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Instrumentation to Aid in Steel Bridge Fabrication: Bridge Virtual Assembly System

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Final Report VTRC 18-R23

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ABSTRACT

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This report describes these improved measurements in detail and compares them to conventional measurement methods, including a detailed analysis of the accuracy limitations of current methods. An assessment of current fabrication processes was conducted and is presented. Based on this assessment, the measurement system was designed and tested; the design features and a system description are provided in this report. The system was deployed on a production bridge job, representing the first time entire lines of girders have been measured with such precision and accuracy and the first time virtual assembly has ever been demonstrated. The report describes measurements for this bridge job and provides recommendations for use of the system.

FINAL REPORT

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INTRODUCTION

Steel bridge fabrication procedures strive to deliver a bridge that fits together as-designed during erection. To minimize fit-up issues during erection, most fabricators employ a match-drilling process. Using this method, girder holes are drilled to fit with a standard pre-fabricated splice plate in order to ensure proper alignment. This method of fabrication is, however, labor and space intensive. Typically, holes cannot be machined into steel plates in the most efficient manner. Holes are now drilled in a fully fabricated girder with the web attached to the flanges, as opposed to placing holes in flat plates using more efficient drilling equipment. In spite of using current match-drilling procedures to guarantee alignment, there are still fit-up issues during erection. The goal of this project was to develop new tools and methods that improve current manufacturing processes and quality control (QC) during fabrication. These tools and methods provide much greater and more accurate information than current practices that rely on manual measurements. This project developed and deployed a BRIDGE VIRTUAL ASSEMBLY SYSTEM (BRIDGE VAS) that improves current steel bridge fabrication processes. More reliable and more accurate information on what is being fabricated will produce a better quality end-product, benefiting both fabricators and bridge owners. The BRIDGE VAS eliminates the need to match-drill girders and has the potential to reduce fit-up issues during erection.

BRIDGE VAS Basic Concept and Background

The BRIDGE VAS system incorporates a unique laser measurement system that makes very high accuracy measurements directly on a girder surface. Details of the overall system and the laser measurement device developed as a part of this project are described in the section *Results: BRIDGE Virtual Assembly System Design*. Starting in 1996, efforts on applying advanced measurement tools to steel bridge fabrication were conducted at the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center (Fuchs et al., 2004a). This included several years of providing high accuracy laser system measurements during the FHWA Curved Girder Bridge Study (circa 1998 to 2006) (White et al., 2012). The National Corporative Highway Research Program (NCHRP) IDEA program sponsored project NCHRP IDEA-127 to continue this effort in 2007 (Fuchs, 2009). While basic concepts were explored in these early projects, an operational system was never realized. This project sought to vastly extend the preliminary concepts and to actually produce and demonstrate the first virtual assembly system. Led by the Virginia Department of Transportation (VDOT), this project was performed under Transportation Pooled Fund TPF (5)-226, which also included Iowa, Texas, New York, and the FHWA. The culmination of this project was deployment of the BRIDGE VAS during fabrication of a bridge for the Tennessee Department of Transportation (TDOT), representing the first-time use of virtual assembly technology.

This report compares the BRIDGE VAS capabilities to conventional methods used in fabrication shops. While the measurement capabilities of the BRIDGE VAS are provided, the details on measurement accuracy of the advanced measurement techniques used are beyond the scope of this report. For a more detailed discussion on these issues, a comprehensive presentation of advanced metrology performance issues, similar to those incorporated in the BRIDGE VAS, was done by the National Institute of Standards and Technology (NIST) (Stone et al., 2004). Readers interested in other information can examine work done on applications of similar laser measurement systems to field measurement of bridges. An early application was to measure girder deflection during a load test (Fuchs et al., 2004b). National Corporative Highway Research Program (NCHRP) IDEA program sponsored NCHRP IDEA-153 to apply a field measurement system to bridge retrofit work. Known as the Bridge Retrofit Laser System (Bridge RLS), the field retrofit work incorporates aspects of the BRIDGE VAS (Fuchs, 2012).

To better understand the BRIDGE VAS, the need for such a tool is first presented, followed by a description of current fabrication procedures. A description is then provided of the two main advantages of the BRIDGE VAS, which are (1) replacing currently practiced fabrication steps with virtual assembly capabilities and (2) vastly improving measurement and documentation of fabricated girders.

The Need for Improved Measurement Tools

Current measurement tools and procedures have served the bridge fabrication industry well, but development of new tools has the potential to greatly improve the steel bridge fabrication. Fabricators use existing measurement tools and follow accepted procedures. The problem, in general, is not poor fabrication procedures, but that the existing tools can be vastly improved. With the development of the tools in this project there exists now the ability to better assess what is manufactured and to better document how close this manufactured girder is to the intended design. An increase in reliable and accurate information during fabrication will make a better end-product and will potentially reduce the number of erection fit-up problems. With a lack of detailed and accurate information about what is manufactured, it is not always possible to really know why there are issues with erection of some bridges. This lack of accurate information is illustrated with an example of the measurement of girder length. When examined closely, the seemingly simple measurement of girder length reveals important information about the accuracy of current measurement tools. Measuring girders with a tape measure will in the majority of, or possibly all, cases produce a girder that is shorter than the shop drawing specified length. To give a practical example of what this means, the length error in a 300-ft span (two

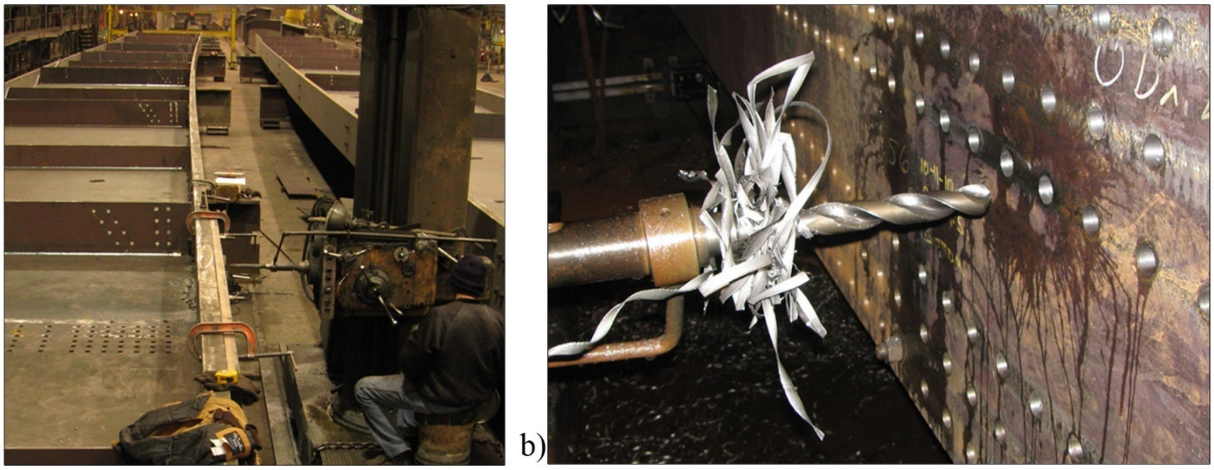
150-ft girders) when measured with a standard tape measure is probably on the order of 1 in (maybe ¾ in, best-case scenario). There are systematic biases in the tape measure that always make the manufactured girder shorter than intended when measured with this tool. Measurements are not randomly distributed, with some shorter and some longer. The *Results* section explores this issue in more detail and provides an explanation of these assertions.

Are these systematic errors important? This current level of accuracy in length measurement may or may not make a practical difference in the erection of a bridge. But knowing of and quantifying this type, or similar types, of measurement error can only reduce fit-up problems and other issues related to fabrication. Looking closely at the measurement of girders with a tape measure as compared to a much more accurate tool has better quantified what is being fabricated. Many more such issues will arise with further examination of fabricated girders using these more accurate tools. At the same time, it is important not to over-specify fabrication tolerances with new and improved tools, but to properly understand and define what is to be measured and to what level of accuracy. Just because it is possible to measure some aspect of a girder to 0.001 in does not mean that it is beneficial to do so. Having better information on what is fabricated should be a benefit to both the fabricator and the bridge owner. The bridge owner will receive a better end-product. The fabricator will achieve greater efficiencies in fabrication by not being burdened with unrealistic or unnecessary requirements.

Current Steel Bridge Fabrication Practices

Steel bridge fabrication frequently involves splicing together individual girders segments in order to create longer length bridge spans. Girders segments are joined together with bolted field splices in which plates are bolted to each girder through holes near the girder ends in the top and bottom flanges and in the webs. Typical bridge girders can have hundreds of holes in a single splice connection. The current fabrication practice for making the holes for this bolted field splice connection involves a match-drilling procedure. One form of match-drilling is known as the laydown process. Girders are fabricated initially with no splice holes. A pair of girders to be joined with a splice is laid on their side and manually aligned based on a string-line reference placed on the shop floor. Once aligned, template splice plates with full-sized holes already in the plates are clamped to the girder pair and used to match-drill the holes in both girders. An alternative method for ensuring hole alignment is the sub-drill and ream process, in which undersized holes are pre-drilled in the member and later reamed to size. Both of these methods are used to ensure the alignment of the holes in the splice plates and the base members.

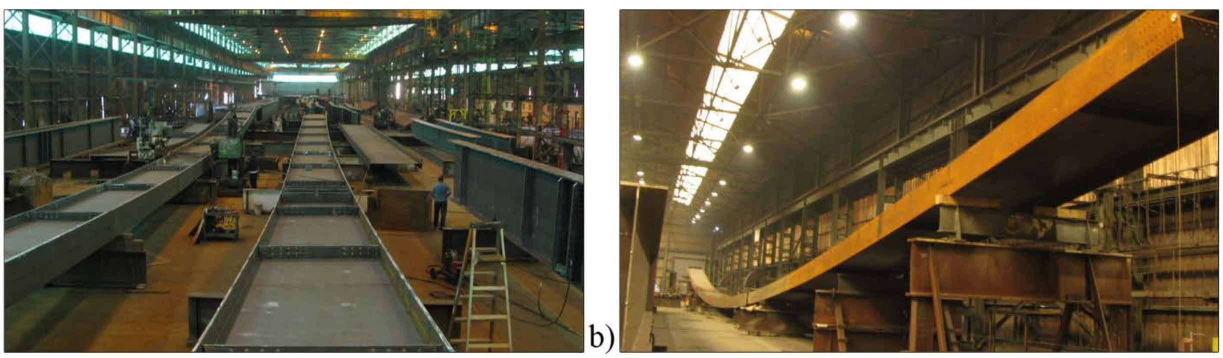
This laydown and match-drilling step in fabrication is one of the most, if not the most, time-consuming and expensive steps in the fabrication of a steel bridge. Some estimates put the cost of this step at 15% to 20% of the total fabrication cost. The process of manipulating and aligning girders and then manually drilling hundreds of splice holes takes considerable time and effort. Flange and web plates must be drilled at different orientations, requiring multiple drills and/or repositioning of drilling equipment. Drilling of welded web-to-flange girder sections is much more difficult than drilling on flat plates. Match-drilling of the bottom flange of a girder pair is shown in Figure 1. The laydown process also takes up considerable floor space.



a) b)

Figure 1. Match-Drilling: a) Girders Lay on Their Side and b) Web and Flanges Drilled Using Template

Depending on the shop, the laydown area may require ⅓ to ½ of the floor space of the entire shop. Girders are laid on their sides and set end-to-end, taking up several hundred square feet of space. Curved girders, when set on their sides, need to be appropriately blocked and can be more difficult to work with, as these girders extend high off the shop floor. Straight and curved girders in the laydown process are shown in Figure 2, which illustrates typical space requirements.



a) b)

Figure 2. Laydown Process in a Typical Fabrication Shop Requires Substantial Floor Space for Both a) Straight Girders and b) Curved Girders

If the laydown process is eliminated, then full-sized holes can be placed at the beginning of the fabrication of a girder using equipment that can drill holes much more efficiently. This would eliminate the need to manually drill hundreds of holes at each splice. Eliminating the laydown process would result in very significant savings on the fabrication of every steel bridge.

Virtual Assembly of Girders

One of the main advantages of the BRIDGE VAS is to improve the manufacturing process by eliminating some time-consuming steps. By virtually piecing together the individually measured girders, the need to physically laydown, align, and match-drill spliced pairs can be eliminated. The match-drilling component of fabrication is a bottleneck in the overall process and the elimination of this step improves fabrication as a whole. Using software tools, girders can now be virtually manipulated and aligned and the operator can produce a combined camber diagram of a girder pair or of multiple girders. Figure 3 shows two girders virtually aligned with software based on the measured combined girder camber optimized to the desired shop drawing combined camber. Based on a virtual assembly, custom-designed splice plates can be made. Using this method, some variation in the placement of holes in each girder can be tolerated. The BRIDGE VAS will simply measure the as-fabricated hole locations and make a splice plate to fit the particular orientation of holes in each girder. The benefits of this virtual assembly process are significant. Girders do not need to be placed in laydown for drilling of holes. Holes can be drilled at more efficient times during fabrication (e.g., in flat plates). Girders fabricated at different facilities can be virtually assembled, thereby eliminating the need to bring girders physically together at one location for fabrication prior to shipping to the project site. Shop floor space previously dedicated to match-drilling can be reused for other purposes.

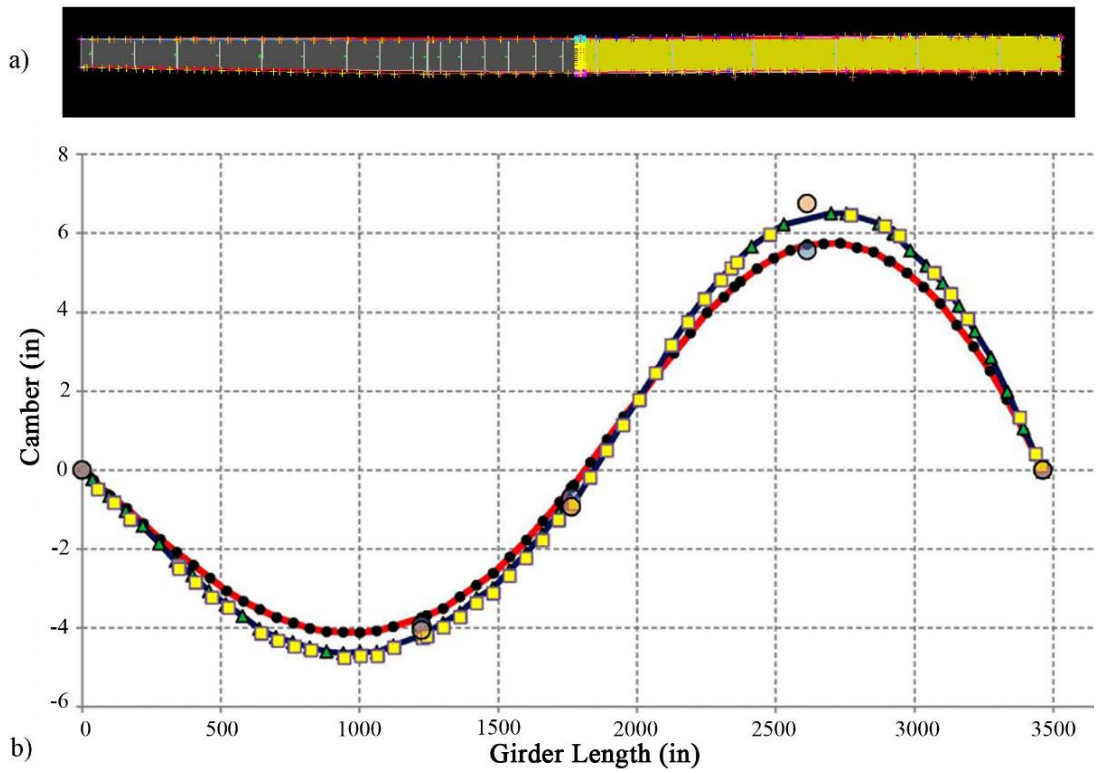


Figure 3. Bridge VAS Software Manipulating a) Individual Girder Pair Measurements Based on b) Optimized Virtual Assembly Based on Combined Camber

Most physical laydowns involve two or sometimes three girders and setup is often dictated by available floor space. With virtual assembly software, any number of girders can be assembled, creating custom-made splice plate and combined camber diagrams. Entire girder lines can be virtually assembled, something that would be extremely difficult, or probably impossible, to physically perform in most shops. Not only can multiple girders in a line be assembled, but multiple lines can be virtually assembled as well.

Improved Manufacturing

The second main advantage of the BRIDGE VAS is that it provides substantially more documentation than currently exists and provides access to types of information that are not currently available. Providing accurate information on what is being made in a shop, in an easily interpretable and useful form, can dramatically improve the quality of the end-product produced.

Conventional Measurements Compared to a Digital Record

Conventional measurements are now based on string lines, rulers, and tape measures (see Figure 4). Most records are kept on paper, with hand-written notes made on the shop floor, and these records are somewhat subjective. This type of manual paper record can lack detail and can be challenged easily if there are discrepancies during erection or other parts of the inspection process during or after fabrication.

a) b)

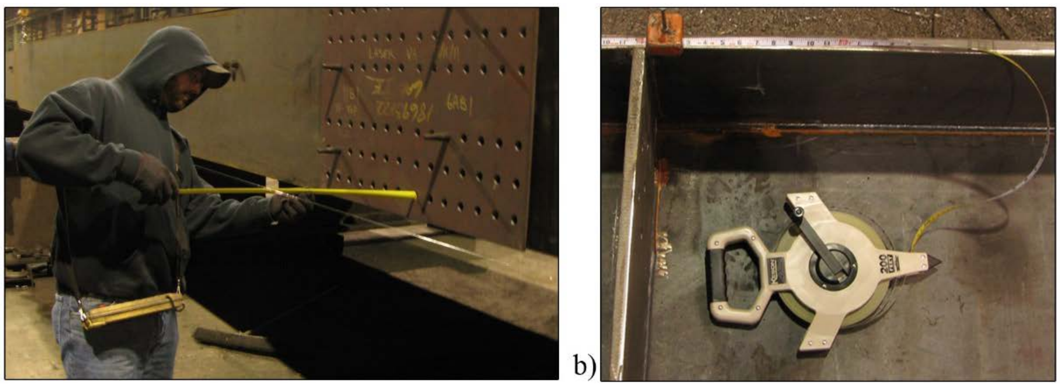
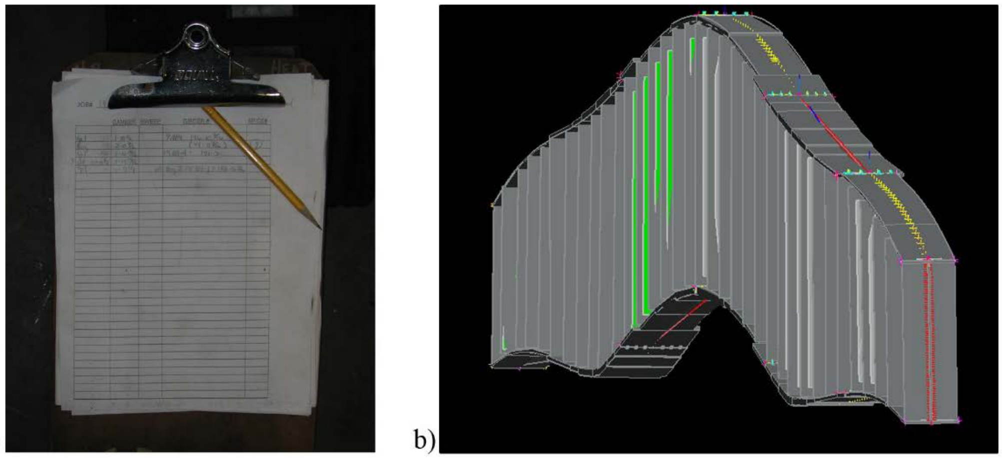


Figure 4. Conventional Measurements a) With Rulers/String Line and b) Tape Measures

The BRIDGE VAS replaces subjective, limited-accuracy conventional measurement methods with a full digital record (see Figure 5). The system provides full-documentation of what is fabricated, much beyond what now exists. This digital record is certifiable, traceable and can be used to fully document the as-built girder at the fabrication shop. From the digital record, any number or form of customized reports can be automatically generated. The digital record encapsulates relevant data and the final measurements for a girder. In addition to the customized paper reports, the digital record can be used to produce data in standardized formats compatible with commercially available software tools. Key aspects of a girder are measured and documented, including length, camber, sweep, stiffener locations, and web panel deformations.

Real-Time Identification of Fabrication Issues

One of the more important quality control features of the BRIDGE VAS is the ability to get immediate feedback of fabrication errors in real-time with actual measurements overlaid with an ideal model created from shop drawings. Figure 6 shows stiffener measurements that are not where they should be as compared with a three-dimensional (3D) CAD model. Discrepancies can be shown graphically, as in the figure, or can be automatically highlighted in a report based on specified tolerances.



a) b)

Figure 5. Using BRIDGE VAS Replaces a) Conventional Paper Records With b) Certifiable, Traceable, Permanent Digital Record

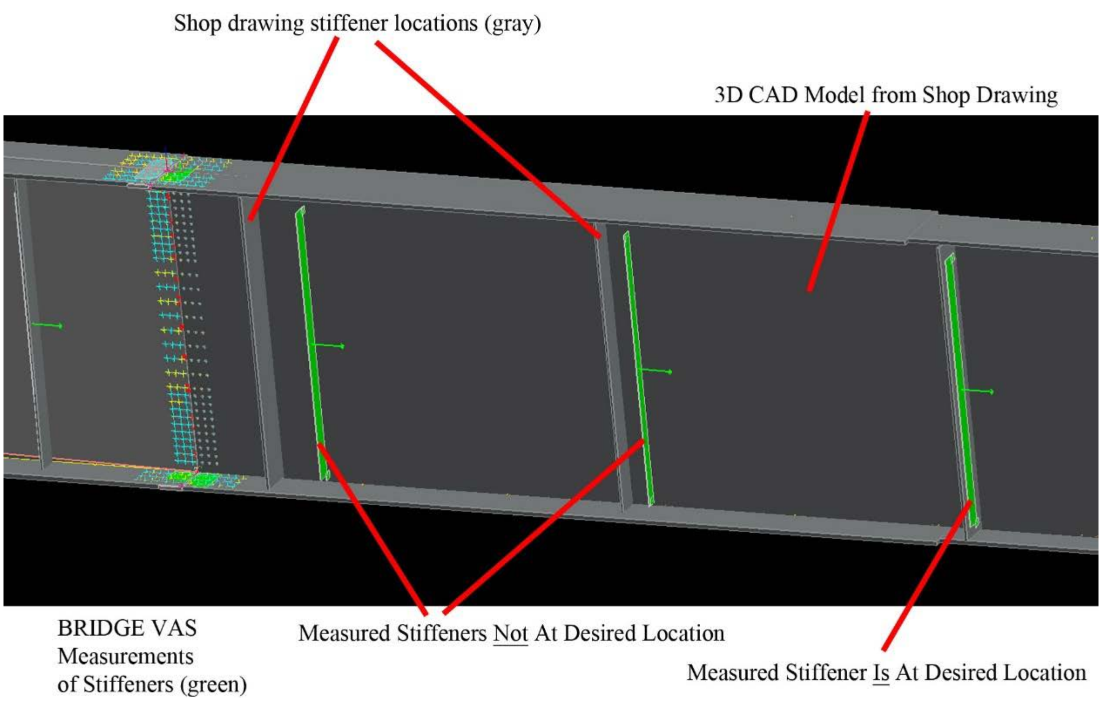


Figure 6. BRIDGE VAS Software Can Automatically Identify Fabrication Errors in Real-Time

PURPOSE AND SCOPE

This project developed improved tools and methods for steel bridge fabrication. This included an in-depth assessment of the current fabrication procedures and practices. The following work was performed from July 2010 through March 2012:

1. Assessment of current steel bridge fabrication practices

2. Identification of improvements in current measurements

3. Design and construction of advanced BRIDGE VIRTUAL ASSEMBLY SYSTEM (BRIDGE VAS)

4. Deployment of the system on a production bridge job

5. Demonstration of the capabilities of the system to process stakeholders.

METHODS

Four tasks were performed to achieve the study objectives:

1. Fabrication process assessment: Visit fabrication shops / assess current process and procedures

2. Measurement process development: Perform initial shop tests to define measurement needs

3. System design and development: Design and build a system capable of making the necessary measurements

4. System deployment: Apply the system on a production bridge job.

Fabrication Process Assessment

An assessment of current steel bridge fabrication procedures was made with multiple site visits to Hirschfeld Industries fabrication shops in North Carolina and Virginia. Currently used fabrication processes were examined in detail with a particular emphasis on match-drilling. In this regard, in-depth focus was placed on currently used measurement tools and techniques and in record keeping procedures. While not conducted under this project, a number of other fabrication shop procedures have been assessed in the development of the BRIDGE VAS. This includes some of the steel bridge fabrication shops of High Steel Structures (Lancaster, Pennsylvania), Egger Steel (Sioux Falls, South Dakota), and PDM (Eau Claire, Wisconsin). The fabrication shops that were assessed represented a range of facilities and capabilities.

Measurement Process Development

Tests were conducted in order to develop initial measurement procedures and to better understand the requirements for full-time work in a shop environment. Measurements of various girders were conducted at the Hirschfeld Industries shop in Abingdon, Virginia, from November 8–12, 2010. In this period, a total of five girders were measured. Measurements were conducted on straight girders, curved girders, and on a large tub girder. Virtual assembly measurements of a spliced girder pair were conducted. Based on initial shop measurements and on other on-site development work, BRIDGE VAS measurement procedures were developed to capture relevant information about a girder. These procedures define where and how data are collected on a girder and how to produce desired output from these data. As part of this process, methods for development of 3D CAD models were also created.

System Design and Development

Based on defined measurement requirements, a complete measurement system, referred to as the BRIDGE VAS, capable of performing all necessary functions within a fabrication shop was designed and built. This system design leveraged efforts from previous work and included both hardware and software components, as well as measurement procedures.

System Deployment

The culmination of the project was to apply the BRIDGE VAS on an actual production bridge job, requiring long-term integration into a fabrication shop. This project not only illustrated the capabilities of the system, but also provided the opportunity to address issues that could only be seen in a production setting (i.e., actual sources of noise/errors, working conditions). Deployment in a fabrication shop was a significant step, as it was the first time girders have been measured in a production setting and the first time entire girder lines and large, complex girders have been measured in this environment.

Deployment Bridge Details

Selection of a suitable bridge job for this effort required collaboration from a State Department of Transportation and the bridge fabricator. The State of Tennessee was supportive of this concept and allowed use of the system on a bridge job that was scheduled for fabrication by the project bridge fabrication partner. The bridge is located in Sumner County south of Gallatin, Tennessee on State Rt. 109 over the Cumberland River.

The three-span bridge has five lines of girders, each with six girders spliced together to form a continuous girder line. The total length is approximately 830 ft. Two full lines (12 girders) were measured with the BRIDGE VAS. Nine-and-one-half girders (9 girders with full-sized holes at both ends, and 1 girder with full-sized holes at one end and no holes at the other end) were fabricated with full-sized splice holes, representing changes to the conventional fabrication process. Two-and-one-half girders (2 girders with no holes at both ends, and 1 girder with full-sized holes at one end and no holes at the other end) were fabricated with the conventional laydown process due to the production schedule. This process provided the opportunity to evaluate the BRIDGE VAS system within a production setting. Girder measurements were used to detail custom-made splice plates for girder pairs.

The 3D CAD model for one entire girder line is shown in Figure 7. The ends of the bridge span have a linear taper, with a maximum web depth of 10 ft. Girder lengths vary from 122 ft to 154 ft. Figure 8 illustrates the size of the girders, showing Girder 11B1-1 with a length of 141 ft 7 in and a constant web depth of 10 ft. The list of measured girders and their nominal lengths is shown in Table 1.

