In some cases, such as in cutting large parts to be welded, the programmers may introduce slight dimensional adjustments to accommodate the heat from cutting and welding in the final product. The types of programs and associated machine language vary depending on the type of equipment being used.

In addition to shop drawings, planning and scheduling affect programming because programs are unique to the particular equipment that will be used on the job. Generally, owner practices do not affect programming except that fabricators do not do programming until shop drawings are approved.

2.10 Fabrication

In association with the other operations described above, the actual processing of material into bridge parts can begin once the following are in place:

- Approved shop drawings;
- Required material; and
- Approved welding procedures.

a. Basic Fabrication Steps

Girder bridges are generally comprised of plate girders, cross-frames, end diaphragms, and sometimes lateral bracing. The following are basic steps in the fabrication of plate girders and cross-frames:

- Plate girders
    - Web and flange parent material is brought into the shop.

- Webs are cut to the intended configuration shown in the shop drawings, including the desired camber, reflecting the no-load condition and tolerances. As needed for length, webs are spliced by welding.
    - Alternately, parent web material may be spliced before cutting.
- Flanges of desired thickness are cut into the desired segments.
    - Preferably, if the design facilitates it, slabs are welded first, and then the flanges are cut ("stripped") from the welded slabs; or
    - If flange segments are unique, flanges are stripped first and then spliced.
- Flange and web heat numbers are documented—this stage may occur earlier or later in the workflow depending upon the fabricator's material control practices.
- Flange and web shop splices are tested by radiographic testing (RT) or ultrasonic testing (UT). If defects are discovered, the welds are repaired and retested.
- Flanges are tack welded to webs—tack welds are small welds that are just intended to hold the flanges and webs together until final welding.
- Flanges are welded to webs—in contrast with tack welding; this is sometimes referred to as final welding.
    - For most girders, fillet welds are used; in some cases, as is sometimes seen with railroad girders, complete joint penetration (CJP) welds are used. If CJP welds are used, the web is beveled for welding before the flange is tacked to it. Also, if CJP welds are used, they are tested by UT and repaired as needed.
- Intermediate stiffeners and connection plates are installed.
    - "Connection plates" are the plates that look like stiffeners but are used to connect the cross-frames to the girders; as such, they have bolt holes that make the cross-frame connection (unless the cross-frames are to be field welded, which is not common); connection plates do indeed stiffen webs as well.
    - Connection plates and stiffeners are generally detailed to fit tight between flanges; therefore, the fabricator will slightly jack the flanges apart to install the plates.
    - Connection plates and stiffeners are fillet-welded to the web.
    - Connection plates and possibly stiffeners are fillet welded to the flanges.
- Bearing stiffeners and, if present, jacking stiffeners are installed; there are a number of distinctions between these and other connection plates and stiffeners:
    - They are generally thicker.
    - They are generally oriented to be plumb under final conditions, rather than being oriented normal to the flanges.
    - At the flanges, they are either connected as finish-to-bear with fillet welds (preferred) or connected with CJP welds.
    - Jacking stiffeners may be partial-depth (preferred) instead of full-depth.
- Welds are inspected either:
    - By magnetic particle testing (MT) for certain welds as required; or
    - By 100% visual inspection.

  - Girder-to-girder connections are accomplished—this step may occur at this point or at an earlier stage in girder production, depending upon the fabricator's equipment and preferences. See "Assembly" for details.
- Cross-frames
  - Cross-frame connection or "gusset plates" are cut, and holes are punched or drilled.
  - Cross member shapes are cut to length.
  - Cross-frames are assembled and tack-welded together—the fabricator will employ some means of geometry control such that the cross-frame will fit properly when, in the field, joined to the girder at the connection plates.
  - Final fillet welding is accomplished.

b. Repairs

Fabricators strive to avoid rework, but repairs are occasionally needed and are normal in bridge fabrication. Repairs range from minor weld and base metal repairs to significant repairs requiring the replacement of material. While it is not desirable to need to make repairs, they are not uncommon, and properly executed repairs do not compromise the structural integrity of the bridge.

Repairs may be divided into two categories: repairs to remediate a condition to its originally intended state, and repairs that might have design implications. For the first category, support from the owner is generally not needed because these repairs can be executed within the allowance of the project specifications. For example, many repairs and remediations are permitted by the *Bridge Welding Code*:

- Clause 5.2.5 allows the fabricator to address surfaces that are cut too rough by faring.
- Clause 5.2.6 allows the fabricator to repair discontinuities in plate edges and other surfaces within certain limits.
- Clause 5.7.2 allows the fabricator to make repairs to address weld convexity, weld overlap, craters, undersize welds, undercut, excessive porosity, excessive slag inclusions, incomplete fusion, and cracks.

Other repairs require approval of the engineer. For example:

- Clause 5.2.5.1 allows repair of occasional cutting notches and gouges with the approval of the engineer.
- Clause 5.3.7.4 allows repair of base metal damaged by the removal of tack weld with the approval of the engineer.
- Clause 5.7.4 allows the repair of delayed cracks with the approval of the engineer.

Further, in association with these repairs, including both repairs that do and do not require the engineer's approval, the Code has many limitations related to the type of repair, allowable final conditions, and inspection, such as the requirement of UT for repairs to surfaces that will be in tension (Clause 5.2.5.2). When the engineer's approval is required, proposed repairs procedures will be submitted through the communication process established for the project.

The repairs above are just a few examples of the many repairs that are common in bridge fabrication. Note that even though some repairs require the engineer's approval, they are routine. Therefore, most bridge owners allow the fabricator to submit standard repair procedures that have prior approval and that the fabricator can use without consulting the engineer each time. Typically, preapproved repairs have limits; for example, a preapproved procedure for repairing gouges may be acceptable for gouges up to 1 in.; for deeper gouges, the fabricator would have to request repair approval on a case-by-case basis.

Over the decades, many repairs have become routine, and fabricators around the country perform repair more or less the same way. Hence, the AASHTO/NSBA Steel Bridge Collaboration has published a guideline for performing routine repairs, "G2.2 Guidelines for Resolution of Steel Bridge Fabrication Repairs." The guide addresses a broad variety of repairs, including bolt holes that are too close to intersecting plates, errant holes through misaligned bearing stiffeners and miscut webs, and mislocated stiffeners and sole plates, to name just a few of the 50 conditions covered. It is an industry standard and accepted resource for the oversight and approval of repairs. The document also clarifies misconceptions. For example, repairing an errant hole, which is a normal and sound practice using the guide's recommendations, is not the same thing as plugging a hole, which is not a good practice.

Distortion is inherent in fabrication. Any time steel is heated and then cools, such as from welding, the possibility of distortion exists. Further, cutting steel releases residual stress and can result in distortion. When such distortions occur, fabricators usually use heat to restore components to the geometry needed for the component to fit or to satisfy tolerances otherwise. Specifications provide heat limits and use of such heat is usually done as a matter of practice and not considered to be a repair. However, large restoration efforts, such as correcting camber by heat, are usually handled with an approved procedure. On complex bridges that have large components with heavy weldments, extra care and measures may be needed so that such components will fit when assembled in the field.

Some repairs have design implications; that is, the best repair resolution involves a change to a design detail. For example, one of the best ways to address a connection that has been misdrilled in a girder flange is to leave the misdrilled holes as they are and instead replace the splice plates with custom plates that match the holes. Or, in another example, if a stiffener is mislocated a minor amount, perhaps an inch, the best course may be to leave the stiffener where it is rather than cutting it out, repairing the base metal, and installing a new stiffener. Generally, the design is not sensitive to such minor errors in the fabrication process. Situations where the design is changed to affect a repair require approval of the engineer.

Summary

- Facilitate expeditious repairs by:
    - Working with the fabricator to establish standard repair procedures, and
    - Facilitating direct communication between the fabricator and engineer to help ensure the procedure is understood.

- Use repair practices that align with "G2.2 Guidelines for Resolution of Steel Bridge Fabrication Repairs."
- When called upon to review and approved repairs:
    - Understand that the design is generally insensitive to most minor repairs;
    - Strive for the "leave as-is" condition; and
    - Return repair requests expeditiously, preferably with a response or indication of a response within a day.

2.11 Shop Assembly

"Shop Assembly" refers to the practice of putting fabricated components together to either produce or check field connections. Methods of producing connections and the need for checking them vary. The connections in question include the following:

- Girder to girder connections, also known as girder field splices—assuming these are bolted splices, shop assembly to produce or check these connections is common but not always used
- Girder to cross-frame connections—assuming these are bolted connections, shop assembly to verify the fit of these connections is rare, and shop assembly to check these connections is uncommon.

Usually, standard specifications address reasonable assembly requirements. Further requirements are generally unnecessary and should be avoided because requiring additional shop assembly adds time and cost to the project. In some cases, the additional time could be weeks or even months. Fabricators are the best judge of how much assembly is needed to facilitate fit. Further, regardless of how the connections are produced and regardless of how much fit checking is done through assembly, the fabricator is responsible for the proper fit of the steel, assuming there is no issue with supports in the field.

a. Welded Field Connections

Except for this section, the discussion about shop assembly in this document addresses bolted connections and not field welded connections. Field welded connections are no longer common. Although welding is an excellent technique for making connections in the field, contractors generally prefer bolted connections over welded connections because bolted connections can be made more quickly, particularly in girder-to-girder connections. Field welded connections are still used on deck plates, such as for orthotropic deck bridges, and on bridges with special aesthetic needs where the appearance of bolted connections is not desired. Further, field welding is sometimes used for welding substructures and for attaching bearing components such as welding sole plates to girder flanges.

When field welding will be accomplished using fillet welds, requiring shop assembly is generally not warranted because fillet-welded connections typically allow for adjustability. However, when field welds consist of complete joint penetration groove welds, the parts in the field must be aligned such that weldable joints result. Thus, shop assembly is generally necessary to effectively prepare parts for making groove welds in the field. A note of caution: the fit of field welded joints is dependent upon the support conditions of the members. In the shop, joints are prepared with the no-load condition and associated orientation. In the field, if members are not at no load (as may be the case if they are under some or all of their own weight), this change in support conditions can cause rotation of the parts such that they will not fit as well. In such cases, some means of properly orienting the members to each other will be needed.

Summing up this section, field welded connections are no longer very common for main member field splices, but this is primarily due to practical reasons. From a technical standpoint, if the use of field welded connections is desired, there is not a technical reason why these should be avoided provided the welding activity is shielded from the elements and properly-qualified welders and inspectors are available. If groove welds are to be used in the field, shop assembly is usually necessary to assure proper field fit-up will be achieved so that the field welds can be made effectively.

b. Bolted Connections

In earlier days of fabrication, the most popular process for producing bolted connections was to make sub-size holes in the parts by punching or drilling (a.k.a., subdrilling), to assemble the parts using the sub-size holes for alignment, and then to ream the holes to full-size. Although not the only method, it is still sometimes used today. Any connection made using this process is made in assembly.

Making holes by reaming in assembly has the inefficiency of processing each hole twice. Thus, fabricators have adopted other means of making connections to improve efficiency over time. There are many, including the following:

- Use of a splice plate as a one-time template—i.e., predrill one splice plate full size, assemble the parts blank, and then carefully drill through the splice plate to make the holes in the other parts.
- Use of templates with hardened bushing to drill parts, either assembled or not. Bushings allow the templates to be used over and again without compromising the hole shape.
- Use of precise measuring technology: for example, drill holes in girders full size, then measure the holes and use the measurements to produce the splice plates.

Another means of making holes is to use computer-numerically controlled (CNC) equipment to drill them. Such equipment locates holes to 0.001-in. accuracy. It can be used to drill holes once, full size; it can also be used to produce sub-size holes, if desired, but the accuracy provided by CNC full-sized drilling obviates the need for sub-sized holes and subsequent reaming. Use of CNC equipment requires the writing of programs to drive the equipment.

c. Support Conditions and Orientation

Shop assembly is performed in the no-load condition. This can be in one of two orientations: with the girders horizontal (i.e., laying down with webs horizontal), or with the girders vertical, or standing up. Because girders themselves are built in the no-load condition, it should be readily apparent that girders are in the no-load condition if they are assembled in the horizontal position. When girders are assembled vertically, they are supported at multiple locations and at suitable frequency such that the no-load camber condition is replicated.

It is important to recognize that fabricators can only conduct shop assembly with steel supported in the no-load condition. If assembly is done with the girders horizontal, the reason is obvious: to reach another condition, such as the steel dead-load camber, very significant and associated reactions would be needed to move the steel to the steel dead-load camber orientation. This simply is not practical. If assembly is done with the girders vertical, reaching the steel dead load condition is also not practical. To do so, girder assemblies would only be supported at bearing points, with no other supports present. Consider, for example, a bridge with a 150-ft span and with a length of at least 150 ft, with only two supports present, one at each bearing. Such girders standing in a fabricator's yard would not be stable. Irrespective of the practicality and safety issues, there is no need to assemble girders in any condition other than no-load.

d. Types, Uses, and Needs of Shop Assembly

Whether or not shop assembly is needed and how much of the bridge needs to be in assembly depends on the nature of the bridge and the fabricator's means and methods. Common types of shop assembly and the associated amount of steel that is included are discussed below.

Line assembly. Also known as "lay down" and "progressive assembly", line assembly is the assembly of girders, end-to-end, for either (1) making the connections, and thereby also checking the connections, or (2) putting the girders together to check the connections, having drilled the holes full-size independently. As described in "Support Conditions and Orientation," line assembly is often done with the girders in the horizontal condition and hence are laying down. This is the origin of the term "lay down" but lay down has come to be a general term used both for line assembly in either orientation or for shop assembly in general.

