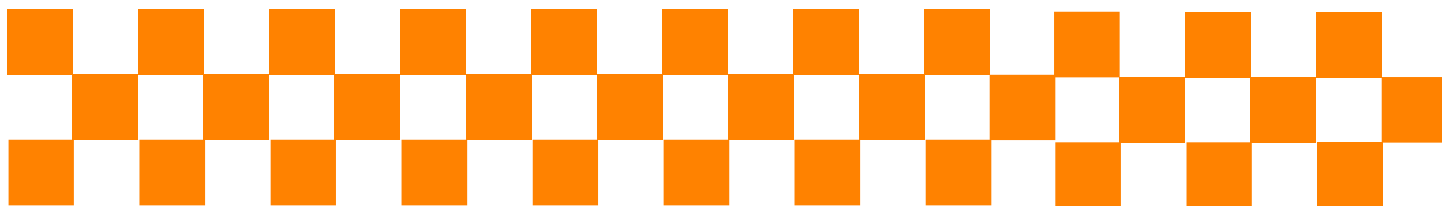
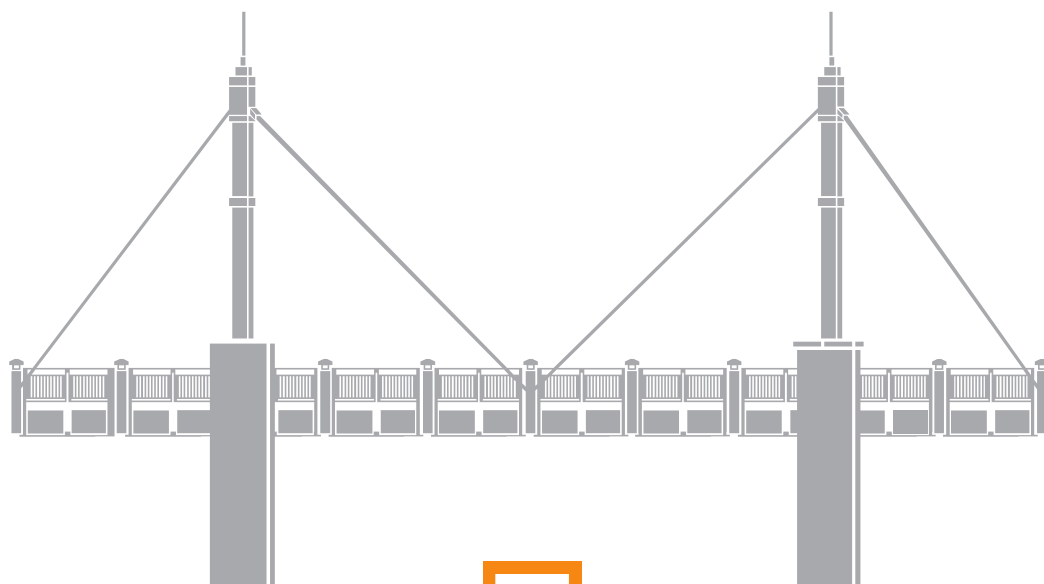


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Accelerated Innovation Development of Laser Metrology for Steel Bridge Fabrication

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ENVIRONMENTAL ENGINEERING

The University of Tennessee is a Public Land Grant University that was founded in 1794 as Blount College. Instruction in civil engineering began at the University of Tennessee in 1834, then East Tennessee College, after Joseph Estabrook became president. In 1993 the department's name changed to Civil and Environmental Engineering to reflect the significance of Environmental Engineering in the department's activities. In 2013, the department moved into the newly constructed John D. Tickle Engineering Building. The bridge connecting the John D. Tickle Engineering Building with Estabrook Road is featured on the cover page of this report series and serves as a symbol for the department.

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Abstract

This report documents the use of a laser metrology technique in the production of splice connections for steel bridge girders which was successfully performed at Hirschfeld Industries steel bridge fabrication plant in Bristol, VA. Over the course of this project, the traditional method of splice connection fabrication was studied and compared alongside a newer method involving the use of laser metrology to enable the use of pre-drilled girder splice connection holes and custom fabricated splice plates. The primary benefit of this new method is that time consuming match drilling of girder splice connections is replaced with automated drilling methods. This new technique was demonstrated on girders that were fabricated for use in a new bridge being built in Dandridge, Tennessee. In addition to documenting the technique and its implementation, this report examines various aspects of the technology used, costs and benefits, possible sources of error, and potential uses and extensions of the technique in the future. Based on the findings in this report and the implementation documented, it is clear that the laser metrology technique studied can successfully be implemented in steel bridge fabrication; furthermore, this technique has great potential to provide significant time, money, and space savings in the girder fabrication process. Funding for the research of this project was provided thru FHWA's Accelerated Innovation Deployment (AID) grant. This program provides funding as an incentive for eligible entities to accelerate the implementation and adoption of innovation in highway transportation.

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1. Introduction

Bridges are a vital part of the transportation network in the United States. Bridges, which span rivers, bays, canyons, mountain passes, and other streams of traffic, connect our world better by allowing people access to more efficient and direct routes to their destinations. Millions of people travel across bridges to and from work, while trucks and trains convey billions of dollars' worth of goods across bridges; consequently, bridges are also a key factor for the nation's economic health. In the 2013 Report Card for America's Infrastructure published by the American Society of Civil Engineers (ASCE), bridges have been given a grade of C+ which is defined as "mediocre" according to their grading scale (ASCE 2013). "One in nine of the nation's (607,380) bridges are rated as structurally deficient..." (ASCE 2013). This is to say that approximately 67,500 bridges are structurally deficient, meaning that these bridges, although not unsafe, have deteriorating structural components in need of repair and should have weight and or speed limitations in place. Additionally, roughly 151,000 (1 in 4) bridges in the country have been declared to be functionally obsolete, meaning that these bridges no longer meet the standards used today.

Despite their importance to the nation's infrastructure, many bridges in the United States are not receiving much needed renovations, renewals, and repairs. According to ASCE, this is primarily due to the lack of funding needed to make these investments. "The FHWA estimates that to eliminate the nation's bridge deficient backlog by 2028, we would need to invest \$20.5 billion annually, while only \$12.8 billion is being spent currently" (ASCE 2013). This is an enormous deficit to overcome and because of it priority is given to projects deemed absolutely necessary and projects that are undertaken in response to emergencies, with many worthy projects going unfunded. While there have been proposed plans to increase funding for infrastructure projects, it

is unlikely that any increase in funding will be large enough to clear the backlog of bridge projects; thus, there must also be work done to lower the cost of construction. In other words, while more money is needed, more also needs to be done with the funds provided.

One of the biggest factors contributing to the cost of a civil works project is time. Utilizing the rapidly improving technological aids for construction can save time during the construction of a bridge. In doing so, the total cost of a project could potentially be drastically reduced by saving many hours of labor on a project. This would allow more bridges to be completed in an allotted time period for less money.

The area of construction being investigated in this report is the fabrication of splice connections between steel bridge girders. The holes in the girders for these splice connections are currently match-drilled manually into the steel plates after they have been welded together to form the girder. This match-drilling process is very time consuming as it requires a full laydown of the girders where a nearly completed set of adjacent girders are laid down next to each other in the fabrication shop. In this laydown, the girders are manually aligned and verified to be in the correct positions for erection. The splice plates that are predrilled with holes in them are then clamped to the girders being joined and then the girders match drilled. “Some estimates put the cost of this step at 15% to 20% of the cost of a steel bridge” (Fuchs and Medlock 2013). This is an expensive and time-consuming process. Additionally, this process takes up a lot of space in the fabrication shop; two girders lying side by side can easily take up hundreds of feet.

Virtual assembly is being implemented in an effort to save factory space, time, and money. The method investigated in this report utilizes laser-tracking technology in order to take measurements of the girders to produce the splice plates virtually and cut and drill the plates using

more efficient automated equipment. This method eliminates match drilling and significantly reduces the time needed for laydowns of adjacent girders.