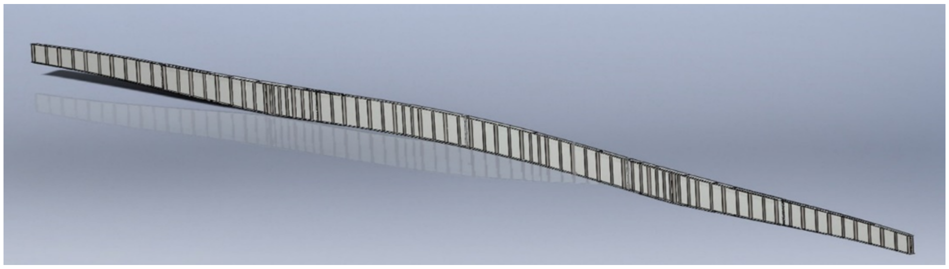


Figure 7. One Girder Line Containing Six Girder Segments Fabricated Using the BRIDGE VAS

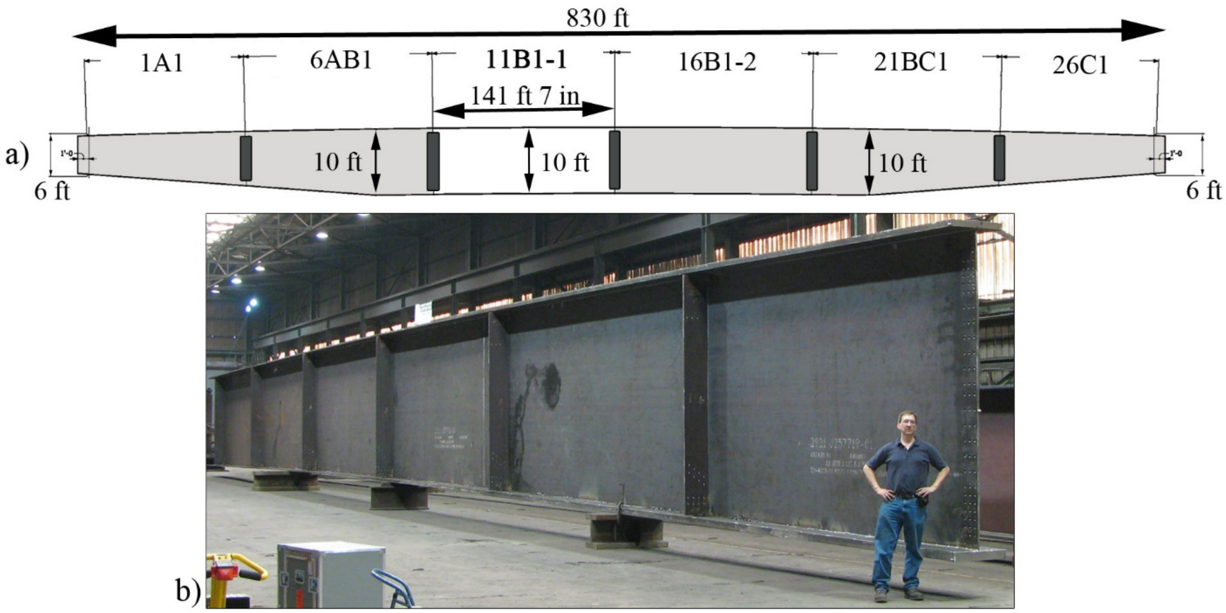


Figure 8. Girder Line: Straight with a Linear Taper, Showing a) the Entire Line Drawing and b) Girder 11B1-1 (Length 141 Ft – 7 In, Web Depth 10 Ft)

Table 1. Shop Drawing (Nominal) Girder Lengths for Girders Measured with the BRIDGE VAS

Girder	Nominal Length	Girder	Nominal Length
1A1	121 ft - 9$\frac{13}{16}$ in	2A2	121 ft – 9$\frac{13}{16}$ in
6AB1	146 ft - 10$\frac{9}{16}$ in	7AB2	146 ft - 10$\frac{9}{16}$ in
11B1-1	141 ft – 7 in	12B2-1	141 ft – 7 in
16B1-2	153 ft - 7$\frac{3}{16}$ in	17B2-2	153 ft - 7$\frac{3}{16}$ in
21BC1	146 ft - 10$\frac{5}{8}$ in	22BC2	146 ft - 10$\frac{5}{8}$ in
26C1	120 ft - $\frac{15}{16}$in	27C2	120 ft - $\frac{15}{16}$in

Fabrication Shop Integration

The BRIDGE VAS was integrated into the Hirschfeld Industries shop in Abingdon, Virginia for over four months, from September 7, 2011–January 18, 2012. The system was operational in the shop for 134 days. In this extended integration period, the system experienced the environment of all normal shop operations, from extreme heat to extreme cold. Ambient temperatures in this period ranged from 14 °F to 83 °F. The equipment was used in and around all normal shop processes.

Girder Fabrication Process

In order to fully operate the BRIDGE VAS on this production job, changes in normal fabrication processes were required. To perform virtual assembly of girders and custom-made splice plates, fully fabricated girders, including splice holes, were needed. The normal fabrication process involved fabricating girders with no splice holes and then match-drilling girder pairs during the laydown procedure. It was necessary to modify this process such that full-sized splice holes were placed while the girders were still being fabricated. In this way, the actual position of the holes could be determined using the BRIDGE VAS. These data were then used to produce a custom splice plate that fit the holes and set the combined camber, without ever requiring the laydown procedure necessary when using normal fabrication processes.

The general procedure for drilling holes for this bridge was based on manual drilling on flat plates using a template clamped to the plate being drilled. Drilling was typically performed with a magnetic-base drill. It is important to note that the bridge shop did not use the most advanced drilling equipment. This demonstrates that it is not a requirement to have the most technological advanced shop in order for the BRIDGE VAS to be used.

Because of fabrication schedule constraints, a subset of girders was fabricated with full-sized holes drilled from templates, as described previously. The remainder were fabricated with conventional match-drilling laydown methods. As new fabrication methods were employed and this was a learning process for the fabricator, the hole-drilling procedures were varied through the process of girder fabrication. With the initial girders, holes were placed in flat plates at both ends prior to web-to-flange welding. Other procedures placed holes by template on flat plates at the working end (WE) of the girder and by template after web-to-flange welding at the right end (RE) of the girder. The WE corresponds to the reference on a shop drawing, typically the left side of a girder in a 2D drawing. The WE will typically be the end toward the front of the shop, as long girders cannot be flipped end-to-end in a shop due to space constraints. Girder length and stiffener locations are determined relative to the WE of the girder. The RE of a girder is simply the other end of the girder. Different fabricators may use other terms for the RE.

Due to scheduling constraints, two and one-half girders were match-drilled using conventional methods. Table 2 summarizes the methods for hole placement in each girder in Line 1 and Line 2. While changing the fabrication procedures to place full-sized holes is an important part of putting the BRIDGE VAS into use, a variety of methods can be used to accomplish this goal and this was not considered a main focus of this project.

RESULTS

The results of this project are divided into four sections:

1. Fabrication process assessment
2. BRIDGE VAS design
3. BRIDGE VAS girder measurements examples
4. Production bridge shop deployment.

Table 2. Hole Drilling Procedures for Girders in Line 1 and 2 (WE=Working End, RE=Right End)

Girder	**When/How Holes Placed**
2A2	Holes only in one end (WE is at bearing).
1A1	Holes only in one end (WE is at bearing).
12B2-1	This the first girder fabricated with holes in both ends. Holes placed in plates at both ends using template before web-to-flange weld.
11B1-1	Holes pre-drilled in plates only in WE web and flanges. After web-to-flange weld, drill holes by template in the RE.
6AB1	Holes pre-drilled in plates only in WE web and flanges. After web-to-flange weld, drill holes by template in the RE.
7AB2	Holes pre-drilled in plates only in WE web and flanges. After web-to-flange weld, drill holes by template in the RE.
17B2-2	Holes pre-drilled in plates only in WE web and flanges. After web-to-flange weld, drill holes by template in the RE.
26C1	Holes only in one end (RE is at bearing).
27C2	Holes only in one end (RE is at bearing).
16B1-2	Holes pre-drilled in plates only in RE web and flanges. Normal laydown fit-up for WE.
21BC1	No holes in WE or RE. Splice made by conventional laydown fit-up.
22BC2	No holes in WE or RE. Splice made by conventional laydown fit-up.

Fabrication Process Assessment

During the course of this project multiple visits were made to Hirschfeld Industries shops in Colfax, North Carolina, and Abingdon, Virginia, to study fabrication processes. These shops are generally believed to be representative of steel bridge fabrication shops in the United States. Procedures used in these shops are, in general, not unusually technologically advanced and do not represent methods that are highly uncommon. The currently used laydown match-drill process, as shown in Figure 9, is used in these shops and was examined in detail.

Figure 9. Conventional Laydown Match-Drilling of Girders

Currently used record-keeping processes in these shops are paper-based. An example of actual laydown measurements records of camber and girder length is shown in Figure 10. This type of record does not contain a high level of detail and is difficult to extract information from at a later date.

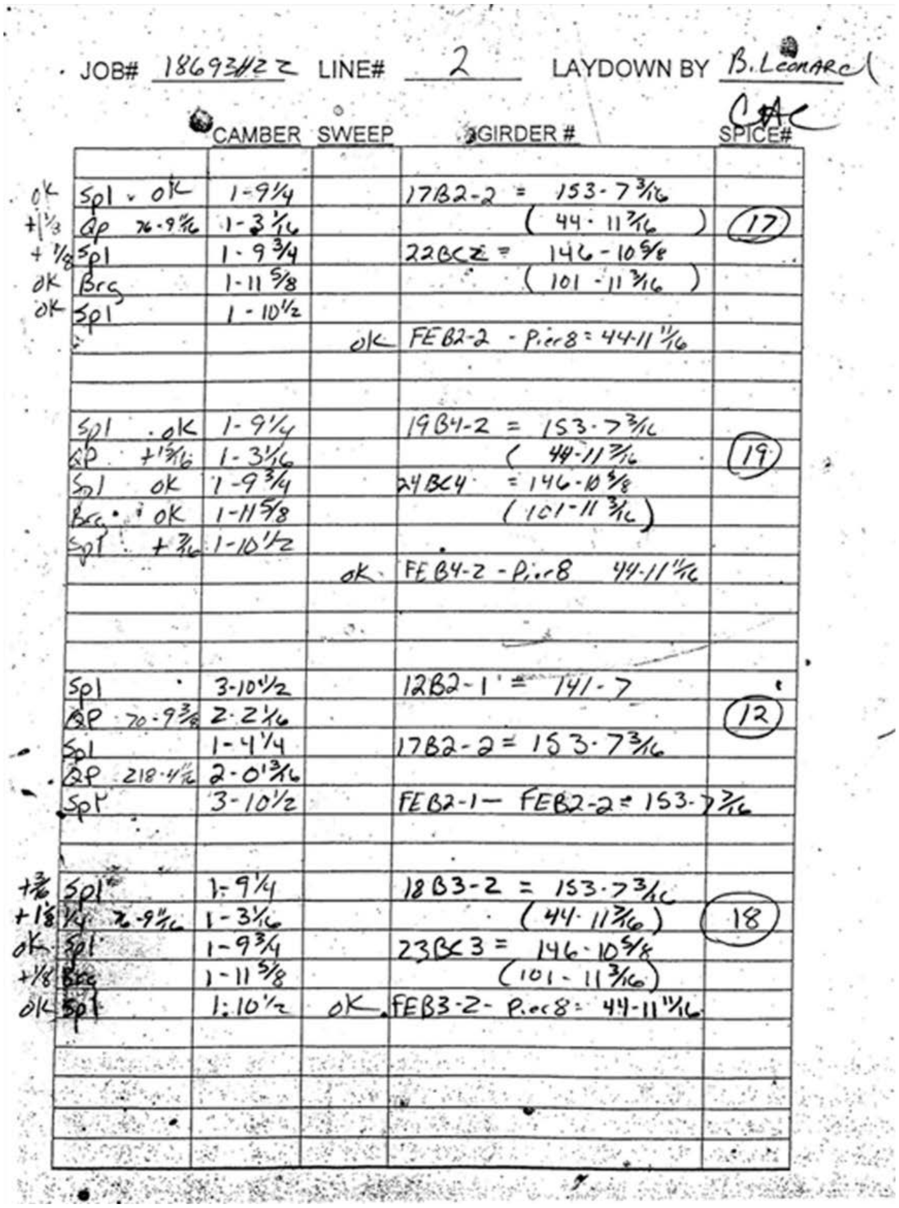


Figure 10. Typical Fabrication Shop Paper Record for Laydown Match-Drilling

BRIDGE Virtual Assembly System Design

In this project the specific application of the virtual assembly concept is referred to as the BRIDGE Virtual Assembly System (BRIDGE VAS). A system capable of working in a production fabrication shop environment was designed, built, and tested. This system design leveraged previous work on girder measurements and resulted in the development of a complete system with unique design features that were demonstrated to work effectively in a typical steel bridge fabrication shop. The system is intended to eliminate the need for conventional match-drilling. The BRIDGE VAS is shown making measurements in a fabrication shop in Figure 11. The BRIDGE VAS measures girders in the standing position, as opposed to the conventional match-drilling process where girders are laid on their sides.

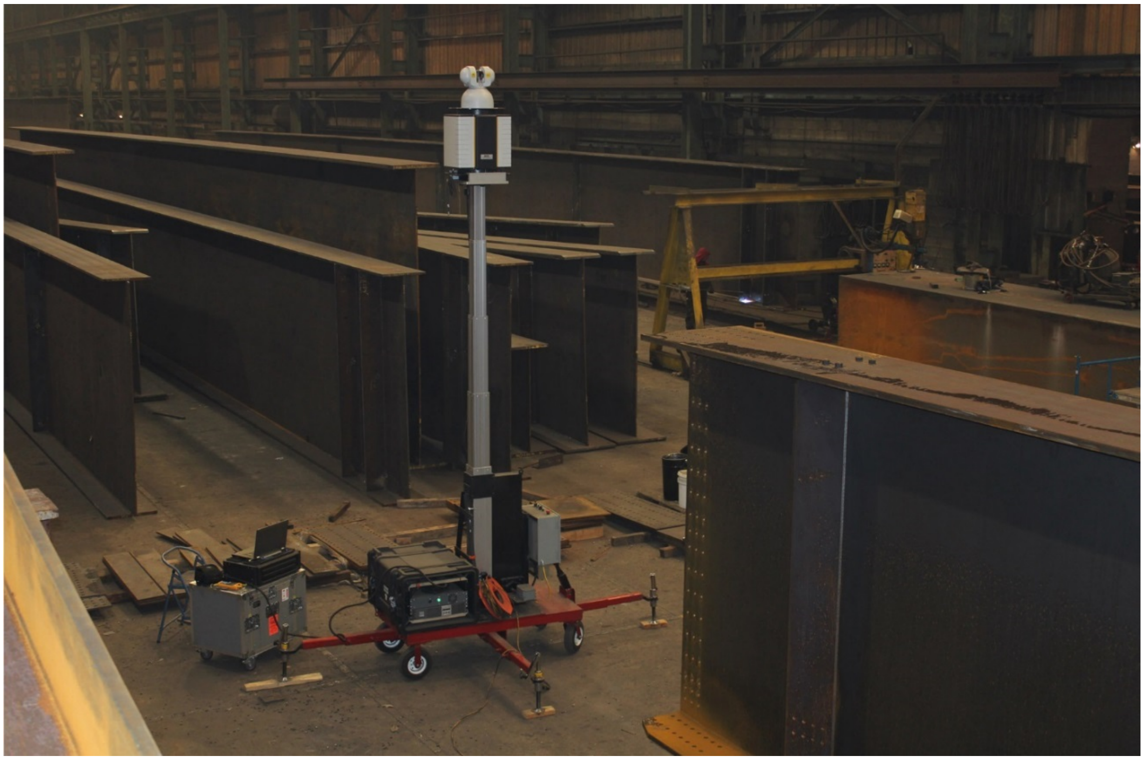


Figure 11. BRIDGE VAS Measuring a Steel Girder in a Fabrication Shop

System Design Criteria

The overall design criteria were identified for a system that can operate in any typical fabrication shop, requires minimal changes to the shop, and works in a near or fully automated manner. These design criteria are as follows:

1. Fits in a common steel fabrication shop with minimal changes
    - Can work in harsh shop conditions (dust, debris, vibrations, temperature)
    - Is not designed to work in only the most advanced shop
    - Does not require dedicated work space/special measurement room.
2. Does not require special gantry or major capital investments to deploy the equipment
3. Is capable of measuring the full range of girders and components to be fabricated
    - Highly flexible, mobile system
        - Standard plate girders, curved girders
        - Large haunched, tapered girders

    - Tubs, boxes, very complex parts

- Use in the shop or in the field.

4. Makes automated measurements

    - Easy to operate
    - Measure directly on a specimen
    - Does not require manual operator measurements or intervention
    - Can measure an entire girder without repositioning the girder during measurement.

5. Works with existing processes

    - 3D CAD models from 2D shop drawings
    - Direct output to CNC drilling machinery.

Works in Any Typical Steel Bridge Fabrication Shop

The system is designed to work in a regular area of shop floor, with no special modifications required (i.e., no need for special lighting, a dust-free clean room, limiting vibrations, or other highly restricted activities). Any open area can be used and the system can work in a limited amount of space if needed. A dedicated area of the shop floor would be beneficial for optimal day-to-day use. The main measurement area requirement is an unobstructed view of the girder, which would entail control of the flow of people and equipment movement within the measurement area. A clearly delineated measurement area can assist in this effort for efficient measurement of girders, similar to safety walk paths used in many shops. Total restriction of access by other shop personnel to this measurement area is not necessary. The worst-case effect will be that a small amount of data may be lost if the line-of-sight laser measurement path is temporarily blocked by a person walking by a girder, a case that can be identified by the system and the measurement repeated.

The system is designed to operate in and around normal shop activities making measurements in a production environment. It can withstand the type of dirt and debris normally encountered in a shop. Figure 12 shows the system working around some of these activities, which includes welding, grinding, drilling, and surface blast machines (e.g., Wheelabrator).

The system is designed to operate on typical shop floors. It can maneuver in and around typical obstacles in a shop. Floor conditions can vary from shop to shop. While most floors are concrete, the condition of the surface may vary and there may be various obstructions. For example, there may be tracks for various equipment (welders, surface blast machines, etc.), tie-down locations, or other obstructions. All of these obstructions need to be successfully maneuvered over or around by the system.

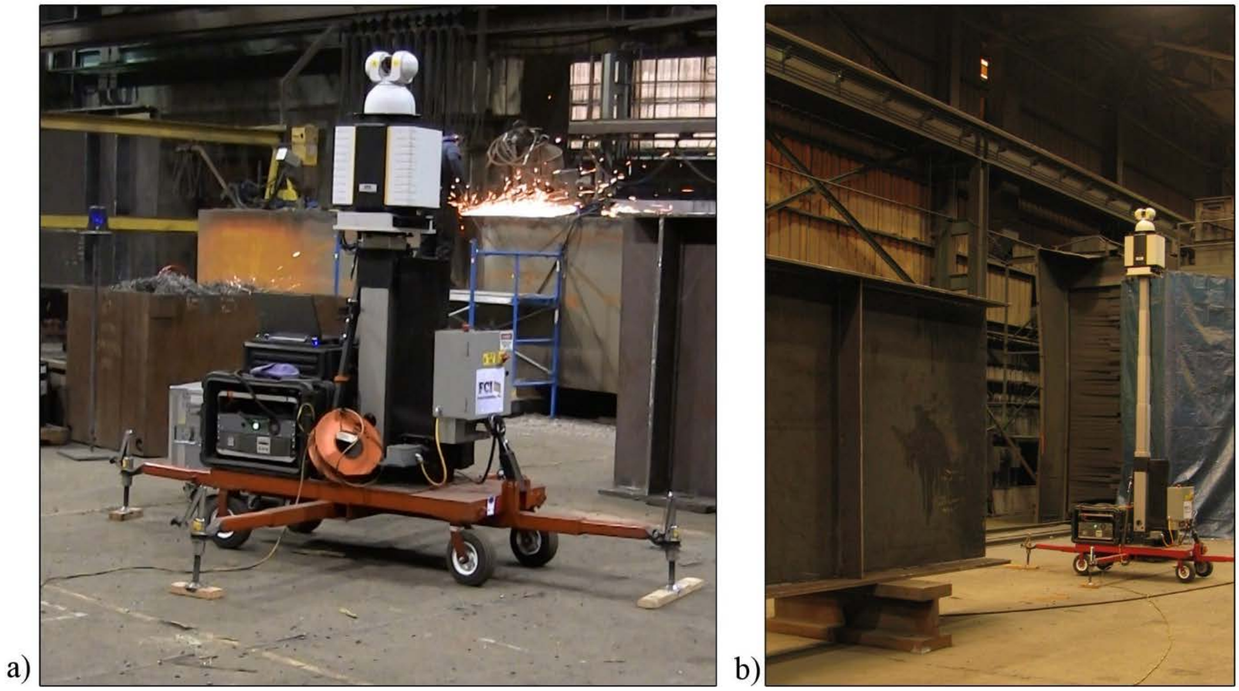


Figure 12. System Operates in Normal Shop Environment Around Existing Processes; Such as a) Grinding and b) Blast Cleaning

Works on All Girders

Bridge girders vary substantially in size and design, requiring a very flexible measurement system. In fact, almost every bridge design is unique. This characteristic separates bridge fabrication from other industries, where more standardized designs and manufacturing processes can more easily lead to automated measurement systems. In order to be robust, a bridge measurement system must be adaptable to a wide range of steel element sizes and shapes that will be encountered. Standard plate girders can range from a few feet to well over 15 ft in height. Tub or box girders can be very deep and can be curved. Curved plate girders can also vary widely in size and curvature.

Because it is a mobile system, the BRIDGE VAS is not restricted by girder size or shape in a shop. A compact, moveable platform maneuvers around girders for measurements. This design enables measurement of standard plate girders and large, complex tub girders, as seen in Figure 13. A girder is placed in the measurement area and then not moved for all BRIDGE VAS measurements. This eliminates the need for operator manipulation of the girder (i.e., precisely blocking a girder to make a level web, flipping over a girder laying on its side, and so on).

Other design approaches restrict the types of girders that can be measured. A common approach to the measurement of large objects is to construct a gantry. In this regard, there are commercial vendors that offer advanced gantry-based drilling equipment that also include various types of measurement capabilities. It is important to note that such gantry-based drilling equipment does not incorporate the full capabilities for virtual assembly. Compared to the BRIDGE VAS design, a gantry-based measurement system for bridge fabrication is not as

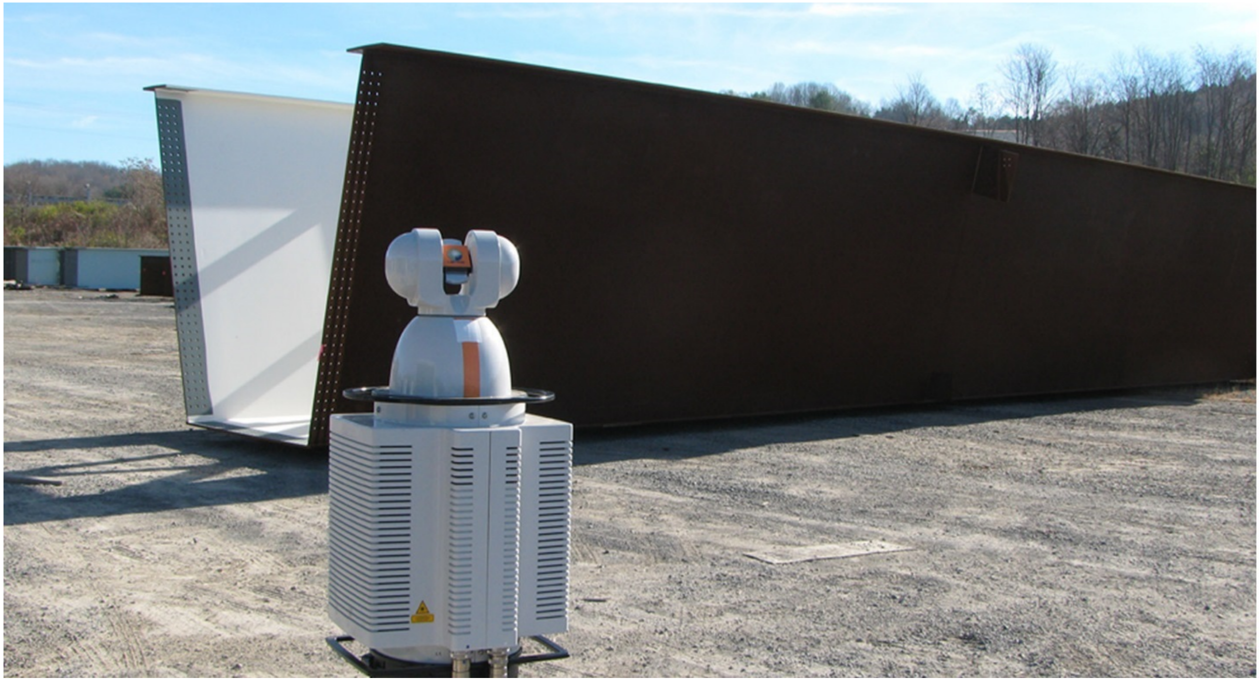


Figure 13. BRIDGE VAS Measures All Types of Fabricated Girders Including Large Tubs

flexible, is significantly more expensive to set up and maintain, and requires substantial changes to a shop. Only certain size and shaped girders can be measured in this gantry type of a system.

The mobile BRIDGE VAS measurement platform has the ability to measure a small depth girder or a large depth girder. A vertical mast positions a 3D coordinate measurement instrument at different heights in order to measure multiple girders sizes. The current system achieves a measurement height of over 16 feet. The design of this vertical mast is critical, in that an extremely stable system is needed in order to make accurate measurements. The mast design is very stiff, permitting accurate measurements in a fabrication shop.

Works in a Semi-automated or Fully Automated Manner

The measurement system is designed to operate in a production setting, measuring girders quickly, efficiently, and with minimal operator intervention. Ideally, system operation should not require highly skilled personnel. The automation capability is centered on the characteristics of the 3D coordinate measurement system designed into the overall BRIDGE VAS. There are a number of ways to make measurements on bridge girders, each with various advantages and limitations. The primary reason the BRIDGE VAS can operate with minimal intervention is the ability to remotely measure directly on the girder surface without requiring a special target or marker. This is contrasted against any method that requires touching a measurement point with a special probe or placing a special target for measurement. This remote measurement capability includes the measurement of splice holes, which the system can measure directly without any special target.

System Overview

The BRIDGE VAS consists of a 3D coordinate measurement system mounted on a mobile frame along with an operator workstation and computer. The main components are shown in Figure 14, with details for each main component provided in the following sections.

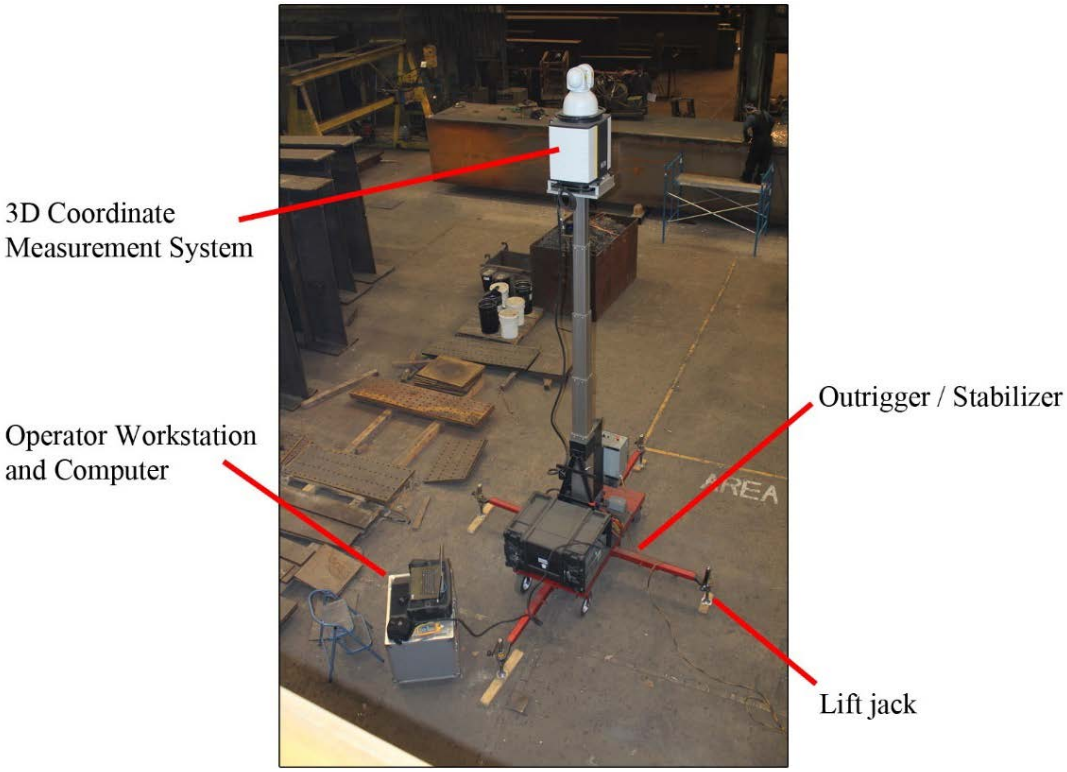


Figure 14. BRIDGE VAS Basic System Components

3D Coordinate Measurement System Characteristics

The measurement component is one of the most important aspects of the overall system and the hardware was specifically designed to provide very unique features that cannot currently be found in any other system. Measurements are made with a 3D coordinate measurement instrument. The system uses a highly specialized laser measurement technique and works over a very large volume, within a 328-ft diameter sphere around the instrument. In this very large volume, measurements can be made with 3D accuracy of 0.0040 in at 33 ft and 0.0118 in at 98 ft. These very accurate measurements can be made directly on the girder surface with no special target. Even holes are measured directly, without a target. The ability to measure directly on a girder, without requiring a special target, enables the ability to achieve full or near-full automation. High measurement accuracy is needed to measure all aspects of a girder, especially the measurement of splice holes, in a challenging environment.

The characteristics of the laser-based system used in the BRIDGE VAS are distinctly different from other LIDAR systems, such as those currently used for roadway surveys and crude as-built plans for bridges. These LIDAR systems do not have sufficient accuracy for many of the types of needed measurements in bridge fabrication QA/QC, with typical LIDAR accuracy of around ½ to 2 in (13 to 50 mm) and high-end accuracy of around ⅛ in (3 mm). These systems often produce very large point clouds of data that require significant labor-intensive post-processing.

Temporary Alignment Targets

The system uses temporary targets for the following two main purposes. A first purpose is for alignment of the physical girder to the 3D CAD model. For the initial measurement with the 3D coordinate measurement instrument, the system needs to know approximately where the girder is located in space. Typically, four targets are placed at known locations. The second main purpose is for moving the mobile measurement platform. Targets are placed on the top flange of a measurement girder for repositioning the mobile base of the system to different vantage points around the girder. These temporary targets are positioned along the length of the girder at both sides of the flange. Each time the mobile base is moved the targets are measured and used to maintain a common coordinate system. Figure 15 shows examples of temporary alignment targets.

a) b)

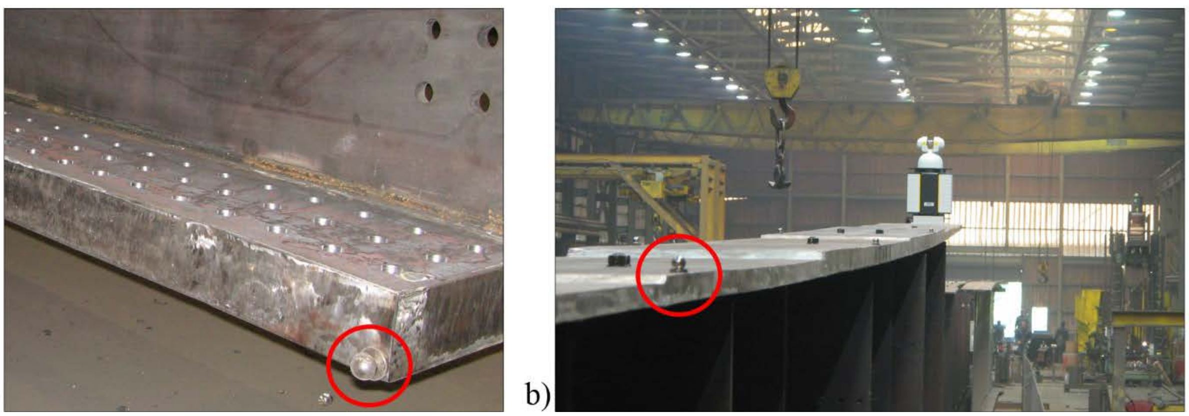


Figure 15. Magnetic Mounted Targets a) for Alignment to CAD and b) for System Repositioning

A number of specialized targets have been designed for customized uses. In its simplest form, the temporary targets are made of a rare-earth magnet and a 1-in diameter steel tooling ball. The design is very low-cost, rugged, and robust. The targets have a backing fixture to prevent erroneous measurements around the target and a unique identification number. Targets easily attach to and detach from a girder.