For longer bridges, line assembly is done progressively. For example, if a bridge girder line has seven field pieces, or girders, then assembly might first include girders field pieces 1, 2, and 3, then 3, 4, and 5, then 5, 6, and 7. Hence, line assembly is sometimes called “progressive” assembly, when multiple groups like this are used (note that progressive assembly can also be used for other systems, such as field sections in cable stayed bridges). There is no particular number of girders that need to be included in a progressive assembly; the correct number for the fabricator depends upon the fabricator’s means and methods for assuring proper geometry. In some bridges, it is only possible to assemble two segments at time. Consider the assembly of two 150’ girders on a curved bridge in laydown. The point of interest, i.e., the actual connection, would be in the middle of the two girders, close to the floor, where it can be readily worked on as needed. This would put the other ends of the two girders high up in the shop; how would it be possible to add a third piece? Conversely, if the girder is not curved, or if the girders are assembled vertically, the fabricator could assemble the entire girder line if the fabricator has the space.

Unit Assembly. Also known as “full shop assembly” or “complete shop assembly,” unit assembly is the name given to an assembly that includes both girders and cross-frames—i.e., the entire unit. Such unit assemblies might include the entire bridge, for shorter and narrower bridges, or progressive units for longer bridges or very wide bridges.

Unit assembly is not very common and for most bridges is not necessary. Fabrication of cross members without is assembly most bridges have enough flexibility to accommodate normal shop tolerances. Consider the tolerances: +/- 1/8 in. per 10 ft for sweep (D1.5 2020 clause 5.5.4) and for camber, +3/4 in. at midspan for spans up to 100 ft long and +1½ in. at midspan for spans over 100 ft (D1.5 2020 clause 5.5.3). Using a simple example of a 120 ft long simple span bridge, at midspan, under D1.5 tolerances, one girder could be as much as 1½ in. higher than an adjacent girder and the same pair could be as much as 3 in. apart from their intended locations—i.e., the cross-frame built to tolerance would be 3 in. too long or 3 in. too short. This sounds like an extraordinary amount of play. In actuality, steel fabrication is such that girders are generally much closer to the actual desired dimensions than this example describes; in practice, girders are seldom built to the edge of tolerances. But the allowable envelope helps make the point: for most I-girder bridges, the inclusion of cross-frames in shop assembly is not necessary.

There are some exceptions, and these relate to the bridge constraints. Take, for example, a situation where the bridge includes a frame-through (integral) bent cap. At the bent cap, the orientation of the girders relative to each other is highly restrained by the bent cap. Therefore, at the first and perhaps second cross-frame away from the cap, the girders may not be flexible enough for cross-frames to fit at normal shop tolerances; if the fabricator thinks that this is the case, the fabricator may choose to include the first one or two cross-frames in the assembly with the girders and cap. Elevated intersections may represent another exception. Such structures often include short, stiff members that do not offer much play. In such situations, the fabricator may choose to include some or all the members in a unit assembly. There is no simple way to define the limits of what may be needed in a unit assembly, particularly since this depends both on the stiffness of the structure and the fabricator’s abilities, means, and equipment. Therefore, it is best to leave the need for unit assembly to the discretion of the fabricator.

Check Assembly. Also known as "one line" assembly, the check assembly process is used when the fabricator has the means to drill the holes in girder-to-girder connections accurately enough that there is no need to put all of the girders into shop assembly. Instead, a sample of the girders can be used in a check assembly. One practice is to put the girders from one of the girder lines into the check assembly. Then, if this group checks out, do not put others into assembly. Conversely, if a fit issue is indeed discovered in the check assembly, then it may be necessary to increase the number of girders in assembly. The key to reducing to a check assembly is the drilling of holes accurately enough such that only a check is needed. The AASHTO Construction Specifications allow such a reduction if CNC equipment is used to produce the holes. On complex projects, check assemblies provide the fabricator and contractor with the opportunity to discuss any specifics that will be needed in the field, such as pinning locations at each connection or the most effective assembly sequence in the field.

Summary

- The best practice is to allow the fabricator to decide how much shop assembly is needed, in conformance with the state DOT specifications or as otherwise approved.
- The most customary practice is to require line girder assembly and not unit assembly—i.e., do not require the cross-frames to be included in assembly. If unit assembly is indeed specified, recognize that this will add time and cost to the project.
- It is also customary for fabricators to use only a check assembly of only some girders instead of requiring all girders to go through line assembly if the fabricator can demonstrate the ability to achieve fit using CNC drilling, or some other method, such as drill templates or laser scanning.

2.12 Cleaning and Coating

Cleaning and coating are a part of fabrication, but they are addressed in this separate section based on how distinct they are from other operations. The choice made for the durability solution of the bridge has significant impact on the cost and schedule of the bridge. Modern durability solutions include the following options:

- Uncoated weathering steel
    - Completely uncoated
    - End-paint coated—i.e., parts of the steel superstructure that are under joints are painted (although modern practice is to avoid joints entirely)
    - Fascia paint
- Paint
    - Organic zinc primer systems
    - Inorganic zinc primer systems
- Galvanizing
- Metalizing

All these methods are common, and the choice is generally made with respect to the cost of the solution, the suitability of the solution, the service environment, and aesthetics. Since environments and conditions are not addressed in this guide, the discussion in this section is about the shop productivity of each coating irrespective of the solutions' performance. Costs vary over time as material and labor costs change over time. To help neutralize this effect, cost differences are presented as percent increases for delivered, fabricated steel.

All coatings discussed in this guide are zinc-based. Zinc is popular because it provides cathodic protection to steel: the zinc oxidizes before the steel does, thereby protecting the underlying steel. The coatings also provide barrier protection, keeping oxygen and oxidizing enhancing agents away from the steel. The zinc oxide that forms from the coating over time becomes part of this barrier.

a. Cleaning

Cleaning in preparation for shop coating application is done by blasting. The Association for Materials Protection and Performance (AMPP) publishes standards for cleaning structural steel, including blast cleaning, and each of these standards describes a different level of blast cleaning based primarily upon the shadows that may be present after blast cleaning and before coating. The most common AMPP standards used in bridges are as follows:

- SP 1 – Solvent cleaning: removal of all soluble substances from steel
- SP 6 – Commercial blast: all foreign matter and mill-scale removed, with 33% staining (or shadows)
- SP 10 – Near-white metal blast: all dust, coating, and mill scale removed, with maximum 5% staining

The staining in the SP 6 and SP 10 standards refers to how much shadows of rust may be present after blast cleaning. As rust is removed during blast cleaning, the color of steel gradually turns from brown/orange to white, and the time and effort needed to reach a completely white surface increases disproportionately as completely white is approached. After considerable study and practice, near-white has been established as satisfactory for providing long life with coatings, and SP 10 has become the standard recommended by most bridge coating manufacturers.

The level of blast cleaning can also be defined by the anchor pattern of the blasted surface. Blasting creates micro peaks and valleys of metal on the surface of the steel, and the sharpness and height of the peaks is known as the anchor pattern or blast profile of the blasted surface. The character of the blast cleaning can be defined by the resulting anchor pattern. The anchor pattern facilitates the adherence of the coating to the steel, and sometimes specific anchor patterns are specified with some coatings.

The cleaning of steel afforded by blasting before coating greatly improves the performance of coatings over time. This is particularly true in comparison with coatings from previous eras. It is not uncommon to see older bridges in service that were painted before blast cleaning became customary with significant coating failures; in such cases, the lack of original blast cleaning is likely a significant part of the reason the coating did not last longer.

Blast cleaning in a bridge shop is usually done in a blast cabinet. Most bridge girder shops have blast cabinets that girders can fit through. The cabinets have wheels inside them that pummel the steel with blast media, typically shot, which removes the surface layer of the steel and associated impurities and markings. Depending on the configuration of the girder, it can take one or two passes of the girder through the cabinet to properly clean it. Depending on the size and configuration of the girder and the associated number of passes needed through the cabinet, blast cleaning can take anywhere from an hour or two for small beams up to an entire shift for very large girders.

b. Weathering Steel

Use of uncoated weathering steel is certainly the fastest and most cost-effective durability solution to process in the shop. Superstructures built of weathering steel can be processed with no cleaning or coating whatsoever. However, an SP 1 is advisable if the steel is to look clean; otherwise, cutting and drilling fluid will be present on the steel for years to come. Further, if a uniform look is desired, such as on fascia surfaces, it is advisable to require cleaning to remove mill scale. If not removed, mill scale will give the steel a mottled look, which is generally undesirable. Mill scale has been known to remain present on bridges in service for decades. To achieve mill scale removal and achieve a pleasing, uniform finish, an SP 6 is sufficient and is recommended. After blast cleaning it will take some time for the steel to reach a uniform rust-colored appearance; this is usually a matter of days if the steel is rained on or weeks otherwise, where rusting is driven by humidity. It is not necessary to spray the steel with water to reach a uniform appearance. Spraying will speed the oxidation process; however, for some shops spraying steel is restricted by environmental regulations.

Sometimes uncoated weathering steel is painted in areas underneath joints; this is commonly referred to as "end painting." End painting increases the cost and time of fabrication in similar proportion, but not as much, as described below for painting. Notably, if end paints are used, going one step further and painting the fascia surfaces does not add significant additional cost and time because the steel is already being processed for end paints. Therefore, when end painting, it is reasonable to paint fascia surfaces to avoid the zebra aesthetic that results from end painting.

Although rusting on weathering steel begins in the shop, rusting continues in the field and therefore can stain concrete substructure. Where substructure is exposed, staining can be mitigated by wrapping the substructure during construction and using drip bars and drip pans. See further NSBA guidance for the use of these controls.

c. Painting

There are two general paint systems that are popular for painting bridges: organic-zinc primer (OZ) plus topcoats and inorganic zinc primer (IOZ) plus topcoats. The material and application cost of each is similar, but the time needed to apply the coatings can be very different. There are two fundamental options associated with painting: either apply the primer in the shop and then the topcoats in the field or apply all three coats in the shop with just splices top-coated in the field. Bridge fabricators have the in-house capability to paint although they might also subcontract painting out, particularly if they need additional painting capacity.

In the shop, the prime coat is applied as soon as possible after blasting so that the primer is applied before the steel begins to rust and shadows begin to appear. Fabricators prefer to begin painting as soon as possible after cleaning, and usually application of the prime coat begins within an hour or so following blast cleaning. When girders are kept indoors, a blast clean condition can reasonably be expected to hold for a day. As mentioned above, it can take as long as a shift to clean a very large girder; it can further take many hours to prime coat such girders. Thus, considering the cycle time of cleaning and painting and the fact that neither cleaning nor painting happen all at once, for very large girders, the time it takes from beginning to clean the girder to finish prime coating it can be the better part of an entire day.

The most common means of topping primer is the use of an epoxy intermediate coat followed by a urethane topcoat. In the case of OZ, the primer can cure when it has been coated, so if topcoats are to be applied in the shop, the epoxy intermediate coat can be applied as soon as the primer is dry. Conversely, IOZ requires moisture to cure, and so the epoxy intermediate coat, which seals the IOZ from moisture, cannot be applied until the IOZ has cured. The curing of IOZ can take one or several days, depending upon the availability of moisture, so if IOZ is used and topcoats are to be applied in the shop, waiting for curing of the primer increases the time it takes to paint the steel, sometimes significantly. Depending upon the volume of painting in the shop and space available in the paint shop, waiting can be a significant challenge. If a large number of girders are being primed with IOZ, the shop may run out of room holding them for curing and waiting to apply the epoxy coat. Then, the fabricator will have to stop painting or take the primed girders outside. Keeping primed girders outside does not compromise the coating provided care is taken but doing so adds time and cost for moving them. Fundamentally, if girders are to receive all three coats in the shop, use of IOZ greatly increasing the cleaning and painting cycle time compared to the use of OZ, and this can have a significant impact on the project schedule.

d. Galvanizing

Galvanizing is the process by which the steel is cleaned chemically in acid and flux baths and then dipped into a kettle of molten zinc. The temperature of the zinc in the kettle is 820 °F to 860 °F, which is well below the transition temperature of the steel, and so this heating has no deleterious effect on the steel. In the bath, iron diffuses from the steel to form three zinc-iron layers and a layer of pure of zinc on top. These layers of galvanizing protect the steel from corrosion. The effectiveness of the protection depends upon the thickness of the coating and the environments where the bridge is located, but generally galvanizing can be expected to perform for many decades without further maintenance.

Most bridge fabricators do not have in-house galvanizing capability; rather, this work is performed by a subcontractor. Thus, the cycle time for galvanizing, from the bridge fabricator's point of view, is highly dependent upon availability in the galvanizer's schedule. If work is to be galvanized, a schedule for galvanizing can be developed early in the project and then firmed up once actual fabrication begins. Thus, getting work to the galvanizer, coated, and returned to the fabricator or sent to the field usually takes a matter of weeks.

When galvanizing is considered, the size of the bridge members is an essential factor. Galvanizing kettles are large, but they are not large enough for most bridge plate girders. The American Galvanizers Association (AGA, www.galvanizeit.org) maintains published online information about the size of members that can be galvanized. The AGA also provides a wealth of other guidance, including important guidelines for designing bridges to facilitate galvanizing.

e. Metalizing

Metalizing, also known as thermal spray, refers to the operation of spraying molten zinc onto the steel where the zinc provides cathodic protection for the steel. The zinc can be sprayed on in layers about two to three mils thick; heavier applications would sag before the zinc solidifies. However, solidification only takes moments, so additional mils can be added fairly quickly to build the coating up. Metalizing has been used on steel structures for decades, but in the last decade it has gained more popularity for protecting steel bridges. A few bridge fabricators have in-house metalizing capability. Others send the steel to a subcontractor metalizing applicator or bring a subcontractor in to do the metalizing at their facility.