This report studies the implementation of virtual assembly in the steel bridge girder fabrication process. In this report, Section 2 provides a literature review related to laser measurement techniques and other technologies that have been implemented or studied to speed bridge fabrication and Section 3 provides an in-depth review of the particular laser tracking system for the virtual assembly measurements considered in this report. Section 4 provides a brief overview of the bridge currently under construction that this virtual assembly method is being implemented on. Section 5 explains the current procedure used for the fabrication of steel bridge splice plates while Section 6 describes the virtual assembly method that will be used for the production of steel bridge girder splice connections. An example of the virtual assembly results obtained from Hirschfeld Industries in Bristol, Virginia is shown in Section 7 and followed by a description of possible errors in the virtual assembly method in Section 8. An overview of the potential cost and benefits of the virtual assembly method for steel bridge girder splice connection fabrication is found in Section 9. Section 10, contains a discussion of provisions, possible improvements, and future plans. In Section 11, conclusions are listed. A list of references is given in Section 12.

2. Literature Review

As stated previously, the high capital costs of construction is a major cause for deferred bridge replacement and delayed bridge maintenance. This fact has been known for many years and has led, in part, to the bridge fabrication industry seeking out cost-savings improvements. Many technologies such as computer numerically controlled (CNC or sometimes just referred to as NC for numerically controlled) cutting and drilling, automated welding, radio frequency

identification (RFID) tagging of materials, and laser metrology equipment have been proposed for or implemented in fabrication shops in order to reduce the time and cost of bridge fabrication projects. In this section, literature related to new technologies that have been proposed or recently introduced for bridge fabrication, including laser based-technologies, will be reviewed.

NC machines are used in the steel fabrication shops to improve the efficiency of cutting and drilling steel plates. “The first NC machines were built in the 1940s and 1950s [by John T, Parsons], based on existing tools that were modified with motors that moved the controls to follow points fed into the system on punched tape” (Wire et al.). These early machines were generally used for milling. Soon, the NC machines rapidly improved and incorporated the use of computer programming to create modern CNC machines. Modern CNC equipment has multiple tools available for use such as a high speed drill and a plasma torch. These tools are interchangeable and selected for use by the computer program used to direct the CNC machine. The CNC machine manufactured by Kinetic Cutting Systems Inc. and used in the Hirschfeld Industries fabrication shop in Bristol, VA is shown in Figure 1.



Figure 1: CNC cutting and drilling equipment

The CNC equipment shown is capable of performing many varying tasks for steel bridge fabrication such as cutting and drilling steel pieces to be used as flange plates, web plates, splice plates, and stiffener plates. The table the steel is placed on can vary in length but is large enough to handle long pieces of steel. The table in Figure 1 is about 250 feet long. Prior to the use of these CNC machines there were specialized workers for torching, drilling, monitoring, and using cranes to move equipment and steel around. Now, one or two workers can complete the task. These workers are responsible for setting the steel on the platform for the CNC equipment, monitoring the process, and removing the completed pieces. Although this machinery is fairly expensive “the enormous demand for these innovative machines in Germany has decreased their prices from about 1 to 0.2 million dollars or less for second hand machines” (Pegels et al. 2003). CNC equipment, which itself is becoming more affordable, can considerably lower the total cost of the project due to time saved from labor. In a state of the art steel fabrication facility in Japan a “continuous unmanned operation exceeding 48 [hours] can be achieved by placing many members in the entire operating range of the [numerically controlled] drilling machines, on a Friday afternoon or the evening before a holiday” (Tamai et al. 2002). The ability to set up the equipment to work unmanned throughout a weekend potentially saves a great deal of money on labor hours and increases the project performance and productivity.

Another technology used to improve productivity in steel fabrication shops is automated welding. “Industrial robotic welding is by far the most popular application of robotics worldwide” (Pires et al. 2003). Automated welding is more commonly used in automobile manufacturing. However, due to the length of the girders and long welds required “single pass welds are the most economical, as the equipment travels the length of the girder only once” (FHWA 2015). Automated welding can achieve this in a highly accurate and repeatable manner.

This makes automated welding very desirable in steel fabrication shops. One type of welding, electroslag welding, is described in an article titled “Electroslag Welding Makes Comeback for Fabricating Bridges”:

Unlike all other welding processes specified by the bridge welding code, electroslag welding of bridge steels takes place in one pass and does not require preheating regardless of thickness. These attributes, plus the need for little edge preparation, makes narrow groove improved electroslag welding (NGI_ESW) highly cost effective and productive. The process is ideal for welding plate girders end to end. It can cut the time for creating complete joint penetration welds by more than 90% (Bong 2005).

This type of welding is just one of 5 allowed by the FHWA in their “Steel Bridge Design Handbook”. The other types of welding are Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Flux Core Arc Welding (FCAW), and Gas Metal Arc Welding (GMAW). “Generally... the submerged arc welding process, which remelts and incorporates the tack welds into the finished weld” (FHWA 2015) is used most often in steel fabrication shops. The SAW welding type uses a gravity feed system for the flux, therefore it “...is semi-automatic and thus highly productive” (FHWA 2015). These improvements in welding and automation technology allow for fully automated and semi-automated welding, which improves production and efficiency in the steel fabrication industry and results in potential price reductions in bridges.

Advancements in technology for steel bridge fabrication have led to the push for the use of Radio Frequency Identification (RFID) tags along with informational systems in order to monitor the steel fabrication process more effectively. RFID tags are small chips that have an antenna and utilize radio frequencies that can be read by a reader, without being in the direct line of sight, in

order to share data. There are two types of RFID tags: active and passive. “Active tags require a power source... [and passive tags are] limited by the stored energy, balanced against the number of read operations the device must undergo” (Want 2006). “...by utilizing RFID technology, the location of each piece [of steel] and the man-hours spent to process different pieces at different stages [of steel fabrication] are captured and transferred automatically to [a] database” (Azimi et al. 2011). The information gathered from RFID tags can be used to develop measures of a project’s productivity as well as other performance indicators. These indicators can be used to more accurately determine the real total cost of steel fabrication (including time, money, and shop space) and where there is room to improve efficiency. RFID technology can also be used to gather and share up-to-date project information among the project participants (i.e. contractors, designers, erectors, owners, etc.). Furthermore, the use of RFID technology with other specialized software has “improved the efficiency of the inspection task, decreased the number of errors and enhanced the technical transfer by promoting and encouraging the users to output, exchange, and share various information and knowledge with each other” (Yabuki et al. 2005). The potential increase in efficiency, reduction in errors, and cost savings make the use of RFID tags a promising technology in the reduction of bridge fabrication costs.

Due to the positive impact technology has had in the steel fabrication industry, many ideas and technologies are being explored through research to determine if they have potential to improve the fabrication process. One such technology, laser metrology, is being explored in this paper. Laser metrology in construction and engineering has already been successfully implemented by using the laser scanners for bridge inspection and assessment. In one report there were two case studies in the field of bridge inspection and assessment where laser scanning was successfully executed:

In the case of Chetwynd Viaduct, laser scanning provided accurate modeling of intricate cast iron members, captured member imperfections, details of historic damage/repair and provided the geometry for direct integration into a finite element model to perform a structural assessment. In the case of Laune Bridge, 3D laser scanning was used effectively to assess and monitor settlement, capture detailed geometry including individual stones and provided valuable information in arriving at the optimum rehabilitation solution. In both instances, 3D laser scanning offered added value to the clients for the future management of each historic asset (Minehane, M. J., et al. 2014).

Based on these case studies and as well as one performed to measure and model historic bridges, “this technology is very useful, especially when the structural analysis requires a complete and accurate 3D model” (Lubowiecka, Izabela, et al. 2009). Since the laser scanner has been useful for complex 3D modeling it has great potential to be able to handle the more relatively simple laser scans required for steel splice plate fabrication.

Previously, “Five weeks of testing and development work were conducted at the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC)” (Fuchs 2009) for the use of laser metrology in steel fabrication. This work demonstrated the capabilities of laser metrology in the steel fabrication industry in a controlled environment. The instrument used here successfully measured the locations of splice plate holes and successfully showed that virtual assembly of bridge girders is a possibility. Now, further research is being applied to perform testing of the laser metrology systems in the steel fabrication shops in order to improve the fabrication of splice connections. This technology aims to cut down the amount of time required

to produce splice connections by allowing virtual measurements to be used along with the CNC machines in order to more accurately and quickly create splice connections in steel bridge girders.

3. Description of the technology being used

Although there are multiple laser trackers and equipment on the market that could be used for the project, Hirschfeld has chosen to use FARO's tracking equipment. The laser tracker used to implement the new method for steel bridge girder splice connection fabrication is the FARO Laser Tracker Vantage, as shown in Figure 2.