Validator Target

A special-made validator target is placed on the girder specimen and is measured during the process of collecting data from the girder. This validator target contains known geometric features, such as steps of known sizes and holes of known size and location, and is shown in Figure 16. The purpose of this validator target is to provide measurement validation and a level of confidence for the BRIDGE VAS girder measurements. The validator target data are permanently embedded in the overall data file along with all other girder data.

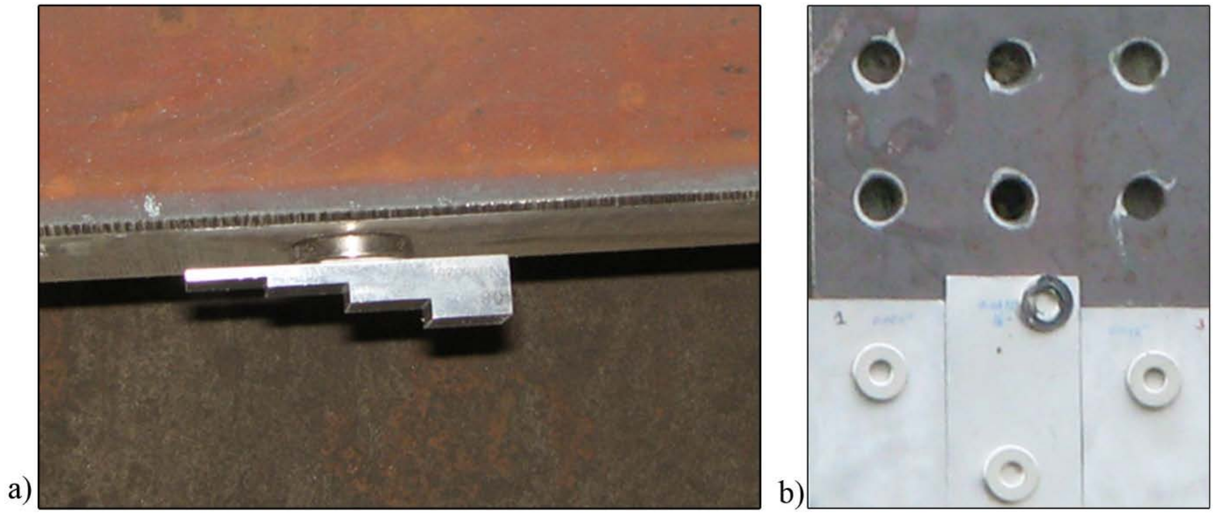


Figure 16. Validator Targets with a) Precision Steps and b) Hole and Step Patterns

System Process Overview

The system encompasses all aspects of integrating virtual assembly procedures into a fabrication shop; from the integration of shop drawings to output of files for CNC drilling machines, see Figure 17. The first part of the overall process is to take the existing 2D shop drawings and turn them into a 3D model of the girder. With a 3D model of a girder, all measurements are preplanned in order that data collection can then be automated. The system processes measurements to produce customized reports and designs for splice plates based on virtual assembly of multiple girders.

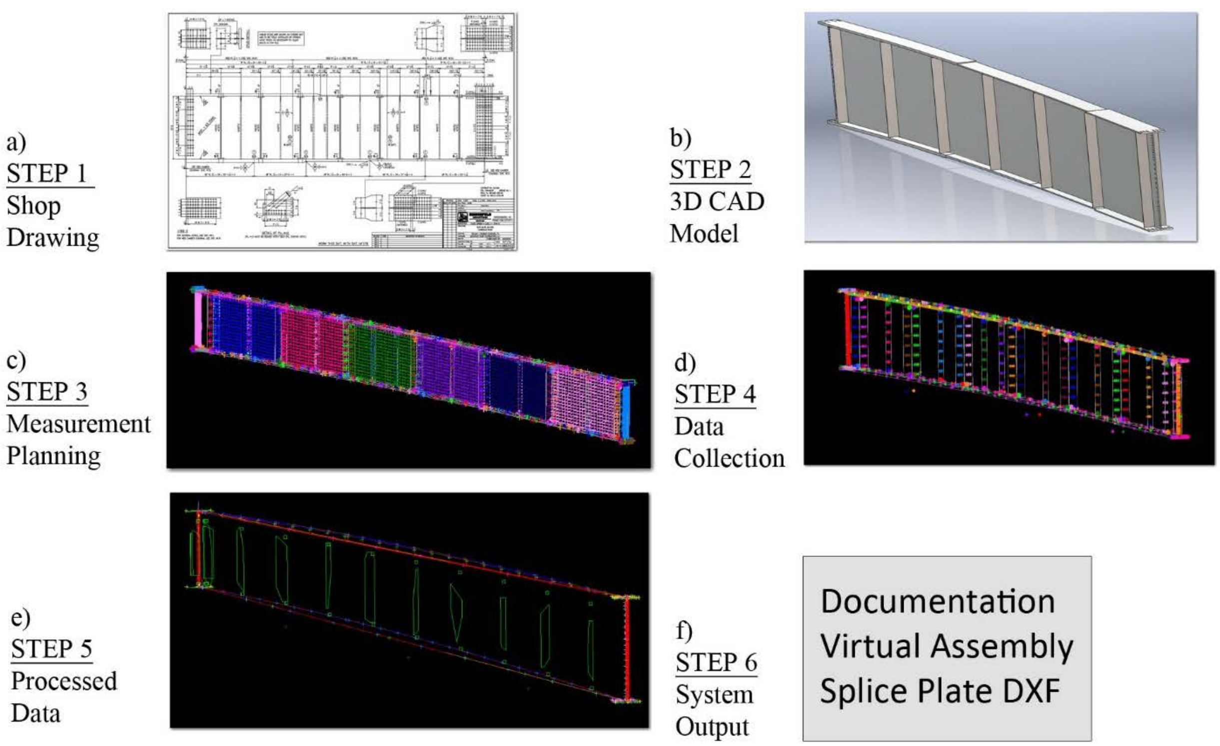


Figure 17. System Processes Steps

Software Components

The system contains a unique collection of software components that perform the following functions:

1. Converts standard 2D shop drawings into a 3D model of a girder

2. Plans measurements based on the 3D model of the girder

3. Automates the measurement process of the noncontact measurement instrument and collects data on the girders

4. Processes the measurements and produces engineering data (e.g., camber, sweep, end-kick, hole locations, length, web panel distortions, etc.)

5. Combines measured data with finite element simulations of girder movement to correct for girder blocking conditions or other movements

6. Produces custom reports

7. Virtually assembles multiple girders and produces custom splice plate designs

8. Stores a permanent digital record of the measure girders.

2D Shop Drawing to 3D Model

Currently used bridge shop drawings are 2D engineering drawings that cannot be directly converted into a 3D model, as shop drawings do not show the components drawn to scale. Given the typical sizes of girders, where they are very long compared to their height, the scale of the drawing must be distorted so that the girder can be displayed on a sheet that is readable. Shop drawings also do not directly show the girder camber and sweep. An off-the-shelf software tool that automatically converts existing 2D CAD files into 3D models will therefore not work directly on a bridge shop drawing. For this purpose, a software component was developed to perform this conversion process. The information needed for this 3D model creation can be manually extracted from the 2D shop drawing or it can be automatically extracted from tables of information used to create the shop drawings. These tables of information include the 2D camber diagram for a girder. A 3D models needs to incorporate camber, sweep, and all other girder geometric features. An actual 3D model created from a shop drawing is shown in Figure 18. The process developed for creating 3D models from 2D shop drawings has been designed as to require minimal operating intervention and training. The BRIDGE VAS can use as input any 3D CAD model that already exists for a girder. While these models are now not always available, in the future the availability of 3D models from the design process is expected to be more prevalent.

a) b)

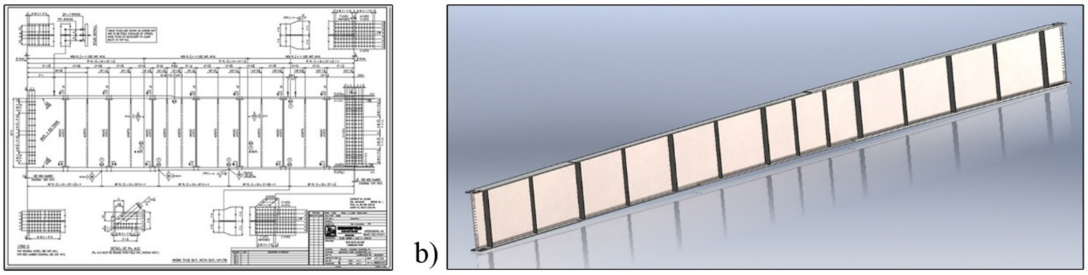


Figure 18. Conversion of 2D Shop Drawing into a 3D CAD Model

Measurement Planning

Once a 3D model has been created for a girder, a software component will define girder measurement locations. Measurements are small collections of specifically identified locations designed to be used for the calculation of specific processed end-measurements. The girder measurements are not large high-density point clouds that need significant post-processing, but are a smaller focused set of measurement points. Measurement planning produces a series of discrete measurement points that can be automatically collected with the 3D measurement system.

Data Collection

Once the measurement planning software component defines the measurement points, another software component can interface with the 3D coordinate measurement instrument to automatically collect the data points. Data collection is fully or near-fully automated. For all girder measurements, the laser scans the girder surface directly with no special targets or markers and no girder preparation needed. Data collection includes an initial alignment of the measurement system to the physical girder using a small number of temporary targets placed on the girder at approximately known positions. Data collection also involves repositioning of the system at multiple locations around the girder.

Data Archive

A software component archives all data collected for a girder. This includes the raw data of measurement points and the processed data with specific calculated measurements (e.g., length, camber, sweep, web panel distortions, etc.). Data archiving provides layers of data security that prevents changes to the original raw data in order to provide a certifiable, traceable data set.

Data Processing and System Measurements

A software component processes the raw measurement points and creates final output data. Raw measurements are made directly from the girder surface and are then processed to produce a final desired measurement. Final output data include, but are not limited to, length, camber, sweep, stiffener locations, and web panel deformations. The system can also create custom measurements to adapt to future measurement needs or specialized girders.

Finite Element Model Adjustment

A software component manipulates the raw measurements from the girder to adjust for both changes in girder shape caused by blocking and for changes in length caused by temperature. Girders are measured in the standing position with the girder resting on blocks. The position of these blocking locations can result in changes in shape of the girder, as the girder will deflect and change shape under the influence of gravity. The system measures the location of the blocking points with respect to the girder. The finite element modeling (FEM) software component performs at least two functions. First, the FEM software component determines if the measured blocking locations result in appreciable deflection. Second, if the girder does experience appreciable deflection, the FEM component can adjust the shape of the measured girder to compensate for this deflection.

Report Output

A software component creates custom-made reports for the end user. The reports include measured data, such as length, camber, sweep, stiffener locations, and web panel deformations. The system can also output final measured data in standard CAD formats (e.g., IGES, STEP).

Virtual Assembly

Processed data from multiple girders can be combined together to perform a virtual assembly. Virtual assembly is analogous to the physical laydown process but can be done using software tools instead of physically placing girder components together. The output of the virtual assembly component is a design for a custom splice plate that will join pairs of girders. Splice plate design files can be generated in a variety of formats, including DXF files, which can be directly sent to a CNC drilling machine to fabricate the plate. The virtual assembly component is provided inputs from the shop drawings that define how the girders are to be fit together. These are typically provided in the form of a line camber diagram or a combined camber diagram for a girder pair. The software component adjusts the position and orientation of girders to optimize the alignment to the nominal camber diagram provided from the shop drawings. Typical adjustments include separation of the girders, defined as the web gap, and the angle of the girders rotated in the plane of the web to optimize ideal shop drawing camber criteria. Adjustment of girders in the virtual assembly software is illustrated in Figure 19. Once the alignment is optimized, then design files are produced for fabrication of splice plates (see Figure 20).

BRIDGE VAS Measurements

The BRIDGE VAS is designed to produce data that provide, at a minimum, the same type of information that is currently gathered in a fabrication shop. This includes currently recorded parameters, such as length, camber, sweep, end-kick, and stiffener locations. The BRIDGE VAS, however, has the ability to provide these currently recorded parameters at a much greater accuracy than conventional methods. This increased accuracy is illustrated with a detailed discussion about the measurement of girder length. In addition to standard girder measurements, the system can make measurements that are not currently possible by

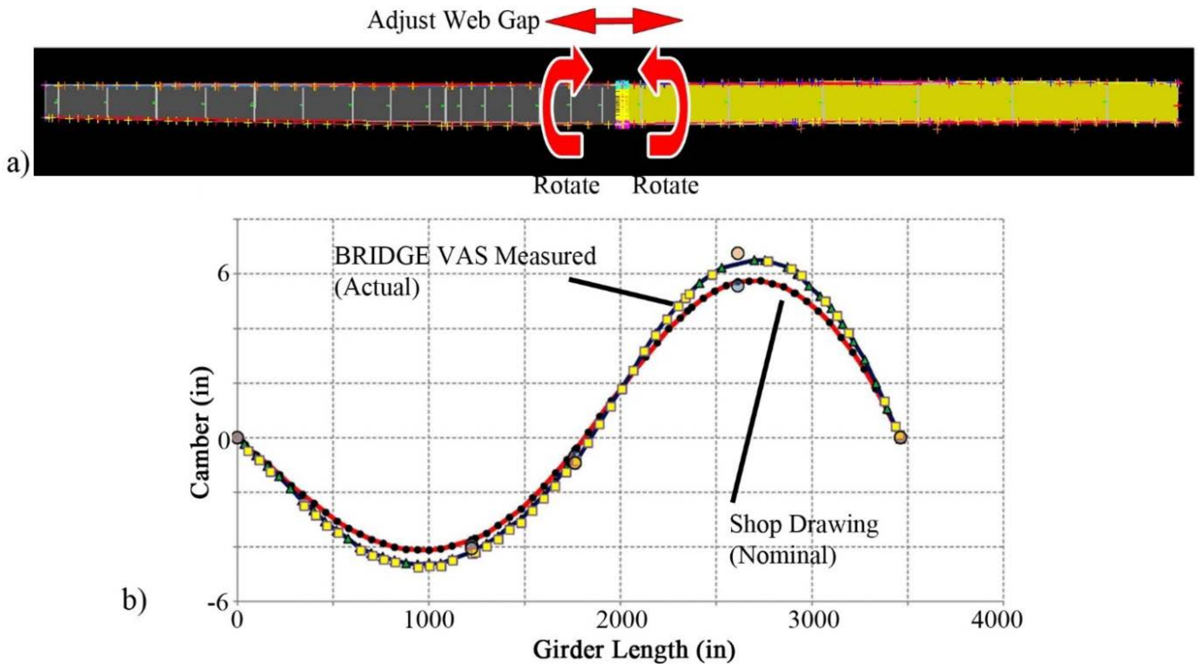


Figure 19. Virtual Assembly of Girder Pair with a) Measured Data from Two Girders Showing How Girder Are Virtually Positioned Based on the b) Combined Camber Shop Drawing Criteria

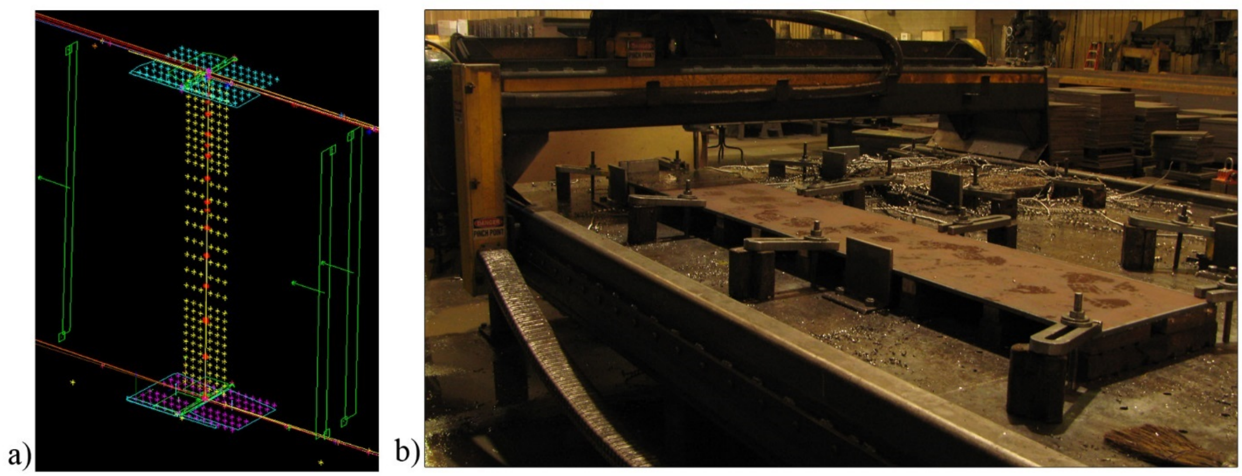


Figure 20. Virtual assembly of Girder Pair Output Showing a) Close-Up of Splice with Measured Hole Locations and b) CNC Drilling Machine Making Custom Splice Plate from BRIDGE VAS Output

conventional methods. One of the strengths of the system is that it can easily be adapted to types of measurements not currently performed or envisioned, to accommodate unanticipated future needs. Details on a subset of the measurements performed by the system are provided for the following parameters:

- Length
- Camber
- Sweep
- Stiffener Location
- Web Panel Deformation.

The following measurement issues were demonstrated:

- Accuracy of measurements with a tape measure
- Comparison of camber measurements in standing versus laydown position
- Comparison of conventional length and camber measurements to the BRIDGE VAS.

The BRIDGE VAS performs multiple levels of measurement validation in order to achieve very high accuracy 3D measurements over a very large volume. The scope of this report does not permit a detailed discussion of all aspects of BRIDGE VAS measurements. Measurement validation includes some of the components that are presented here, such as the validation target, and other aspects that deal with long-term operation of the instrument. For example, the BRIDGE VAS, when operated full-time in a shop, will require a periodic in-shop calibration and validation procedure. This procedure involves the measurement of a number of specialized targets that are arranged in the shop. This in-shop validation is quick and easy to perform.

Conventional Measurement Comparison

Measurements in a shop are typically made with tools such as tape measures, straight-edges, and string lines. Figure 21 shows a string line and straight edge used to make measurements by hand. Length, or the distance between objects, is one of the more common measurements in a shop. These length measurements are typically made with tape measures. Most day-to-day measurements are made with a reel several hundred feet long. There are also calibration standards that are periodically used to check other tape measures used in a shop. The certified tape measure is functionally equivalent to the day-to-day tape measure, but is purchased with a traceable calibration certificate. All of these shop tape measures are not designed to be tensioned to a specific value for length measurement, as is done in some surveying applications.

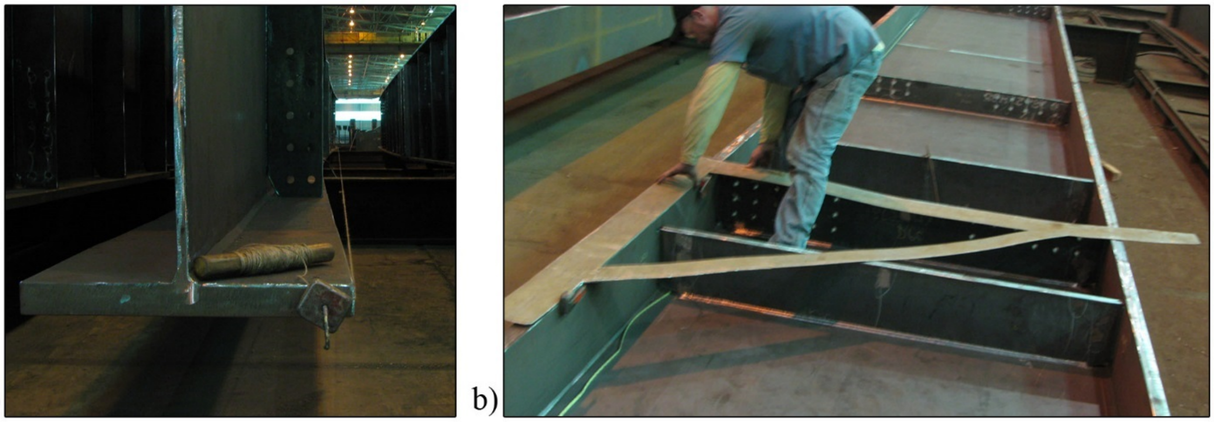

a) b)

Figure 21. Conventional Measurement Tools Showing a) String Lines and b) Straight-Edges

BRIDGE VAS Measurement Overview

BRIDGE VAS measurements are performed with a girder in the standing position. The system is moved around a girder in order to take measurements. This is fundamentally different than most current shop measurements, where girders are typically laid flat for measurements.

Girder Measurement Position

The BRIDGE VAS measures girders in the standing position, allowing the entire girder to be measured in one girder orientation (i.e., features on both the near side and far side of the girder web can be measured). Sweep is most easily measured in the standing position, because the girder sweep can change considerably due to blocking when on its side. However, girder camber can change in the standing position depending on the blocking locations. Because of this, blocking locations are measured with the BRIDGE VAS. Blocking location information can be used to either correct all measurements for dead load deflections or verify that these dead load deflections are negligible.

Additional Measurements

The BRIDGE VAS uses wireless sensors placed on the measured girder. These sensors measure the girder temperature and vibration during data collection. The girder temperature measurement is used to correct for changes in girder length due to ambient temperature changes. These temperature data can be used with software components that use finite element models and structural engineering equations to compensate the girder measurements. Magnetically attached wireless accelerometers are used to monitor girder movement during measurements. Excessive vibrations (e.g., if a girder was moved or hit by a crane) could invalidate measurements and can be used to filter out bad data points. Sufficiently low vibrations can validate measurement quality and are recorded in the overall data set for the girder.

Basic Procedure

The basic procedure for girder measurement starts with the girder to be measured being placed in the measurement area. The girder is placed upright and crudely blocked along its length at multiple points. The BRIDGE VAS is then moved to multiple positions around the girder to take measurements (see Figure 22).

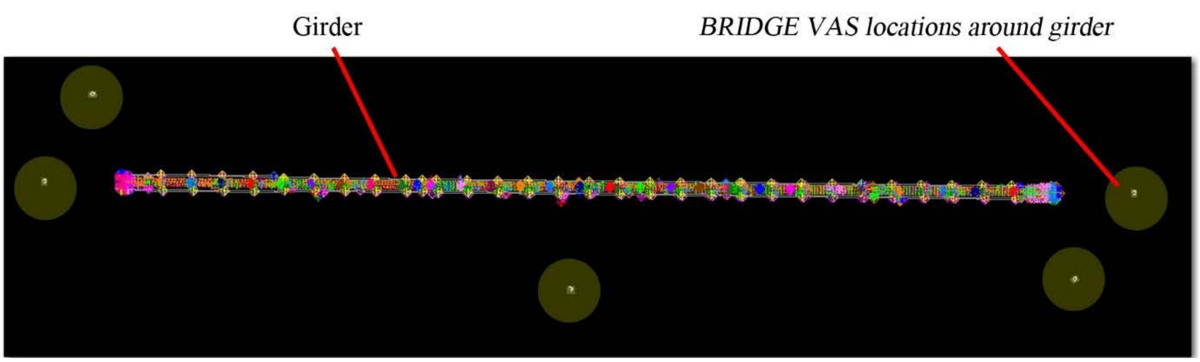


Figure 22. Typical Measurement Positions Around Girder

The following steps provide more details on the basic measurement procedure:

1. Perform initial setup.

   - Place CAD alignment targets on the girder (typically 4 targets).

- Place repositioning targets on the top of the top flange of the girder (or use other targets in the measurement area) (typically 4-8 targets).

- These targets are used solely for repositioning of the measurement system and are not used for any measurements.

2. Place the system in Position 1.

   - Align the CAD model.

   - Measure CAD alignment targets and perform alignment.

   - Data collection software components collect data.

   - Measure right end of the girder web holes, girder end surfaces, features on the near side of the girder (stiffener locations), bottom flange camber, and sweep.

   - Measure the repositioning targets.

3. Reposition the system to Position 2.

   - Measure the repositioning targets and maintain common coordinate system.

   - Data collection software components collect data.

   - Measure right end of the girder top flange and bottom flange holes, right end surfaces, and camber on the top flange.

   - Measure the repositioning targets.

4. Repeat for all other measurement positions.

5. Measure blocking locations.

6. Measure validator target.

Approximate Measurement Time

In general, a single typical-sized girder can be measured in about one hour. The amount of measurement time required per girder is dependent on the amount of data required and the manner in which the data are collected. Instrument repositioning can be manual or can be automated, affecting data collection time. The number of splice holes measured also affects total data collection time. For situations where splice hole patterns can be more tightly controlled, it is possible to decrease data collection time by reducing the number of measured holes.

Length

Measurement of length is commonly made in a shop, starting from flat plates at the beginning of the shop to the completed girder at the end of the shop. Length would at first impression seem to be a straight-forward measurement, but on a closer examination there are many subtleties. Measurements of flat plates of steel, such as for cutting web or flange plates, can be made by laying tape measures directly on the plate (see Figure 23). While the surface is not completely flat, the tape will follow the contour of the plate. Shop drawings typically specify chord distances. Measurement of a completely fabricated girder is more challenging because it is hard to make a direct straight-line chord measurement. For the fabricated girder, the tape cannot be placed directly where a measurement is needed due to obstructions and shape of the girder. The girder camber makes direct length measurements on a chord impractical in most cases. Tapes placed on a flange (or web along the flange) measure arc length. Stiffeners and other interferences often make a direct chord measurement of the girder web more difficult or impossible. Girders with tapers or haunches add additional difficulty to a length measurement.

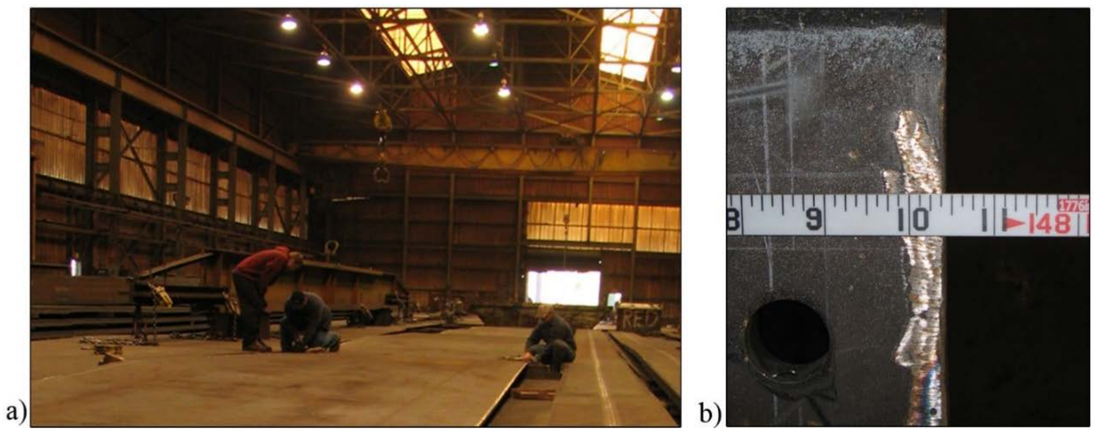


Figure 23. Tape Measurement a) of Flat Plates and b) Showing Measurement of an Irregular Edge

Current Girder Length Measurement Procedure

Fabricated girder length is measured using steel tape measures, placed on both ends of the web plate and read visually by eye. Girder web plates are measured with the girder in a horizontal (laydown) position. Measurements on girders with stiffeners are made by running the tape measure on the web plate behind the stiffener clips (small space between the top or bottom of the stiffener and the flange plate), as shown in Figure 24.

These manual tape measurements are used to verify girder length dimensions at the end of fabrication and for trimming girders prior to match-drilling a splice plate. Similar measurements are made to lay-out and place stiffeners along the length of a girder. Measurements to ends of girders are made by visually reading where the tape measure crosses the edge of the web plate. For measurements referenced to a stiffener, the tape must be placed sighting the position of the tape by eye behind the stiffener. Measurements to edges require the fabricator to determine where the end of the tape measure crosses the edge of the web plate. Web plate ends may contain irregular features and the exact end point is judged by the person performing the tape measurement.