In metalizing, the zinc is sprayed onto blast-cleaned steel. However, metalizing requires a deeper anchor pattern in the blast profile than paint to achieve proper adhesion, and, therefore, blast cleaning takes much longer. Small to moderate sized girders will require a shift to clean; very large girders can take multiple shifts. As with paint, it is desirable to begin thermal spray soon after cleaning but beginning metalizing any time within a day after cleaning is fine providing girders are reasonably protected.

Because only thin layers of zinc can be sprayed at one time, metalizing is applied with spray guns that form a wide spray pattern; this pattern helps the layers apply uniformly and facilitates productivity. Consequently, metalizing is better suited to large surfaces than smaller surfaces. In the case of bridges, therefore, when considering metalizing, a good strategy is to metalize the girders and galvanize the cross-frames. The hot dipping of galvanizing is excellently suited to getting into and coating all the crevices found cross-frames—places where metalizing may not be able to reach as well. However, if cross-frames are also to be painted, metalizing cross frames may be better than galvanizing to facilitate the surface preparation for painting.

Summary

Regarding cleaning and coating:

- For the best speed and cost, use uncoated weathering steel.
- When painting and all coats are to be applied in the shop, use organic zinc primer system.
- When metalizing bridges, galvanize the cross-frames and other smaller members.

Regarding weathering steel:

- Require an SP 1 cleaning for all surfaces.
- Require an SP 6 for fascia surfaces to facilitate a uniform appearance.
- Do not require misting or wetting of the weathering steel.
- Consider the use end-painting if the deck has open joints.
    - Further, if end-painting, consider painting the outside fascia surfaces to match the end-paints.
- Use proper stain mitigation to avoid marring concrete substructure.

Regarding painting:

- If painting both primer and topcoats in the shop, use organic zinc primer as the prime coat to facilitate throughput.
- Follow the coating manufacturer's requirements for surface preparation; for zinc primers, this is usually an SSPC SP 10.

Regarding galvanizing:

- Use proper detailing to allow the molten zinc to flow through the members, following the recommendations of the AGA.
- If considering galvanizing for girders, ensure the girders will fit into galvanizer's kettle; follow the guidance of AGA size recommendations or check with a local galvanizer.

Regarding metalizing:

- When metalizing girder bridges, metalize the girders but hot-dip galvanize the cross members and other components that fit into the galvanizer's kettle.

2.13 Quality Control

Quality control activities are conducted concurrently with the fabrication steps described in sections 2.10 through 2.12. Quality control activities include a blend of informal, continual checking of the work; formal, documented inspections, such as measurement of the work for conformance with tolerances; formal non-destructive examination (NDE), performed in accordance with D1.5 requirements; and formal auditing or less formal general monitoring of fabrication activities to help ensure required fabrication practices are followed.

Quality is often thought of as being achieved through diligent examination by company inspectors, but in modern manufacturing, it is recognized that quality is best achieved from a top down organizational commitment to quality throughout the organization. Bridge fabricators develop and implement quality manuals that affirm this commitment and document their quality policies and practices. Further to facilitating quality, such manuals are required by AISC certification. These manuals are dynamic, being updated as needed as fabrication practices and bridge project complexities evolve. These manuals are also private and proprietary: fabricators may be willing to show their manuals to auditors, but copies are not shared publicly or otherwise released from the fabricator's control.

The fabricator's quality control department conducts or organizes many of the formal inspections, but formal inspections are also done by fabrication coworkers. The first checker of any fabrication activity is the coworker who performs the work: this is logical and effective because it is that coworker who is first responsible for quality. Shop coworkers do many informal activities, such as checking dimensions and layouts before fitting components; checking material preparations before welding or coating; checking preheats and weld joint tolerances before welding; checking weld pass sizes during welding; ensuring proper welding or coating consumables are being used; or ensuring proper, approved welding procedures are being followed.

Shop coworkers also conduct formal activities, such as checking and documenting dimensions for conformance with tolerances; these may also be done by shop quality control inspectors at the fabricator's option. Non-destructive examination (NDE) may be conducted by either shop coworkers or quality control inspectors provided the individual conducting the NDE is properly certified in accordance with D1.5 and associated American Society of Non-destructive Testing (ASNT) requirements. The same is true for coatings and visual weld inspection; these activities may be conducted by shop coworkers who are properly qualified or certified and the inspection is properly documented although in most cases fabrication quality control personnel do these inspections.

Regardless of who conducts discrete inspections, the fabricator's Quality Control (QC) department controls the fabricator's quality control manual. The QC department is usually the liaison with owner verification inspectors, owner auditors, and certification entities, such as AISC. The QC department may also control the development, control, and approval of shop welding procedures.

Summary

- Quality is the responsibility of every shop coworker in a bridge fabrication shop.
- To help ensure quality is achieved and to conform with AISC certification requirements, fabricators develop and maintain quality control manuals; these manuals are held controlled by the shop Quality Control (QC) department.

- Inspection activities include both informal checking activities and formal, documented inspection, both of which may be conducted by shop or Quality Control (QC) department personnel.
- Typically, the shop QC department is the liaison with owner inspectors and certification entities.

2.14 Shipping

Transporting steel bridge girders is an extraordinary type of shipping. Girders are commonly over 100 ft or even over 150 ft long; most girders weigh 20 to 30 tons, but large ones can weight 60 or 80 tons or even up to 100 tons. Thus, delivery of girders safely and on time takes extraordinary skill and equipment.

Most girders and other bridge parts are delivered by truck. Rail delivery is also a possibility but is usually not advantageous for shipping bridge members, particularly because most bridge girders are too long to fit on one rail car. Longer girders can be shipped by rail using a triple-set rail car arrangement but doing so gets particularly expensive. Further, most bridge projects are not located at or near the railroad, which means that if girders are shipped by rail to a location near the bridge, they must be loaded onto trucks for the balance of the trip. Thus, loading activities and equipment utilization are not saved. Finally, truck shipping provides the fabricator with more flexibility than rail. With truck shipping, girders can usually leave the shop in the morning any day of the week and be on the jobsite that same day, but with rail, the fabricator would need to work to the railroad's schedule. Hence, with the possible exception of projects comprised of many smaller parts going a long distance, such as over 1000 miles, use of rail for delivery of final bridge products is usually not advantageous. For bridges crossing navigable waterways, the contractor may seek opportunities to have select components delivered via barge. The necessity for and feasibility of this alternative should be evaluated carefully.

Fabricators prefer to ship girders vertically because doing so avoids the need of laying the girder over and the girders are easier to handle this way. Also, contractors prefer to receive girders in the vertical orientation for the same reasons. For curved bridges, sweep is a consideration; loads get wider as radii get smaller while lengths grow, but generally sweep is not a fundamental limiting shipping factor since field splices can be introduced to manage shipping widths. Rather, the primary limiting factor regarding whether a girder can be shipped vertically is that the girder will have to pass under bridges along the way. On each girder job, the fabricator will study the route to the jobsite, consider the height of the girder loads and the bridge clearances along the way, and determine if some or all of the girders can be shipped vertically. Thus, the suitability for shipping vertically depends on the route and the available equipment; a reasonable girder height limit for shipping vertically is about 10 to 10½ ft. Beyond this height, girders probably will be shipped laying down. There is no specific girder height limit in shipping with girders laying down; primarily, limits vary depending upon local site constraints. For example, delivery of wide loads to urban areas can be constricted if there is no space to make needed vehicle turns along the way. Recent decades have seen shipment of girders in heights of 12 ft, 14 ft, and 17 ft, but on any project where girders taller than 10 ft are considered, it is advisable to consult with local fabricators about the viability of using them based on shipping constraints.

Girder length is also a shipping constraint. However, because field splices can be readily added or moved to accommodate length constraints, girder length generally is not an issue. Shipping piece lengths of up to 150 ft or greater are common. As with height, shipping length can be limited by local site constraints. Allowing flexibility in field splice locations is the best means of addressing this.

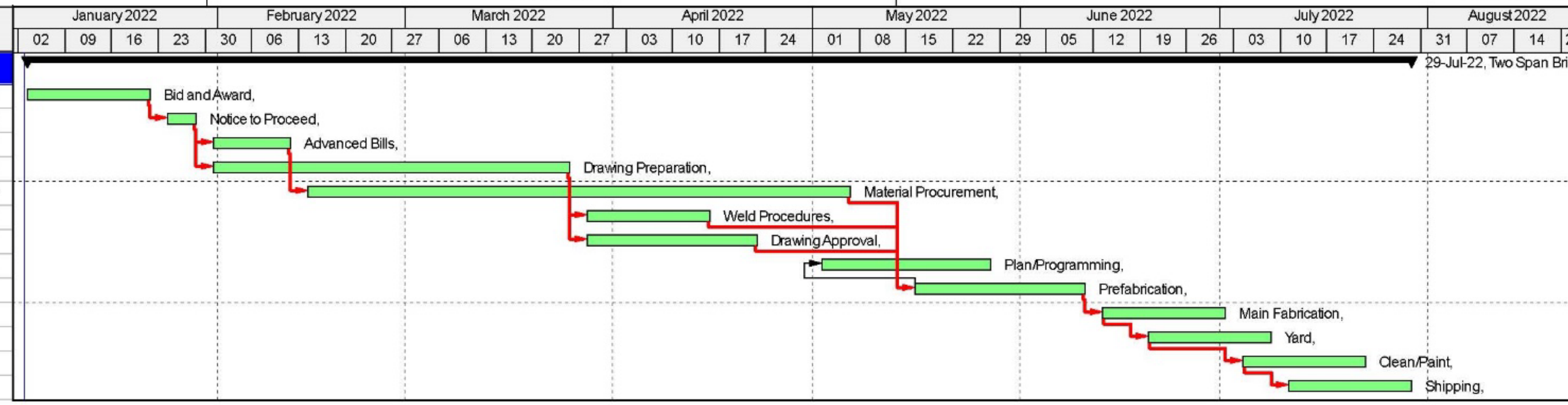
The prospect of large girders being permitted as superloads is another constraint with regards to shipping. A superload is a load that is so large that a police escort is required to ship it. There is no specific length, width, or weight that makes a load a superload, but the superload designations would probably not come into play on girders that can be shipped vertically. The key constraint associated with superloads is that some states limit the number of superload permits they issue, such as perhaps only three or four per week. Thus, if a bridge has a large number of superloads, the delivery and associated erection of the girders will have to consider this.

Summary

- When considering the use of girders above 10 ft tall, consult with local fabricators to ensure the girders can reach the site effectively.
- Be flexible about allowing field splices to move or be added to accommodate shipping lengths and sharply curved girders.
- Avoid superloads if possible.

Two Span Bridge — Gantt View — 06-Dec-21 15:31

Activity Name	Original Duration	Start	Finish
Two Span Bridge	150	03-Jan-22	29-Jul-22
Bid and Award	15	03-Jan-22	21-Jan-22*
Notice to Proceed	5	24-Jan-22	28-Jan-22*
Advanced Bills	10	31-Jan-22	11-Feb-22*
Drawing Preparation	40	31-Jan-22	25-Mar-22*
Material Procurement	60	14-Feb-22	06-May-22*
Weld Procedures	15	28-Mar-22	15-Apr-22*
Drawing Approval	20	28-Mar-22	22-Apr-22*
Plan/Programming	20	02-May-22	27-May-22
Prefabrication	20	16-May-22*	10-Jun-22
Main Fabrication	15	13-Jun-22	01-Jul-22*
Yard	15	20-Jun-22	08-Jul-22*
Clean/Paint	15	04-Jul-22	22-Jul-22*
Shipping	15	11-Jul-22	29-Jul-22*



Actual Work — Critical Remaining Work — Summary — Remaining Work — Milestone

Page 1 of 1

TASK filter: All Activities

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Figure 1: Typical Project Fabrication Schedule.

3.0 BEST PRACTICES ON BEHALF OF THE OWNER

This section describes the best practices on behalf of the owner for executing steel bridge projects. This narrative treats the engineer as an entity distinct from the owner, as though the engineer responsible for the design is a consultant, although it may be that the owner and engineer are one and the same if the design is done in-house by the owner.

3.1 Overview

The owner's responsibilities for achieving an effective steel bridge project include the following:

- Choose an engineer with the knowledge and skill to produce an economical, constructable, and safe design.
- Ensure the engineer's contract has the scope to include all needed services, including both upfront design services, services during fabrication and services during construction.
- Establish the basis of design and associated design criteria.
- In cooperation with the other project parties, establish effective communication workflows.
- Establish effective inspection practices for fabrication that are based on quality verification.
- Establish effective inspection practices for erection to include defining the responsible parties for performing quality control and quality assurance.
- Resolve changes or disputes within contractually allowed timeframes.

Note that regarding bullets five, fabrication inspection practices, and six, erection inspection practices, the owner may take care of these directly or have the retained engineer do so, depending on the owner's resources and preferences.