Figure 2: FARO Laser Tracker Vantage

Three key aspects of the laser tracker are its portability, durability, and accuracy. This technology could potentially replace conventional tools such as wires, plumb bobs, and measuring tapes. Many of these tools are used in the fabrication process for steel bridge girders. The tracker is portable because it is less than 40 lbs. Similar to most technology, the laser trackers have become smaller and lighter as the technology has improved. This is important for the workplace because for the limited set of girder measurements required at Hirschfeld, it is necessary to move the equipment two or three times. The tracker is also moved to each girder laydown location, which can occur at different places in the shop, as well as where the completed splice plates are measured. Limiting the equipment's weight makes moving across the fabrication shop faster and more straightforward. As far as durability, the tracker is designed to be water and dust resistant. This allows the tracker to function in demanding industrial conditions, such as would be expected in bridge fabrication shops. For accuracy, the laser tracker has a maximum 262.5 ft working range with accuracy up to 0.0006 in. To ensure proper functionality and accuracy of the equipment, the tracker performs self-checks discussed in Section 8.

The tracker works along with a Spherically Mounted Retroreflector (SMR) which reflects the laser back to the tracker so that it can measure its location. The tracker then uses the information gathered from the reflection to determine the elevation and distance in order to establish the 3D position of the SMR. There are many types and sizes of SMR's that can be used and each of them affects the maximum working distance and accuracy of the tracker. FARO makes an "affordable" SMR, a break resistant SMR, a heavy duty break resistant SMR, and a glass panel SMR. The "affordable" SMR comes in three variations. These variations include a standard model (visibly differentiated with a black ring), a long-range model (green ring), and a high performance model (blue ring). The break resistant SMR is designed to remain clean in harsh environments by using

a replaceable window collar and special window. The heavy duty SMR is a solid stainless steel ball with a gold coating. This SMR can operate in extreme temperatures and environments. The glass panel SMR is the simplest with a protective silver coating and a standard and high accuracy model. Almost all SMR models come in three sizes: 0.5, 0.875, and 1.5 inches in diameter.

The SMR used by Hirschfeld is the heavy duty break resistant SMR (Figure 3) with a diameter of 1.5 in. This SMR model has a range of 197 feet and a centering accuracy of plus or minus 0.0005 in. This accuracy is related to the centering of the laser beam in the SMR rather than the overall accuracy of the tracker. Hirschfeld chose this model due to the ability it has to work in extreme environments. A fabrication plant has many sources of heat from the steel work and can also be cold during the winter. There is also a significant amount of dirt and dust in the area so it is important to have the tracker that will resist malfunctioning in the everyday fabrication shop work environment. A diameter of 1.5 in is chosen because this diameter is easily placed in the holes being measured for the splice plates. If the diameter was smaller, multiple measurements around the hole would be needed to determine the location of the center. The “affordable” SMR models are shown in Figure 4



Figure 3: Heavy duty SMR



Figure 4: "Affordable" SMR model

The SMR's come with many pieces of equipment such as magnetic mounts and small extensions as shown in Figure 5. The black magnetic mounts are used for the control points discussed later in section 6, the description of the new splice connection fabrication process. The other equipment is helpful for measuring more complex geometry, such as edges of objects, or to measure points which are less accessible.



Figure 5: SMRs and SMR accessories

Although Hirschfeld does not currently utilize it, the laser tracker can also be used along with the FARO Track Arm. The Track Arm is used to track the path designated by the user in order to gather multiple points to virtually form a line. The track arm could easily be used to trace the outline of steel splice plates, holes on the plates, and the ends of the girders. This would give the virtual plates more detail rather than just the hole locations and a limited number of reference points. This level of detail is not needed for the virtual assembly technique examined in this report; however, depending on the future needs and uses of the virtual scans, this equipment might be useful.



Figure 6: FARO Track Arm

Comparison of Laser Tracking vs. Scanning

Laser tracking is utilized in the work documented in this report; however, laser tracking is frequently confused with laser scanning, another type of laser metrology. The laser tracker works in conjunction with an SMR, or some other type of target, to determine a three-dimensional point in space corresponding to the location of that target. The location of the target can be recorded at a given frequency or it can be recorded when the operator decides to record its location (usually when the target has arrived at some point of interest). The result of a measurement with a laser tracker is a limited set of three-dimensional points in space based on the location of the target. Alternatively, the laser scanner uses a point cloud system to construct a given surface shape, texture, and potentially color. The scanner is better used at capturing a larger object with a high level of detail, as opposed to the location of a few specific points. This type of metrology is useful if the entire girder or splice plates need to be virtually constructed and analyzed. For this same task, a tracker would take much more time to create this more extensive data set because the features and shapes of interest would require more contact or measuring points from the tracker to obtain all the details, while the scanner processes the entire object in one scan or more. For the measurement of the splice connections detailed in this report, it is more beneficial to use the tracker due to the simple shapes and limited amount of data required; only the girder hole locations are needed, along with some assumptions, to model the splice plates for fabrication. However, if the goal was to take measurements along a whole girder, then a scanner may prove to be more useful.

4. Description of the bridge being constructed

The girders being fabricated with the new process using laser metrology that is the focus of this report are used for the demonstration of this technology incorporated into the new Tennessee State Route 92 bridge that is being constructed over the French Broad River near

Dandridge, Tennessee. This bridge is replacing a truss bridge that no longer meets the structural or functional needs at this crossing. To meet the span configurations, the new design features a welded plate girder approach. Shown in Figure 7, Figure 8, and Figure 9 are pictures of the location of the bridge and the construction of the new span.

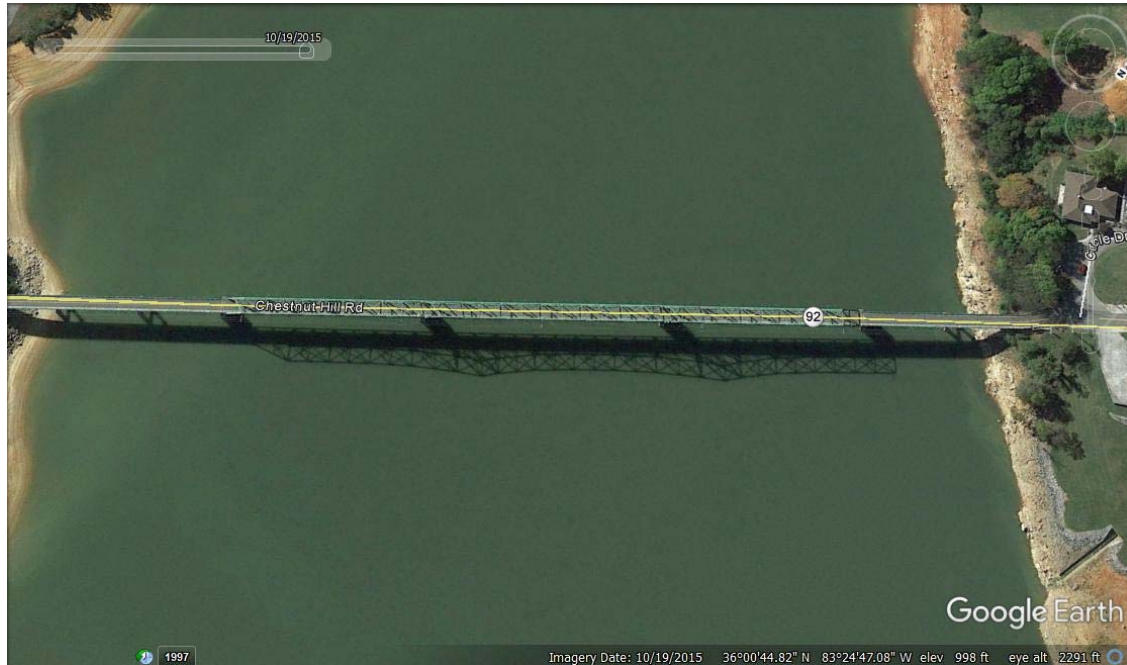


Figure 7: Tennessee SR-92 bridge being replaced near Dandridge, TN (Image courtesy of Google Earth)



Figure 8: Road view of bridge (Older bridge on the left, newer on the right)



Figure 9: Bottom view of bridges (Older bridge on the right, newer on the left)

5. Description of the traditional splice connection fabrication process

In order to fully understand the commonly used traditional laydown procedure, the entire fabrication process of the girders must be explained from the beginning. The traditional fabrication process examined in this report is the one commonly utilized in the Hirschfeld Industries fabrication shop in Bristol, VA. While other fabrication shops and companies may deviate from exactly following this process due to space limitations, availability of advanced machining equipment, and specific job demands, this process is largely representative of the traditional process commonly used for steel bridge girder fabrication. The fabrication process, up to the completion of the quality control check of the match drilling of the splice connection is as follows:

1. Steel plates are prepared for computerized numerically controlled (CNC) drilling equipment.
2. The CNC machine cuts web and flanges out of the steel plates.
3. The flanges and webs are welded to form the girder using an automated welding machine.
4. Stiffeners are welded to the girder.
5. The girder is moved for the laydown.
6. Heating of girders for desired horizontal sweep.
7. Trimming of girders to correct length for laydown.
8. Quality control and quality assurance (QC/QA) check
9. Holes for the splice connections are match drilled on the girder with splice plates which were cut and drilled with the CNC machine used as a template.
10. Hole QC check for proper alignment of splice plates.