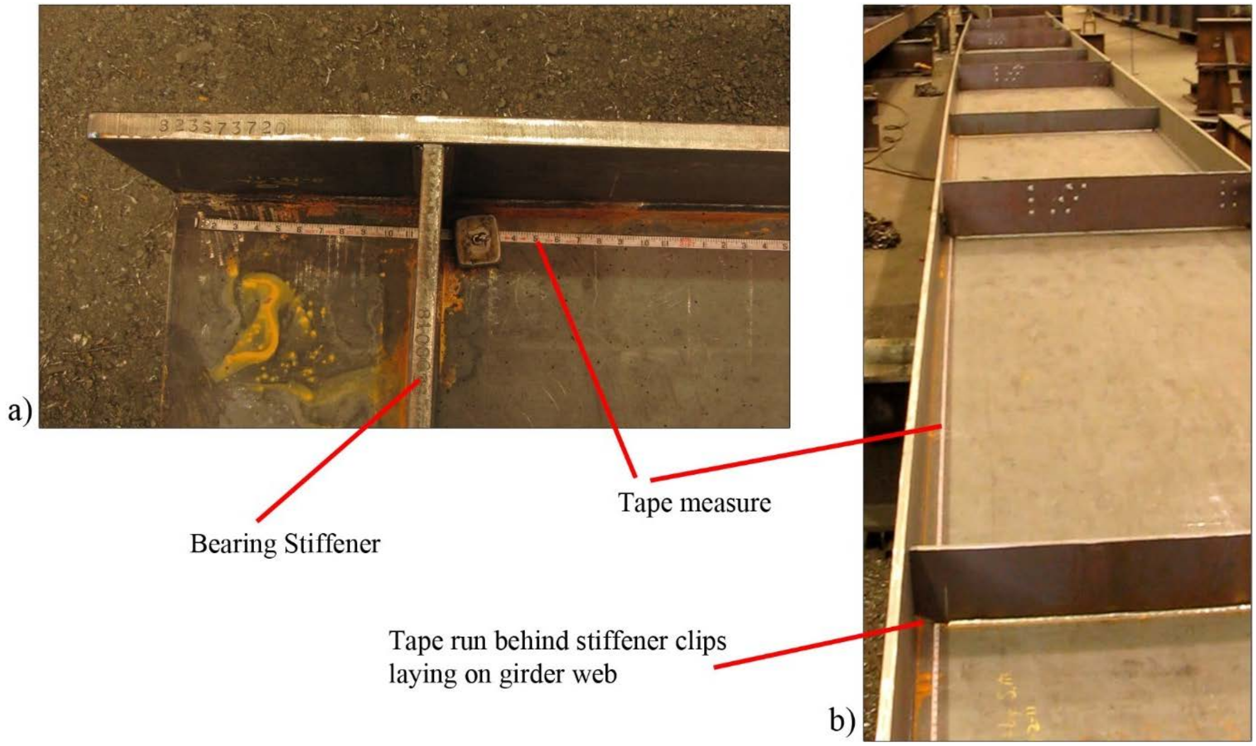


Figure 24. Conventional Length Measurements Using Tape Measure Showing a) Measurements Around a Stiffener and b) Measurements Behind Stiffener Clips

The data in the following sections show how the BRIDGE VAS measures length much more accurately than conventional tape measures and also quantifies accuracy of conventional length measurements with a tape measure. These examples highlight the importance of advanced measurement tools and show how they can uncover sources of error that may affect the overall structure.

Systematic Biases in Tape Measurements

Measurements with a tape contain systematic errors due to (1) kinks in the tape, (2) the tape not running in an exact straight line, and (3) measurement of arc length instead of chord length. All of these systematic errors work in the same direction, resulting in a tape measurement that is always longer than the true length. Therefore, all girders measured with a tape will be made shorter than intended. Additionally, all of these systematic error sources will increase with length (i.e., longer girders will result in greater measurement error).

A tape that has been used for a period of time or a tape that has not been handled with extreme care may contain kinks along the length. Each kink, if not stretched out with a tension on the tape, would result in a measurement greater (longer) than the true value. A kink in a steel tape will probably not pull out with tension, as the tape will in most cases be permanently deformed. An actual steel tape measure observed in use in a fabrication shop is shown in Figure 25, showing kinks along the tape length.

a) 

b) 

Figure 25. Tape Measure Used on Shop Floor Showing a) Bends and b) Kinks in Metal Tape

The second systematic bias is that the tape will meander along the girder and deviate slightly from an ideal straight line. Since tapes are typically used without tension, the tape will not be pulled straight. Even if a calibrated tension is applied, the physical constraints of stiffeners and other geometric features make it difficult or impossible to eliminate this error source. A meandering tape will also produce a resulting measurement that is greater (longer) than the true value.

The third systematic error in measurement with a tape is related to arc length versus chord length. Shop drawings typically provide girder length dimensions as straight-line chord lengths. Using conventional tape measurements, chord length is difficult or impossible to measure, particularly once stiffeners are in place (i.e., a string or tape cannot be directly pulled in a straight line from one end of the girder to the other). Typically arc lengths are measured, as opposed to the true chord length, as this is the only practical method to measure length of a fabricated girder with stiffeners. Measurements are made along the web near a flange, following the contour of the flange. Longer girders and greater amounts of camber will result in a greater difference in arc length to chord length.

This arc length versus chord length difference is known, but is generally assumed to small in magnitude. A practical example of the order of magnitude of this arc length measurement error is given for an actual girder fabricated in a shop. The difference between the chord length and arc length of the web plate at the bottom flange is 0.073 in (data shown in Table 3). Therefore, for a 153-ft long girder with 7¼-in camber, the difference in chord length to arc length is about 1⁄16 in.

Table 3. Example Arc and Chord Length Difference for a 153-ft Long Girder with 7 in of Camber

Measurement	**Length (in)**	**Length (fractional inches)**
Arc Length	1,840.011	153 ft - 4 in
Chord Length	1,839.938	153 ft - 3 15⁄16 in
Difference	0.073	1⁄16 in

Expected Accuracy of a Conventional Tape Measurement

Based on the systematic errors described previously, the question becomes what is the expected measurement accuracy for a tape measure. Prior to this project, the measurement accuracy of a standard tape measure used in a fabrication shop was not known and was not addressed in standard shop procedures or codes. To start, it is important to note that measurement accuracy using a tape for linear distance measurement is not defined by the smallest increment of distance delineated on the tape (i.e., $^1/_{16}$ or $^1/_8$ in), which is the resolution. Additionally, tapes can be purchased that have been calibrated and this calibration can be certified against some standard. However, this calibrated tape measure is fundamentally the same as any other tape measure in use in the shop and is subject to the same measurement errors.

To provide a basis to determine the basic accuracy of a tape measure in a fabrication shop, use of tapes in surveying applications was examined. Accuracy data from conventional civil engineering surveying applications indicate that in the best case scenario, reasonable accuracy achievable with a tape measure would be 1 in 5000 (Burtch, 2008; Wahhab, 2009). This level of accuracy is probably only achievable with very rigorous measurement procedures (i.e., very well-kept and maintained tapes, standard tension on tapes, measured temperatures). To illustrate this level of measurement accuracy, the following examples are given for some typical steel bridge girder dimensions. Estimated errors are shown in Table 4 and can be about ¾ in for a 300-ft measurement.

Table 4. Estimated Measurement Accuracy for Various Lengths Using a Tape Measure

Length Measurement	Estimated Best Case Accuracy (in)	Estimated Best Case Accuracy Fractional Dimension
120-ft long girder	120 ft · 12 in · ($^1/_{5000}$) = 0.288 in	≈ $^5/_{16}$ in
150-ft long girder	150 ft ·12 in · ($^1/_{5000}$) = 0.360 in	≈ $^3/_8$ in
Bearing to bearing for a 300-ft span	300 ft · 12 in · ($^1/_{5000}$) = 0.720 in	≈ ¾ in

Basic Length Measurement Example

Since no literature was found on the accuracy of length measurements for steel bridge fabrication, a series of tests were performed in a fabrication shop to quantify the measurement accuracy of a tape measure. Measurements were performed in the Hirschfeld Industries shop in Abingdon, Virginia. The purpose of these tests was to demonstrate typical measurement accuracy with a standard tape measure used in a steel bridge fabrication shop. Measurements were made with two different shop tape measures (actual tape measures used for work in the shop). The first tape measure was a 100-ft steel shop reference tape measure, which was a certified tape measure and is not used for day-to-day measurements. The second tape measure was a 200-ft steel tape measure that is used for day-to-day measurements. Measurements were made on the concrete shop floor and on the top of the bottom flange of a steel girder. Length measurements were made with these tape measures and compared with BRIDGE VAS measurements. In this case BRIDGE VAS measurements were made with a special 1-in diameter target that is used to track a consistent measurement location, as it is desired to precisely know the BRIDGE VAS measurement location relative to the tape measure. For analysis purposes, the benchmark is considered to be the BRIDGE VAS measurements. The plan view (looking down on the shop floor) of the measurement setup is shown in Figure 26. Targets P1 to P8 were placed on the bottom flange of the girder. Additional targets K1, K2, and K3 (bottom of the figure) were placed on the shop floor next to the girder. The position of the BRIDGE VAS is also shown relative to the floor and girder measurement locations.

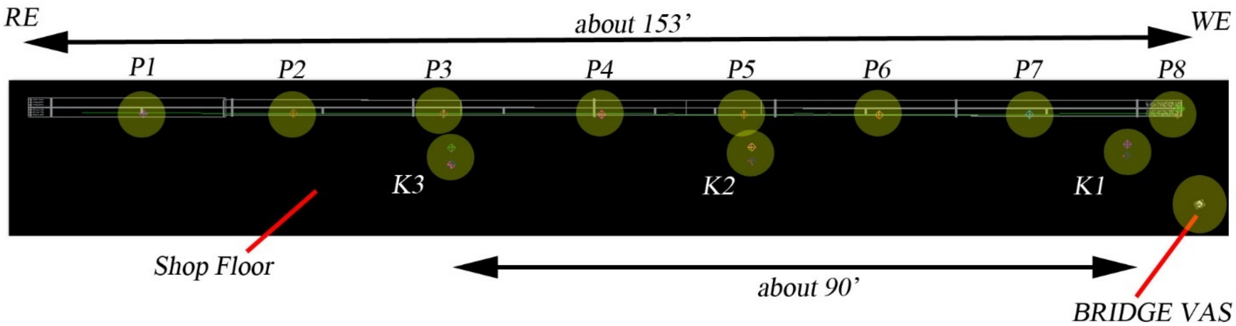


Figure 26. Setup of BRIDGE VAS, Tape Measure, and Targets for Tape Measurement Tests

These basic measurements show that the tape measurement accuracy is on the order of no better than 1 in 5,000 and are probably in the order of 1 in 3,500 to 1 in 4,000. Tape measurements are shown to be consistently greater than the true value. Tape measurements are systematically biased to produce a measurement greater than the true value. Kinking in the tape and the tape not running in a straight line were observed when performing the measurements in the shop.

Length Test 1: Certified Tape on Shop Floor about 50-ft Distance

The first test was a certified steel tape measure placed on the shop floor and secured in place with magnets (see Figure 27). The shop floor has a steel grid embedded in the concrete, nominally every 10 ft. These magnets secure the tape and also served as holders for BRIDGE VAS targets. The magnets and BRIDGE VAS targets were aligned by eye on the tape measure. The edge of the magnet was aligned with a tick mark on the tape and a known and fairly precise

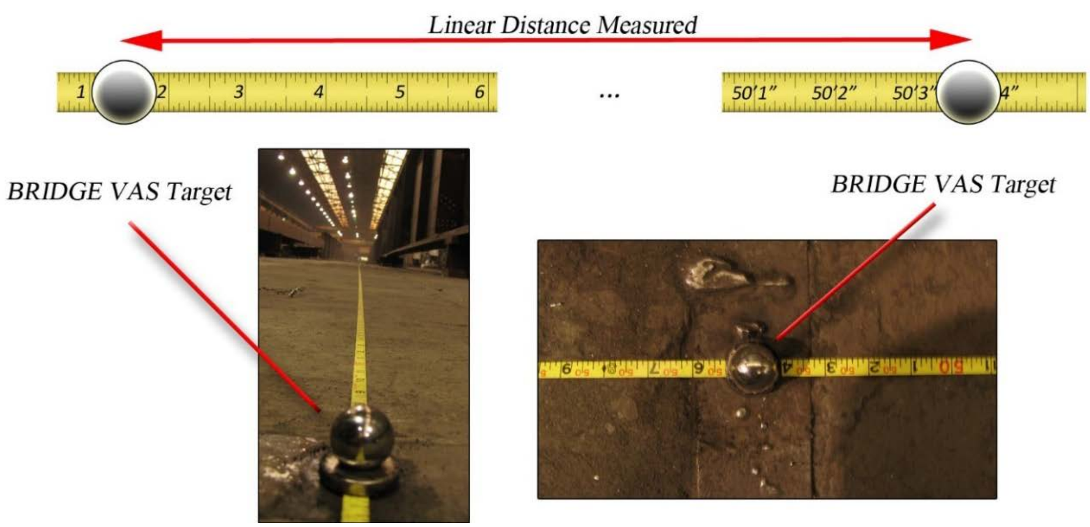


Figure 27. Certified Tape Measured Over About 50 ft on Shop Floor

offset from the edge of the magnet to the center of the target was used to determine the center of the target sphere. This BRIDGE VAS target alignment is subjective and will result in some measurement error in the following data. However, this error will be more random and will be very small compared to the other errors being quantified (placement of magnets can be achieved to at least the smallest increment on the tape measure).

The measurement procedure was to place the steel tape measure on the shop floor, place two BRIDGE VAS targets on top the tape measure by eye, and then make measurements with both the tape measure and BRIDGE VAS. Table 5 shows the tape measurement is greater than the actual distance.

Table 5. Certified Tape Measure on Shop Floor with 50-ft Distance

Measurement	Tape (in)	BRIDGE VAS (in)	Difference (in)	Difference (fractional in)
Distance K1-K2	600.250	600.179	-0.071	≈ -1⁄16

Length Test 2: Certified Tape on Shop Floor about 100-ft Distance

Tape measurement was made over a distance of about 100 ft. BRIDGE VAS targets were slightly repositioned on the tape measure and an additional target was added from the 50-ft distance test (Figure 28).

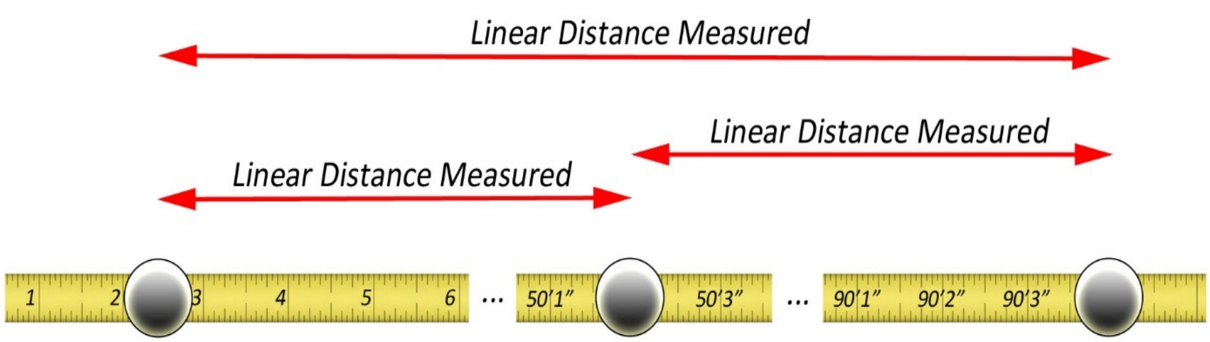


Figure 28. Certified Tape Measured Over About 100 ft on Shop Floor

The measurement procedure was to place the steel tape measure on the shop floor, place three BRIDGE VAS targets on top the tape measure by eye, and then make measurements with both the tape measure and BRIDGE VAS. Table 6 shows that the tape measurement is greater than the actual distance and that the difference is greater than measurements over a distance of 50 ft.

Table 6. Certified Tape Measure on Shop Floor with 100-ft Distance

Measurement	Nominal Distance	Tape (in)	BRIDGE VAS (in)	Difference (in)	Difference (fractional in)
Distance K1-K2	≈ 50 ft	600.250	600.205	-0.045	≈-1⁄16
Distance K2-K3	≈ 40 ft	479.500	479.272	-0.228	≈ -1⁄4
Distance K1-K3	≈ 90 ft	1,079.750	1,079.473	-0.277	≈ -1⁄4

Length Test 3: Certified Tape on Shop Floor about 100 ft Repeat

A third test repeated the 100-ft tape measure test. The tape measure and three BRIDGE VAS targets were picked up off the shop floor and repositioned about 1 to 2 ft from the first two test locations. The measurement procedure was to place the steel tape measure on the shop floor, place three BRIDGE VAS targets on top the tape measure by eye, and then make measurements with both the tape measure and BRIDGE VAS. Table 7 shows the tape measurement is greater than the actual distance and that the difference is greater than measurements over a distance of 50 ft.

Table 7. Certified Tape Measure on Shop Floor, 100-ft Distance After Pick-Up and Replace in a New Position

Measurement	Nominal Distance	Tape (in)	BRIDGE VAS (in)	Difference (in)	Difference (fractional in)
Distance K1-K2	≈ 50 ft	599.750	599.657	-0.093	≈ -1⁄16
Distance K2-K3	≈ 40 ft	480.250	480.170	-0.080	≈ -1⁄16
Distance K1-K3	≈ 90 ft	1,080.000	1,079.824	-0.176	≈ -3⁄16

Length Test 4: 200-ft Tape on Top of Girder Bottom Flange

The next set of measurements involved using a tape measure on a girder with camber. This test adds the issues of arc length, but reduces errors in surface flatness of a rough concrete shop floor. A 200-ft steel tape measure was placed on top of the bottom flange of a steel girder that was in the standing position, blocked at three locations along its length. The tape measure was placed about 3 in in from the edge of the bottom flange. The tape was run from the right end to the working end of the girder and secured in position with magnets at either end. The measurement setup is shown in Figure 29. For this measurement the tape is placed on a curved surface (the bottom flange is cambered with a maximum camber of about 8 in). The tape will measure along an arc, not a straight line distance. Normally girder length would be measured along a web plate near the bottom flange (unless there is a taper or haunch). Since this girder was in the standing position, this bottom of the web measurement was not possible. However, the measurement location used is nominally the same dimension as the bottom of the web.

As seen in Table 8, for short distances of about 20 ft, the error in the tape measurement is about 1⁄16 to 1⁄8 inch. This is equivalent to a measurement accuracy of about 1 in 4000, close to the best case estimated accuracy of 1 in 5000. Values measured with the tape are always greater than the true straight line value. The measurement from P7 to P8 is considered to be an inconsistent measurement resulting probably from errors in manual placement of BRIDGE VAS targets on the tape measure.

As the measurement length increases the measurement error also increase. This is shown in Table 9. Tape measurements are shown to always produce a measurement that is greater than the true value. The data in Table 9 contain errors due to a difference in arc length to chord length, in addition to the other systematic errors in the tape measure. The difference of arc length to chord length for the ideal shop drawing data for the bottom of the web is 0.073 in. This difference is much smaller than the other systematic errors shown in the table, showing that this arc length versus chord length error is smaller than the other error sources when using a tape.

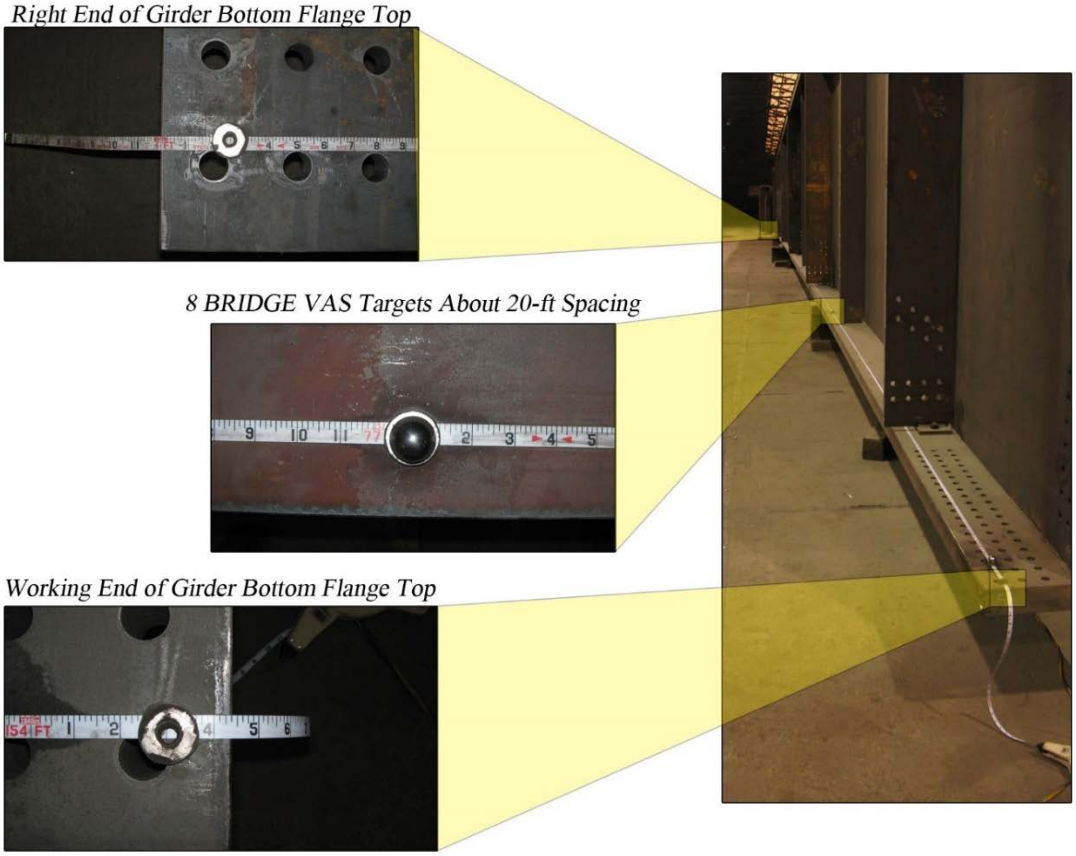


Figure 29. 200-ft Tape Measure Placed on Top of Girder Bottom Flange

Table 8. Short Range 20 ft Measurements Along a 200-ft Steel Tape: Top of the Bottom Flange of a Girder

Measurement	Nominal Distance	Tape (in)	BRIDGE VAS (in)	Difference (in)	Difference (fractional in)
Distance P1-P2	≈ 20 ft	240.000	239.908	-0.092	≈ -1/16
Distance P2-P3	≈ 20 ft	240.000	239.951	-0.049	≈ -1/16
Distance P3-P4	≈ 20 ft	252.000	251.938	-0.062	≈ -1/16
Distance P4-P5	≈ 20 ft	228.000	227.886	-0.114	≈ -1/8
Distance P5-P6	≈ 20 ft	216.000	215.996	-0.004	≈ 0
Distance P6-P7	≈ 20 ft	240.000	239.952	-0.048	≈ -1/16
Distance P7-P8	≈ 20 ft	237.000	237.079	+0.079	≈ +1/16

Table 9. Long Range Measurements along a 200-ft Steel Tape: Top of the Bottom Flange of a Girder

Measurement	Nominal Distance	Tape (in)	BRIDGE VAS (in)	Difference (in)	Difference (fractional in)
Distance P1-P2	≈ 20 ft	240.000	239.908	-0.092	≈ -1/16
Distance P1-P3	≈ 40 ft	480.000	479.857	-0.143	≈ -1/8
Distance P1-P4	≈ 60 ft	732.000	731.792	-0.208	≈ -1/4
Distance P1-P5	≈ 80 ft	960.000	959.670	-0.330	≈ -5/16
Distance P1-P6	≈ 100 ft	1,176.000	1,175.654	-0.346	≈ -3/8
Distance P1-P7	≈ 120 ft	1,416.000	1,415.585	-0.415	≈ -7/16
Distance P1-P8	≈ 140 ft	1,653.000	1,652.635	-0.365	≈ -3/8

Actual Girder Length Measurement Examples

The following data are shown to illustrate actual length measurements of fabricated girders and to illustrate the increased accuracy with the BRIDGE VAS length measurement as compared with a tape measurement. The BRIDGE VAS measurements show the true chord length from one end of a girder to the other. These measurements, since they are made using software, are not encumbered by obstructions such as stiffeners as are physical measurements with a tape.

Table 10 shows BRIDGE VAS girder length measurements compared to shop drawing length measurements and tape measurements. In addition to the final girder length measurement, these girders were also measured with a conventional tape measure at various stages of the fabrication process. It is important to note that tape measurements were measured and recorded in the shop that exactly match the nominal shop drawing length ("Shop CAD/Measure" in the table). This is a function of the precision of the tape measurement (i.e., measurements are not accurate, but the same measurement can be achieved when repeated) and procedures in the shop. Some of the measured girders had a linear taper at the bottom of the web and all shop measurements were therefore taken at the top of the web. BRIDGE VAS measurements are shown for twelve girders and are taken at the top of the web. All BRIDGE VAS measurements were made on completely fabricated girders. The mean difference in BRIDGE VAS-measured to shop nominal length was 1:3760, with a range from 1: 2378 to 1: 5312. This tape measure accuracy is consistent with the surveying application level of accuracy noted earlier from literature. It is important to note from this table that all measured lengths with a tape measure are longer than the true length (resulting in a fabricated component shorter than desired) verifying the systematic bias in making length measurements with a tape measure.

The length of an entire line of girders was then found. Line 1 is created from the girders 1A1, 6AB1, 11B1-1, 16B1-2, 21BC1, and 26C1. Line 2 is created from the girders 2A2, 7AB2, 12B2-1, 17B2-2, 22BC2, and 27C2. There was no tape measurement of the entire line length as the line was too large to be physically assembled. For comparison purposes, the nominal line length from the shop drawings is used. BRIDGE VAS software was used to virtually assemble each of the two girder lines and then used to measure the actual line length. To virtually assemble the girder line, the web gap at each splice must be known. To maintain consistency from the BRIDGE VAS virtual assemblies to the other three girder lines where match-drilled splices were created using conventional methods, a ¼-in web gap was used. Actual tape-measured web-gap spacing was recorded for three of the splices. A nominal ¼-in inch web gap was assumed for all other splice connections, which would be consistent with shop practices. It is possible that the other non-measured web-gap spacing is not exactly ¼ in. However, the total error would be small compared to the overall error in length (line 1 would have three non-measured web gaps, line 2 would have four non-measured web gaps). Table 11 shows the BRIDGE VAS line length measurements compared with the shop nominal line length measurements. These data further illustrate the inherent measurement accuracy issues with a tape measure and that this error increases with length. Over this approximately 830-ft length, the fabricated line is about 3 in shorter than designed.

Table 10. Girder Length Measurements Compared to Shop Drawing Length ("Difference (fractional in)" are fractional differences rounded to the nearest 1/1000 in, in decimal format)

Girder	Shop CAD / Tape Measure (in)	BRIDGE VAS Measure (in)	Difference (in)	Difference (fractional in)	Tape Error (in)
1A1	1,461.813	1,461.396	-0.416	-0.438	1:3513
2A2	1,461.813	1,461.367	-0.445	-0.438	1:3284
6AB1	1,762.562	1,762.230	-0.332	-0.313	1:5312
7AB2	1,762.562	1,762.131	-0.431	-0.438	1:4092
11B1-1	1,699.001	1,698.666	-0.335	-0.313	1:5079
12B2-1	1,699.001	1,698.628	-0.373	-0.375	1:4556
16B1-2	1,843.188	1,842.700	-0.488	-0.500	1:3778
17B2-2	1,843.188	1,842.554	-0.634	-0.625	1:2907
21BC1	1,762.625	1,761.954	-0.671	-0.688	1:2628
22BC2	1,762.625	1,762.214	-0.411	-0.438	1:4289
26C1	1,440.938	1,440.502	-0.436	-0.438	1:3307
27C2	1,440.938	1,440.332	-0.606	-0.625	1:2378
				Minimum	1:2378
				Maximum	1:5312
				Average ± σ	**1:(3760 ± 894)**

Table 11. Girder Line Length Measurements Compared to Nominal Shop Drawing Length

Line	Shop (in)	BRIDGE VAS Measure (in)	Difference (in)	Error (%)
1	9,969.750 (830 ft - 9¾ in)	9,966.497 (830 ft – 6½ in)	-3.253 (-3 ¼ in)	1:3065
2	9,969.750 (830 ft - 9¾ in)	9,967.150 (830 ft 7⅛ in)	-2.600 (-2⅝")	1:3835

Camber

Camber is currently measured with a girder on its side in order to eliminate dead load deflections, with offsets measured from the flange of a girder to a reference string line (see Figure 30). Measurement of camber is typically made at only a few discrete points along the length of the girder, possibly only at midspan. The BRIDGE VAS measures camber with a girder in the standing position and measures blocking locations and uses this information to determine if any compensation is needed for dead load deflection.

To validate camber measurement in the standing position, a comparison was made of girder camber measured in the standing position to the same girder laid on its side. Girders in the standing position were supported at three locations along the length. Girders laid on their side were supported at two locations per normal shop camber measurement procedures. Two separate girders were measured. The first girder, 11B1-1, was a straight girder with a length of 142 ft and a constant web depth of 10 ft. The second girder, 6AB1, had a variable web depth

Figure 30. Conventional String Line Measurement of Camber

(bottom flange linear taper transitioning to a constant web depth). The BRIDGE VAS can measure camber at both the top and bottom flange. However, for Girder 11B1-1 space limitations in the shop did not permit a BRIDGE VAS measurement of the top flange camber with the girder in the laydown (side) position. Because of the bottom flange linear taper on Girder 6AB1, the bottom flange camber is not presented. The two girder measurement positions are shown in Figure 31 for Girder 11B1-1.

a)  b) 

Figure 31. Girder 11B1-1 Camber Measurements with a) Girder on Side and b) Girder in Standing Position

Camber was measured manually per shop procedures with a string line only when the girder laid on its side. There is no standard procedure for string line measurement of camber with a girder in the standing position. The BRIDGE VAS measured camber when the girder was both standing and laying down. Camber data are shown at mid-span in Table 12. Figure 32 shows the BRIDGE VAS measured camber along the entire length of Girder 11B1-1. Figure 33 shows the BRIDGE VAS measured camber along the entire length of Girder 6AB1. For Girder 11B1-1, difference in BRIDGE VAS camber to string line camber is a maximum of about $3/16$ in. For Girder 6AB1, the BRIDGE VAS measurements are close to the string line measurements. For both girders, the camber measured by the BRIDGE VAS in the standing position is essentially the same as in the laydown (side) position.