3.2 Choosing an Engineer

Selection of the engineer plays a critical role in determining the overall success of the project. The engineering design services should be chosen on a qualifications-based selection process. The qualifications in this case relate specifically to the designer's overall familiarity with providing the full complement of engineering services required for project completion, and these services are much broader than the bridge design component. This guide only addresses the skills of the consultant as they pertain to steel superstructure, including assisting the owner in their selection of an appropriate bridge type, the execution of a constructable steel bridge design, and support of steel bridge fabrication and erection for items like RFI responses and procedure and drawings reviews. However, the engineer also needs to be competent to perform these similar design and construction support services as they pertain to the substructure and foundations of the bridge.

There are two basic aspects of bridge design in the engineer's scope. First, the engineer has a fundamental obligation to ensure that the bridge will be safe. This is not only the expectation of the owner and the community; it is also the legal responsibility of the engineer under the engineer's professional engineering license. To ensure public safety, the engineer accomplishes the design in accordance with applicable bridge design codes that define limit states for the bridge properties, such as strength, stiffness, and fatigue. Second, the engineer has a responsibility to the owner to provide a design that is constructable. "Constructability" in design means designs that are cost-effective and offer the best schedule opportunity. For an engineer to accomplish a constructable design, the engineer must be familiar with bridge fabrication and erection practices and must use constructability guidance available from the steel bridge industry. Details about how to accomplish a constructable design are presented in section 4.1a of the Engineer section of this guide. The key for the owner is to choose an engineer who, in addition to the characteristics expected of any designer, has the skills and experience for accomplishing a design that is structurally sound while also being cost-effective and who is committed to achieving good constructability, particularly regarding following industry standards related to constructability.

3.3 The Engineer's Scope

To achieve an effective project, the owner must provide procurement of services documents to the engineer that anticipate the complete range of services needed during design and construction. Otherwise, the engineer may not have the appropriate skills and resources required or the contractual obligation and fees required to address all these services.

Although the engineer's activities are primarily concentrated in the design phase, they may not be exclusive to it. Rather, the designer may have roles that extend to completion of construction. This varies by owner. Although designers will always answer RFIs regarding design issues, DOTs often have materials engineers handle RFIs related to fabrication practices and materials concerns. Other owners will expect the retained engineer to provide these services. If so, the solicitation for services—i.e., a request for qualifications (RFQ) or request for proposals (RFP)—must provide for the continuum of services needed to support the owner through completion of the bridge and needs to include the following:

- Preliminary and Final Design and Specification Services
    - This requirement includes selecting an appropriate structure type and providing the plans needed for soliciting the contractor's bid. The choices made by the engineer and approved by the owner during preliminary design are the key drivers to project cost and success. Therefore, regarding aspects of steel bridge design, selecting an engineer who understands factors like bridge type selection, industry economics, and the capabilities and preferences of local contractors is a crucial step and as important as selecting an engineer with an impressive design resume.
- Post-Design Services
    - Assistance in selection of the responsible bidder. At the discretion of the owner, the engineer can help with this process.
    - Fabrication support services. During fabrication, support is needed for the tasks listed below. The engineer's contract should provide for these services unless the owner has the resources for handling some of them. Even if the owner has such resources, the engineer will be needed for questions that relate directly regarding the intent of the designer.
        - RFI responses during shop drawing development and fabrication. In particular, during the early stage of shop drawing development, the

fabricator will need support for geometry corrections such that materials can be ordered. Then, support will continue as needed through the shop drawing preparation and approval process.

        - Shop drawing review and approval.
        - Welding procedure review and approval, as well as approval of any other procedures that may be required.
        - Once fabrication begins, RFI responses and repair procedure review and approval.
    - Construction phase services.
        - Similar to during fabrication, there are often questions that arise during construction, whether simply to verify certain elements of the designer's intent or adjustments that may be needed due to changes in conditions, conflicts that arise during construction etc. These questions should be addressed through the RFI process. Although these are common and easily resolved, they are also time sensitive and having the engineer under contract and available to respond is essential to the continued progress of the constructed work.
        - Review of temporary works design submittals, especially for temporary works carrying public traffic or crossing over public traffic.
        - Construction inspection, including both on-site inspection of the structure and material testing (concrete strength tests, etc.) and other related services.
    - Project closeout. At the end of construction, the construction inspector commonly has a final role of memorializing via an as-built plan set any changes that occurred during fabrication and construction. This set documents the changes and supplements or supersedes the original bid-phase plan set.

Summary

- Procure engineering services using a qualifications-based selection process.
- Among the qualifications, ensure that the engineer has the proper experience needed with steel bridge design and construction such that the design will be constructable and the engineer can effectively support fabrication.
- Ensure that the engineer's contract includes all of the scope that will be needed, including the following (note that these items are not unique to steel bridges):
    - Preparation of the project plans and specifications.
    - Response to RFIs during bidding and throughout construction, including answering design RFIs during shop drawing preparation and procedure and repair RFIs during fabrication, and erection.
    - Shop drawing review and approval.
    - Reviews of field change requests.
    - Construction inspection.
    - Preparation of as-built drawings upon completion of the work.

3.4 Communications

Good communications are essential for achieving an effective steel bridge project. Once the project goes to contract, important information must be exchanged to support many fabrication steps, including support for shop drawing review and approval, welding and repair procedure approval, and fabrication RFIs. For the most part, the exchange of information for these needs is between the fabricator and the engineer; however, there is not always a direct communication channel between these parties, which can delay the response time.

Formally, communications like RFIs and procedure submittals flow from the fabricator through the general contractor (GC) and then the owner to the engineer. However, there are several approaches for establishing expeditious lines of communication that protect everyone's interest and provide answers and approvals as quickly as possible. These are described in the contractor section of this guide, and, as described there, it is primarily the GC's responsibility to establish these communication channels. However, the owner also plays an important role. The owner should cooperate with the GC's communication plans and also establish the expectation with the engineer that the engineer cooperates. As discussed in the Contractor section, project communications such as RFIs, RFI responses, shop drawing review and approval, construction inspection reports, and material testing reports should be documented using a robust documentation system. This helps avoid miscommunications and is invaluable in the case of disputes or disagreements, protecting all parties.

Summarizing, the owner should help facilitate the most effective communication possible, particularly in allowing the GC to establish open and expeditious lines of communication, with the owner being kept in the loop as needed or desired by the owner.

3.5 Quality Verification

Most owners perform inspection onsite at the fabricator's facility. The inspector may work for owner directly or be retained, either as a third party contracted by the owner or as part of the engineer's scope. The inspector ensures that the fabricated steel is in conformance with the project specifications to facilitate acceptance of and payment for the steel. This section describes the best practices of the owner's inspector for ensuring specification conformance.

Conformance with specifications reflects the quality of fabrication. Quality is achieved by the workers in the shop and not by inspection. The owner's inspector cannot control the shop workers and must not direct or otherwise interfere with their work. The owner's inspector can check that the work meets the requirements of the contract documents, but it is not possible for the owner's inspector to check all aspects of it. Therefore, the owner inspector's role is neither about the inspector controlling production nor about the owner's inspector checking everything to see that it is correct. Rather, the owner's role is about verification of quality.

Quality is achieved when the fabricator performs work correctly. To do so, the fabricator adopts practices that keep fabrication under control. Some practices are based on the fabricator's knowledge; for example, the fabricator will choose the best sequence of fitting, tacking, and welding girder webs and flanges together such that, given the distortion that results from welding and the effect of gravity on the steel during building, the girder camber and sweep will be within tolerance. Other practices are prescribed by project specifications; for example, minimum preheat and interpass temperatures for welding are prescribed by the AASHTO/AWS D1.5 Bridge Welding Code and these temperature limits help assure weld quality. The fabricator also has administrative practices in place for control, such as practices for ensuring the correct material is used for various components of the bridge and practices for effectively tracking heat numbers for main member materials. Among the shop floor activities of cutting, fitting, welding, heating, drilling, cleaning, coating, testing, and inspecting—and including administrative activities—fabricators have hundreds of practices in place for quality control.

The fabricator's quality control practices include both high-level, documented practices and lower level, less formal practices that are known by shop coworkers. Fabricators gather the higher-level practices into a published collection that becomes the fabricator's quality control manual. In earlier days, only some fabricators had such a manual, but under the American Institute of Steel Construction (AISC) quality certification program, a quality control manual is required, and therefore they are nearly ubiquitous in the U.S. bridge fabrication community. The certification program also requires that the fabricator have a commitment to quality, including a quality statement; quality goals; and a robust means of documenting and addressing errors. Therefore, requiring that the fabricator be AISC certified is a good step for helping ensure quality in bridge fabrication. Fabricators in the United States who already produce steel bridges already have this certification. For new fabricators or fabricators new to bridges, getting this certification is the first step. Having the certification does not mean that the fabricator will not make mistakes. Rather, it means that the fabricator has adopted the basic systems and controls needed to facilitate the achievement of quality in bridge fabrication.

From the owner's standpoint, then, the best means of ensuring quality is to ensure that the fabricator has quality control practices in place and that the fabricator is following them, and the best first step to doing this is to require that the fabricator is certified for bridge fabrication by AISC. With this in place, the owner's inspector can adopt a role of verification: the most effective use of the owner's inspectors time is for the inspector to verify that the fabricator is adhering to the shop practices it has adopted to keep fabrication in control as defined by the fabricator's quality control manual.

In fabrication parlance, the work of owner's inspectors has come to be known as quality assurance, or QA, and the owners' inspectors are known as QA inspectors. However, QA is a misnomer because in manufacturing philosophy, including under the International Organization for Standardization (ISO), quality assurance actually refers to the practices that manufacturers adopt to achieve quality. There is a movement in the bridge fabrication community to correct the name of the activities performed by the owner's inspectors to quality verification, or QV. Both QV and

QA are used, but QA is still much more common. Regardless, the inspector's activities should be that of verification. If the owner requires practices of the shop inspector beyond verification, the owner's solicitation to prospective bidders should include them.

To be effective, the quality verification inspectors should have strong knowledge of fabrication based on experience. Verification includes observation of fabrication and quality control practices, and it may include some spot checking of the work. The most subjective means of ensuring the inspector has proper knowledge is to require certifications, and two are key: certified welding inspector (CWI), administered by the American Welding Society (AWS) for welding, general fabrication knowledge, and certification from the Association for Materials Protection and Performance (AMPP) for coatings. Inspectors with these credentials can be contracted; considering that fabricators also have certified inspectors, another option sometimes used by local owners is to have fabricators conduct verification inspection themselves, also known as "self-inspection."

Finally, for an effective project, it is important for the QV inspector to approach the inspection with an unbiased position and be cooperative with the fabricator, just as it is important for the fabricator to be cooperative with the inspector. Here are some key elements of such cooperation:

- Communication – The fabricator should identify specific individuals that the QV inspector should go to with questions or issues. This will be the fabricator's QC manager or a designated QC inspector.
- Timeliness – If there are discrete inspection activities that the owner wants the inspector to perform, then the inspector should be ready to perform them as soon as the work is ready so the fabrication can proceed effectively. Conversely, the fabricator should provide the inspector with an effective schedule.
- Escalation – It is prudent to establish an escalation practice for handling disputes. There may be times when the QV inspector and the QC inspector do not agree on the condition of the work or a requirement. Therefore, it is prudent to discuss in advance of fabrication to whom such issues will be taken for resolution, probably including going to the QV inspector's manager and, if needed, eventually to the engineer.

Summary

- Recognize the quality is achieved by correct performance of work on the shop floor and not by "inspecting in" quality.
- Require that the fabricator has AISC bridge certification.
- Have inspectors adopt a role of verification, with focus on verifying that the fabricator is following their established practices and effectively controlling the fabrication for achieving quality.
- Expect inspectors to be objective and cooperative, including respecting the fabricator's schedule, communication with the appropriate fabricator representatives, and establishing an escalation practice for resolution of disputes.

4.0 BEST PRACTICES ON BEHALF OF THE DESIGNER

On a steel bridge project, the engineer's role may be divided into two parts: bridge design, generally pre-bid, involving the various activities of providing the drawings and specifications, and construction support for the fabricator and erector, after bidding, including responses to RFIs; review and approval of shop drawings, welding procedures, and repair procedures; and support of field activities. This document addresses all roles as those of the "engineer" although it may not be the same engineer who handles all roles.

4.1 Bridge Design

Aspects of bridge design that relate to a bridge being effective include the following:

- Constructability: achieving a design that best facilitates efficient work in fabrication and construction based on material and design detail choices; and
- Correctness: distinct from design errors, correctness refers to aspects of design that satisfy code requirements but may be a geometric mistake or may not represent executable practice.

Each of these aspects of design, if not well executed or effectively remedied early in the project, can delay schedules, and also add costs.

a. Constructability

Achieving constructability in design is different from achieving code conformance in design. It is one matter to create a design that satisfies design code requirements, which is crucial for the suitable performance of the bridge; it is another to create a design that both satisfies the code and also facilitates the best use of materials, equipment, and practices in fabrication and construction, which is crucial for achieving a cost-effective bridge on a good schedule.

Many complications in the fabrication and construction process are linked to decisions made by the engineer during preliminary and final design. The complications are rarely matters of "adherence to the code" but rather reflect choices the designers make about materials such as type and grade, and the various details included in the design plans. For example, designing to the code will result in the need for a certain minimum size flange cross-section to carry design loads, but once the minimum cross-section is established, there are still important design choices to make. Should the designer use thick, narrow flanges? Or wide, thin ones? Since the load demand varies along the length of the girder, should the designer keep the flange size the same along the length? Or vary the thickness by introducing welded butt splices? And if introducing splices, should the designer change the flange thickness, or the flange width, or both? All these approaches are valid from the standpoint of satisfying the design code, recognizing that flanges are cut from wide slabs, minimizing thickness changes and aligning thickness transitions clearly results in the most constructable solution (see discussion in section 5.1, of the AASHTO/NSBA Steel Bridge Collaboration Guideline, G12.1, Guidelines to Design for Constructability and Fabrication).