In order to begin this process, steel plates are delivered to the plant by train and unloaded into a yard used for storage and preparation. The workers in this area prepare the steel for the fabrication process by organizing the steel plates by job. The plates that are needed for the CNC equipment are laid out prior to being cut and trimmed to the appropriate length.

Upon completion of the preparation work, the steel plates are moved to the CNC equipment using overhead cranes. These plates are laid out on the platform for the CNC equipment, which uses an automated program to cut the flange and web plates to the desired width and length as shown in Figure 10 and Figure 11. Additionally, the CNC equipment can cut the webs with an arch to produce the required camber when the girder is later assembled.



Figure 10: Steel plates on CNC machine



Figure 11: Full view of CNC machine

After the CNC equipment is used to cut the flange and web plates to the dimensions specified for the job, the surfaces of the flanges and edges of the web are cleaned by grinding off any rust and debris. This cleaning is done in preparation for the web and flanges to be welded together. After the cleaning, the webs and flanges are temporarily held in place by a “squeezer” machine (Figure 12) to form the girder. Tack welds are placed every couple of feet to temporarily

hold the girder together. Once this temporary welding is complete, the girder is released by the “squeezer” machine and an automated welding machine begins to lay down the final weld to permanently join the flanges to the web, as shown in Figure 13 and Figure 14. The automated welding machine used for this step in the Bristol fabrication shop is made by Arcmatic Welding Systems.



Figure 12: Squeezer machine used to temporarily hold girder plates together in preparation for welding



Figure 13: Arcmatic automated welding machine shown prior to welding

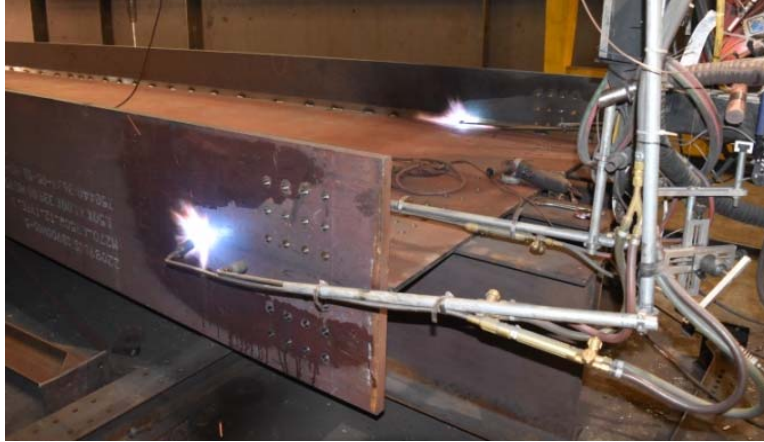


Figure 14: Arcmatic automated welding machine shown welding together girder plates

After welding the girder plates together, the girder is moved to another location where the stiffeners are placed on the girder. The stiffeners are fitted to the girder by hammering them between the flanges and then a dart welder is used to secure them in place. For some stiffeners that are tough to fit on to the girder, Hirschfeld has made a “jacking-jig” to help make the job easier. This equipment, shown in Figure 15, primarily consists of a hydraulic jack that is used to press the flanges apart in order to make a slightly larger gap for the stiffener to fit in. Once the stiffeners have been added, the girder is then ready to begin the laydown procedure.



Figure 15: Hydraulic jack used in fitting stiffeners to girders

Normally, the laydown procedure requires a three piece laydown; however Hirschfeld was given a waiver that allowed them to use a minimum of two connecting girders. Additionally, for all successive assemblies on the same girder line, at least one carryover girder was required from the previous assembly. For the laydown, the girders are set down in an orientation such that their webs are positioned horizontally, similar to the position shown in Figure 16. In this position, the girders are more readily accessible on both sides of the flange. This makes it easier to match drill, heat, measure, and work on the girders in general. If the girders were laid out vertically it would generally be more difficult to complete the required work potentially due to how high and low the flanges could be.



Figure 16: Beginning of girder laydown procedure

Strip heating is used for camber correction and approved heat curving procedures on flanges are used for sweep. Heat curving is shown in Figure 17.



Figure 17: Heat curving of a girder

The heat curving, shown in the Figure 17, is known as “vee heat” pattern. The pattern is used along with external passive restraints in order to bend the girder along the weak axis to the desired sweep of the girder. Strip heating (not shown) is used to remove any localized damage of the girder and may also be used to complement the “vee heating” by repairing bulges and or assisting in the corrections.

Once the girders are ready for laydown, a quality control and quality assurance (QC/QA) check verifies that the distances to bearing and splice points, as well as camber, sweep, and center to center bearing dimensions are correct. The QC check is completed using a tape measure, a plumb bob, and a wire that runs the length of the laydown. Measuring from the wire to the plumb bob attached to the girder by a magnet checks camber. The plumb bob assures that the measurement is

straight and not being recorded at an angle. This is done every few feet as specified for the QC. Also, the sweep is accounted for by measuring from the floor to the center of the web of the girder every few feet as well. When moving the girder for the next laydown, the dimensions recorded in the previous laydown that do not exceed the acceptable tolerances are maintained. Variations are checked such that they will not excessively accumulate throughout the assembly. This means that the dimensions recorded at specified points (i.e. camber, sweep, etc.) must be maintained during the procedure when the girder is moved for the next laydown so that all of the connecting pieces align correctly during erection and large single variations or accumulated variations are not present and do not lead to any misfits. The locations of the field splices, bearings, and midpoints are used in order to assure that the girders are in the proper location and that tolerances will be maintained.

Once the QC/QA check confirms all measurements for the laydown, the girders will be pulled back and final cuts to the specified design lengths will be performed and the edges will be cleaned. This is necessary because the steel plates are originally cut with additional length for girder growth during the welding processes. A torch (Figure 18) that is guided by an automatic track that slides the torch across the girder is used to make the final cuts to the girders. Once the cuts are made, any rough edges and slag are removed by using a grinding wheel to clean the surface. The girders are then positioned together again in preparation for drilling the splice connection.



Figure 18: Trimming girder to length. Note that the girder holes would not be present in the traditional method at this point in the process

Prior to drilling the girders, a QC/QA check of the splice plates is done to ensure correct dimensions and hole pattern alignment. This check is completed because the splice plates are cut and drilled by the CNC machine using a standard hole pattern without the consideration of measurements of the actual built dimensions of the splice. The check is performed by stacking together plates that will match up in the splice connection, the two plates for the top and bottom for the web and flange splice connections, then confirming that the hole patterns align. The splice plates are then match marked before unstacking to ensure the orientation of the plates remain the same when the splice is made. Match marking is a mark made on the splice plates using designated lettering codes to ensure that the plates are assembled in the field in the correct relative positions.

To drill the holes in the girder flanges and web for the splice connection, the predrilled flange splice plates are clamped in position with large “C” clamps and the web splice plates are positioned on the top of the web. Each splice will then have at least four full size holes drilled

through the splice plates (two on each of the girders being connected) and into the web or flange plates. Using these initial holes, full size shop bolts are placed and tightened to secure the splice plates in proper position on the girder. Prior to drilling the remaining holes, the layout of the plates is verified by QC. The remaining holes are then drilled through the splice plates and into the flanges and web. All of the holes drilled in this process are drilled by using match drilling (the holes in the girder are drilled through the predrilled splice plates). The holes on the web are drilled with a magnetic drill, while the holes in the flange are drilled with a large drill specially made for fabrication shop applications (see Figure 21). The drilling process is shown in Figure 19, Figure 20, and Figure 21.