Table 12. Comparison of Camber Measured in Standing Position and on Side for Girders 11B1-1 and 6AB1

Girder	Position	Date Measured BRIDGE VAS	Shop Drawing Camber (in)	Shop Measure (in)[a]	BRIDGE VAS Measure Top Flange (in)	BRIDGE VAS Measure Bottom Flange (in)
11B1-1	Side	9/15/11	5 15/16 (+5.94)	7 (+7.00)	-	+7.03
	Standing	9/27/11	5 15/16 (+5.94)	6 15/16 (+6.94)	+7.16	+7.10
6AB1	Side	10/10/11	-3 7/8	-	-4.56	-
	Standing	9/28/11	-3 7/8	(-4.56) -4 9/16	-4.62	-

[a] Shop camber measurement only in laydown position.

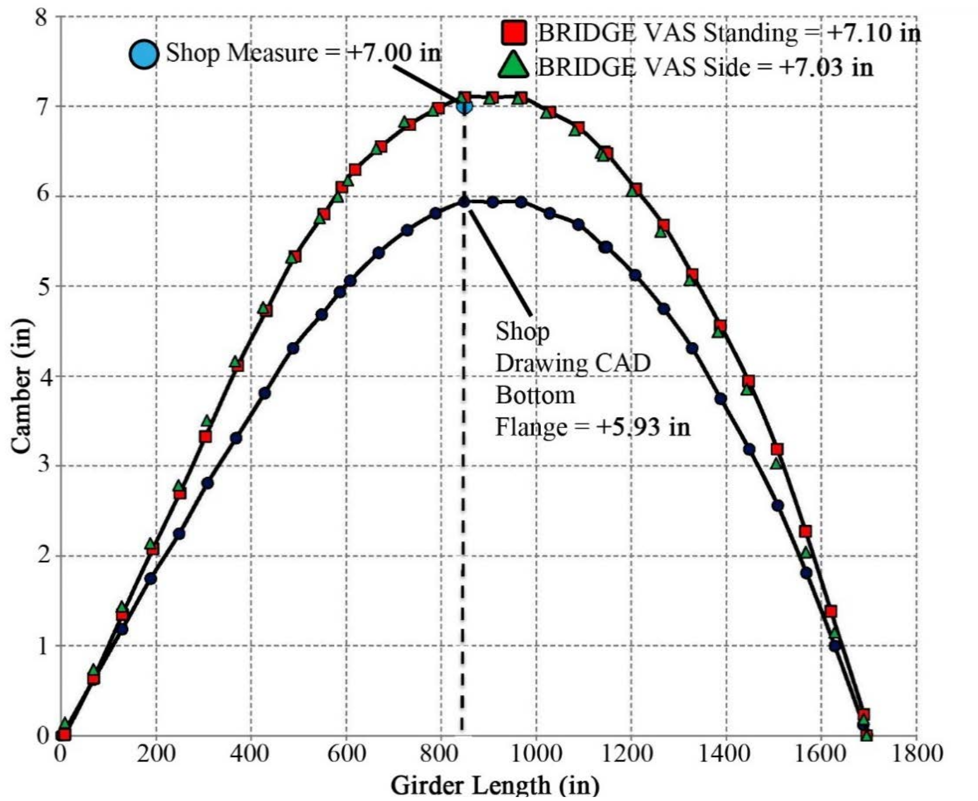


Figure 32. Camber Measurements on Girder 11B1-1 Comparing Standing and Laydown Measurements

Camber measurements were made on 12 girders (described in the *System Deployment* sub-section of the *Methods* section) comparing conventional string line measurements to the BRIDGE VAS with the results shown in Table 13 (plots of camber for all 12 girders are shown in the Appendix). The columns labeled "Location" in the table refer to the position along the girder length from the working end to where the camber measurement was made. For BRIDGE VAS measurements, camber was taken at one of the discrete measurement points along the girder length (typically about 32 points along the girder). It would be possible to interpolate these BRIDGE VAS camber data at any position along the girder length and produce a measurement at the exact point as the shop string line measurement. However, no interpolation was performed (the change in camber would be negligible) and the closest discrete location for

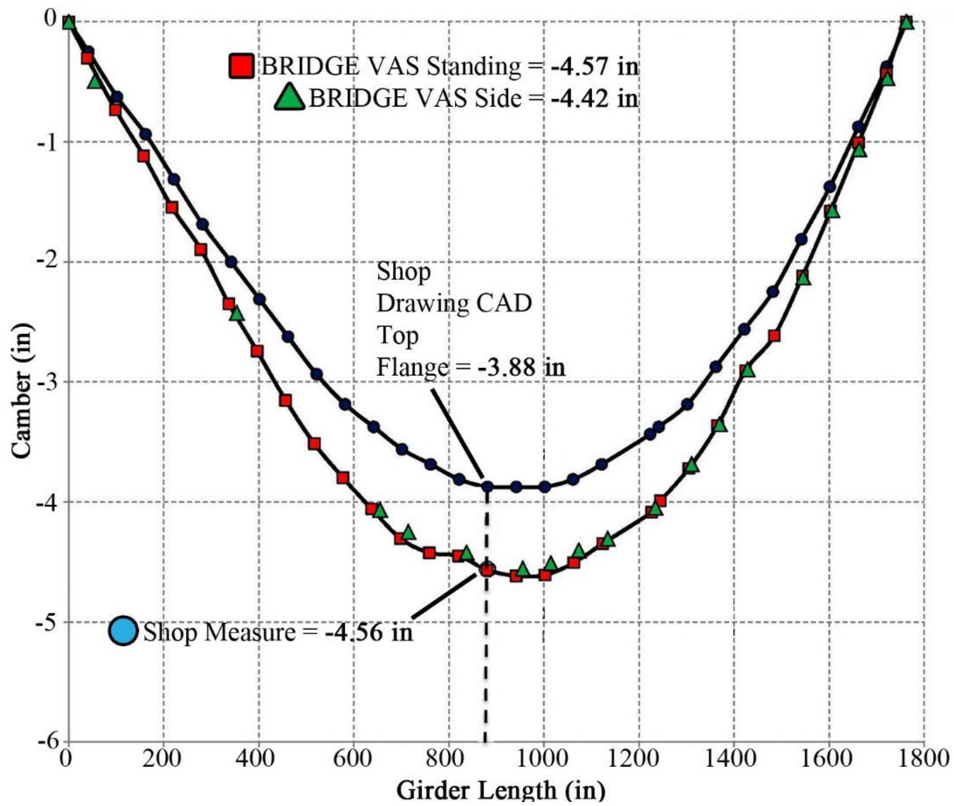


Figure 33. Camber Measurements on Girder 6AB1 Comparing Standing and Laydown Measurements

Table 13. Camber Measurements for Twelve Fabricated Bridge Girders

Girder	Shop CAD		Shop Measured	BRIDGE VAS		Difference (in)
	Camber (in)	Location[b] (in)	Camber (in)	Camber (in)	Location[b] (in)	
1A1	5.063	731.000	6.250	6.205	730.370	-0.045
2A2	5.063	731.000	6.125	6.349	730.914	0.224
6AB1	-3.875	881.250	-4.563	-4.566	880.499	-0.004
7AB2	-3.875	881.250		-4.195	880.557	
11B1-1	5.938	849.501	6.938	7.149	851.920	0.212
12B2-1[a]	5.938	849.501	6.813	6.936	842.087	0.124
16B1-2	7.188	801.501		8.325	810.563	
17B2-2	7.188	801.501	8.000	7.794	803.506	-0.206
21BC1	-3.938	881.250		-3.997	879.903	
22BC2	-3.938	881.250		-4.086	880.372	
26C1	5.000	720.500	6.000	6.498	720.420	0.498
27C2	5.000	720.500	5.688	5.921	720.327	0.234

[a] Girder 12B2-1 measurement is from the bottom flange.
[b] Location of measurement as distance along beam from the working end

the BRIDGE VAS measurement was chosen for comparison. No paper record of a shop string-line measurement was recorded for four of the girders. BRIDGE VAS measurements were made on the girder top flange since the girders have a linear taper on the bottom flange. Except for Girder 12B2-1, where BRIDGE VAS camber measurements were made using bottom flange data. For this girder, both top and bottom flange BRIDGE VAS camber data were measured (see Figure 34). However, the bottom flange data contained a measurement location closest to mid-span, where the string line measurement was made. String line measurement errors of about – ¼ in to +½ in were observed on the eight girders when compared with BRIDGE VAS measurements.

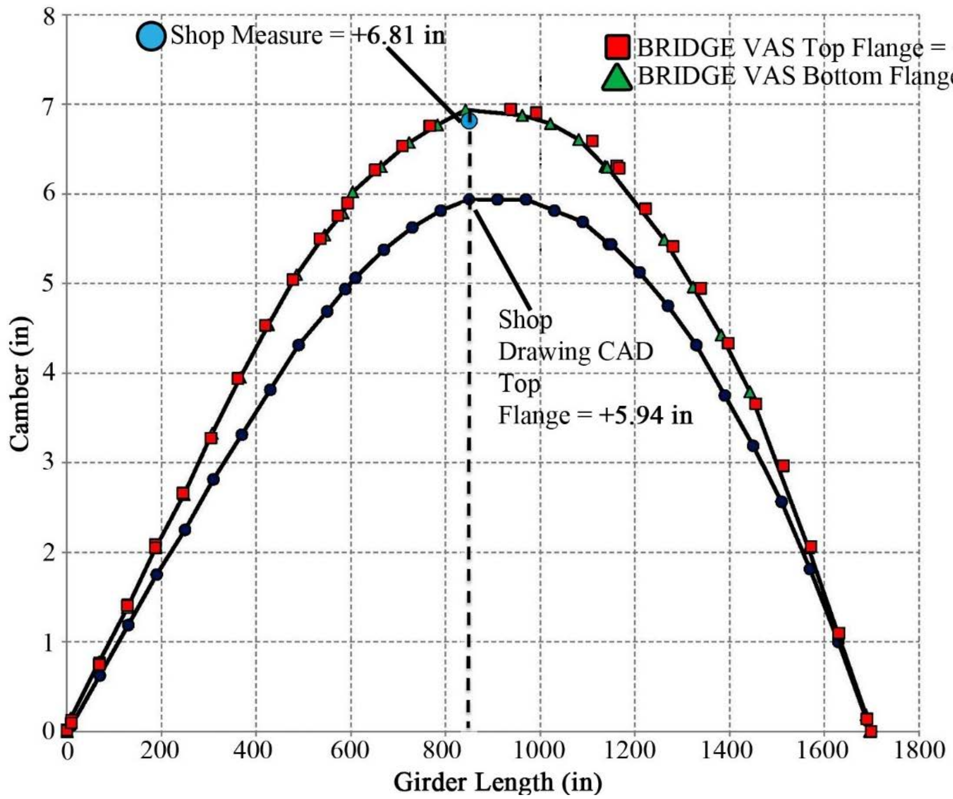


Figure 34. Girder Camber for 12B2-1 Showing Both Top Flange and Bottom Flange Camber

The conventional measurement of camber is cumbersome because it involves setting a string line reference and as a result has inherent accuracy limitations. Probably the most significant limitation of string line camber measurement is the need to measure 2 or 3 girder segments at a time using one string line and then convey these measurements to the next set of girder segments. In contrast the BRIDGE VAS measurement is more accurate and provides information along the entire length of the spliced girder. The BRIDGE VAS can also easily measure camber of various parts on a girder, including both the top and bottom flanges (both near side and far side of flanges). Camber would normally be expected to be the same for the top and bottom flange, but these data are a good consistency check of the overall girder camber. Collecting both top and bottom flange (both near side and far side of the flange) camber requires very minimal additional data collection time with the benefit of extra data validation.

Figure 34 shows both top and bottom flange camber measurements for girder 12B2-1, where the top and bottom flange camber are nominally the same. Camber can be presented for a single girder, pairs of girders, or complete lines of girders (see Figure 35).

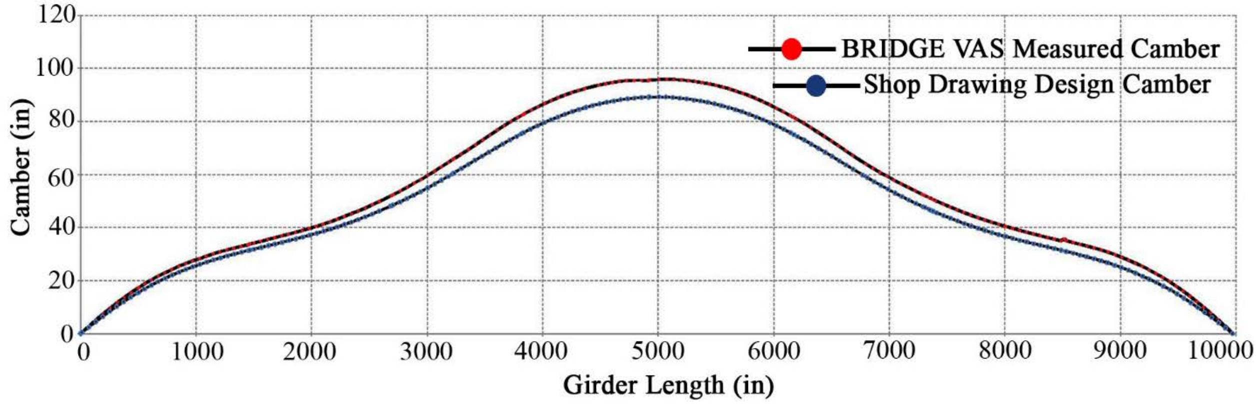


Figure 35. BRIDGE VAS Camber Measurement of a Six-Segment Girder Line Total Length of About 830 ft) (BRIDGE VAS Measured, top line; Shop Design, lower line)

Sweep

The conventional measurement of sweep is similar to that of camber where the curvature of a girder is measured with respect to a string line reference. This process is illustrated in Figure 36, where a reference string line is placed at the bottom flange. Sweep is typically measured with the girder in the standing position, as girders are normally very flexible along the longitudinal direction. Girder sweep can easily be changed in the horizontal position by blocking the girder differently. This characteristic makes the tolerance on girder sweep less stringent, since girder sweep can be adjusted very significantly by manipulating the girder.

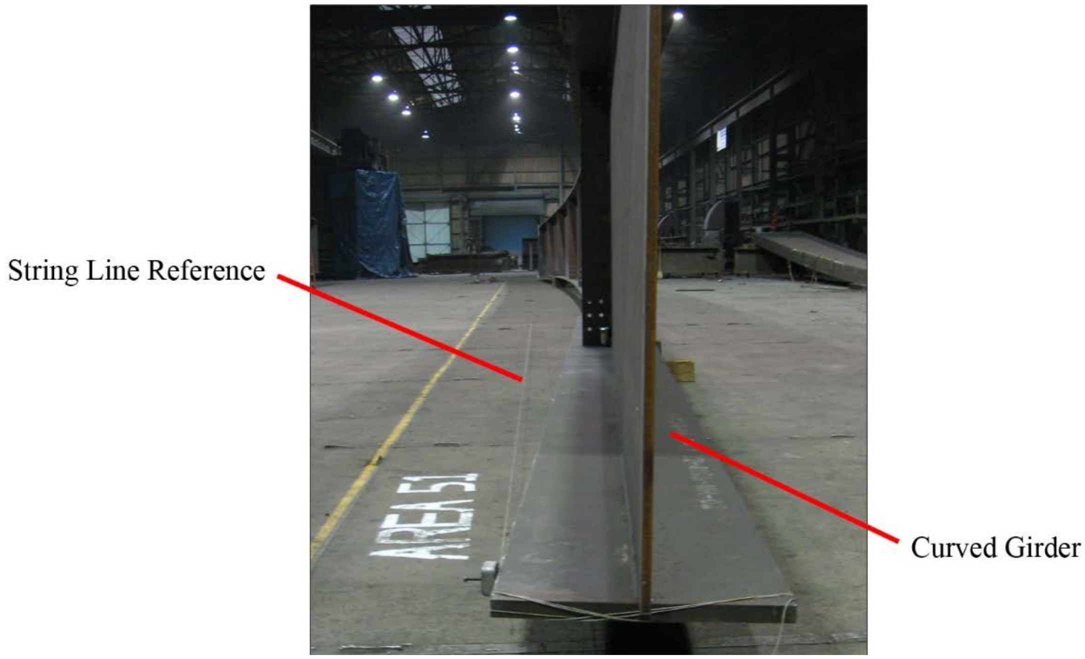


Figure 36. Conventional Measurement of Girder Sweep

Figure 37 shows an example BRIDGE VAS measurement of sweep on a curved girder with a length of 100 ft. The figure shows sweep measured on a number of different parts of the girder (top flange edges, bottom flange edges) compared to the nominal shop drawing sweep. The BRIDGE VAS measures sweep in the standing position and can collect redundant measurements of sweep on different parts of the girder. As with camber measurements, these additional measurements take very little additional measurement time and provide an extra level of confidence of the overall sweep measurement.

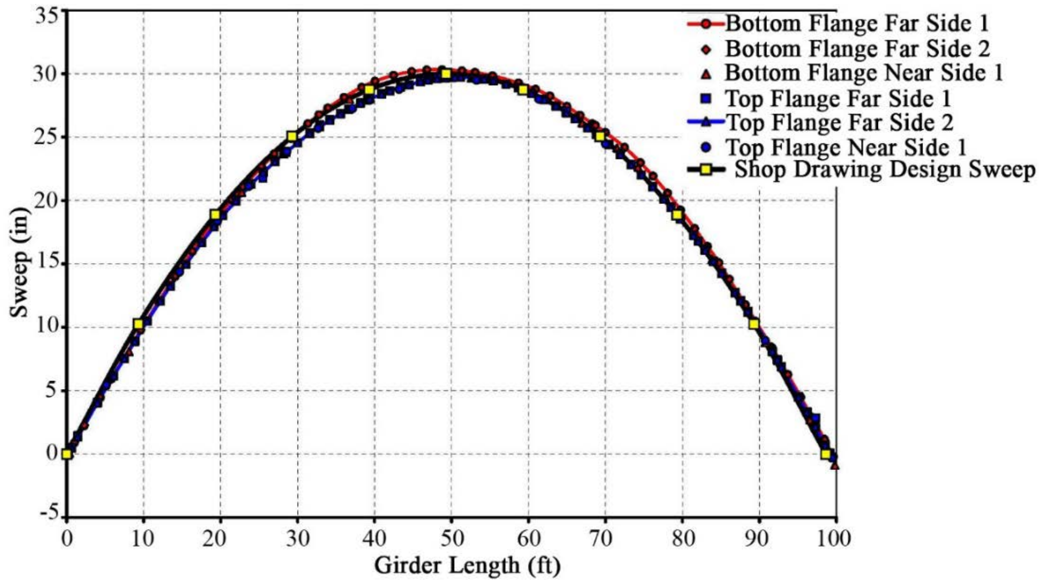


Figure 37. Sweep Measurement of 100 ft Long Curved Girder Showing Shop Drawing Nominal Sweep (Yellow Square) and BRIDGE VAS Measurements at Multiple Locations on the Girder

Stiffener Locations

The BRIDGE VAS measures stiffener position along the girder length and determines the orientation (kick) of each stiffener. Stiffeners on both the near side and far side of the girder are measured. By contrast, a measurement system that measures girder while lying flat would not be able to measure both sides with manipulating (flipping) the girder. An example of stiffener measurements is shown in Figure 38.

Web Panel Deformation

Conventional web panel measurements are done with straight-edges and rulers. A straight-edge reference is typically placed vertically on a web and the offset from the web to the reference is measured by hand. These current measurements depend on where and how the straight-edge is applied on the web. The basic measurement process is shown in Figure 39a. Based on this somewhat subjective measurement, a significant amount of rework is applied to change the shape of the web (see Figure 39b). Conventional measurements are localized to a specific area of a girder web. It is possible that improved web panel measurement could reduce the amount of effort in reworking web panels to change the shape or that specifications could be improved to take advantage of the measurements provided by the BRIDGE VAS and improve the fabrication and inspection process.

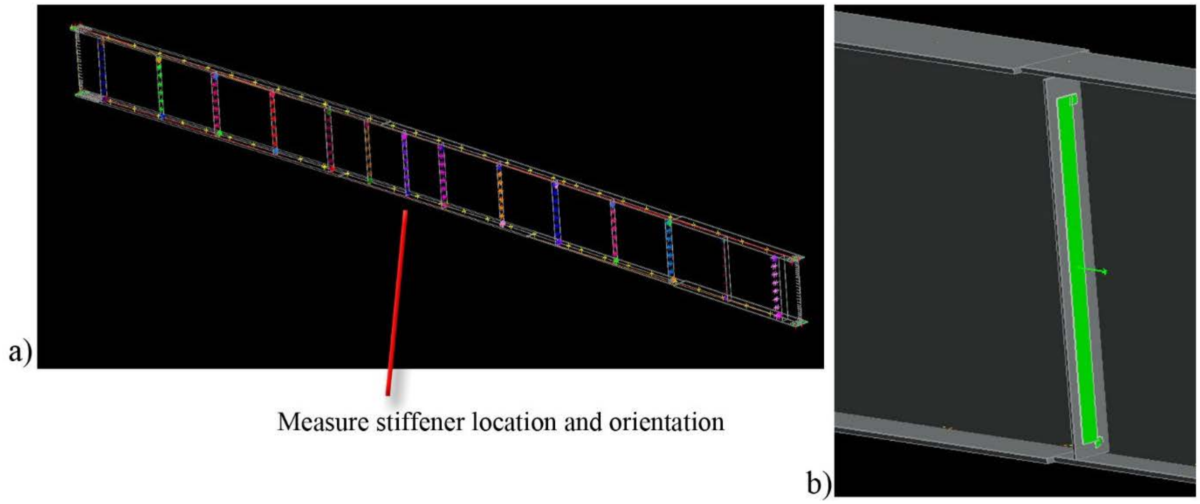


Figure 38. Measurement of Girder Stiffener Location and Orientation Showing a) Multiple Stiffeners Along Length of Girder and b) Close-Up of Stiffener Measurement (Green) Overlaid on Ideal 3D CAD Model

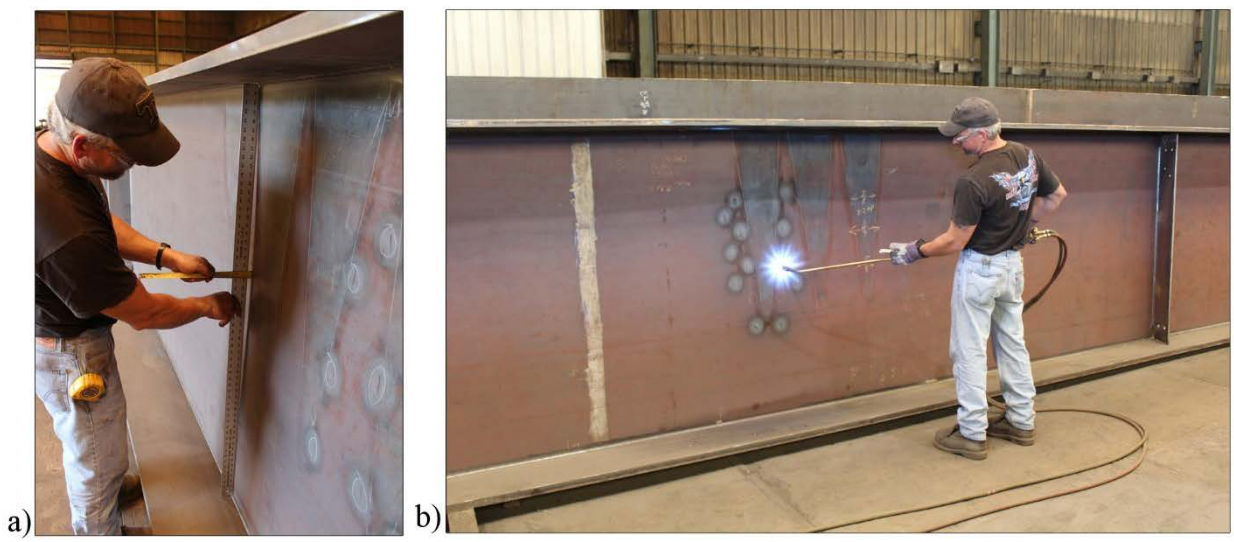


Figure 39. Reworking of Girder Web Showing a) Conventional Straight Edge Web Panel Measurement and b) Heating of Web to Change Shape

By contrast the BRIDGE VAS can provide information on web panel deformations that is currently unavailable. Accurate, quantifiable, fully documented out-of-plane deformation measurements of an entire girder web can be made with the BRIDGE VAS. Figure 40 shows the out-of-plane deformations of one very large girder web (142 by 10 ft). This was collected from one instrument position in less than 15 minutes with measurements directly on the girder web (no targets). The color in the plot is proportional to the out-of-plane deformation (more red closer, more blue farther away). The color plot shows the entire web referenced to a single plane. To display the deformation information more analogous to the conventional measurement method, localized two-dimensional cross-sections can be extracted from the original data set.

Here each cross-section is referenced to the top and bottom of the web at the cross-section (i.e., the same as the vertical straight edge reference). The data provided by the BRIDGE

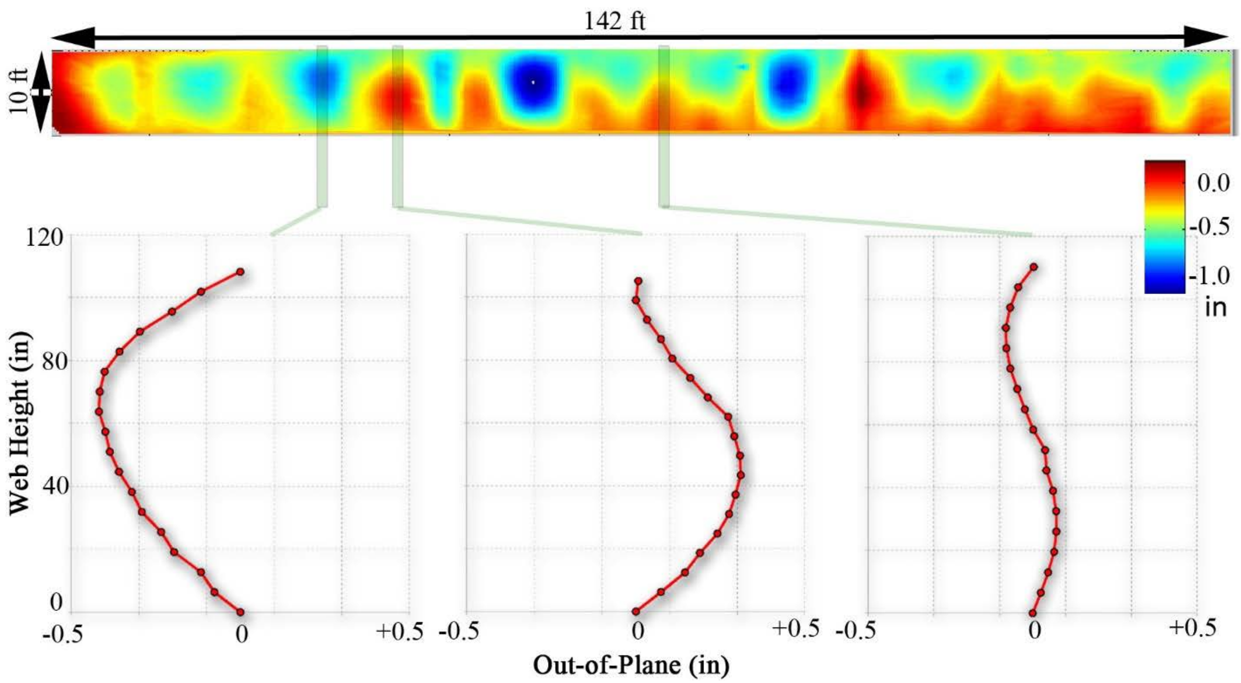


Figure 40. Web Panel Deformation Measurements Shown for a Very Large (142 × 10 ft) Girder Web

VAS can be processed to quantify deformations at any orientation and is not limited to the same output as conventional straight edge measurements. These data on a girder web can help document better what was fabricated and can be used to satisfy VDOT (or other agencies) inspection requirements.

The accuracy and spatial resolution of the BRIDGE VAS data allow features that are not easily observed. A butt splice on a girder web results in some degree of deformation around the splice. While this feature will typically not be visible by eye, it can easily be seen in the BRIDGE VAS web deformation data. An example of the deformation around a web butt splice is shown in Figure 41. The color is proportional to the out-of-plane deformations, showing the raised butt splice (red) relative to the web panel (blue). The image is intended to illustrate the change in shape in this localized region and the color scale (magnitude of deformation) is referenced to the measurement of the entire girder.

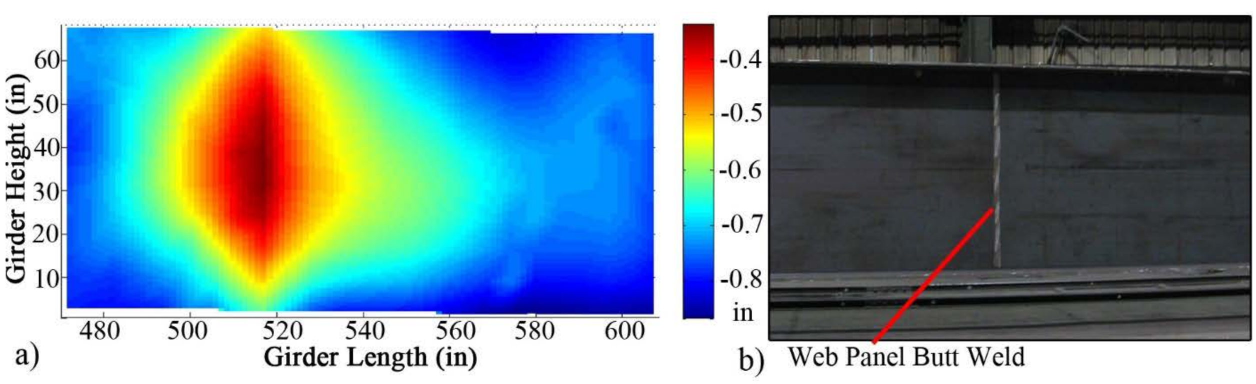


Figure 41. BRIDGE VAS Measurements Showing a) Web Panel Deformations at a Web Plate Butt Splice and b) a Photograph of the Butt Weld

The measurement of web panels for large girders is difficult, especially large girders with complex shapes. Tub girders can be very large and often have webs that are not vertical, but sloped. Accurate measurement of web deformations on this type of a girder is difficult with conventional methods. A typical 65-ft long tub girder is shown in Figure 42 and the corresponding web panel deformations for the far side web is shown in Figure 43. The color is proportional to the out-of-plane deformation and is referenced to one plane. The data show that the webs are not in one plane and one end of the girder is not in line with the other end. One common color scale for the entire web makes it difficult to see localized deformations. Therefore, subplots of the near side web, using different color scales to highlight the smaller details, are shown in Figure 44.