Also indirectly related to constructability is the question, "What is the best way to represent information in the design drawings?" It is important that the fabricator and the contractor understand the design, and therefore it is important to use standard industry practices for showing the design on the drawings.

The success of a steel bridge project begins with the fundamental constructability decisions a bridge designer makes at the project outset. These include important items such as:

- Span arrangement and erection sequence – single span; multiple span; length of various spans; simple or continuous spans, and the suitability of the span arrangement for erection.
- Girder type – I-shape or box shape; if I-shape, then use of rolled beams or welded plate girders.
- Girder spacing – narrow versus wide spacing; effect of girder spacing on girder weight and depth; and effect of spacing on deck construction.
- Materials – grade selection; homogeneous or hybrid material choices; ready availability of chosen plate sizes and rolled shape sizes.
- Bracing – cross-frame versus plate or shape diaphragms; consideration of lateral bracing.
- Details – intermediate stiffener, bearing stiffener, and connection plate details; field splice locations.
- Fit – what is the designated fit condition of the bridge and is this fit condition suitable or necessary for erection.
- Joints and bearings – details at expansion joints, particularly considering durability; bearings to support the loads and provide for movement.
- Corrosion protection – use of weathering steel or coated steel, and if coated, then paint, galvanizing, or metalizing.
- Erection and erection sequence – particularly for complex bridges, whether the bridge requires a specific sequence of erection.

For each one of these items there are many possible solutions that comply with the design specifications and owner requirements. This is the fundamental constructability challenge: how to develop a code-compliant design that is also practical and cost-effective and can facilitate the best possible schedule.

To aid in the selection of practical and cost-effective details, it is important that designers are aware of current industry practices and understand where to find design assistance. Since 1997, the National Steel Bridge Alliance (NSBA) has partnered with AASHTO to jointly develop and publish the best practices in design, fabrication, and erection of steel bridges. This partnership, known as the AASHTO/NSBA Collaboration (www.steelbridges.org), publishes a series of guidelines and specifications used throughout the steel bridge industry to promote constructability in steel bridges. Each contains important information for designers, owners, fabricators, and contractors. In the design phase, the following documents are of particular assistance to the designer:

- G1.2 Design Drawings Presentation Guidelines – G1.2 assists engineers in the development of design drawings. An important aspect of a constructable design is presentation of the design in a way that is easily understood, and the use of standard practices is the best means of doing so. G1.2 provides guidance on the minimum design information required to detail and fabricate a structure. It includes sample drawings illustrating the needed information.

- G1.4 Guidelines for Design Details – G1.4 provides sample design details that allow for the economical fabrication and erection of bolted splices, cross-frames, stiffeners, and connection plates. Included in this guideline are economical solutions for rolled beams, plate girders, and tub girders.
- G9.1 Steel Bridge Bearing Design and Detailing Guidelines – G9.1 presents steel bridge bearing details that are cost-effective, functional, and durable. The document covers the design and detailing of elastomeric bearings; high-load multi-rotational bearings; and steel bearings.
- G12.1 Guidelines to Design for Constructability and Fabrication – G12.1 is intended for use throughout the design and fabrication process to ensure efficient and economical girder bridge design and construction. It complements the AASHTO LRFD Bridge Design and Construction Specifications with guidance and best practices that can lead to highway bridges that are more economical to fabricate, construct and maintain. The latest edition features numerous updates that reflect advancements within the industry along with changes to related specifications.
- G13.1 Guidelines for Steel Girder Bridge Analysis – G13.1 provides a comprehensive treatment of issues in steel girder analysis. Included in the document is guidance pertaining to the appropriate level of analysis based on geometric complexity.

All of these guidelines are available for free from the NSBA website.

In addition to the various Guidelines briefly introduced above, the NSBA maintains a variety of other design resources that collectively aid in promoting efficient and cost-effective, fabrication and construction-friendly designs. Among these resources are:

- Steel Span-to-Weight Curves – These curves are a simple way to determine the weight of steel in various simple- and continuous-span bridges for a wide variety of girder spacings and span lengths. These are an important tool in determining programming-level project costs and as a sanity check of final design.
- Continuous Span Standards – These standards serve as a guide for the development of cost-effective bridge cross-sections and span arrangements for three-span continuous plate girder bridges. Standardized solutions for center spans ranging from 150 ft to 300 ft, girder spacings between 7 ft, 6 in. and 12 ft, and plate girder designs using both homogenous and hybrid steel options, are provided. Additionally, with the complimentary download are input files for each standard design for use in the LRFD SIMON program (see below) so an engineer can adjust the standard designs to suit project-specific conditions.
- LRFD Simon – LRFD Simon is a line-girder software program that has the capability to design straight and low-skew plate girder and tub girder bridges. The program is user-friendly and can be used to quickly study various beam types and bridge configurations, including cost comparisons, during the preliminary design phase. LRFD Simon is available for free from the NSBA website.

- NSBA Splice – In final design, design of bolted field splices is a source of cost and complexity that benefits from this NSBA standard tool automating the design of practical and cost-effective splices. NSBA Splice is available for free from the NSBA website.
- Steel Bridge Design Handbook – A 19-volume set with an additional six design examples, the Steel Bridge Design Handbook covers most aspects of steel bridge design, fabrication, and construction from the basics of steel as a material and bridge design topics. Each of these volumes reinforces the concepts of design efficiency and demonstrates the proper application of the AASHTO LRFD Bridge Design Specifications. The Steel Bridge Design Handbook is available for free from the NSBA website at www.aisc.org/bridgehandbook.
- NSBA Guide to Navigating Routine Steel Bridge Design – This guide helps designers readily use the AASHTO LRFD Bridge Design Specifications for typical bridges. The Specifications cover a broad variety of steel bridge types and complex geometries, but most bridges are straightforward and do not require use of the Specifications' specialized provisions. This Guide helps designers sift through the Specifications and focus on the provision that apply to typical bridges.

In addition to the previously mentioned resources, dozens of other important resources are available for designers at the NSBA design and estimation resources website, https://www.aisc.org/nsba/design-and-estimation-resources/.

b. Code Compliance, Correctness, Suitability, Practicality

A design may satisfy code requirements but may still not be correct, practical, or suitable in the sense that it cannot be built effectively. For example, a design may specify a shape that is not readily available in the market, and although the shape, by its dimensions, would properly carry loads, the use of the shape in a design is not appropriate because if the shape cannot be procured, either because it is not actually produced, is rarely produced, or is not available domestically, the design cannot be executed.

Dimensional errors are a common source of lack of correctness in designs. Many plans have at least a few inconsistencies which affect the detailing and fabrication of the structural steel. Some projects have few issues, typically inadvertent errors, and are easy to resolve. Other projects have more significant issues that are more difficult to resolve; in extreme cases, especially if the resolution process is not clear and efficient, clarifying the issues can hold up a project for weeks or even months. In all cases, issues require a formal request for clarification and associated formal response, potentially impacting the project schedule. Common dimensional errors include the following:

- Incorrect elevations (most common), including:
  - Pedestal or bearing pad elevations
  - Bearing elevations
  - Bottom of slab elevations
- Concrete haunch issues, such as:
  - Variable haunch depth creating girder sag in elevation
  - Variable haunch depth with no provision on how to calculate the haunch
  - No haunch depth given

- Camber issues:
    - Distorted girder shown in the output, indicating a camber error
    - Incorrect camber because cross slope effects were ignored
    - Incorrect vertical curve
    - Straight girder on curved PGL shown in the output, creating girder sag
    - Design provides a fully cambered "as fabricated" camber diagram with no means to check it
    - Proper dead load deflections required to calculate steel fit conditions not shown

As the first step in the detailing process, detailers work through the bridge geometry to develop the specific bridge dimensions needed to fabricate the bridge. It is during this step that these geometric errors come to light. Modern detailers use sophisticated computer programs that compile the bridge geometry and provide the coordinates and other geometric output needed to produce shop drawings. These programs are particularly robust with regard to establishing and checking geometry and therefore discover these errors. In fabrication, such dimensional errors cannot be tolerated and must be corrected. If the geometric information in the design plan has errors, such as in the examples reflected above, the shop drawings cannot be completed, and the steel bridge cannot be fabricated. Hence, RFIs are common at this stage of the project. The process of correcting geometry by RFI adds time to the project; a large number of geometric errors combined with slow responses to RFIs can lead to significant project delays.

Further to dimensional issues, there are other areas in design that affect project correctness:

- Poor or misleading drafting such as details that are out of scale and really don't work as shown.
- Conflicts between web or flange butt welds and framing elements.
- Lack of coordination between trades like bearings and utilities.
- Details that cannot be fabricated, or details that cannot be erected.
- Issues related to construction staging and field erection.
- Incorrect or misused weld designations.
- Misuse of nonredundant steel tension member designations (formerly referred to as fracture critical members).
- Inadequate means of access for in-service inspection.
- Designs attempting to detail internal components of cross-frames and diaphragms, providing gusset plate sizes, edge distances, clips, and copes, without consideration of the variables associated with internal geometry or for hole spacing and edge distance requirements prescribed by AASHTO.

c. Special Specifications for Fabrication

State DOTs have standard specifications for fabrication, and toll authorities and local owners within the state usually adopt these standard specifications. These standard specifications are generally suitable for typical bridges, such as I-girder and wide flange beam bridges, under usual situations. Conversely, for other types of bridges or highly complex structures, normal fabrication tolerances may not be suitable. For example, tolerances from D1.5 for I-girder sweep are intended to provide enough lateral control to facilitate installation of cross frames in the field using typical construction methods. For most I-girder bridges they do, but if the I-girder bridge is on a very tight radius, the curvature of the girders will stiffen the girders such that the D1.5 tolerances will be insufficient. Similarly, sweep tolerances may or may not be suitable for members of other types of bridges, depending upon the framing situation and flexibility of the bridge.

For atypical bridges, the designer should consider whether special tolerances will be needed for fabrication, and if so, provide a special specification that addresses them. Depending on the bridge type and the history of fabrication of the bridge type, there may be knowledge in the community about suitable tolerances which the designer can get from industry experts or fabricators. If not, the designer should work with the fabricator as fabrication progresses to discover and apply suitable tolerances.

Summary

- Strive for a design that is constructable, such as:
  - A design that makes the best use of materials based on actual availability and minimizes size variations and not just necessarily least weight; and
  - A design that facilitates the best practices in the shop based on common fabricator equipment and capabilities.
- Use the design support resources of the AASHTO/NSBA Steel Bridge Collaboration and the NSBA.
- Strive for designer correctness, particularly considering and avoiding the most common pitfalls (described above).
- Solicit constructability feedback from fabricators, detailers, and erectors, particularly during the preliminary design phase.

4.2 Construction Support

Once the project has been let and awarded, the engineer plays an important role in supporting the fabricator and contractor to help achieve an effective schedule.

a. Responses to RFIs

As described in the fabrication stage of this document, development of shop drawings proceeds in earnest once a fabricator has been selected and must proceed efficiently to allow for material ordering and delivery of drawings to the shop to support the fabrication schedule. As discussed in section 4.1b, design inconsistencies do occur, and these issues must be resolved to keep the project moving. The issues come to light during shop drawing preparation, particularly while the detailer is working through the bridge geometry. The best way to avoid significant schedule impacts due to inconsistencies is to avoid the issues in the first place, but when they do occur, it is imperative that RFIs be answered expeditiously. The best practice is to respond within a day or as quickly as possible. If developing the response will take longer (such as occurs for complicated issues), then at least provide an indication of an anticipated response time. Note that the maximum review time is sometimes dictated by Owner Standard Specifications. Further, responses can be expedited by keeping communication channels as direct and open as possible.

b. Shop drawing review and approval

In the United States it is customary that design engineers review and approve or accept the fabricator's shop drawings. Used effectively, the process is a productive way of helping ensure that the bridge produced by the fabricator is consistent with the engineer's design intent. However, if not used effectively, the process can result in a significant amount of effort that is not necessary and can lead to significant project delays. The best practices in steel bridge fabrication shop drawing review and approval are found in G1.1, Shop Detail Drawing Review/Approval Guidelines for Fabricated Structural Steel, published by the AASHTO/NSBA Steel Bridge Collaboration.

Most bridge owners require that shop drawings be approved before fabrication begins. Further, even if the fabricator is permitted to begin fabrication without approval, fabricators prefer to avoid this because owners stipulate that such work is done at the fabricator's risk, with the fabricator bearing responsibility for any rework associated with drawing changes that result from the review Therefore, expeditious return of shop drawings is crucial for the project schedule.

A key aspect of shop drawing review and approval is understanding the level of responsibility assumed by the engineer when approving drawings. The bottom line is that despite the review and approval, the engineer is not responsible for the correctness of the shop drawings. Taking responsibility for the fabricator's work is inappropriate. The engineer is not doing the work of creating the drawings and the engineer cannot influence how the drawings are used. NSBA G1.1 emphasizes the fabricator's responsibility in section 2.1.