Figure 19: Drilling the web (side view). Note the flange splice plate temporarily secured with clamps.



Figure 20: Drilling the web plate (top view). Note the four shop bolts used to hold the plate in place during the drilling process.



Figure 21: Match drilling flange plate

During this process, the splice plates may not be used as a template for more than one drilling because they are specifically used for each connection and will be shipped with the girders

they are made for. If the splice plates are reused as templates, small differences resulting from splice plate production and the match drilling process may result in a misfit. By uniquely pairing up the splice connections and splice plates, a possible misfit during the erection phase of the bridge, which would be very costly in terms of both time and money, is made less likely.

Once drilling is completed, the holes are then verified for accuracy by QC inspection. Additionally, the plates will be match marked again with the splice number from the erection drawings to match up with the girder it is shipped with.

6. Description of the new splice connection fabrication process

The current laydown procedure takes a large amount of time and space. In order to reduce the amount of time, and perhaps space in the future, a new laydown procedure is being developed. This procedure will utilize newer technology, primarily the combination of laser metrology and CNC fabrication, to attempt to improve efficiency in the fabrication plant. The new procedure, which is similar in many steps to the old one, is laid out below:

1. Steel plates prepared for the CNC drilling equipment.
2. The CNC machine cuts web and flange plates out of these prepared steel plates and drills holes in them for the splice connection.
3. The flanges and web plates are welded to form the girder using an automated welding machine.
4. Stiffeners are welded to the girder.
5. The girder is moved for the laydown.
6. The girder is heated to allow for corrections to camber and sweep.
7. Trimming of girders to correct length for laydown.
8. Quality control and quality assurance (QC/QA) check

9. Measurements of girder hole layouts taken with laser tracker.
10. Splice plate hole layouts are customized based measurements.
11. Splice plates are fabricated and then drilled using the CNC equipment.
12. Hole QC check for proper alignment of splice plates.
13. Test fit of the completed splice connection (periodically performed)

This procedure is very similar to the old girder fabrication procedure; however, a key difference in this process is that the flange and web plates also have holes drilled in them by the CNC machine after the plates are cut rather than match drilling during the laydown procedure. This is very beneficial because the CNC equipment is much faster than match drilling (especially when the steel is very thick). Cutting and drilling with the CNC machine is a nearly fully automated process; the only task needed to be done manually by a worker is to make sure that the steel plates are aligned on the CNC table properly to ensure that the machine cuts the plates to the correct dimensions.

After the flange and web plates are cut and drilled, the plates are welded together and stiffeners are added as described in the traditional procedure. After this, the girders are moved for the laydown, heating for sweep and camber correction is performed, the girders are trimmed, and a QC/QA is performed, all also done as described in the traditional procedure.

After this, the locations of the holes predrilled in the girders web and flange plates are measured using a laser tracker system. Hirschfeld uses a FARO laser tracker system and has written a procedure for taking the measurements. This procedure begins by setting up the computer and folders for the measurements. It then leads into setting up the laser tracker and calibration of the equipment. Hirschfeld advises that the girder and the splice connections should not be in direct sunlight to prevent local heating of the girder. The laser tracker should also be in a location that

provides a view of all of the control points, drift points, and as many of the splice connection holes to be measured as possible. Control points are used to provide a stationary reference frame that allows the trackers built in spatial analyzer program to locate the tracker and subsequent measurements in three-dimensional space. Drift points are located on the girder itself and are used to measure the possible change in length of the girders due to heating and cooling. A diagram of the setup is shown in Figure 22.

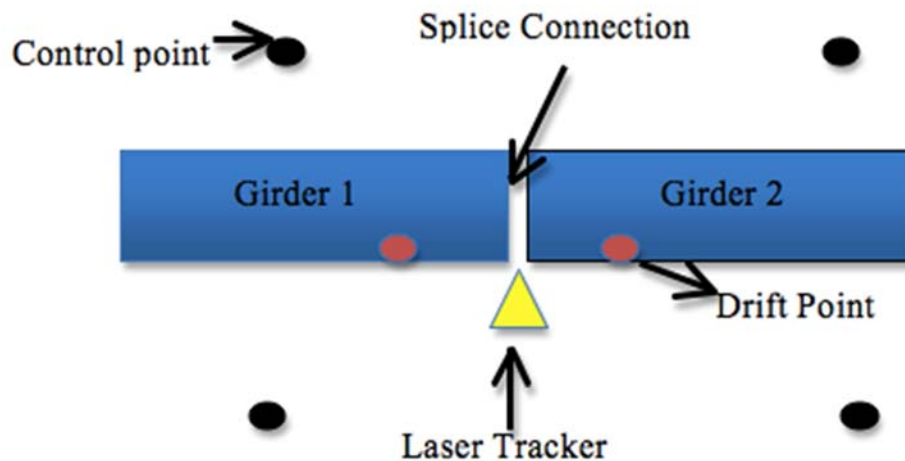


Figure 22: Diagram of laser tracker set up

Once the physical location of the tracker is established, the equipment will be set up. In order to reduce the chances of unintentionally disturbing any equipment and altering its location, hot glue is used to keep equipment in place. The equipment that is fixed with hot glue includes the tripod, magnetic drift point fixtures, magnetic control point fixtures, and temperature probes. Next, the computer equipment is calibrated by going through a number of checks; these checks are discussed in detail in Section 8. This calibration process can take up to 45 minutes and once it is complete the equipment is ready to begin measurements of the holes in the girder web and flanges.

The measurement of the location of each of the drift points, control points, and the splice connection holes is done by moving the laser tracker's target, the SMR, to each point being measured. For the drift and control points, the SMR is placed within a magnetic fixtures to ensure that there is no unintended movement of the SMR while measuring these points, for example small shaking which might result from unsteady hands. When measuring the location of the splice connection holes, the SMR is placed on the hole. Because the SMR has a larger diameter than the connection holes being measured, it can be placed on the hole and reliably held there for the measurement. A picture of a worker measuring the splice connection holes is shown in Figure 23.



Figure 23: Measuring the locations of the splice connection holes in the girder flange with the laser tracker

Measurement of all the splice connection holes on the girder is typically done with the laser tracker positioned in two or three locations. Moving the laser tracker is necessary to complete a

full measurement of the splice connection holes because the tracker needs a line of sight to measure the location of the holes, which cannot be done from only one position. When the laser tracker is moved, the stationary control points will again be measured from the tracker's new position to establish where the laser tracker is located in the three dimensional space already established.

Once completed, the measurements of the girder holes are then used, along with computer software (AutoCAD and Spatial Analyzer), to generate input for the automated CNC machine to cut and drill the splice plates. For Hirschfeld, the modeling of the splice plate's holes based on these measurements and the computer programming of the CNC machine is completed by a remotely located technician. The CNC machine in the process of drilling the splice plates is shown in Figure 24. As shown in this figure, the CNC can drill the holes into the splice plates while lubricating and vacuuming up the cut steel to keep the work area clean. The speed of this computerized drilling process saves time. After drilling the holes, the CNC plasma cuts the splice plates out of the steel plates, as shown in Figure 25.



Figure 24: CNC machine drilling a splice plate



Figure 25: CNC machine plasma cutting a splice plate

Once the splice plates are drilled and cut, the locations of the holes on the plate are measured by the laser tracker. Each measurement is virtually compared to the laydown measurements from the girder in order ensure the fit is within the tolerance set by Hirschfeld. A report of the virtual stacked comparisons is created and checked by the QC and the person performing the stack comparison.

To ensure the accuracy of the measurement process and the splice plate fabrication, a test fit is performed on the first two connections and then 20% of the remaining splice connections throughout the fabrication of the girders. During the test fit, the splice plates fabricated by the CNC machine based on the laser tracker measurements are physically hung on the flanges and webs at the splice connection. Drift pins are used to keep the plates in place. A QC then verifies that the holes are accurate through a visual inspection. Portions of a test fit are shown in Figure 26

and Figure 27. When a test fit is not completed, only the virtual check of the completed splice plate and the girder holes is performed.