Figure 42. Measurement of a Tub Girder in the Shop Assembly Yard

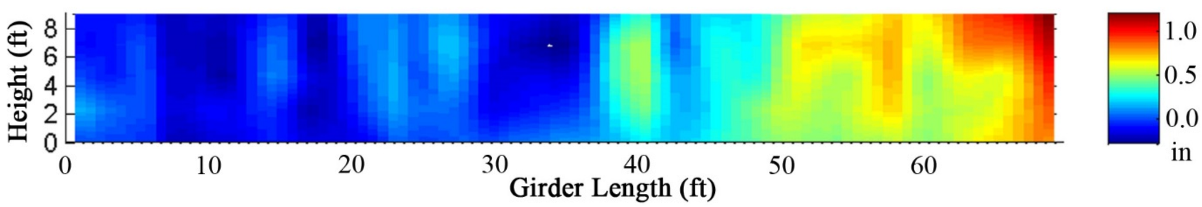


Figure 43. Web Panel Deformations of Tub Girder Far Side Web

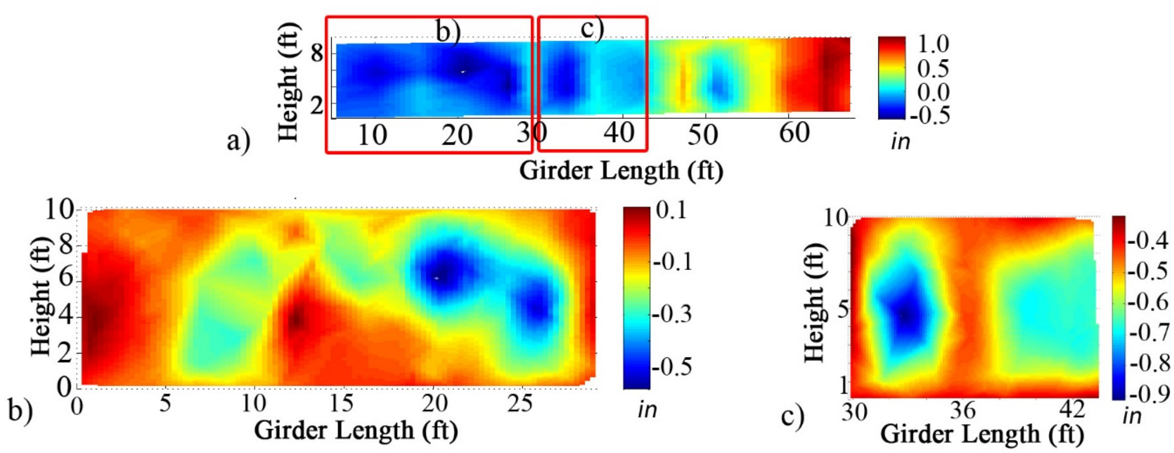


Figure 44. Close-Up View of Tub Girder Near Side Web Panel Deformations Showing a) Entire Web Panel and b) Close-Up Section from 0 to 30 ft and c) Close-Up Section from 30 to 42 ft

Virtual Assembly

Virtual assembly procedures were performed on multiple girder pairs. Measurements of fully fabricated girders were made independently, with each girder blocked in the standing position. Solely as a validation step (i.e., not required for actual virtual assembly), girder pairs were placed in laydown and aligned manually after these independent measurements. An additional set of BRIDGE VAS measurements were then made on the girder pair in laydown. With these additional measurements, actual girder pair spatial measurements (with pairs physically aligned) could be directly compared to virtual assembly of girder pairs.

Combined Camber

Virtual assembly can be performed on different combinations of girders. A pair of girders can be virtually assembled or an entire line of girders (or multiple lines) can be virtually assembled. This is shown in Figure 45 with the virtual assembly of an entire girder line of six girders. These data are produced from actual BRIDGE VAS measurements of individual girders that are then positioned in software. Figure 45a shows the actual measured data and virtual assembly. and Figure 45b shows the 3D CAD model superimposed on the measurements. Figure 46 shows data from Girder Line 2 comparing the measured line camber to the shop nominal camber. At the scale of the figure, the shop nominal camber and the measured camber are not distinguishable. For this particular girder line, the entire length is about 830 ft and would be impossible to physically assemble in most bridge shops.

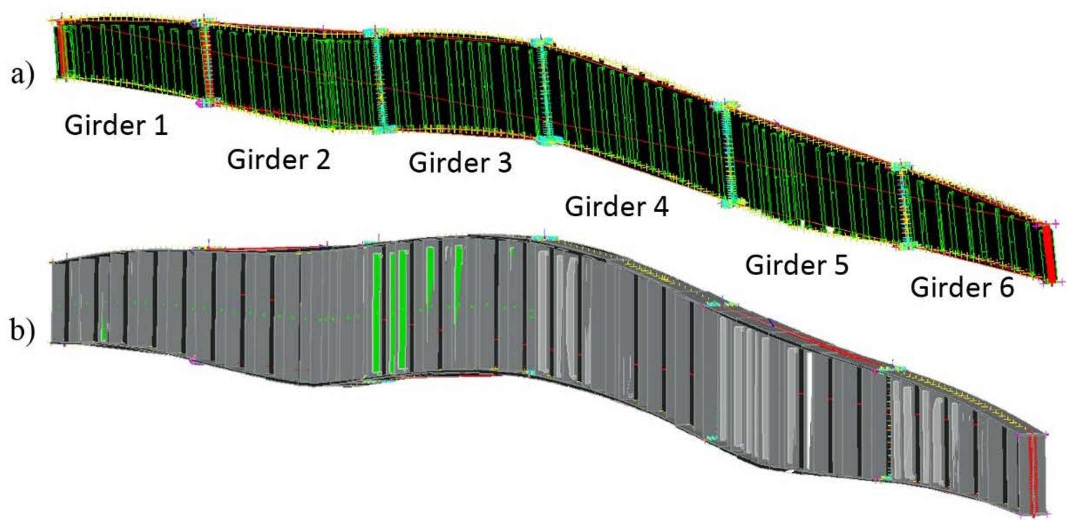


Figure 45. Virtual Assembly of an Entire Girder Line:
a) Measured Data and b) Measured Data with 3D Model

Splice Fit-up Details

The BRIDGE VAS system can fully characterize fit-up details of girders. The web gap can be quantified not just at a few discrete points, but at any point along the entire web depth. Figure 47 shows graphical data from the virtual assembly of a girder pair with a close-up view of the web gap near both the top and bottom flange.

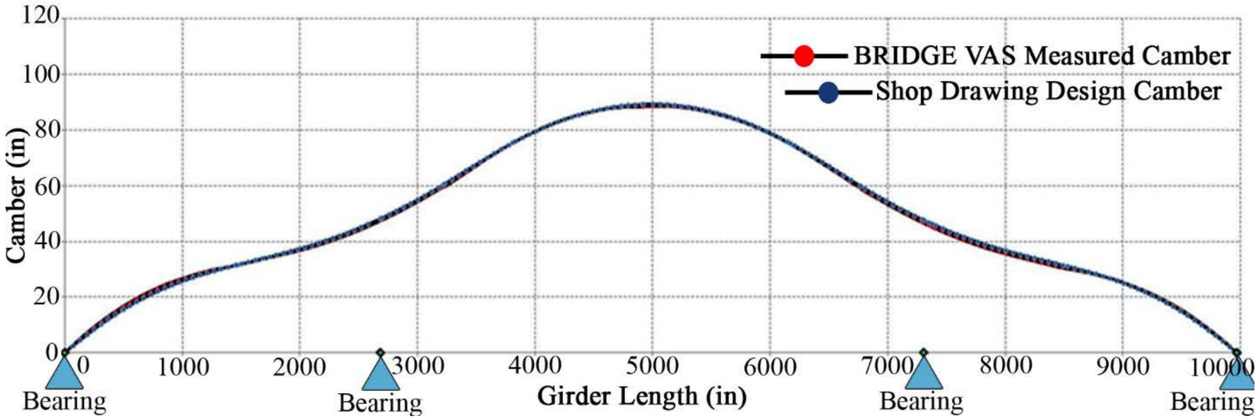


Figure 46. Line Camber Data Comparing Measured Values to Shop Nominal Data for Girder Line 2

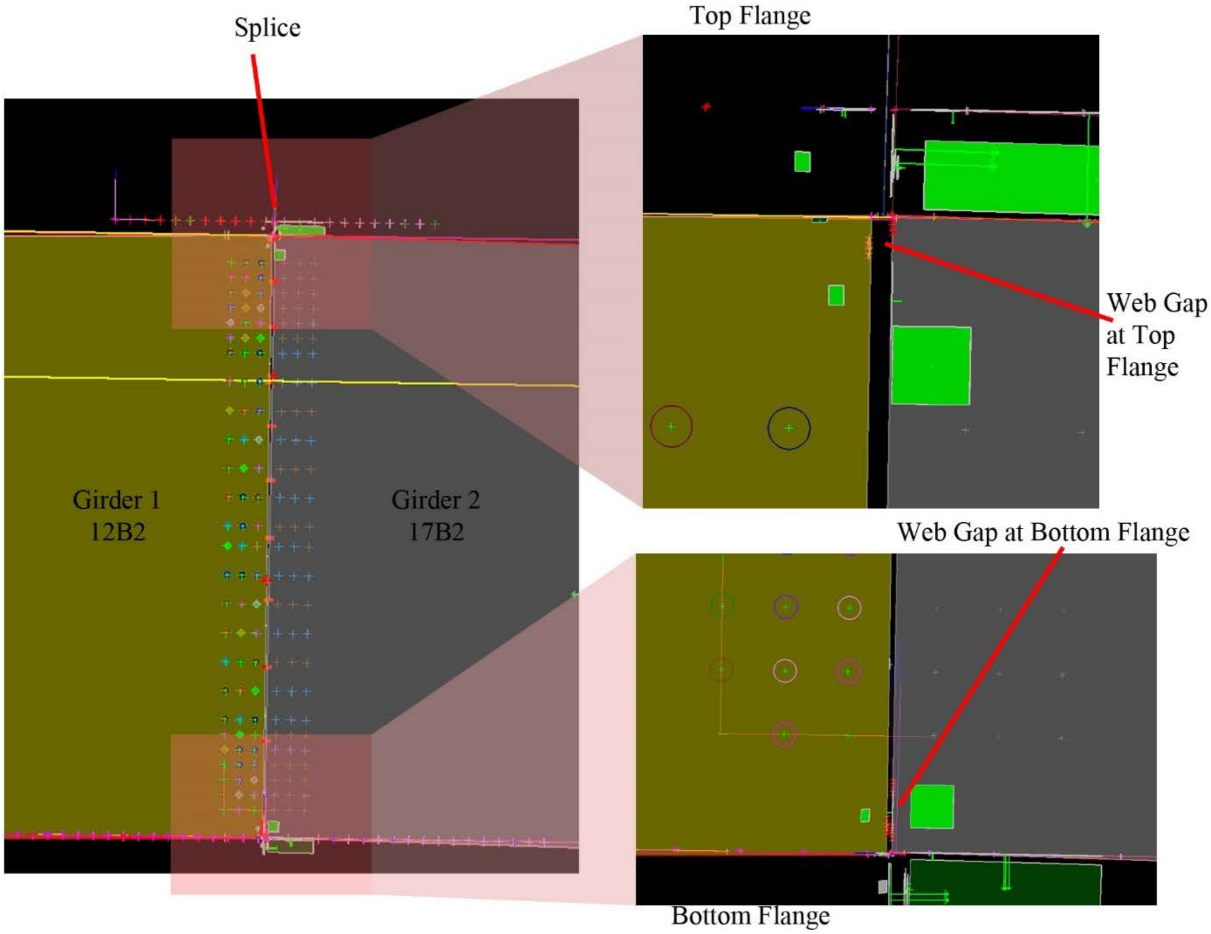


Figure 47. Virtual Assembly of a Girder Pair Showing Details of the Splice Fit-Up

Manual measurements of a small number of localized features were measured with rulers and calipers on a subset of girders in order to provide some validation of BRIDGE VAS measurements. Measurements were made of features that were easily accessible for conventional measurement tools. This included measurement of the web gap along the height of the web, distance of splice holes to plate edges, and splice hole to splice hole spacing.

It is important to note that a ruler/caliper measurement is taken by hand, up-close to the girder. Only certain measurements can be easily and accurately made in this manner. In comparison, the BRIDGE VAS measurements are made at a distance, completely remotely, without having to touch or interact with the girder. BRIDGE VAS measurements can be made of any feature, regardless of physical obstructions in between measurement points (i.e., stiffeners, flange transitions). BRIDGE VAS measurements can be made completely virtually, such as for web-gap spacing and flange alignment, without having to physically setup and align girders.

The following measurements show a comparison of BRIDGE VAS data from the virtual assembly (not a physical assembly) and ruler/caliper measurements from the physical laydown. Table 14 shows the distance from the outer row of top flange holes to the edge of the top flange (for Girder 1A1), both from the BRIDGE VAS and from ruler/calipers. The outer row of holes was chosen as it is more easily measured with ruler/calipers. Data show essentially identical measurements. Additional comparison measurements are shown for a girder pair placed in laydown position and aligned. Table 15 shows the distance between bottom flange holes in the right side girder (1A1) to the bottom flange holes in the left side girder (6AB1). Holes were measured from the bottom of the bottom flange. Ruler measurements were made from the outside edge of the hole and then offset by the nominal hole diameter. The two measurements are shown to be essentially the same, within the accuracy of measurement with the ruler.

Table 14. Ruler/BRIDGE VAS Measured Distance from Top Flange to Edge of Top Flange

Hole	Nominal Location	BRIDGE VAS Measured (in)	Tape Measured + ½ Hole Diameter (in)
P7	RE at NS[a]	1.98	1.97
P0	−	1.96	1.97
P14	−	1.95	1.97
P21	RE at FS[a]	1.93	1.97

[a] RE = Right End, NS = Near Side, FS = Far Side.

Table 15. Ruler/BRIDGE VAS Measurements for Bottom Flange Hole Separation: Girders in Laydown

1A1 to 6AB1	BRIDGE VAS Measured (in)	Tape Measured +1 Hole Diameter (in)
P8 – P24	3.92	3.94
P0 – P16	3.93	3.94
P16 – P0	3.93	3.94
P24 – P8	3.94	3.94

Table 16 shows ruler/caliper measurements of the web gap at two locations (one near the top flange and the other near the bottom flange) compared to BRIDGE VAS measurements. The two measurements are shown to be essentially the same.

Table 16. Ruler/BRIDGE VAS Measurements for the Web Gap Near the Top and Bottom Flange

Location	BRIDGE VAS Measured (in)	Tape Measured (in)
Web near Top Flange	0.31	0.31
Web near Bottom Flange	0.25	0.25

The flatness of the web plate at the splice and the tilt of the flanges can also be measured. Figure 48 shows data from the virtual assembly of a pair of girders showing a close-up view of the flange edges at the splice. The flange tilt cannot be observed visually and is greatly exaggerated in the figure in order to visualize the effect. Figure 48a shows a measurement view similar to viewing the actual splice, where this flange tilt is not visible.

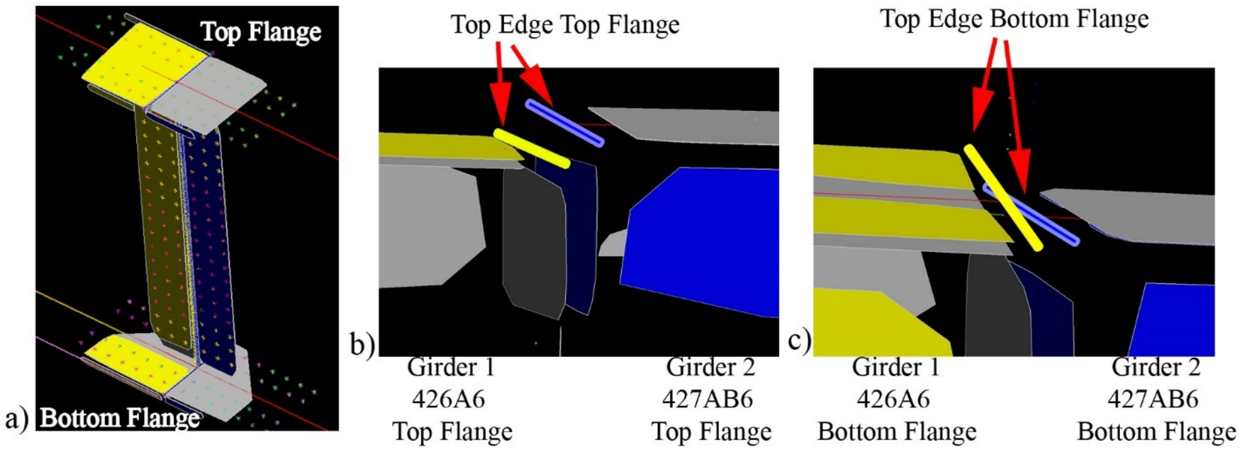


Figure 48. Virtual Assembly Fit-Up Details Showing a) a Splice and b) Close-Up of the Top Flange and c) Close-Up of the Bottom Flange

Measurement Validation

The BRIDGE VAS uses multiple methods to validate the collected data. One of the methods uses a special validator target that is placed on the girder and is measured along with the girder. Multiple validator targets are available and an example of one version is shown in Figure 49a. This target is a steel block with steps of known height. The BRIDGE VAS makes measurements on the validator target and finds the height of each of the steps. Figure 49 shows the validator target being measured at a very long distance, about 157 ft. In this case, the target was placed on the side of a stiffener. For validation, the BRIDGE VAS measurements are compared to the known step heights. To illustrate the measurement of this target, data from two separate measurement distances are given. At a range of 85 ft, the step features were measured with an accuracy of ±0.002 in. At a range of 157 ft, the steps features were measured with an accuracy of ±0.006 in.

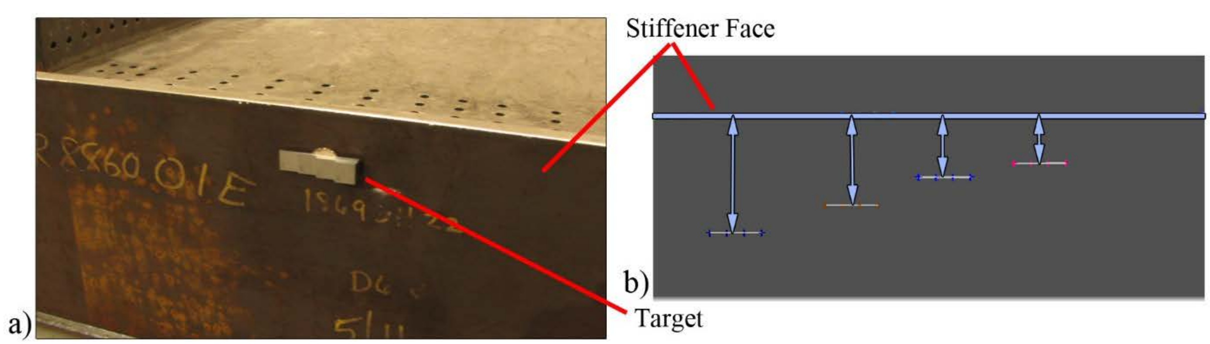


Figure 49. Validator Target Measurement at 157 ft Showing a) the Target on a Stiffener and b) the Measurement of the Target Steps

The BRIDGE VAS incorporates other sensor data in order to validate measurements. These data monitor girder vibrations and temperature. Yet other sensors within the BRIDGE VAS itself monitor system operation and measurement conditions.

System Application

As previously discussed, BRIDGE VAS was used during fabrication of a bridge for the State of Tennessee (see sub-section *Deployment Bridge Details* in the *Methods* section), where two complete girder lines were measured, out of five total lines, for a total of twelve girders.

Individual Girder Measurements

BRIDGE VAS measurements for the twelve girders (two complete lines) completely characterized each girder and created a digital record. For the two-and-one-half girders manufactured with the conventional match-drilling process, these girders were measured after being fully fabricated (trimmed to length and with splice holes). Therefore, each of the twelve girders in lines 1 and 2 were measured completely and independently in the standing position. From these individual-girder measurement records, virtual assemblies of girder pairs and lines were created.

Web Gap at Splice

The issue of length measurement accuracy using a tape measure, as previously discussed, affects the manner in which virtual assembly was performed on this bridge. The *Length* portion of the *BRIDGE VAS Measurements* subsection in the *Results* section discusses in detail the inherent limits in accuracy of length measurement with conventional tape measures. The result in these bridge girders was that the actual girder was shorter than the desired shop drawing nominal length, as measured with a conventional tape measure. Since two of the five girder lines were measured with the BRIDGE VAS system and intended for virtual assembly and the remaining three lines were completed with conventional laydown match-drilling, it was necessary to make all the lines nominally the same length. After fabrication of the girders in line 1 and 2, the length of the line was set by the web gap in each splice, as this was the only means to change the length of the line. In order to make all five girder lines nominally the same, the web gap of lines 1 and 2 were set at about ¼ in.

Virtual Assembly Laydown Verification

Measurements of girder pairs in the laydown position were made with the BRIDGE VAS, with girders aligned to the shop drawing criteria using string lines and rulers. This laydown measurement was used to compare to the output of the virtual assembly software where girders were not physically placed together as a pair. Three girder pairs were measured in the laydown position in order to validate the virtual assembly software and to examine the fit-up process in detail (see Table 17).

Table 17. Summary of Virtual Assembly of Girder Pairs for Girder Line 1 and 2

Number	Girder Pair	Additional Measure in Laydown	Total Holes in Splice (TF, Web, BF) [a]
1	1A1 to 6AB1	10/7/11 10/11/11	234 (56, 114, 64)
2	2A2 to 7AB2	10/22/11	234 (56, 114, 64)
3	7AB2 to 12B2-1	10/27/11	348 (84, 180, 84)
4	6AB1 to 11B1-1	none	348 (84, 180, 84)
5	12B2-1 to 17B2-2	none	472 (88, 156, 228)

[a] TF=Top Flange, BF=Bottom Flange

As mentioned previously, all girders were measured in the standing position, completely independently and these data were used to virtually assembly girder pairs (no physical laydown). Girder pairs were also physically placed in laydown position and aligned. In this aligned position, additional BRIDGE VAS measurements were taken that included combined camber, splice-hole locations, and details of the girders at the splice (including web gap and alignment). BRIDGE VAS measurements of the girders while physically aligned were then directly compared to the virtual alignment of the girders using only software tools.

Laydown Verification Example

An example of a laydown virtual assembly verification measurement is shown in Figure 50 for Girders 1A1 and 6AB1. The girder pair was placed in laydown and aligned. Once aligned, the BRIDGE VAS measured the girder pair. The combined camber of the girder pair is shown in Figure 51, where the shop nominal camber is compared to the actual measured camber. Also, the BRIDGE VAS combined camber (as produced by the virtual assembly software from independent girder measurements) is compared to an actual physical measurement of the girder pair with the BRIDGE VAS (with the girders setup and aligned in the laydown position). Camber was measured in the laydown position on the bottom of the top flange due to field-of-view availability. The combined camber is essentially the same in both cases, validating the virtual assembly software. Table 18 shows a comparison of BRIDGE VAS and string line combined camber measurements. The column labeled "Location" refers to the position along the length of the girder from the working end to where the measurement was taken. BRIDGE VAS measurements are shown for virtually assembled data (taken independently in the standing position) and as measured in the laydown position with the girder pair manually aligned.

As described earlier, Girders 1A1 and 6AB1 were fit together with a nominal web gap of about ¼ in to maintain consistency between girder lines fabricated with virtual assembly and those fabricated with conventional match-drilling. After physical laydown fit-up, web gap measurements were found to be identical between the BRIDGE VAS virtual assembly and a manual ruler measurement. This was shown in Table 16 in a previous section ("*Splice Fit-Up Details*"). Length measurements of the girder pair were made from the virtual assembly of the girders (with the girders in the standing position) and straight-line chord measurements were made at the top center of the web (see Table 19). Measurements made from the bearing were

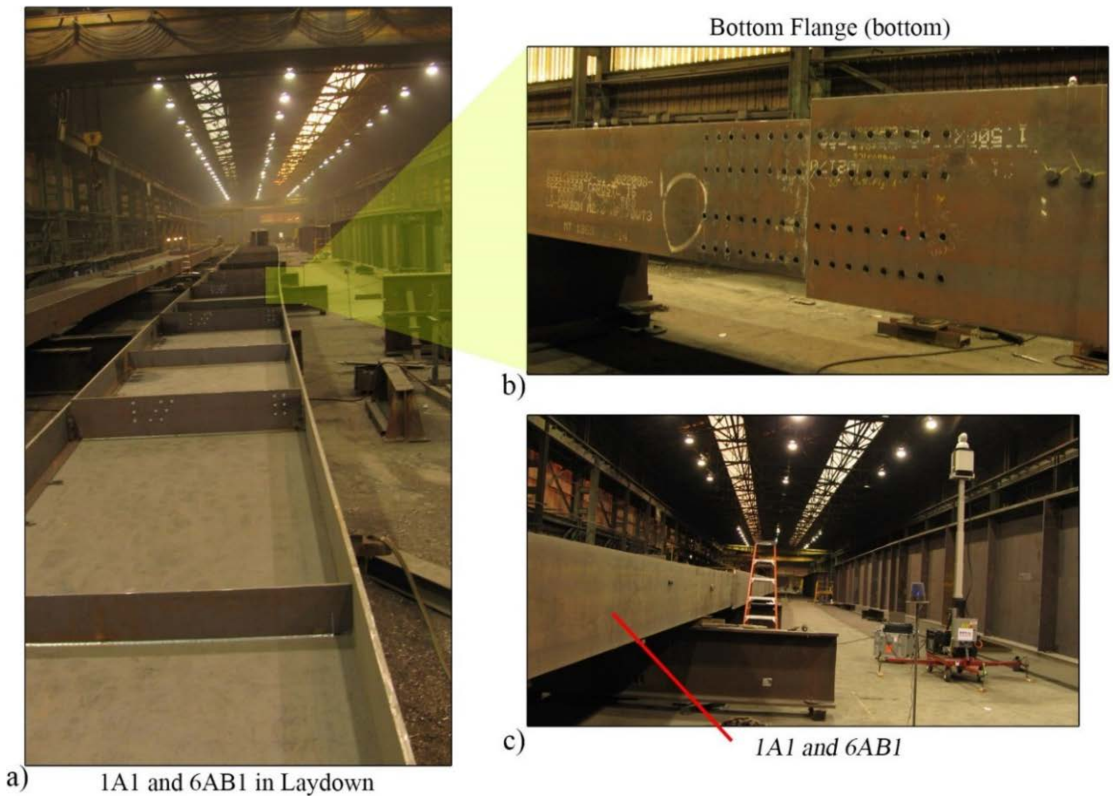


Figure 50. Laydown Measurement of Girders for Comparison to Virtual Assembly Showing a) the Girder Pair and b) a Close-Up of the Girder Pair Splice Bottom Flange and c) the Measurement Location of the BRIDGE VAS for Laydown Measurements

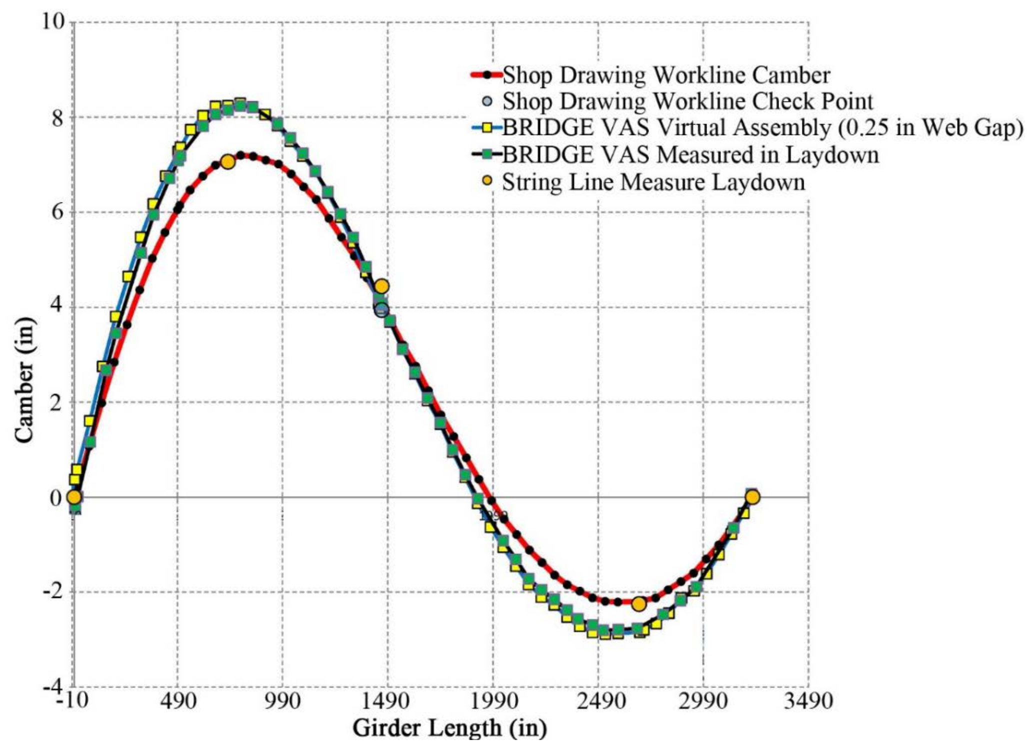


Figure 51. Combined Camber Diagram Comparing Actual Laydown BRIDGE VAS Measurement to BRIDGE VAS Virtual Assembly

Table 18. BRIDGE VAS and String Line Measurements of Combined Camber for Girders 1A1 and 6AB1

Location	BRIDGE VAS Location (in)	BRIDGE VAS Virtual Assembly Camber Standing (in)	BRIDGE VAS Measure Laydown Camber (in)	Shop Drawing Target Camber (in)	Shop Measure String Line Camber (in)
Bearing 1A1	0.000	0.000	0.000	0.000	0.00
¼ Point	730.383	8.243	8.154	7.063	7.06
Splice	1,461.702	4.082	4.083	3.938	4.44
Bearing 6AB1	2,688.294	-2.844	-2.764	-2.250	-2.25
Splice	3,223.928	0.000	0.075	0.000	0.00

Table 19. Girder Pair Lengths for 1A1 and 6AB1 Comparing BRIDGE VAS to Tape Measurements

Location	BRIDGE VAS Measured (in)	Shop Measured (in)	Difference (in)
Top of Web: 1A1 Bearing Stiffener Center to 6AB1 End + ⅛ in Nominal Web Gap	3,223.928	3,224.688	-0.760
Bearing 1A1 to Bearing 6AB1 at Top of Web	2,684.523	2,685.188	-0.665

with respect to the center of the bearing. Corresponding shop tape measurements were made using conventional shop procedures (tape run behind the stiffeners at the top of the web). The actual combined length was about ¾ in shorter than the shop-measured length, which was taken to be the same as the length specified in the shop drawing.