Further supporting the level of responsibility, recognize that the engineer does not have all the information needed to fully check every dimension in the shop drawings. Just as the engineer does not provide design calculations on design drawings, geometric calculations used to produce fabrication dimensions are not in the shop drawings. As an example, consider girder web geometry. In the framing plan, design drawings show girder webs in their final condition, under all dead loads. Elsewhere, design drawings provide camber associated with different dead load conditions. Shop drawings provide information telling the shop how to cut the web, and the dimensions shown on the shop drawings reflect a geometry that considers design camber plus manufacturing assumptions as well as tolerances. The detailer calculates the web cutting geometry in software and does not provide the calculations to the engineer. Therefore, it is not possible for the engineer to check or be responsible for the fabricator's work in establishing the web cutting geometry. Rather than taking responsibility for the shop drawings, the engineer's review is only to ensure that the fabricator has "correctly interpreted the intent of the contract drawings and that the details properly reflect the material and connection requirements" as defined in section 2.1.1 of standard G1.1. G1.1 also provides guidance on shop handling the review and a checklist of what should be checked. Following G1.1 is the best means of conducting shop drawing reviews.

Concerns about responsibility in checking shop drawings have prompted some owners to change their vocabulary from "approved" to "accepted," "conforms with contract plans," "reviewed," or other similar terminology. From the perspective of fabricators, any of these terms is suitable; the verbiage makes no difference provided it is understood that the terms used communicate that the review is complete, with no further review and changes, and no concern on the part of the owner that the fabricator may proceed with work.

For expediency, when there are mark-ups on drawings, engineers should use "approved-as-noted" when reasonable and avoid rejecting the drawings outright. Certainly, if an item of significance is wrong and cannot be clearly communicated with a correction, then "revise and resubmit" is appropriate. But if a discrepancy is found that can be resolved by simply writing the correct number, symbol, or word on the drawing, then approved-as-noted is much more prudent. In such cases, the reviewer should clarify whether a revision and resubmittal of the drawings to reflect the "as-noted" items will be required of the fabricator. Further, if "revise and resubmit" is needed on one drawing or a few drawings, then only require resubmittal of these drawings and not the whole job.

Section 2.3 of G1.1 speaks to the need for team effort among the owner, engineer, fabricator, and contractor in the shop drawing review process, and 2.3.1 emphasizes the need for good communication. As an example, an excellent practice in review is for the engineer to contact the fabricator if the engineer has questions or does not understand something in the drawings.

c. Welding Procedures

Most owners require the fabricator to follow AASHTO/AWS D1.5 for welding, and D1.5 requires that all welding be performed with an approved welding procedure. Given these requirements is it essential that the engineer recognize that because of these rules, fabrication cannot begin until approved welding procedures are in place. Therefore, as with shop drawings, it is important to be expedient when reviewing and approving welding procedures. Details about welding procedures and best practices are addressed in section 2.8 of the fabrication chapter of this guide.

d. Repair Procedures

Repair procedures are a normal part of fabrication. Details about repairs and procedures for handling them are found in section 2.10b of the fabrication chapter of this guide.

e. Field Construction Support

As with fabricators, design issues arise for general contractors that need to be addressed with RFIs, usually for clarification of a design detail or specification requirements. Occasionally, issues are greater in scope, such as if the general contractor is seeking to use an erection sequence the significantly changes aspects of the design. As with fabrication, contractors have the same needs in terms of expediency of responses for RFIs, as well as other typical submittals, such as work plans, materials, and non-conformance related corrective actions. Also, as with fabrication, the engineer should use the clearest lines of communication possible, including direct communication, to facilitate understanding.

Summary

- Be expedient in the review and approval of RFIs, shop drawing reviews and approval, welding procedures, and repair procedures.
- In shop drawing review, follow the practices of G1.1, recognizing that the engineer is not responsible for the correctness of the shop drawings.
- In the case of welding procedures, see section 2.8.
- In the case of repair procedures, encourage the fabricator to put pre-approved procedures in place for typical issues that need repair.

5.0 BEST PRACTICES ON BEHALF OF THE GENERAL CONTRACTOR

This section describes the key practices for the general contractor (GC) for achieving a successful and timely steel bridge fabrication project.

5.1 Communication

The general contractor (GC) plays an especially important role in facilitating communication among all parties involved in the project, particularly regarding responses and approvals. To keep the project on schedule, the fabricator will need expeditious responses to RFIs during shop drawing development, expeditious shop drawings review and approval, and expeditious responses to RFIs and repair procedures issued during fabrication. Also, the fabricator will need expeditious responses when approvals are needed for welding procedures and, if needed, procedures for other fabrication practices. Generally, responses and approvals come from the engineer, but the GC also has a stake in exchanges that have contractual, schedule and field implications. It is also the GC's responsibility to provide coordination among the trades including utilities and subcontractors who need to provide information to the fabricator, such as for bearings. Further, the fabricator's customer is the GC, and the official communication channel on the project is not from the fabricator to the engineer but through the GC to the owner and then on to the engineer. Thus, a crucial best practice for keeping fabrication on schedule is for the GC to establish the most direct lines of communication possible while keeping all parties informed as needed.

The project team should always use written communication to document decisions that are made leading up to and during the execution of the work. However, many project communications from the fabricator are a matter of routine and do not need involvement from the GC in their preparation. For example, if the owner requires approval of welding procedures on a project basis or requires a procedure for a particular aspect of fabrication practice, these will be submittals that the GC will basically pass through to the owner. For such communications, one effective approach is to use email directly between the two parties concerned with cc's to others to keep them in the know. On larger projects, the GC may set up a formal document control system for tracking shop drawing submittals and reviews and for tracking RFIs. Even if so, group emails can be a good supplement to help expeditiously exchange simpler information.

Further to email, verbal discussions between the person responsible for developing the solution and the person approving it are often the best way to facilitate understanding of complicated problems. This is often the case with issues between the fabricator or detailer and the engineer responsible for review and approval of procedures or drawings. A good practice is to allow direct discussion between these parties with the requirement that decisions be memorialized in writing. This can be the drawings or procedures themselves, as eventually approved, or, if desired notes documenting the verbal exchange.

Although the GC often plays a pass-through role in the fabricators' submittals, there are some cases where the GC's involvement is needed, such as with RFIs that affect the GC's means and methods of erecting the bridge. For example, fabricator proposals to either add or eliminate a field splice or to define or change the scope of shop painting versus field painting have a significant impact on the GC. However, such cases are more the exception than the rule, so the best practice is to establish communication workflows that best facilitate the pass-through communications but also have protocols in place for such exceptions.

In some cases, particularly on complex projects, a significant amount of communication is needed to work through shop drawing development or to handle complex work in the shop. If so, it is prudent to set up routine conference calls or virtual meetings, perhaps once a week, to discuss open items, to help ensure the items are getting the attention they need from all parties, and to help keep them moving. Such regular meetings are usually best facilitated by the GC and include the GC, the fabricator, the engineer, and the owner. During shop drawing development, such meetings should also include the detailer, and during fabrication, they should also include the inspector.

Prefabrication meetings are discussed in the fabrication section. Such meetings provide an excellent opportunity to establish effective communications protocols and to discuss them to ensure they are understood. It can be useful to hold these meetings at the fabricator's facility so that the fabricator can describe their intended approach for executing the project and thereby help the project parties understand where support may be needed during the project.

Summary

- Take the lead in establishing the lines of communication upfront when the project starts, including the identification of designated individuals from each party responsible for communications and any allowances for direct communications.
- For items that do not affect the GC's scope or schedule, facilitate the most direct communication possible between the fabricator or detailer and the engineer and, if needed, the owner. Such practices may include:
    - Direct email communication between the fabricator and engineer, with cc to the GC and owner.
    - Direct verbal communication between the fabricator or detailer and the engineer with follow-up written documentation, particularly for complex issues.
    - Expeditious workflow for submittals that must pass through the GC to the engineer or owner.
- For larger projects, set up a formal document control system for tracking shop drawings and RFIs.
- Require that the following communications go through the GC without exception:
    - Any item that affects the fabricator's scope to the extent that the item affects cost or the project schedule.
    - Any item that affects the GC's practices during erection, field coating, or other field practices.
    - Any item that affects—or might be perceived by the owner to affect—the quality or serviceability of the completed project.

5.2 Field Information Needed from the General Contractor

Depending on the project, the fabricator may require information that comes from the GC, including both information needed during shop drawing preparation and during fabrication. Information needed for shop drawings and the fabricator's timely receipt of the information can have a significant effect on the project schedule.

Field dimensions are the most noted information needed from the GC early in a project to help preserve the project schedule. Rehabilitation projects and widenings are especially noteworthy. In both cases, dimensions for assuring that the fabricated steel will fit and will be compatible with the GC's intended field practices are of critical importance. As with any other item, field attachment details must be in the fabricator's shop drawings, thereby making field information critical for shop drawing preparation.

Summary

- Establish a protocol and schedule for the GC to provide field information to the fabricator as soon as practical once the project begins but no later than as needed by the fabricator to preserve the shop drawing preparation schedule.

5.3 Erection Practices and the Fabrication Schedule

The GC will establish the plan to erect the bridge. Such plans are well described in Section 2 of AASHTO/NSBA Standard S10.1, *Steel Bridge Erection Guide Specification*. Plans vary in detail, complexity, and whether they have erection calculations, depending upon the complexity of the bridge and the GC's preferences. In developing the plan, the GC will consider factors like the erection equipment to be used and where to place it, site access, temporary shoring and other supports, and the design fit condition.

The GC's plan, especially the erection sequence, can significantly affect the fabricator's approach to executing the project. Therefore, it is recommended that some level of discussion of the GC's erection approach occur with the prospective fabricators during the bidding phase. Further, as the project progresses, the fabricator will need to clearly understand the GC's intent regarding the extent necessary to incorporate erection information into the shop drawings. The GC's erection approach on most standard DOT bridge projects does not affect fabrication or shop drawings, but some do, particularly as projects become more complex or if accelerated bridge construction methods are intended.

As discussed in the engineer section, the engineer designates the desired fit condition on the plans, and as discussed in the fabricator section, this condition is reflected in the geometry of the cross frames and on girder connection plates. Further, the GC should confirm that the designated fit condition will be conducive to its erection approach. Many bridges can be erected in any detailed fit condition, but this is not always the case. For instance, highly curved bridges that are very stiff can be a struggle or even impossible to erect if they are detailed to a full dead-load fit. Like the fabricator, the GC should be on the lookout for fit conditions designated on the plans that are not constructable and raise this concern with the owner as early as possible in the project development. AASHTO requires the fit condition to be provided in the plans, and the fabricator and GC are contractually obligated to use the condition designated on the plans, but if the fabricator or GC have a concern with the designated fit condition, raising this concern may facilitate an effective change and avoid significant challenges in the field. Failure to do so can be highly detrimental to project quality and schedule.

As projects become more complex, GCs must give more attention to the support conditions of the steel during erection, including the possible need for shoring. This may or may not affect how the fabricator details and fabricates the bridge, so it is desirable for the GC and fabricator to collaborate on the intended erection scheme early in the project to ensure the needs in the field are clearly understood. Further, if the project requires that the engineer approve the GC's erection procedure, this should be addressed very early in the project in case the approval results in details that must be reflected in the shop drawings.

For bridges with complex geometry and tight tolerances such as cable-stayed bridges, arches, trusses, or other complex bridges, the fabricator and general contractor should discuss any specifics that need to be captured during the check assembly process for later use in the field for geometry control, such as pinning locations at each connection, for replication during field erection. For instance, steps like these, if not taken, can result in out-of-tolerance geometry after erection between a stay cable anchorage and its corresponding concrete pylon anchorage, which can be hundreds of feet away along an x/y/z geometric alignment. It is critical that complex projects such as these be executed by professionals from the GC and fabricator who have requisite experience with similar work, so project staffing and responsibilities should be shared and discussed early in the GC-fabricator and detailer relationship.

If the GC intends to use erection braces or lifting devices that are temporarily bolted to the steel, the connections must be shown in the shop drawings so that the steel can be fabricated this way. This timing is particularly important in the modern era of CNC drilling. For example, if an erection fixture is going to be bolted to a girder flange, the fabricator may produce a flange connection by drilling the flange upfront during CNC plate processing before the girder is built. This improves both productivity and the accuracy of locating the fixture. Adding a fixture after the fact, when the girder is already built, is also possible but takes more time and handling and is more costly. As a best practice, the GC should provide a supplemental attachments mark-up to the fabricator early in the shop drawing development process to avoid impacting the fabricator's schedule and production efficiency. When practical, the GC may prefer that erection bracing and lifting devices be affixed only through clamping means because often owners will often require that unused holes be filled with bolts after erection. Access and the timing of this follow-on work can be challenging, particularly on longer-span flyover structures with active roadway travel lanes below.

The fabricator also needs to know the GC's desired sequence for component delivery and, for large components like girders, the desired orientation of the girder such that the girder does not need to be rotated upon delivery. This information is not necessarily needed for shop drawing development, but the desired delivery sequence does affect fabrication sequence and thus procurement sequence, and orientation is needed before the girders are loaded for shipment. Special delivery methods, such as by barge, also should be a part of the sequence and orientation discussions. While not always required, some owners and engineers will expect to review a shipping drawing showing the fabricator's intended blocking and cribbing locations along the girders. Likewise, the GC may wish to review how the fabricator will protect shop-painted surfaces during shipping, so this drawing provides an opportunity for all parties to ensure the delivered structural steel arrives in the best possible condition for erection in the field.

The AISC Erector Certification Program is an excellent program for helping ensure that the bridge erector has the knowledge, skills, and experience to effectively erect the bridge. The program ensures that the erector has implemented and is using a quality management system that holistically addresses the business aspects of an erector that will make the erector successful. Owners should consider requiring this program of erectors on any significant and complex steel bridges project.