Figure 26: Test fit (side view)

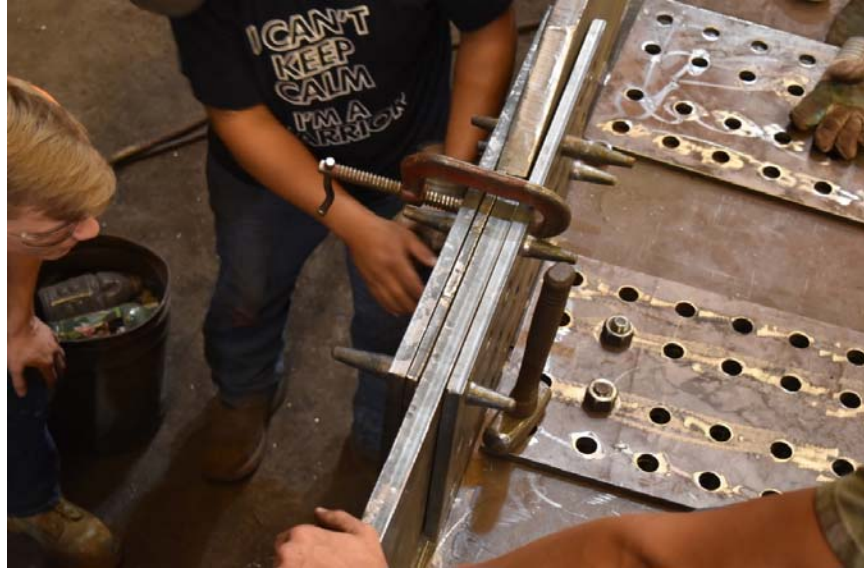


Figure 27: Test fit (top view)

After the virtual check, or the test fit, the splice plates (now match marked) and girders are then ready to be sand blasted, painted, and prepared for shipment.

7. Example results from SR 92 bridge

As discussed previously, this new procedure was implemented on the new Tennessee State Route 92 bridge that is being constructed in 2017 over the French Broad River near Dandridge, Tennessee. In this section, examples of the output reports produced for the splice connection hole comparison are provided along with a summary of the measured comparison errors in all of the connection holes produced for this bridge with this procedure. Additionally, the overall assessment by the erector upon completion of the erection of the girders is provided.

Example output reports

In the new procedure used for girder splice connection fabrication, Hirschfeld uses laser tracker measurements of the splice connection holes on the steel bridge girders and the splice plates to produce a comparison and perform several checks. These checks are then summarized in output

reports. The two primary reports are the control drift check report and the stacked comparison report.

During the control drift check, the location of the control points at the beginning of a set of girder hole measurements is compared to the location of the control points taken at the conclusion of a set of girder hole measurements. This check ensures that the tracker has not moved from the beginning of the measurement set to the end. This check is important because the raw data collected by the laser tracker is relative to the laser's position; thus, changes in the position of the laser tracker in the middle of a set of measurements would corrupt the data from those measurements.

The stacked comparison check compares the measurements of the splice connection hole layout on the girders to the hole layout on the splice plate to ensure that they will properly connect together. The splice plates used in this process were configured based on the girder hole tracker measurements, so it is expected that this comparison check will indicate that the holes align correctly and are within the tolerances designated by Hirschfeld; however, this check provides confidence that the correct girder splice connection and splice plate have been paired together and indicates if any design or manufacturing irregularities will impede the alignment of the connection. Hirschfeld has designated that any error over 0.1250 inch is unacceptable.

Examples of the control drift check report and the stacked comparison report are found in Figure 28 and Figure 29, respectively. In order to facilitate their inclusion as a figure in this report, both of the reports have been shortened to provide only the basic outline of the reports and the results they convey. In their original format, the reports feature more details and a larger number of points that are checked and compared.

JOB 18900H01 SPLICE 1

Summary: Group to Group Relationship CONTROLS to CONTROL-CHECK-1				
Statistic	dX (in)	dY (in)	dZ (in)	Mag (in)
Min	-0.0025	-0.0072	-0.0069	0.0022
Max	0.0020	0.0016	0.0131	0.0135
Average	0.0003	-0.0021	0.0010	0.0063
StdDev from Avg	0.0016	0.0032	0.0065	0.0038
StdDev from Zero	0.0017	0.0039	0.0066	0.0078
RMS	0.0015	0.0036	0.0061	0.0073
Tol Range				
In Tol				
Out Tol				
Count	7			

Group to Group Relationship CONTROLS to CONTROL-CHECK-1 (Reported in Default:WORLD)									
Name	CONTROLS			CONTROL-CHECK			Delta		
	X1 (in)	Y1 (in)	Z1 (in)	X2 (in)	Y2 (in)	Z2 (in)	dX (in)	dY (in)	dZ (in)
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-1	-301.5073	-137.6442	8.9085	-301.5085	-137.6472	8.9072	0.0008	-0.0003	-0.0013
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-2	-415.4680	-115.0865	13.7734	-415.4681	-115.0936	13.7759	0.0002	-0.0072	0.0025
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-3	-356.1553	75.4762	-10.4150	-356.1578	75.4778	-10.4004	-0.0025	0.0016	0.0131
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-4	-129.3756	128.3799	-6.6785	-129.3767	128.3766	-6.6747	-0.0011	-0.0033	0.0038
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-5	185.4189	71.5936	-11.4952	185.4304	71.5931	-11.4968	0.0015	-0.0005	-0.0015
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-6	195.0565	-22.9038	-11.2482	195.0585	-22.9012	-11.2435	0.0020	0.0016	-0.0034
CONTROLS/DRIFT-SETUP1:CONTROLS-CP-7	56.8982	-210.5783	2.2194	56.8997	-210.5821	2.2125	0.0015	-0.0037	-0.0069

Drift Check (DriftCheck1) (Details)				
Working Frame (Default:WORLD)				
6/13/2016 4:08:18 PM				
Reference Group	CONTROLS/DRIFT-SETUP1:DRIFT			
Drift Group	CONTROLS/DRIFT-SETUP1:DriftCheck1			
Drift Check Measurements				
Point Name	dX	dY	dZ	dMag
D-1	-0.0011	-0.0018	0.0037	0.0043
D-2	0.0009	-0.0007	-0.0005	0.0012
Count	2			
Tolerance	0.0078			In Tolerance
Drift	RMS 0.0032	MAX 0.0043		

Figure 28: Control drift check report

Virtual Assembly Stack Comparison Report
18900H01 - Splice 1 - Top Flange



Point	A dX	A dY	AA dX	AA dY	B dX	B dY	H dX	H dY	0.0221	0.0227
									X Max	Y Max
1001	-0.008	0.000	0.014	-0.015	0.003	0.002			0.022	0.017
1002	-0.009	-0.002	-0.005	0.004	0.011	0.001			0.020	0.006
1003	0.000	0.003	-0.003	-0.008	0.010	-0.007			0.012	0.012
1004	0.005	0.004	0.003	-0.010	0.010	-0.004			0.007	0.014
1005	-0.013	0.010			0.002	-0.001			0.015	0.011
1006	-0.012	0.006			-0.006	0.003			0.006	0.003
1007	-0.015	0.021			-0.004	-0.002			0.010	0.023
1008	-0.017	0.004			-0.008	-0.001			0.009	0.005
1009	-0.005	-0.002	-0.004	-0.006	0.006	0.004			0.011	0.010
1010	-0.003	0.008	-0.002	0.006	0.008	0.005			0.011	0.004
1011	0.006	-0.002	0.008	0.001	0.011	0.001			0.006	0.004
1012	0.009	0.008	-0.010	-0.010	0.005	-0.005			0.019	0.018
1013	-0.001	0.009			-0.003	-0.002			0.002	0.011
1014	0.009	0.019			-0.006	0.002			0.015	0.017
1015	-0.007	0.011			-0.012	0.004			0.005	0.007
1016	-0.016	0.015			-0.014	-0.003			0.001	0.017
1017	0.001	-0.002	0.003	0.001	0.006	-0.009			0.006	0.010
1018	-0.004	-0.001	0.003	0.004	0.013	0.008			0.017	0.009
1019	0.000	0.000	-0.003	0.005	0.010	0.004			0.013	0.005
1020	0.003	0.002	-0.007	0.004	0.004	0.000			0.011	0.004
1021	-0.006	0.002			-0.012	0.008			0.006	0.006
1022	-0.003	0.000			-0.002	0.008			0.001	0.008
1023	-0.008	0.009			-0.014	-0.011			0.006	0.021
1024	-0.011	0.010			-0.018	-0.005			0.007	0.015
1025	0.004	-0.009	0.004	0.004			0.008	-0.003	0.004	0.012
1026	0.013	-0.009	0.002	0.000			0.000	-0.004	0.013	0.009
1027	0.015	-0.015	-0.001	0.006			0.007	0.001	0.016	0.021
1028	0.004	-0.001	0.008	-0.002			0.011	0.004	0.007	0.005
1029	0.008	-0.001					-0.006	0.000	0.014	0.002
1030	0.007	0.001					-0.006	-0.001	0.013	0.001
1031	-0.003	-0.002					-0.006	0.003	0.003	0.005
1032	-0.009	0.000					-0.009	0.003	0.000	0.003
1033	-0.001	-0.007	-0.003	0.013			0.001	-0.003	0.003	0.020
1034	0.010	-0.010	-0.002	-0.013			0.003	-0.002	0.012	0.011
1035	0.016	-0.009	-0.004	0.003			0.003	-0.006	0.020	0.012
1036	0.009	-0.011	-0.003	0.011			0.006	0.007	0.012	0.022
1037	0.004	0.009					-0.007	-0.008	0.011	0.017
1038	0.001	0.000					0.005	-0.002	0.004	0.003
1039	-0.007	-0.003					-0.004	-0.005	0.003	0.001
1040	-0.008	0.002					-0.007	0.001	0.001	0.001
1041	0.002	-0.010	-0.001	0.000			-0.004	0.005	0.006	0.015