Compare Virtual Assembly Holes to Laydown Measured Holes

To validate the virtual assembly software, a comparison between hole locations was made between the following two conditions: (1) a virtually assembled girder pair based on independent measurements of girders in the standing position, (2) physical measurements of the girder pair placed in laydown position and aligned. Hole patterns were measured for the web, top flange, and bottom flange and the 2D position (out-of-plane dimension is not used) of the holes were compared. Table 20, Table 21, and Table 22 show the results of the comparison for the virtual assembly of Girders 1A1 and 6AB1. The physical alignment of the girder pair in laydown showed an offset of the top flange of Girder 1A1 as compared to the virtual assembly. This offset is due to the manner in which the assembly was performed (both virtually and physically) and the web panel deformations in the girder (i.e., girders with large web depths are very flexible and can be moved into different positions). Essentially, the girders are positioned (bent) differently when comparing the laydown position to the position of the girders standing up-right. For these measurements, the near side (NS) edge of the top flange of Girder 1A1 was

Table 20. Compare Virtual Assembly Holes to Measured Holes for the Web Hole Pattern

Statistic	1A1		6AB1	
	X (in)	Y (in)	X (in)	Y (in)
Mean	-0.008	-0.018	-0.019	-0.049
± σ	0.004	0.000	0.004	0.000
Min	-0.015	-0.019	-0.026	-0.049
Max	-0.002	-0.018	-0.013	-0.048

Table 21. Compare Virtual Assembly Holes to Measured Holes for the Bottom Flange Hole Pattern

Statistic	1A1		6AB1	
	X (in)	Y (in)	X (in)	Y (in)
Mean	-0.003	0.007	-0.002	0.020
± σ	0.002	0.002	0.034	0.032
Min	-0.006	0.004	-0.045	-0.029
Max	0.000	0.010	0.042	0.068

Table 22. Compare Virtual Assembly Holes to Measured Holes for the Top Flange Hole Pattern

Statistic	1A1		6AB1	
	X (in)	Y (in)	X (in)	Y (in)
Mean	-0.029	0.064	-0.029	0.001
± σ	0.003	0.002	0.023	0.018
Min	-0.034	0.061	-0.058	-0.027
Max	-0.025	0.068	0.001	0.029

moved over approximately ½ in with respect to the position of the girders standing up-right. Table 22 contains a manual offset in the Y dimension to compensate for this different girder position.

For the hole pattern in the web, bottom flange, and top flange, the statistical differences are small, indicating that the positions under virtual assembly of the girders are very similar to when the girders are aligned physically by the conventional shop procedures. The main source of the differences in the two measurements is the inability to physically align the very large girder pair with extreme precision (i.e., while very close, the girder pair was not sitting on the shop floor exactly as predicted and intended by the virtual assembly software).

Virtual Assembly Splice Plate Design

BRIDGE VAS software was used to detail custom-made splice plates for five of the ten possible splices on girder lines 1 and 2. This process was incrementally advanced on splice pairs with the initial girder pairs additionally measured with the BRIDGE VAS in the laydown position (detailed previously). The culmination of this effort was virtual assembly on a girder pair with all splice plates (top flange, bottom flange, web) detailed by the BRIDGE VAS without any other verification measurements. This is illustrated with the girder pair of 6AB1 and 11B1-1. Both girders were fabricated with full-sized holes and made nominally to the desired length without using any laydown match-drilling processes. Holes were completely independently placed in each girder early in the fabrication process (they were not drilled in the laydown position to ensure alignment). These two girders were completely independently and separately measured with the BRIDGE VAS, on different days, while in the standing position as shown in Figure 52.

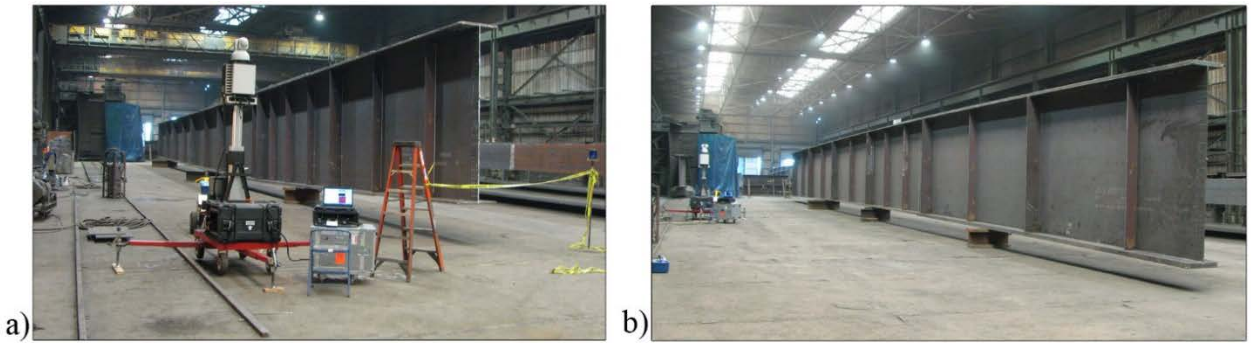


Figure 52. Independent Measurement of Girders a) 6AB1 and b) 11B1-1

With independent measurements of each girder, the BRIDGE VAS virtual assembly software was used to fit the girders together. Figure 53 shows output from the virtual assembly software tools that shows the girder pair (a), a closer view of the splice (b), and the output web splice plate design drawing (c). The virtual assembly software fits the girders together and manipulates these girders to the desired criteria, which are based on the combined camber diagram specified in the shop drawings. Once in alignment, the actual combined camber diagram is generated and compared to the combined camber diagram from the nominal shop drawing. Figure 54 shows the camber data for this girder pair (6AB1 and 11B1-1). The BRIDGE VAS software produces CAD drawings for the top flange, bottom flange, and web splice plates. Output is in standard formats, directly readable by drilling equipment (DXF format). The CAD files for the three plates for the splice of Girders 6AB1 and 11B1-1 were sent to the CNC drill and the plates were fabricated (see Figure 55).

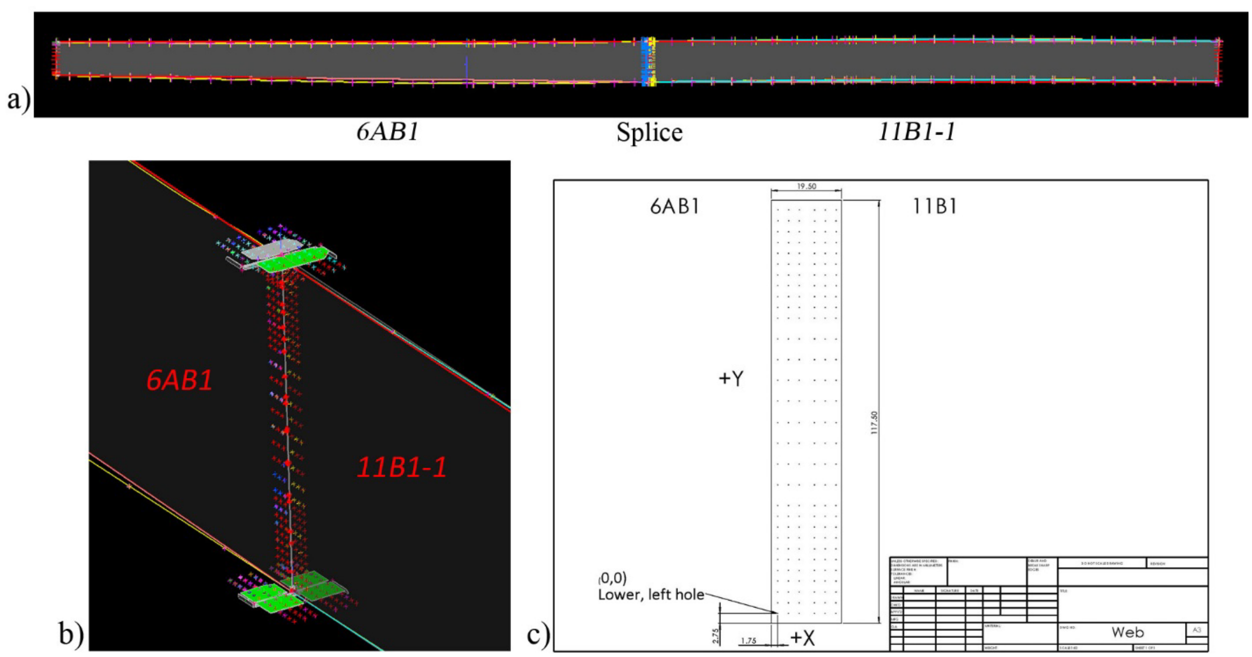


Figure 53. Virtual Assembly of a) Girder Pair 6AB1 to 11B1-1 Showing b) Close-Up of Splice and c) Resulting Custom Splice Web Plate Detail

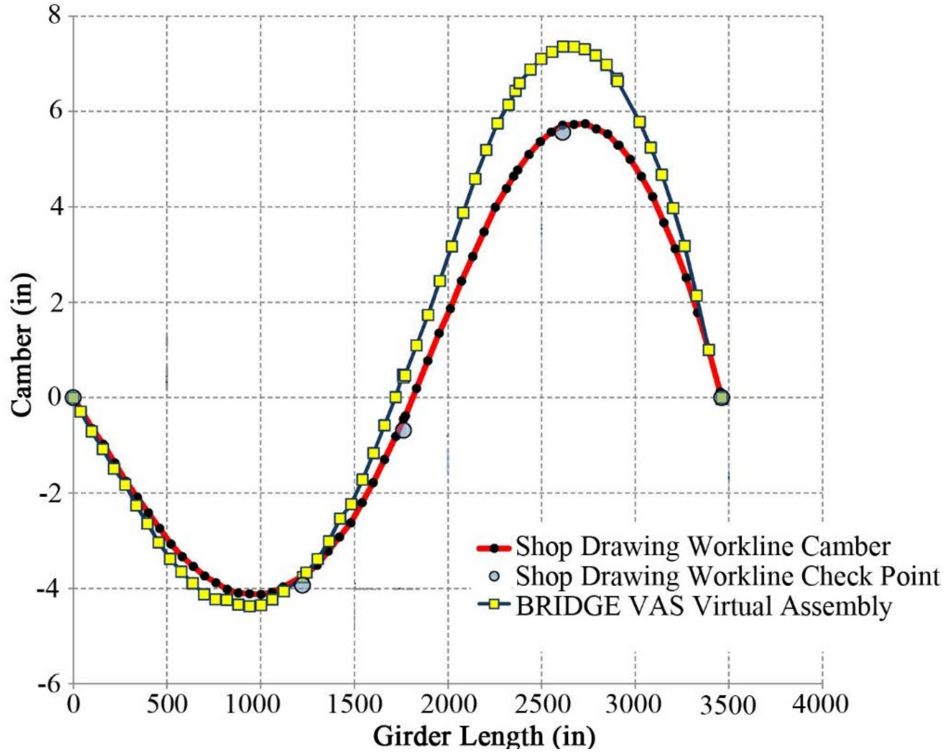


Figure 54. Combined Camber Diagram of Girder Pair for Virtual Assembly of 6AB1 and 11B1-1

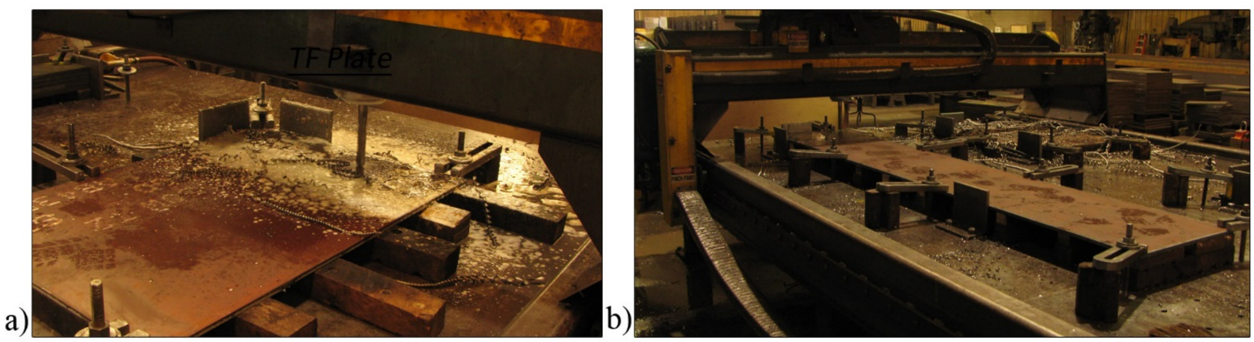


Figure 55. Fabrication of BRIDGE VAS Detailed: a) Top Flange Plate and b) Web Plate

Laydown Verification of Splice Plates

The Tennessee Department of Transportation (TDOT) allowed the virtual assembly process to be implemented, but required a shop laydown verification. The girder pair 6AB1 and 11B1-1 was placed in laydown and aligned. The BRIDGE VAS detailed splice plates were then placed on the girders and pinned in place. Figure 56 shows the plates for the top flange, bottom flange, and web on the girder pair. All 348 of the splice holes were tested with a bolt to ensure alignment. A conventional string line was placed along the length of the girder pair and the camber was inspected, verified and approved by a TDOT representative using a ruler (see Figure 57).

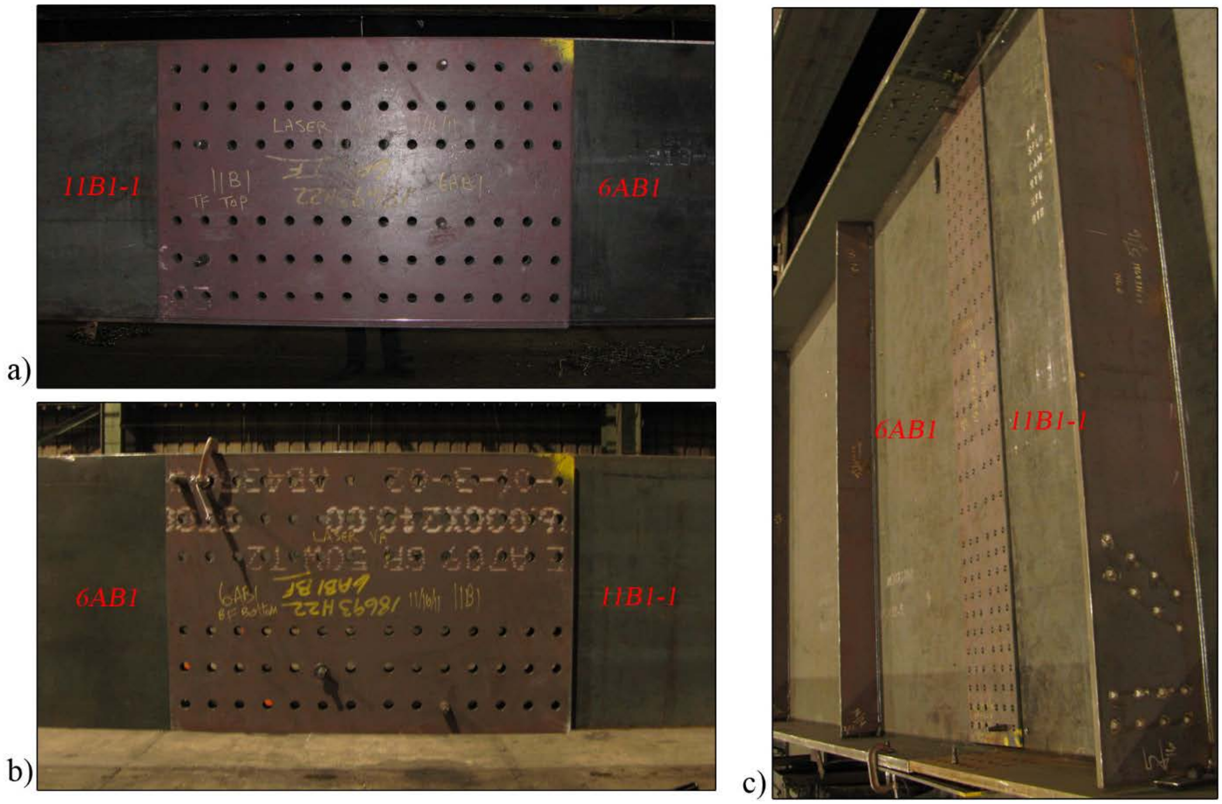


Figure 56. BRIDGE VAS Detailed Splice Plates Fit-Up in Girder Laydown Showing a) Top Flange, b) Bottom Flange, and c) Web Plates

Figure 57. TDOT State Laydown Inspection of Girder Pair for BRIDGE VAS Detailed Splice Plates

Field Erection of the Bridge

The TDOT bridge was successfully erected without any fit-up issues of the girders. All field splices that were fabricated using the BRIDGE VAS fit together in the field without any issues. The end spans of each girder line (1A1, 6AB1, 2A2, 7AB2, 21BC1, 26C1, 22BC2, 7C2) were erected in July 2012. The middle span of girders in each line (11B1-1, 16B1-2, 12B2-1, 17B2-2) was erected in August 2013. There was a significant delay in erection due to a construction issue related to a concrete pier that prevented erection of the girders at one time. Figure 58 shows Girder 6AB1 and 11B1-1 being positioned for fit-up. This splice was created completely with the BRIDGE VAS with full virtual assembly and validated with a shop laydown check. A close-up view of the web and flange splice plates after fit-up is shown in Figure 59.

a) b)

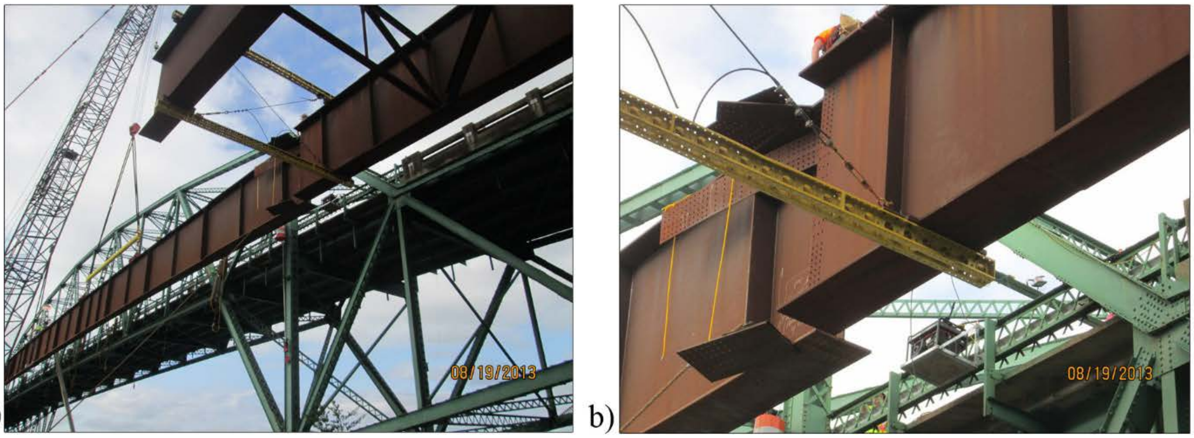


Figure 58. Erection of a) Line 1 Splice 2, Girder 6AB1 to 11B1-1 and b) Close-Up of Splice (Photos provided by H. Pate, Tennessee Department of Transportation)

a)
b)

Figure 59. Line 1 Field Splice 2, Girder 6AB1 to 11B1-1, Showing Final Fit-Up of a) Top Flange and Top of Web Plate and b) Bottom of Web Plate and Bottom Flange (Photos provided by H. Pate, Tennessee Department of Transportation)

Girder lines 1 and 2 were completely measured in the fabrication shop with the BRIDGE VAS system. The final successful erection of these two lines is shown in Figure 60.

Figure 60. Field Erection of Girder Lines 1 and 2 Showing Successful Fit-Up of All Girders with a) View Under Pier and b) View Beside Pier (Photos provided by H. Pate, Tennessee Department of Transportation)

DISCUSSION

During this project an advanced bridge girder measurement system was designed, built and deployed that can substantially improve steel bridge fabrication. The system was used for the first time on a production bridge job, representing the first time entire lines of girders have been measured with such precision and accuracy. The production bridge job chosen was an aggressive choice for a first effort. While the girders were straight, they were very large both in length and depth. These large girders presented additional challenges comparing with a short and shallow girder. Girders of the size measured in the production job are very flexible and present more complex fit-up issues than a smaller girder.

The use of the BRIDGE VAS on a production bridge job made possible observations and lessons that were not possible in earlier testing. This is particularly highlighted in the discussion of the accuracy in length measurement of bridge girders. The close observation of measurements allowed detailed assessment of current measurement practices and provided an opportunity to quantify the measurement accuracy of currently used tools. This project helped solidify understanding of girder dimensions and where measurements need to be made. This included identification of what needs to be measured and quantification of how accurately it needs to be measured.

Operating BRIDGE VAS on a production bridge job also allowed the system to be rigorously tested under real operational conditions. Operation in a production environment over a four-month period provided the opportunity to assess the system’s full capabilities in and around all steel fabrication shop activities. The current design was found to be very robust and performed without any difficulties. It is important to note that the fabrication shop used for the production job in this study did not use the most advanced available drilling equipment. This demonstrates that it is not a requirement to have the most technologically advanced shop or equipment in order for the BRIDGE VAS to be useful and functional. The use of more advanced drilling equipment will improve the quality of fabricated girders and will be better utilize BRIDGE VAS measurements. However, the ability of the BRIDGE VAS to produce custom-made splice plates based on commonly used drilling equipment proves the BRIDGE VAS system is very robust and can operate in nearly any fabrication shop.

The additional types, precision and accuracy of information provided by the BRIDGE VAS are not accommodated in existing codes and specifications (Bridge Welding Code, AISI). Existing specifications are written based on conventional measurement processes. One area specifically that would provide much more flexibility in taking advantage of a virtual assembly system is allowing greater web gaps in a splice. The current nominal web gap of about ¼ in does not provide much ability to adjust the overall length of the bridge based on the actual measurements of individual girders. Instead of using very time-consuming procedures to create an individual girder with a length that is very precise, it is potentially more economical to fabricate girders with current procedures and then adjust the overall length with the web gap in the splices. If bridge girders are fabricated using a tape measure, then as demonstrated earlier in this report, the fabricated girder will always be shorter than the nominal shop drawing intended length. Therefore, these differences can be made up, if necessary, in the web gap.

CONCLUSIONS

- *The BRIDGE VAS is the first virtual assembly system and this project was the first demonstration of a virtual assembly system on a production bridge job.* This project demonstrated the capabilities of virtual assembly systems and illustrated the benefits of this concept.

- *Match-drilling and laydown procedures can be completely eliminated by using a virtual assembly system.* Girders can be fabricated with full-sized holes at the most efficient stage of fabrication.

- *Virtual assembly can be performed in existing fabrication shops.* Conventional drilling equipment and other current fabrication procedures (not just the most technologically advanced shops) can be used. A virtual assembly system is robust enough to work in a typical fabrication environment.

- *Virtual assembly systems can more accurately characterize the full three-dimensional geometry of a fabricated bridge girder.* Conventional measurement methods have limited ability to accurately document fabricated girders. Virtual assembly systems in this project revealed unknown systematic errors in conventional measurements of girder length whereby girders are fabricated shorter than designed. Using virtual assembly systems on a continuing basis will reveal other unknown fabrication issues that should lead to better quality end-products.

- *Virtual assembly systems can help improve steel bridge fabrication processes by providing greater detail and more accurate documentation of exactly what has been fabricated compared to conventional methods.*

- *Virtual assembly systems as demonstrated in this project can capture and perform certain types of measurements that are not currently possible (i.e., full-girder web panel deformations).*

- *Better quality control during fabrication has the capability to reduce fit-up problems during steel girder erection.*

RECOMMENDATIONS

1. *State departments of transportation (DOTs) should continue to consider the use of virtual assembly technology for the fabrication of steel bridge girders.* By doing so, transportation agencies would receive higher quality products, as well as better documentation of those delivered products. State DOTs should consider the virtual assembly approach as outlined in this report as an acceptable interpretation of computer numerically controlled drill.

2. *State DOTs should allow greater tolerances in the web gap for spliced girders.* This greater web gap tolerance would allow normal fabricator length variation to be accommodated in the splice plate, while not requiring expensive and time consuming measures to fabricate girders to a highly accurate length.

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Dr. William Wright (Wright Structural, LLC)
Dr. Joseph Hartmann (Federal Highway Administration).

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Mr. Wayne Segar (Director of Structures Division)
Mr. Tom Quinn (Steel Bridge Fabrication)
Mr. Henry Pate (Structural Design Office).

REFERENCES

Burtch, R. *Fundamentals of Surveying: Tape Corrections.* 2008. Surveying Engineering Department, Ferris State University, Big Rapids, MI. http://www.ferris.edu/faculty/burtchr/sure110/notes/tape_corrections.pdf. Accessed October 26, 2011.

Fuchs, P.A., Washer, G.A., Chase, S.B., and Moore, M.E. Applications of Laser-Based Instrumentation for Highway Bridges. *ASCE Journal of Bridge Engineering*, Vol. 9, No. 6, November/December 2004a, pp. pp. 541-549.

Fuchs, P.A., Washer, G.A., Chase, S.B., and Moore, M.E. Laser-Based Instrumentation for Bridge Load Rating. *ASCE Journal of Performance of Constructed Facilities*, Vol. 18, No. 4, 2004b, pp. 213-219.

Fuchs, P.A. *NCHRP Idea Project 127: Instrumentation to Aid in Steel Bridge Fabrication.* Transportation Research Board, Washington, DC, 2009.

Fuchs, P.A. *NCHRP Idea Project153: Bridge Retrofit Laser System.* Transportation Research Board, Washington, DC, 2012.

Stone, W.C., Juberts, M., Dagalakis, N., Stone, J., Gorman, J. *Performance Analysis of Next-Generation LADAR for Manufacturing, Construction, and Mobility.* NISTIR 7117. National Institute of Standards and Technology, Gaithersburg, MD, 2004.

Wahhab, H. I. Chapter 2: Tape Measurement, 2009. PowerPoint presentation. http://faculty.kfupm.edu.sa/CE/hawahab/WEBPAGE/CE260/NOTES/2Chapter%202%20Linear%20Distance%20Measurement.pdf. Accessed October 1, 2011.

White, D., Coletti, D., Chavel, B., Sanchez, A., Ozgur, C., Chong, J.M.J., Leon, R., Medlock, R., Cisneros, R., Galambos, T., Yadlosky, J., Gatti, W., and Kowatch, G. *NCHRP Report 725: Guidelines for Analysis Methods and Construction Engineering of Curved and Skewed Steel Girder Bridges.* Transportation Research Board, Washington, DC, 2012.