Summary

- Together with the fabricator, verify the suitability of the fit condition shown in the plans for actual construction of the bridge and address this with the owner through official written correspondence if changing the fit condition is recommended.
- Discuss the erection scheme as early as possible with the fabricator, particularly the sequence of erection, before shop drawings are developed, in case this will affect the overall approach to fabrication.
- Convey any information to the fabricator as early as possible regarding any intended erection braces or lifting devices which require supplemental attachment holes in the structural steel members.
- Provide the fabricator with sequence and orientation preferences for component delivery and do so ahead of fabrication to help ensure the fabricator's schedule facilitates the GC's delivery preferences.
- Consider requiring AISC certification for the bridge erector.

5.4 Shop Instructions Reflecting the General Contractor's Preferences

There are items in the project scope not related to erection that may need to be addressed early in the project. The following are examples that need to be addressed upfront so that the fabricator can incorporate them not only into the fabrication plan and shop drawings but also in the contract scope between the GC and fabricator:

- Conditions that require shop bolting instead of field bolting. Unlike erection fixtures, shop bolting does not introduce new holes. However, the instructions for shop bolting need to be in the shop drawings to provide the shop with direction, and so the GC's desire for shop bolted assemblies needs to be addressed while shop drawings are being developed.

- Shop assembly verification. Shop assembly for fit verification is usually not within the GC's realm, but occasionally it is, particularly for complex projects. In particular, if a bridge is very stiff and is to be shop assembled, it may be useful for the GC to visit the shop when the steel is erected to review and understand any special practices or sequence the fabricator may have used while assembling the steel. If the GC would like this opportunity or is looking for any special inspection documentation, this should be identified upfront. Shop assembly is addressed in section 2.11 of the fabrication section of this guide. As described there, the GC may join the fabricator in discussions with the owner regarding justification for the amount of shop assembly to be used.
- Undefined painting or changes to painting. The GC needs to communicate any shop painting preferences during the bidding phase and then again during shop drawing development to ensure this scope is understood and agreed upon, particularly because there are aspects of painting that can be done in either the shop or the field and the GC may have special painting preparation requirements or expectations.
- Application of shear studs. Customs and rules vary across the United States regarding the shop application or field application of shear studs. The customs which are specific to the jurisdictional area of the bridge project must be well understood by the GC and communicated timely to the fabricator, and the decision about where shear studs will be applied needs to be made before shop drawings are developed.
- Coordination with other trades. Examples include suppliers of bearings, expansion devices, fasteners, or coatings suppliers if the fabricator is involved in procurement on behalf of the GC. For components the field bolt to the structural, like expansion devices, coordination is needed to help ensure they will fit.

5.5 Facilitating Approval of Routine Fabrication Practices

Many shop floor practices require approval by the owner. The scope of what requires approval varies among owners and may include welding procedures, other fabrication procedures (if any), and some repair procedures. The GC should act to facilitate the most expeditious approval of these as possible to help keep the project moving once fabrication starts.

All welding done under the Bridge Welding Code must be done in accordance with an approved welding procedure (Bridge Welding Code clause 1.9, 2020). Some owners require approval of welding procedures on a per-project basis. Also, on some projects, situations arise where the fabricator needs a new welding procedure. Also, the owner may require a submittal of other fabrication practices, such as for coating application or shop assembly. Thus, there may be a need for submittal of welding procedures by the fabricator for approval by the owner or engineer. Regardless, there is usually little if any need for the GC to get involved with the approval procedures to be used in the shop from a technical standpoint. However, in some cases approval can bog down. The owner may be slow to respond, or it may take multiple iterations to gain approval. Although the need is unusual, it may be necessary for the GC to help if approvals bog down.

Some repairs also require owner approval, either under requirements of the Bridge Welding Code or requirements under the owner's specifications or customs. Because the need for repairs arises on the shop floor, expeditious approval of repairs can be particularly important for keeping a project on schedule. Many repairs are routine, such as repairing torch gouges, removing and replacing a plate, or remediating errant bolt holes. For routine matters, the best practice is for the fabricator to have pre-approved procedures in place. The allowance for preapproved procedures falls to the owner, but to the extent possible, the GC should facilitate use of preapproved procedures. Also, where discrete approval is indeed required, the GC may be needed to help resolve items requiring a timely response.

Summary

- To the extent possible facilitate that establishment of preapproved procedures that will not require approval once a project starts.
- Allow procedures to be submitted directly to the owner unless the procedures affect the GC.
- As needed, help the fabricator by facilitating expeditious review and approval of repair procedures.

6.0 BEST PRACTICES ON DESIGN/BUILD PROJECTS

Design/build (D/B) projects, including special versions like public private partnership (3P) projects, can significantly accelerate project delivery compared to traditional design, bid, build (D/B/B) projects because

- Planning, design, and construction activities can be done concurrently;
- The entire process can be incentivized instead of just construction; and
- Time can be saved from the improved constructability that results from having the designer work for the contractor and thereby getting contractor input during design and, similarly, getting fabricator input.

For steel bridge projects, getting fabricator input and getting the fabricator moving are key to saving time. Practices vary on D/B projects regarding when the fabricator is brought on board; the earlier this happens, the sooner the fabricator can get started and the more likely that the fabricator can help improve design constructability and associated project speed with feedback to the designer. Even before the fabricator is chosen, the D/B team should get fabrication input from industry representatives and fabricators interested in the project to improve constructability and facilitate time savings.

6.1 Design/Build Project Workflow and Roles

In D/B projects, there are significant differences in workflows and the relationships of the parties compared to traditional design/bid/build (D/B/B) projects. On D/B/B projects, the engineer works for the owner and the plans are 100% complete in advance of bidding: when the project goes to letting, all requirements needed for the contracting team to execute the project are defined in the plans and specifications and, in conjunction with the owner's standard construction and fabrication specifications, a traditional construction process is followed.

In contrast, the process of developing and communicating information on a D/B project is significantly different. To meet the accelerated D/B schedule, the owner, designer, contractor, and fabricator interact differently, using information that is only partly complete when major decisions are made. Hence, for an effective D/B project, the roles of the owner and designer must adapt as follows:

- Owner: The owner establishes the project design criteria as a condition of the advertisement and selection of the contractor's team. Sometimes included in these criteria are restrictions on certain structural types, reflecting the owner's preferences; materials requirements; and various schedule requirements. The key is for the owner to keep the design prescriptions and criteria as high-level as possible, only placing limits on structure types and design features that are essential due to needed owner constraints, such as commitments to permits, aesthetic commitments to the community, or environmental constraints. Unnecessarily prescribing design criteria can constrain structural choices and limit the creativity of the D/B team, defeating the purpose of this contracting method. The D/B team has all the key parties needed on the project delivery team to develop the best solution, and given flexibility, the designer, contractor, erector, and fabricator can collaborate to advance the most expeditious and cost-effective steel solution possible. If their collective wisdom concludes a that certain type of bridge meets the functional requirements of the project, is cost effective, best fits the construction capabilities of the team, thereby fundamentally delivering the innovation that D/B contracting is intended to foster, then overly constraining those selections diminishes the value of using the D/B project, increases cost, and lengthens delivery of the project.

  Frequently owners incentivize the responding D/B teams to propose schedule and cost-savings initiatives in their technical proposal through value engineering (VE). This practice can lead to significant project savings for an owner entity if the selected D/B contractor's proposal is sufficiently vetted for requisite qualifications and experience. The Owner should use such an incentive practice or allow value engineering or alternative technical concepts whereby the D/B team has the opportunity to request relief of project limits after justifying improvement to the project schedule, constructability, safety, or otherwise fundamentally improving the project.

  To help facilitate the project schedule, owners should allow separate substructure and superstructure design submissions. Typically, fabricated superstructure elements like steel girders and bearings have longer lead times than supplies for substructure elements, which mostly consist of cast-in-place concrete and reinforcing steel. Separating the submissions allows the D/B team to focus on the superstructure design submittal and helps expedite review and approval of the superstructure.

- Designer: Because the designer and contractor work together to develop the project concepts, it is essential for the designer to seek constructability advice from the contractor throughout the development of the design. Items like terrain, equipment availability, site constraints, the presence of waterway or railroads, and many other factors have a profound influence on the characteristics of the design and the associated schedule. On a D/B project, the designer has the advantage of the contractor's knowledge of the site and the contractor's equipment and strategies for tackling it, and the designer can incorporate this information in the design. For example, the design can reflect the optimal limits on steel piece length and weight given the contractor's crane availability and crane placement opportunities on the site.

  To help ensure project success, at the onset of forming their D/B partnership, the designer and contractor must reach agreement regarding the expected completion of the design that is to be provided for bidding, and it is important for the designer to understand the lead time and current availability of bridge products, so their design schedule can accommodate these lead times. Lead times vary over time, depending upon typical market dynamics. Lead times also vary by type of bridge as complex structures, like arches and trusses, generally have longer lead times than plate girder bridges or rolled beam bridges. Later, when designs are more complete, fabricators will be able to provide schedule information for the specific bridge in question, but in the early stages of project development, designers should be aware of lead times for their advance planning. Such information is available from fabricators and from the NSBA.

- Contractor: The contractor will provide coordination for the team throughout the project, typically through the implementation of an owner-approved Project Management Plan (PMP) which defines the review processes and individual roles for each involved party. As the design advances, the contractor will decide on the erection sequence and means and methods. These will inform the designer and detailer's work sequence and schedule, the fabricator's procurement priorities and associated scheduling, and the owner's review planning effort. During design, the contractor will identify any critical design details and the controls that need to be in place via contractor and fabricator constructability reviews of the design. During detailing, formal RFI process or decision logs should be used by the D/B team.

  The contractor will identify any specific controls or unique specifications needed during design, fabrication, shipping, and erection, including any special provisions that need to be submitted to the owner for approval. If an internal design or detailing matter arises during the D/B team's coordination effort that causes conflict with the owner's contract requirements, the contractor is responsible for addressing such matters because the contractor holds all contractual obligations to the owner. The contractor will also manage any notice requirements for erection, including disruption to general public spaces, railroad operation, navigable or recreational waterways, and roadway traffic.

The contractor may desire mock-ups from the fabricator to assist in final design and possibly to provide the owner or designer with confidence in the eventual quality of the finished product. Mock-ups can be useful for working through the best fabrication steps, particularly regarding weld joint design and weld sequencing. However, they also take time and can be costly, so if they are desired, they must be identified early in the process and properly scheduled and budgeted.

To facilitate erection of the steel in the field, the design must address several factors on behalf of the contractors, including:

- Erector access to the work. This includes both site access, such as contractor's delivery area, laydown, marine equipment, and access to bolted or welded connections in accordance with the erection sequence. Such access must be continually considered by the team during design.
- Fall protection safety.
- Material receiving and laydown space.
- Field bolting methods.
- Field welding needs.
- Preassembly work.
- Local and global geometry control.
- Quality control and quality assurance.

The designer will advance their design in pieces and in a D/B environment take on an amount of risk that typically has direct cost implications to them via their contract with the D/B contractor. The designer must provide an early estimate of the steel layout, weight, and material types and some information on bracing and bearing loads to facilitate the D/B team's bid preparation. For the D/B team to submit a bid for the project with the goal of being chosen, the designer will need to have advanced the design to the point that major steel quantities are certain, with allowances for unknowns that are typically carried as a risk cost.

Summary

On D/B projects, owner, designer, and general contractor roles should be adapted as follows to achieve the best schedule and most cost-effective solution:

- Owner
    - Keep design prescriptions and constraints to a minimum to allow the D/B team the most flexibility possible.
    - Provide value engineering (VE) incentives, including a VE practice that allows the D/B to share VE cost savings.
    - Consider separating the superstructure and substructure submissions to give the D/B team the best opportunity to optimize the project critical path.
- Designer
    - Be aware of current lead times for fabricated steel, including the type of fabricated steel bridges being considered for the project, and incorporate this into the schedule.

    - In the early stages of the project, get general design feedback from fabricators and the NSBA, and consider the high-level recommendations at the final section of this section.
    - As the design is refined, get more refined fabrication recommendations from fabricators, and follow the practices of AASHTO/NSBA Steel Bridge Collaboration G12.1.
    - Continue to engage with fabricators as described in the "Working with the Fabricator" sections (prebid and post bid) of this section.
- General Contractor
    - Provide coordination, such as through a project management plan (PMP), keeping lines of communication as open as possible.
    - Coordinate with the fabricator regarding the erection sequence and as needed, means and methods. Identify critical design details and plan for associated constructability reviews from the fabricator.
    - Identify any mock-ups that are needed or desired and ensure time for them is in the project schedule.
    - Facilitate engagement with fabricators as described in the "Working with the Fabricator" sections of this chapter.

6.2 Working with the Fabricator—Prebid

To achieve the best project schedule and cost, the designer needs constructability advice and fabrication schedule information from the fabricator. However, the fabricator is usually not an initial member of the D/B team but comes onboard later after the design is underway. Generally, this delay is prudent: to get accurate cost and schedule responses from potential fabricators, the D/B team needs to provide them with some level of design to consider. The design does not need to be complete for general bidding and scheduling; rather, it only needs to be advanced to an initial stage where fabricators can provide a budget cost and initial schedule. Usually this is about the 50% point of design. At this early stage, fabricators can get a general idea of what it will take for them to get the job done, including whether the type of bridge and members being recommended are within the fabricator's skills and whether the fabricator has the capacity to do the job in the timeframe desired by the team. For example, say the bridge will be a large, tied-arch. Some fabricators may not find a large arch in their skill set. Or, if the arches may be comprised of particularly large sections that might be outside of the capability of the fabricator to move and turn due to crane capacity or some other consideration. The example illustrates a key point: if very large elements are anticipated in the design, the D/B team should check with fabricators about the ability to handle such members as soon as they are being considered in the design. As members get larger, fewer fabricators will be able to handle them for fabrication. The D/B team should be aware of fundamental industry limitations before the design is advanced too far to take this into consideration.