Angular Accuracy Details
Wed Jun 15 07:32:20 EDT 2016

Synopsis

Item	Value
Date	Wed Jun 15 07:31:47 EDT 2016
Report	AngularAccuracyChecks
Tracker	V01001606044
Operator	bri.va
Air Temperature (degrees C)	23.7
Air Pressure (mm Hg)	710.01
Humidity (%RH)	48.1

Angular Accuracy Check Deviations

Point	Az (deg)	Ze (deg)	D (mm)	Tolerance (Deviation)	In Tolerance
1	57	88	7984	0.12	0.006 Yes
2	60	95	4771	0.088	0.04 Yes
3	-2	102	2173	0.062	0.031 Yes

Report Produced By: richard.martinez

QC Supervisor Signature	
Printed Name	Date

6/15/2016

4 of 4

Figure 29: Stacked comparison report

Measured errors in splice connection hole alignment

Based on laser tracker measurements of the girder holes and measurements of the holes in the splice plates, a comparison report (like those examined in the previous subsection) can be produced for every splice plate in every connection manufactured with this new fabrication procedure. In this section, the resulting error measurements for each of those hole comparisons is compiled and reviewed for the SR 92 bridge.

Figure 30 shows the error magnitude measured from every hole comparison made for the girder splice connections of the SR 92 bridge. This figure includes the error magnitudes from 16245 hole comparisons taken from 370 splice plates across 37 splice connections. These error magnitudes are computed based on the X and Y measurement comparisons from the reports with the Z measurement comparison not utilized to produce this magnitude. The reasoning for disregarding the Z measurement comparison is that the faces of the splice plate and girders are assumed to be level planes and that the fit of the connection only depends on the location of the holes on that plane. As shown in Figure 30, the vast majority of the error magnitudes from the 16245 hole comparisons are under the 1/32" threshold and all but a few isolated measurements are under the 1/16" error magnitude threshold. Based on all of the comparisons, the average comparison error magnitude is 0.011" and the standard deviation of the error is 0.0097".

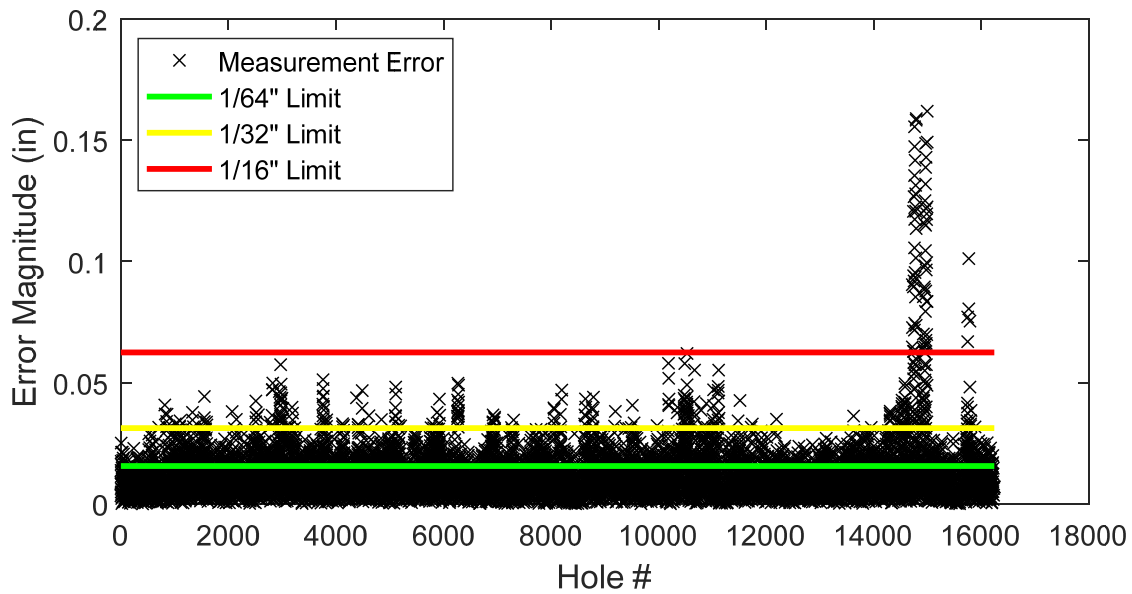


Figure 30: Magnitude of error for each hole comparison

The error magnitudes from these measurements are also summarized in Table 1. This table considers error thresholds of 1/64", 1/32" and 1/16" and provides the number of holes with error measurements above the thresholds, the number of plates with measurements above the thresholds, and the number of complete splice connections with measurements above the thresholds. This table shows that there is a relatively modest number of measurements with errors greater than 1/64" (3175 out of 16245) and that those errors are relatively well distributed with the majority of splice plates and all splice connections possessing errors above this threshold. There are fewer errors above 1/32" (421 out of 16245) and once again these are relatively well distributed among a modest number of splice plates and most splice connections. Unlike the 1/64" and 1/32" error thresholds, there are very few errors over the 1/16" threshold (70 out of 16245). Additionally, unlike the other thresholds, the error magnitudes over 1/16" are concentrated on a total of three splice plates which are a part of only two splice connections. This suggests that these large errors

are not due to a systematic problem, rather related to an isolated issue. Possible sources of error, including human errors, are discussed in the next section. While these large errors are problematic, by the very nature of the hole comparison check, these errors are identified and the problem can be addressed before the girder and splice plates are sent to the erector.

Table 1. Error measurements above thresholds.

	Threshold		
	1/64"	1/32"	1/16"
Number of Holes with Error Measurement above Threshold (out of 16245)	3175	421	70
Number of Plates with Error Measurement above Threshold (out of 370)	289	66	3
Number of Connections with Error Measurement above Threshold (out of 37)	37	30	2

Using the 16245 hole measurement comparison error magnitudes, an empirical cumulative density function can be produced and plotted (see Figure 31). This function can be used to examine the distribution of comparison errors as well as identify the percentage of comparison errors that are under any specific error level of interest. Also plotted in Figure 31 is a fit cumulative density function. This function was produced with the mean and standard deviation of the comparison error magnitude data as well as the assumption that the error magnitudes can be modeled with a lognormal distribution. This fit cumulative density function can be used to model the distribution of possible comparison error magnitudes present in a larger group of data. These distribution functions show that the comparison errors fall well within the TDOT specification 602.11 standards for accuracy. This specification states that “when holes are reamed or drilled, 85% of

the holes in any contiguous group shall, after reaming or drilling, show no offset greater than 1/32 inch between adjacent thicknesses of metal” (TDOT 2015). The fit results show that around 95% of the holes produced with this technique are forecasted to fall within the 1/32” limit and 78% within the 1/64” limit. This demonstrates that the technology is accurate and reliable enough for the intended application.