APPENDIX

CAMBER DATA FOR TENNESSEE DEPARTMENT OF TRANSPORTATION GIRDERS

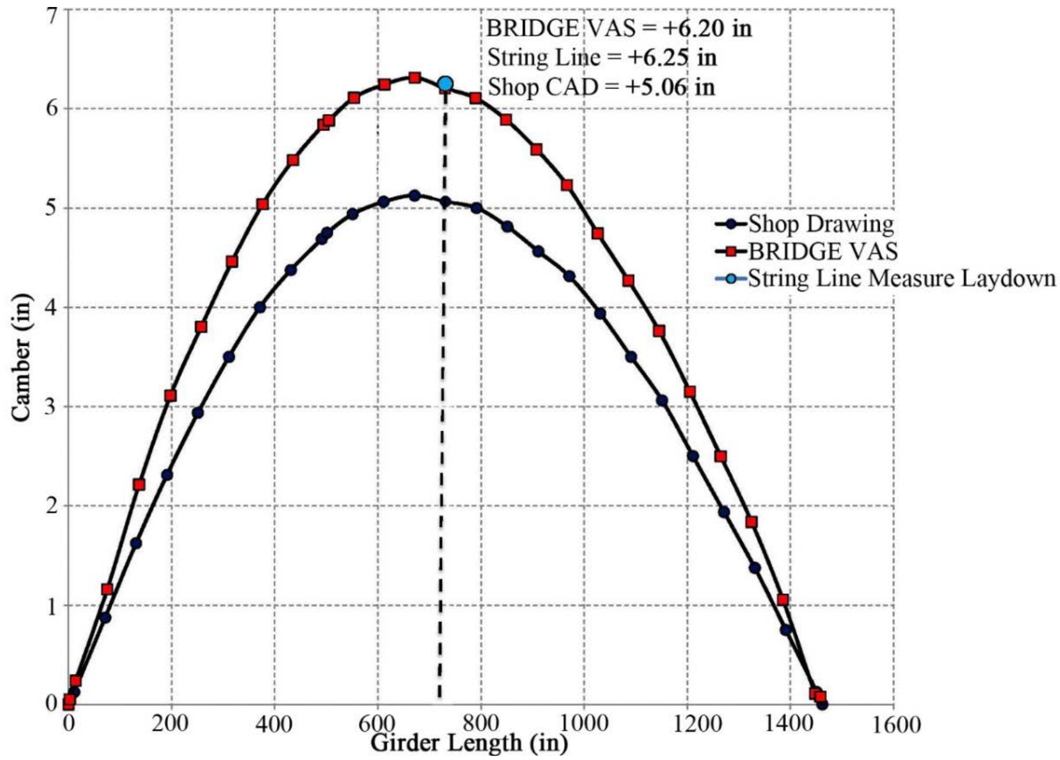

Figure A1. Girder 1A1 Top Flange Camber

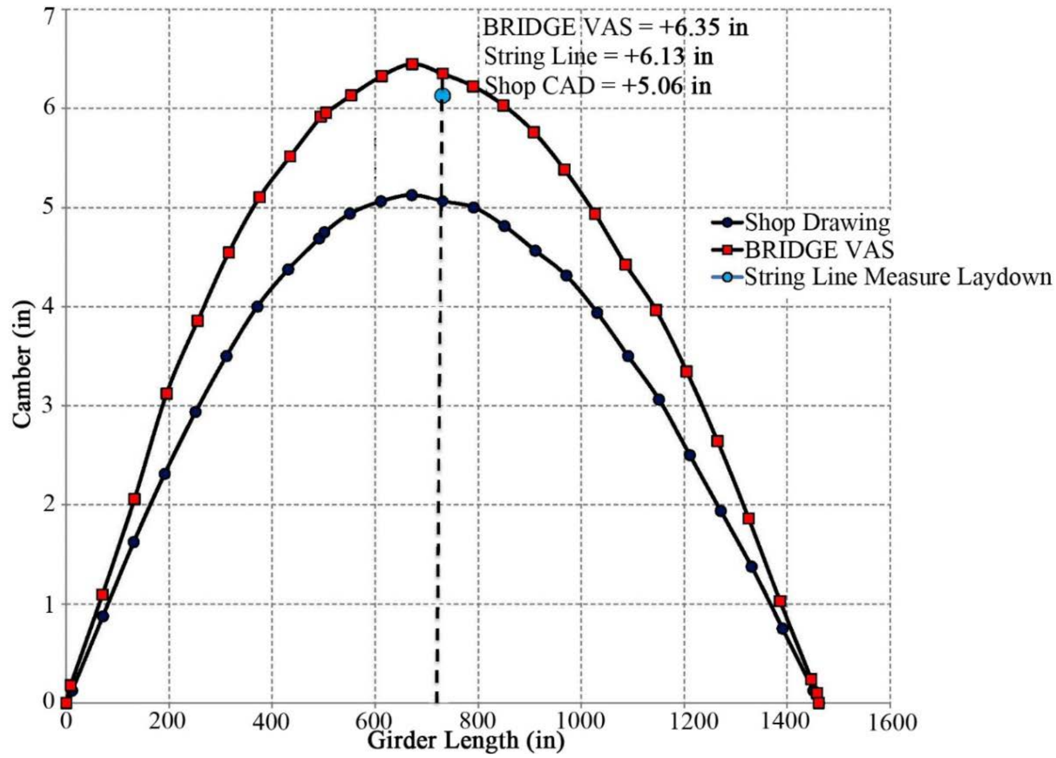

Figure A2. Girder 2A2 Top Flange Camber

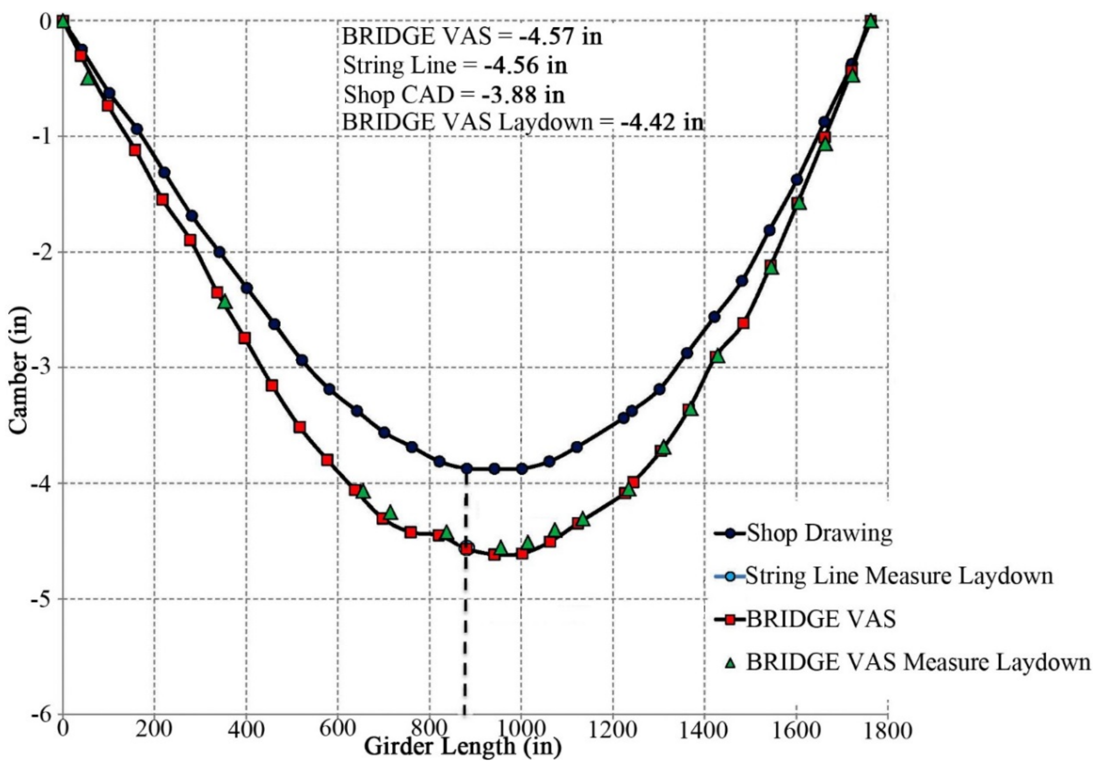

Figure A3. Girder 6AB1 Top Flange Camber

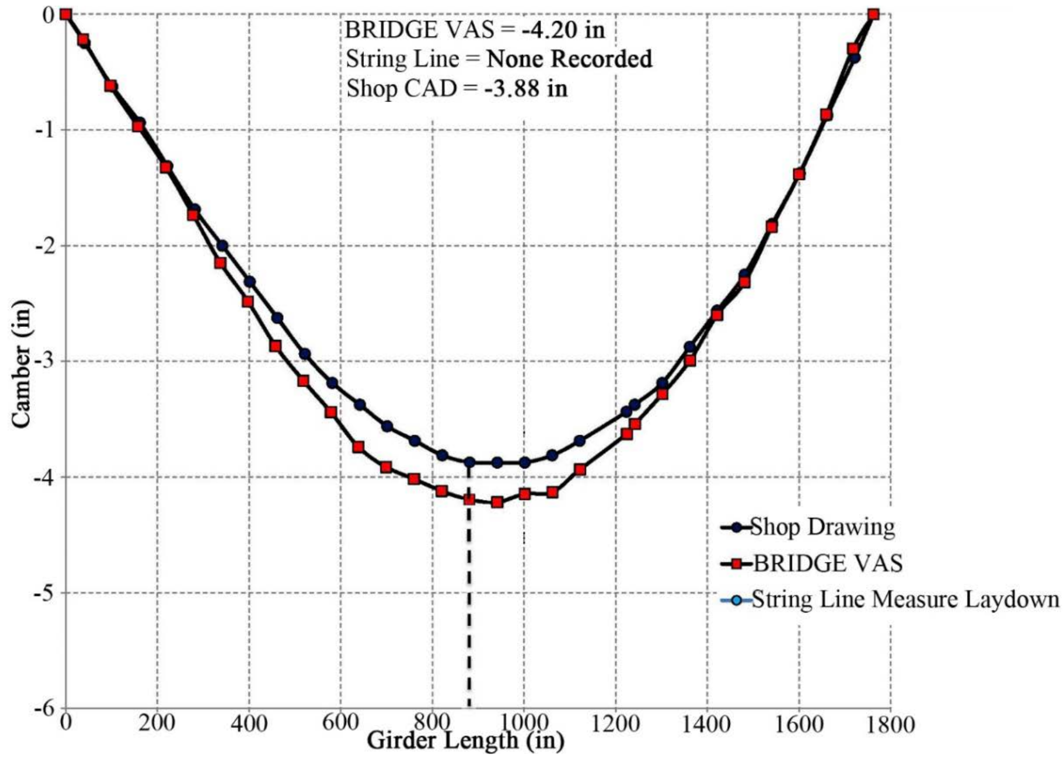

Figure A4. Girder 7AB2 Top Flange Camber

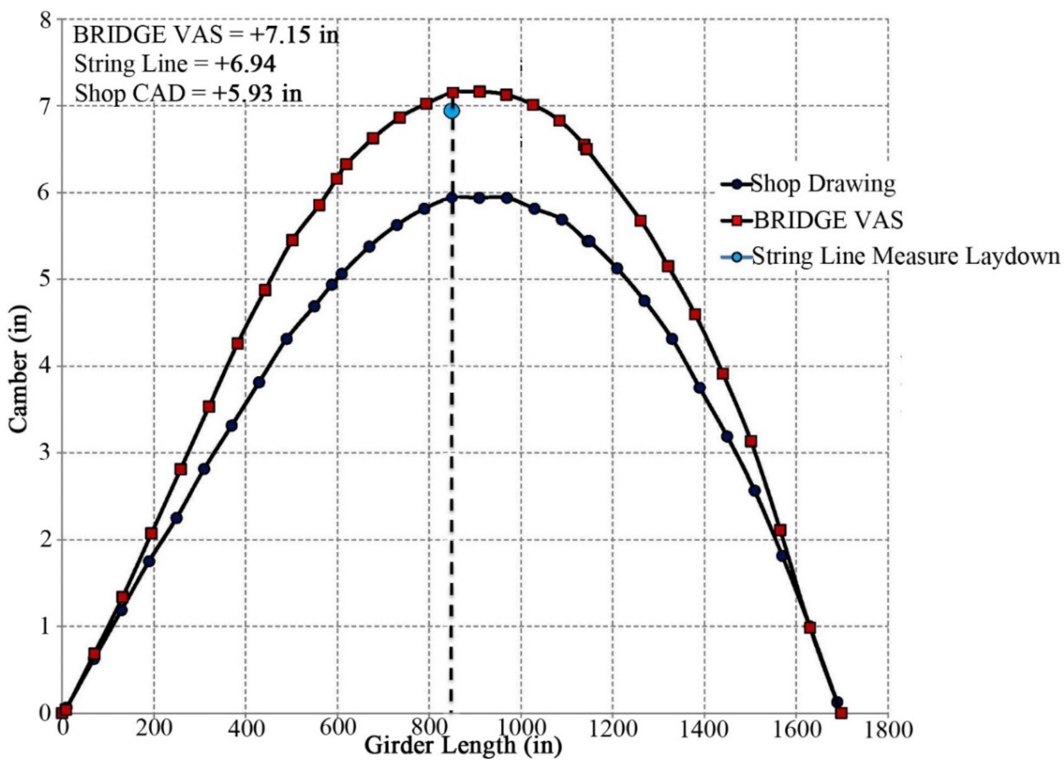

Figure A5. Girder 11B1-1 Top Flange Camber

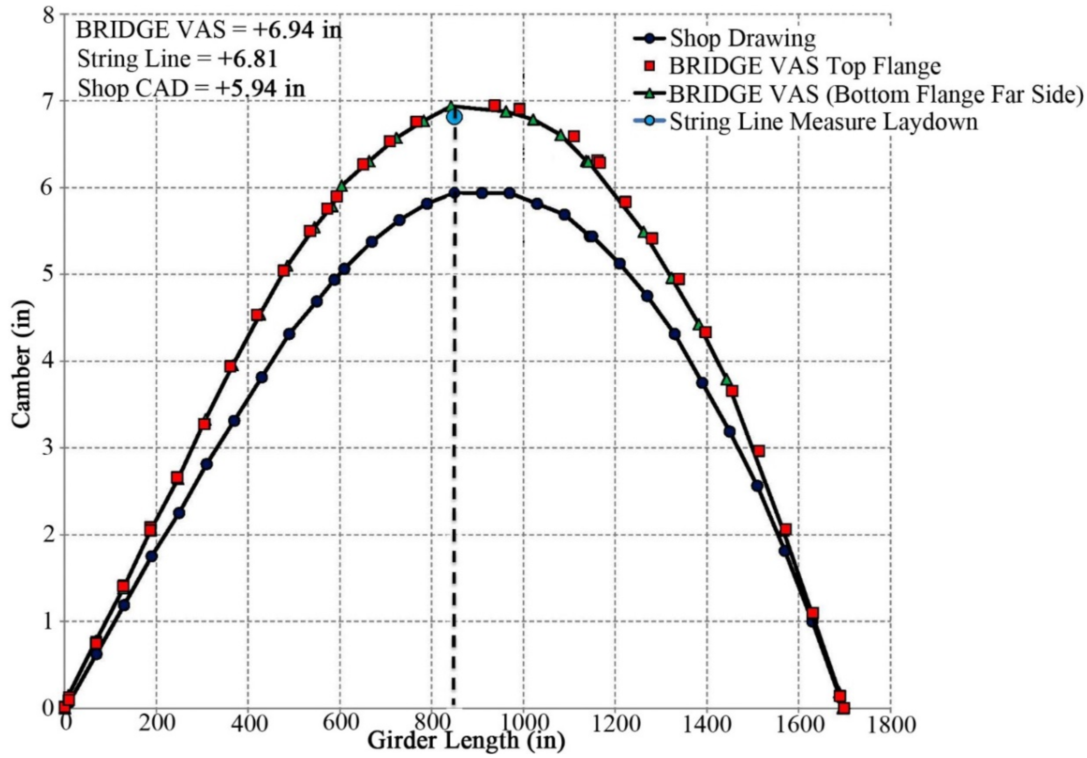

Figure A6. Girder 12B2-1 Top and Bottom Flange Camber

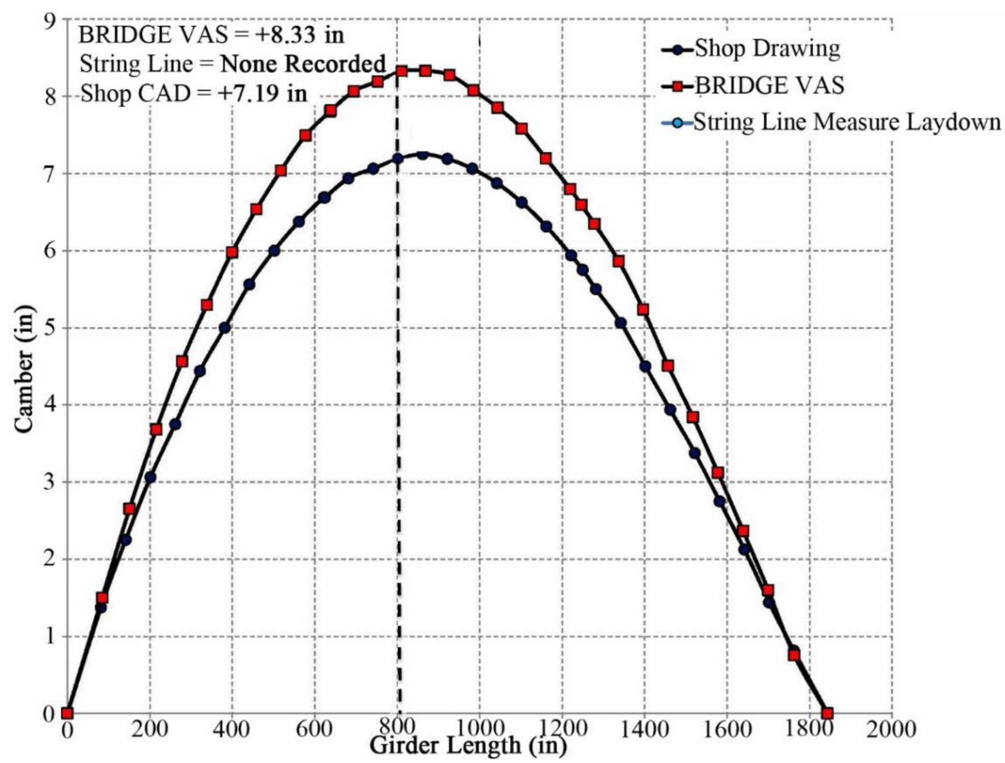

Figure A7. Girder 16B1-2 Top Flange Camber

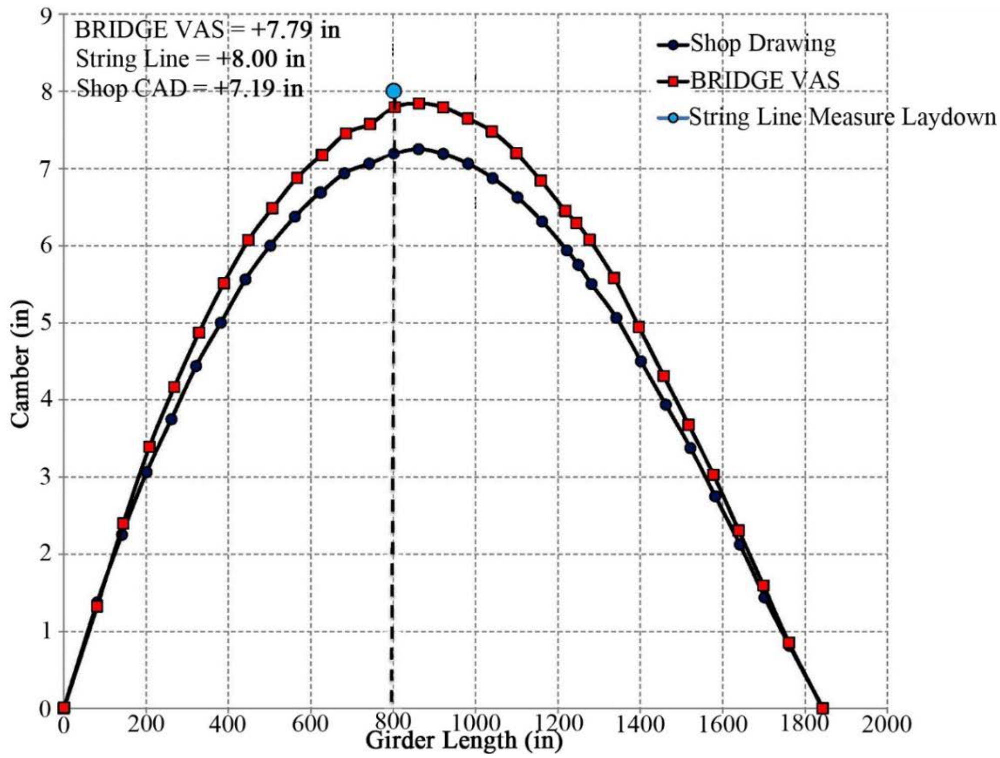

Figure A8. Girder 17B2-2 Top Flange Camber

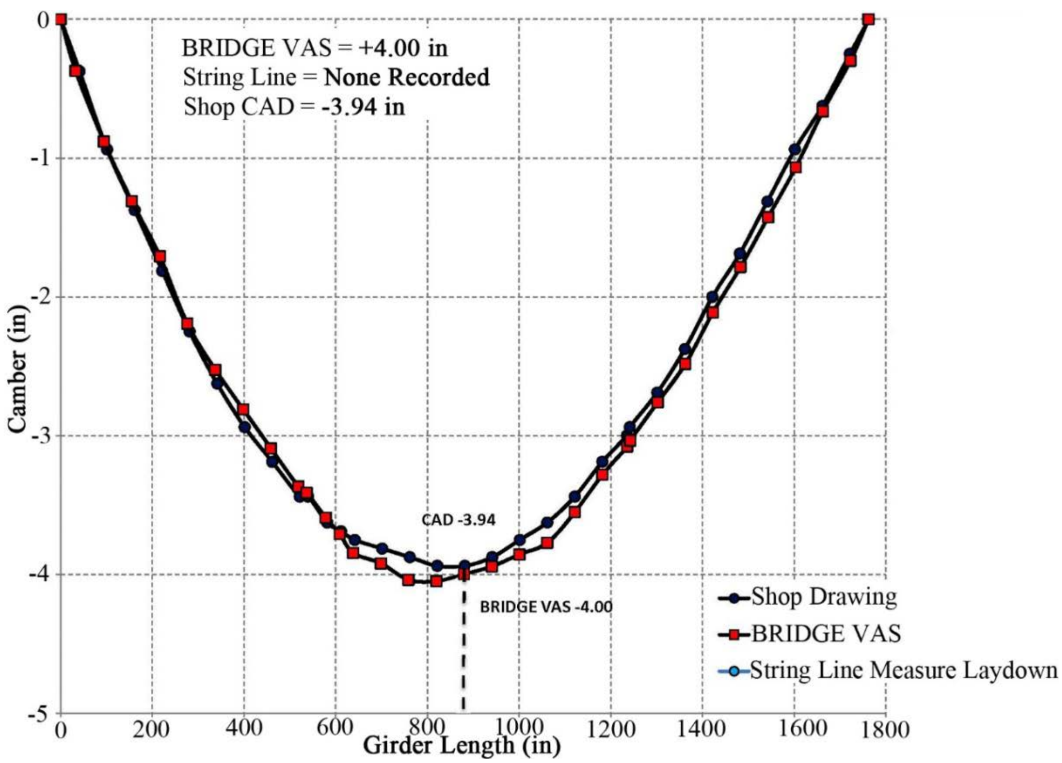

Figure A9. Girder 21BC1 Top Flange Camber

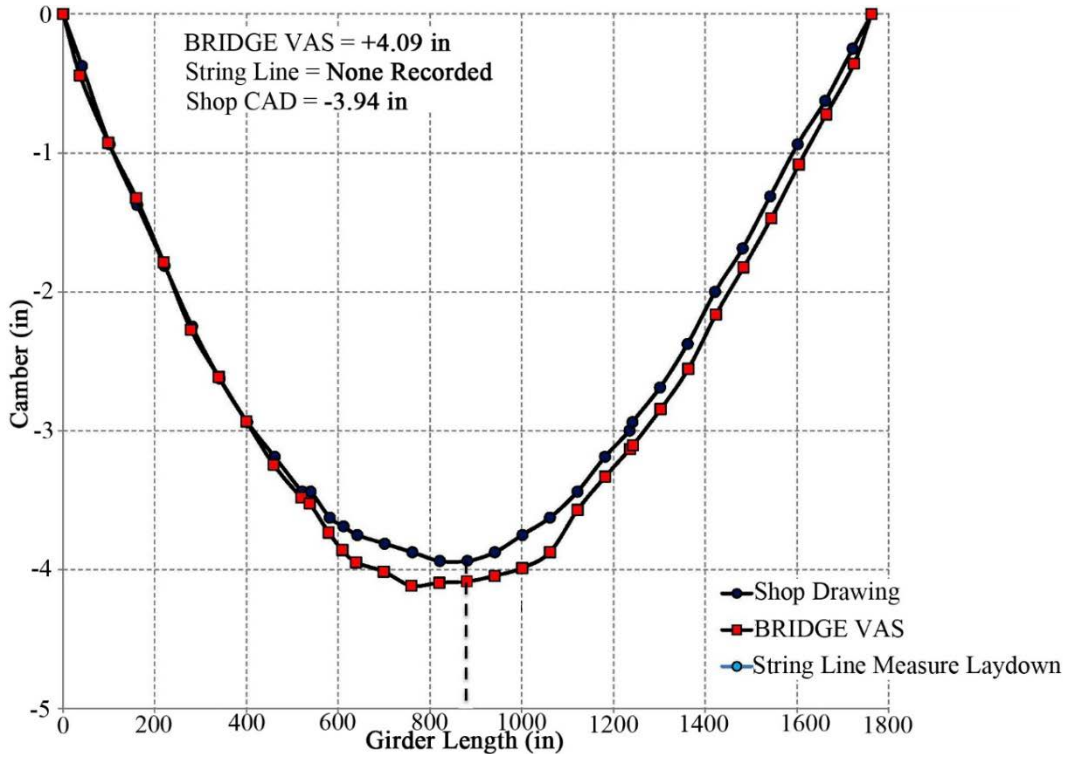

Figure A10. Girder 22BC2 Top Flange Camber

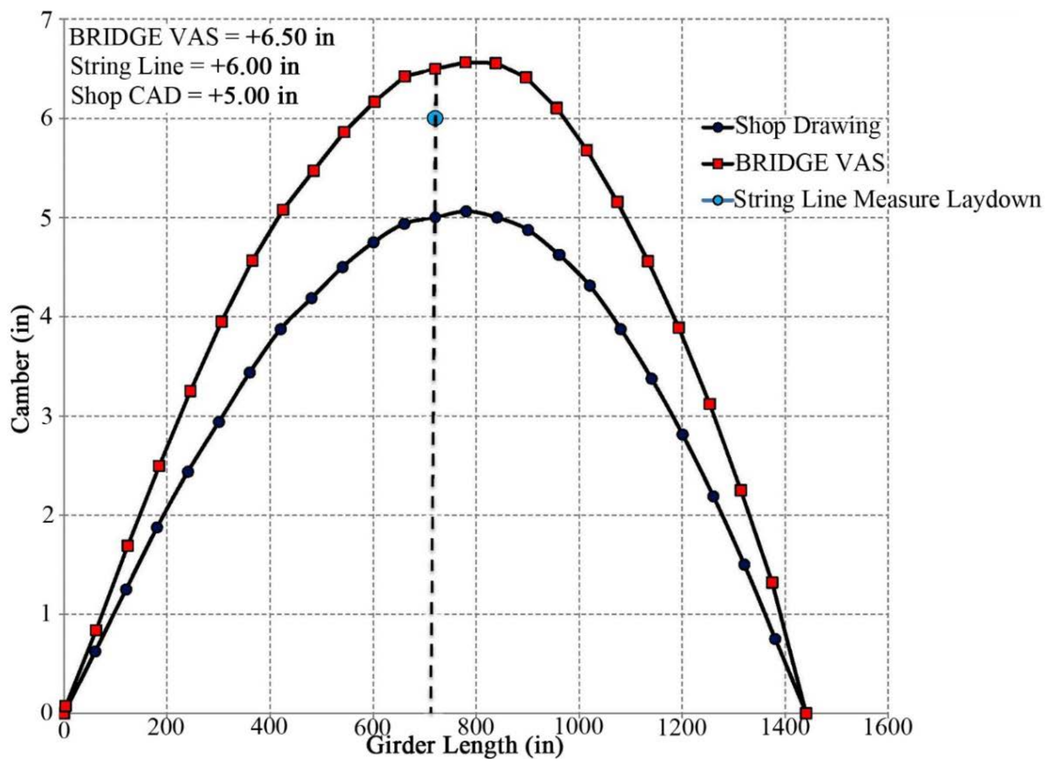

Figure A11. Girder 26C1 Top Flange Camber

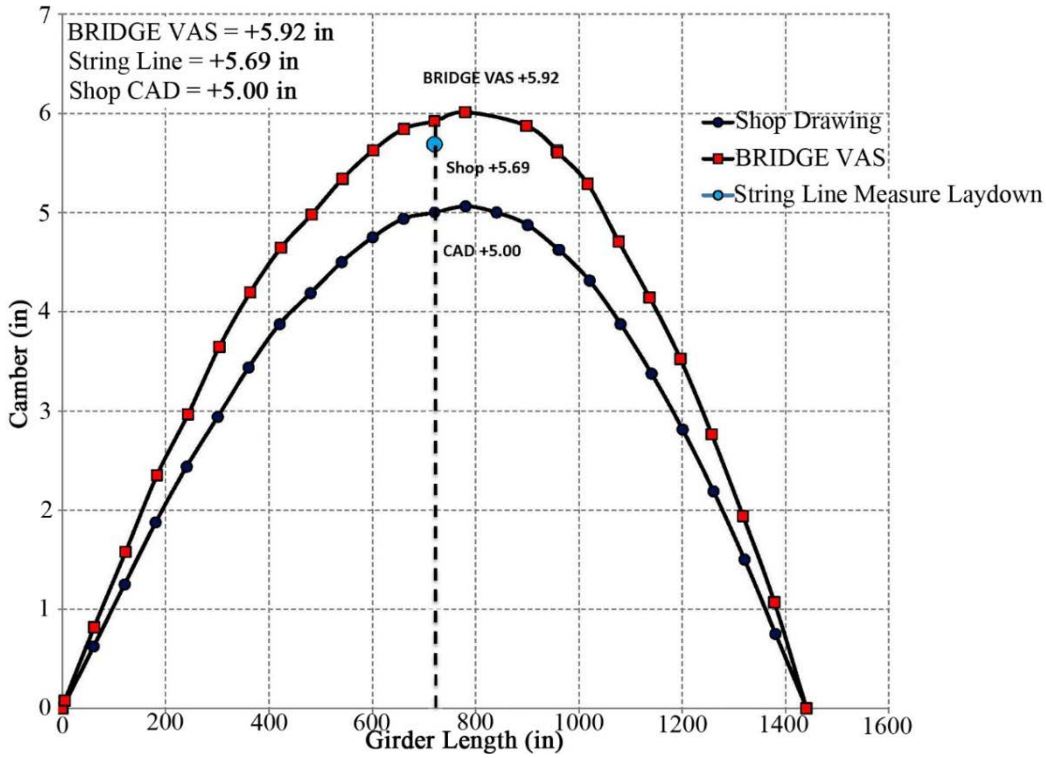

Figure A12. Girder 27C2 Top Flange Camber