Although the 50% level is usually a good milestone for preliminary scheduling, this is not the case if the balance of design involves changes that have a significant time impact. Welding details are one example of this: a change from fillet welds to complete joint penetration groove welds, particularly for long welds like web-to-flange connections, significantly impacts the schedule. Coatings are another example; taking uncoated weathering steel as a base, each of the following coatings takes successively more time going down the list (see the fabrication section for more details about each):

- Prime coat only – least time in coating in the shop.
- Three-coat shop painting, with organic zinc as the primer.
- Three-coat shop painting, with inorganic zinc as the primer.
- Galvanizing – assuming all components can fit in a galvanizing kettle.
- Mix of metalizing and galvanizing – i.e., metalizing for large components (like girders) and galvanizing for smaller ones (like diaphragms).
- Use of metalizing for all components, small and large.
- Duplex, which is a combination of metalizing or galvanizing with paint – greatest time in coating in the shop.

Any change in coating solution moving down this list adds time to the fabrication schedule.

Because D/B projects are competitions, teams are sometimes reluctant to share preliminary design information with fabricators because they want to protect their ideas. Such restraint precludes the team from getting fabrication cost and schedule information and from getting constructability input from the fabricator about the design. If there are concerns about ideas getting leaked, the better practice is to have the fabricator sign a non-disclosure agreement (NDA). This practice protects the team's ideas and allows the fabricator to provide cost, schedule, and constructability to the team before being under contract and without further concern for idea protection.

Although fabricators can provide feedback to the D/B team beforehand, it remains important to formally retain the fabricator as early as possible. This way, the fabricator can engage with the rest of the team from the standpoint of having the job. At this point, with design still underway, the contract with the fabricator will need contingencies tying the fabricator's schedule to completion of the design deliverables. Usually, these contingencies are tied to receipt of release for construction (RFC) drawings

6.3 Working with the Fabricator—After Award

Once the fabricator is retained, there are two key initial steps for the fabricator: ordering material and beginning shop drawing production. Both are crucial to the fabrication schedule, and neither take place until the design is complete enough such that material orders and shop drawings do not need substantial changes.

Lack of understanding about how shop drawings are produced sometimes leads to confusion about the effect of design changes and their impact on the project schedule. A common perception is that discrete design changes are not significant because, perhaps, they only affect a handful of drawings, but for many changes, this is not the case. Producing shop drawings is much like building a building: a frame is erected, then systems can be added, and walls can be built out. If construction is nearing completion, a significant change to the frame affects the systems and other improvements as well. Similarly, in shop drawings, the geometry is the framework, and other details follow. If the geometry isn't set, not much can be done, or it will simply have to be redone. Further, given the complexity of bridge geometry, where curves, cross slopes, superelevations, and three-dimensional geometric conditions must all accurately tie together, modern detailers use a workflow of inputting the geometry of the bridge into their detailing software and then using the output to create the drawings. Changes to the bridge geometry after shop drawing production is underway could mean that the only way to accommodate the change is to start over with the initial geometry. Not all changes are this significant—but some indeed are. For an understanding of the significance of potential design changes, the D/B team should keep an open dialogue about this topic with the fabricator.

Regarding materials, lead times for mill-ordered plates are usually about three months but can be greater, depending upon market conditions and the specialization of the material or section. To keep a project on an aggressive schedule, material must be ordered early. As described in the fabrication section, fabricators do order material before shop drawings are complete; however, material cannot be ordered effectively until the geometry is complete and correct. Until field section length and camber are provided and the flange plate widths and thicknesses, and the location of flange shop splices are established, mill orders cannot be advanced.

Therefore, on D/B projects, where fabricators are on board before designs are complete and design drawings are being exchanged for feedback purposes, it is important to have a very clear milestone that identifies when the design is complete to the stage that material can be ordered and shop drawings begun. By custom, this stage is known as “release for construction” or “RFC.” Once the fabricator has received RFCs, the fabricator can take these key initial steps and firm up scheduling.

On a D/B project, when the designer designates drawings as “RFC,” the designer is communicating that the design is complete enough for materials to be ordered and shop drawing work to begin. Given the importance of materials and shop drawings to the fabrication schedule, it is important to define fabricated steel delivery durations during the bid phase as a function of RFCs. Doing so provides the D/B team with an accurate understanding of steel deliveries relative to their design schedule and set appropriate RFC delivery targets. If there are issues getting the geometry set but there is a desire to get material ordered, the designer can work with the fabricator on rough material sizing provided the D/B recognizes there will likely need to be some cost adjustments once the design is set. Mill orders can be placed using 90% superstructure designs provided there the D/B team understands the risk involved when placing mill orders prior to RFCs.

Material procurement and shop drawing development illustrate an important point: even in the accelerated delivery process of D/B projects, the process is still in many ways linear and relies on the engineer providing clear direction through the design drawings even though they are incrementally being advanced. It is also critical, given the just-in-time nature of the design development and fabrication process, that all parties on the design team, and those on the owner’s team, understand the time-sensitive nature of the reviews and provide their reviews, comments, and approvals in a timely manner. Under select circumstances, the contractor may elect to have the fabricator proceed at the contractor’s risk with shop drawing production for critical fabrication schedule items before the completion and approval of the related steel design. However, many owner contracts will dictate that shop drawing approval hold points may not be released before design approval unless authorized by the owner at their sole discretion. If this is the case, the owner must act expediently to maintain an accelerated schedule.

6.4 Contract Cost Terms

Retaining a fabricator before the design is complete requires some flexibility in the contract between the contractor and the fabricator. To keep things simple, there is often a desire to base the cost on a $/lb basis, but use of $/lb is not always effective. Often projects get more complicated as designs evolve, particularly on the type of complex projects like those that are often featured in D/B contracts, and such complexities are not consistent with $/lb costing. Rather, most fabricators prefer lump sum pricing and contracts with terms that provide flexibility. Done effectively, such terms will not only protect both parties but also help improve the project schedule. For example, the fabricator may see that a change in material type, such as from grade 50W to grade HPS 70W plate might provide cost savings by using material of higher strength to reduce the material section. Conversely, lead-times of grade HPS 70W tend to be longer than those for 50W, so the fabricator may see that project time can be saved using 50W. Provisions in the contract with the fabricator the provided the flexibility to take advantage of such dynamics facilitate improved project schedule and cost.

Summary

- Generally, engage the fabricator as a member of the D/B team as soon as possible so that the fabricator can provide optimal schedule information as well as constructability support.
- Until a fabricator is on board, engage with fabricators to provide schedule information and constructability feedback as follows:
    - Advance the design to an initial stage with the general type of bridge established so that potential fabricators can evaluate their capabilities and general availability to do the project. The initial stage should identify:
        - The general type of bridge.
        - The type of large pieces is anticipated, i.e., box, I-girder, or other; and
        - The weight, length, and height of the pieces.
    - Use the following resources for initial constructability guidance:
        - Seek general design advice from fabricators and the NSBA.
        - Consider the high-level steel bridge design recommendations of the next section.
        - Use the NSBA's Steel Span Weight Curves during early design to get rough structural steel quantities.
        - Follow published guidelines regarding steel bridge constructability, such as AASHTO/NSBA Steel Bridge Collaboration G1.4 and G12.1.
    - As the design progresses, share details with prospective fabricators for more specific feedback.
    - If there are concerns about the secrecy of competitive design innovations or strategies, have the fabricator sign a non-disclosure agreement (NDA) so that this specific feedback can be provided.
- Provide designs at about the 50% completion level for fabricator to provide budget prices and an estimated schedule:
    - Recognize that certain factors in the completion in the design can have a significant impact on cost and schedule, including:
        - A shift in weld details from fillet weld to complete joint penetration groove weld.

        - A change in coating to a more time-consuming solution.
- Once a fabricator is chosen, facilitate the use of value engineering to provide still more opportunities for improving the project cost and schedule. In the contract, include terms that provide flexibility.
- Recognize that the fabricator will need “release for construction” (RFC) sets of drawings to order materials, initiate shop drawing production, and start the clock on the fabrication. schedule. Further recognize that design changes after RFC designs are provided may restart the clock on material orders and shop drawings, impacting the schedule and adding cost associated with the changes.

6.5 Design Considerations

Use of design-build (D/B) contracting is often chosen projects to achieve faster speed in designing and building the bridge. Using the best design practices has a significant impact on the project speed. As described above, it is best to get fabricator input as early as possible; the following are high level guidelines for achieving constructability in the early stages of a project before fabricators can provide more direct feedback:

- For longer, multi-span bridges where the desire is to optimize substructure, start with 10-ft-deep I-girders as a reasonable maximum depth.
    - As girders become larger, they become more challenging to fabricate, but, up to about 10 ft deep, fabrication remains reasonable and straightforward.
    - Between 10 ft and 12 ft deep, fabrication becomes more challenging as girders get particularly heavy and, from a cleaning and painting standpoint, surfaces become particularly large—for example, it might take an entire shift to clean a 12- ft-deep girder in preparation for painting. Most bridge fabricators can produce girders up to 10 ft deep, but the number of fabricators who can build girders drops off approaching 12 ft.
    - Above 12 ft, material availability for girder webs becomes a limiting factor. Twelve-foot-wide plate produced to normal mill tolerances is available; above this width, there is one mill that can go to 14 ft, but not within normal tolerance for flatness. This means that fabricators would need to put in significantly more effort to build girders, slowing production. Optionally, longitudinal butt splices can be used to produce webs for girders over 12 ft deep, but once again, this takes time and slows production.
    - Shipping is a significant consideration in selecting a girder depth. The first shipping factor is getting under bridges on the route from the fabricator to the jobsite. Bridge heights vary and so do the depths of available shipping equipment, but at 10 ft, and perhaps 10 ft, 6 in., girders can usually be shipped vertically and still clear most bridge along the shipping route. Deeper girders can indeed be shipped horizontally (i.e., with the girder laying down), but vertical shipping saves the time of rotating girders down for loading and standing them back up again at the jobsite. Further, girders that are large enough to be shipped laying down tend to approach the size

of being superloads. Superloads take more time and effort to load, require police escort, and in some states are under special shipping window constraints.

- Consider use of parabolic haunch girders to optimize span-to-depth ratios.
    - I-girders with parabolic haunches take more effort to produce than parallel flange I-girders, but not significantly so. Further, on a bridge with parabolic haunches, not all girders need to be haunched. Rather, pier girders have haunches, and girders in between the piers or out from the piers to the abutment can be parallel-flange.
    - For very long spans, stacked haunch girders can be used to take I-girder designs out to over 500 ft. A longitudinal bolted splice with mini-flanges can be used to make the stacked condition. Such flanges provide stiffness for shipping the haunch girder pieces to the field and in services provide a longitudinal stiffener.
- For complex bridges, I-sections are preferable to box sections. Bridge fabricators are optimized for I-girder production, and their use significantly speeds fabrication compared to boxes. However, if boxes are needed, such as to provide greater stiffness, they are a viable solution.
    - Consider multiple I-girders instead of box sections for straddle caps. Though it is counterintuitive, using multiple girders instead of a box provides significant time and cost savings. Multi-girder straddle caps can be half the cost of box sections (see article, "Bent on Innovation," *Modern Steel Construction*, February 2021, www.modernsteel.com).
- In welding, fillet welds are preferred, then partial joint penetration (PJP) groove welds, and then complete joint penetration (CJP) groove welds. Using groove welds instead of fillet welds adds joint preparation and usually increases the number of weld passes; use of CJP groove welds over PJP groove welds adds back gouging or wider joints with backing. Further, despite some perceptions to the contrary, groove welds do not offer higher quality than fillet welds.
    - On I-girders, avoid use of groove welds to join webs to flanges.
    - At bearing stiffener ends, use finish-to-bear connections with fillet welds and not CJP groove welds.
    - On boxes, if possible, join corners with fillet welds, and if possible, use them only on the outside of the box.
- Seek recommendations from fabricators and the NSBA. Fabricators readily provide feedback to designers and are the best resource for up to date and detailed information about how to optimize a design. Further, the NSBA can provide design and can reach out to multiple fabricators at one time and provide collective information for the designer.
- Consider putting a detailer on the D/B team, but do not produce the shop drawings in advance
    - As discussed in the fabrication section, many fabricators use a sublet detailer. Sublet bridge fabrication detailers are very knowledgeable in current fabrication preferences. Use of a sublet detailer for fabrication advice does not necessitate their use by the fabricator after the fabricate is on board but, if the sublet detailer is indeed knowledgeable of the fabricator's preferences, use of this sublet detailer on the job can speed shop drawing production and help the project schedule.

- Detailers can effectively aid the designer and contractor with constructability design choices and cleaning up design details before involving fabricators.
- However, it is not a good idea to produce shop drawings in advance of retaining a fabricator. Shop drawings include many details that are important yet unique to individual fabricators, including how information is presented on the drawings and understood by the shop. Whichever fabricator gets the job will much prefer to have the shop drawings produced in accordance with their preferences, including using either the detailer who is on the team or a detailer of their choosing.

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