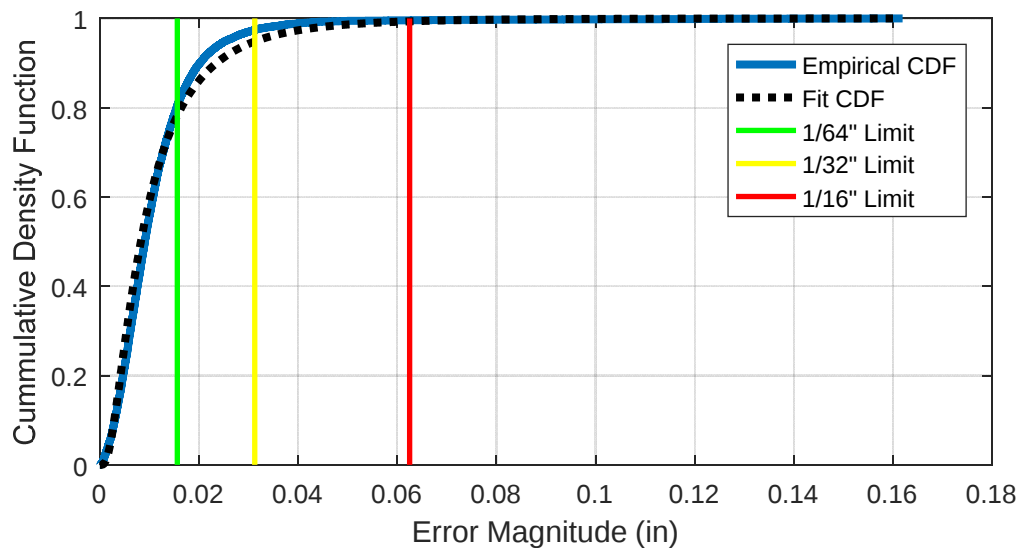


Figure 31: Empirical and fit cumulative density functions

Assessment from erectors

Upon completion of the erection of girders for the SR 92 bridge, a site visit was made to examine the construction of the bridge and review the assessment of the erectors. The erectors commented that the erection of the girders proceeded smoothly and that, from their perspective, there was no practical difference in erecting girders produce with the new procedure and girders produced with the traditional procedure including match drilling. The erectors reported that no misfits in the splice connections were encountered and that no holes needed reaming out.

8. Error sources and prevention

Errors in the fabrication of steel bridge girders can lead to extremely costly delays in erection; therefore, it is important to understand the potential sources of error that might result from the implementation of the innovative technique considered in this report. There are two primary sources of error related to this technique; the first is related to the technology itself and the second is human error.

Technological errors and error prevention

While all laser tracker systems will likely have built-in checks that help detect, prevent, and resolve technical errors, these systems will likely vary with the manufacturer of the tracker system. In this section, the error prevention routines of the FARO laser tracker are described in more detail as this was the laser tracker system used in the work at the Hirschfeld fabrication shop in Bristol, Virginia outlined by this report.

Although laser tracker technology has proven to be extremely reliable, it is susceptible to errors and imperfections in the design. Also, with heavy usage most equipment will undergo some deterioration that could lead to inaccurate performance of the technology. These potential errors, although not common, can result in inaccurate measurements. In order to prevent technological errors, the FARO laser tracker has multiple built-in automated routines to check the tracker and ensure that it is in working condition. The four main checks consist of a startup check, a health check, an angular accuracy check, and a quick compensation. The startup check takes about one minute to perform and in doing so checks the equipment's stability, the motors in the tracker, the encoders, and the absolute distance measurement (ADM). The tracker can be configured to also run a thermal stability check during the startup check; however, this adds approximately 40 minutes to the routine. The thermal stability check is used to ensure that the equipment is operating

steadily at the proper temperature. Once all of the tests are complete and verified to be working properly a health check is then performed.

As the name implies, the health check is another performance check on the equipment that is more detailed than the start up check. The parts being checked here are as follows:

1. Encoders
2. Motors
3. Weather
4. Kinematic Model
5. PSD/Intensities
6. Coarse level
7. Precision level
8. External temperature sensors
9. Internal temperature sensors
10. ADM

Following the health check are the angular accuracy check and quick compensation. The angular accuracy check should be run after each session using the tracker or if the ambient temperature changes by 5°F. This check verifies the system's angular accuracy, which is vital to overall accuracy, during each measurement session. In this check, the position of the SMR is measured in the front sight and back sight, and the angular difference between the two sights (back sight error) is calculated. This error is compared to the FARO laser trackers maximum permissible error based on the FARO Laser Vantage specifications. If the error is greater than the limitation, it is recommended to perform the quick compensation check. The quick compensation adjusts the parameters in the laser tracker measuring head to improve accuracy for the upcoming measurement

of the girder holes. The quick compensation adjusts the parameters in the laser tracker measuring head to improve the accuracy for the upcoming scan of the girder. The tracker performs this by repeatedly measuring the SMR in one location and checking the back sight error in order to adjust parameters within the tracker to perform more accurately.

Along with the built-in checks, it is important to perform routine maintenance on the equipment. This consists of visual checks and any specialty cleaning of the SMR, the tracker's measuring head, and the tracker's tripod. It is important to handle the SMR with care and avoid cleaning it improperly as the optical surface of the SMR (the laser tracker's target) is easily scratched and destroyed.

These routine checks ensure that the SMR and laser tracking head are working properly. All of these inspections and tests are put in place to ensure that the possible errors from the technology are fully investigated and limited routinely. Furthermore, FARO recommends that the tracker is repaired and recertified every year so that the equipment is up to date and meets any required specifications. The FARO software requires some of the startup checks to be completed before the laser tracker can be used. Other checks are optional and are not required by the software to be completed before tracking; these checks can be done at any time (Hirschfeld recommends doing these at least once a week). If, for some reason, the equipment is malfunctioning and the checks cannot fix the machine, the equipment can be sent back to FARO for repairs.

Human errors and error prevention

The second primary source of error is human error. While numerous potential sources of human error exist, the following potential sources are considered more likely to occur in a fabrication shop environment and are discussed in more detail below:

- Unintentional displacement of the laser tracker's tripod

- Moving too fast in measurements with the tracker
- Dynamic movement of the girder during the tracker measurements
- Large angle/distance of target during laser tracker measurement

Displaced Tripod

The raw measurements gathered by the laser tracker are the angles the laser is directed in, as well as the distance of the target from the physical position of the laser tracker; therefore, a small change in the position of the tracker, perhaps caused by an accidental bump may lead to inaccurate measurements. In order to prevent this, the position of the tracker in the virtual “world” is designated by the measurement of the position of a number of static points, known as control points. These control points are measured before and after every set of tracking measurements. If the tripod holding the tracker has been moved during the measurement process, then the check of these control points will indicate that the allowable drift tolerance in the position has been exceeded and that the measurements should be redone. As discussed in the description of the laser tracker system in a previous section, the use of common control points also allows for the tracker to be purposefully repositioned and for the new sets of measurements which share the same virtual space as previous sets of measurements.

Speed of Tracking

While the technology behind the laser tracker makes it difficult to move too fast during the measurements for the system to keep up, there are possible human errors if the workers move hastily or without care. A common mode of operation during measurements is for the tracker to be programmed to record a measurement once the target has held at a constant position for a preset duration (typically only a few seconds). Errors in this mode of measurement could occur if the

operator holding the target moves too quickly and misses a measurement or holds an unintentional position too long. In order to prevent either of these two errors, a second worker manning the computer the tracker interfaces with should alert the worker holding the target of any irregularities. The measurement should then be either repeated or voided as necessary.

Dynamic motion of the girder during measurements

A pair of simple tests was performed to dynamically excite a girder during measurements in a manner designed to simulate the effect of activities that may occur on a daily basis in the fabrication shop. In these tests, the girder was hammered on and jumped on. These two activities both cause the girder to vibrate; however, with much different frequencies and amplitudes for the two loadings. During both of these tests, the tracker is able to recognize the vibration when the measurement was attempted and, because the tolerance level was exceeded, displays a warning. An example of the warning produced by the system during this scenario is shown in Figure 32 below. If the movement does not exceed the tolerance specified for the machine (0.0078") the measurement will be recorded. This is potentially a reason to keep the tolerances on the machine set very low; however, if the tolerance is set too low, negligibly small motion of the girder will prevent measurement from being recorded. Measurements with too much movement should be avoided in order to prevent any unnecessary error in the results. Additionally, there were also certain occasions where the vibrations were strong enough that the SMR did not maintain enough stability so that the tracker could record a measurement.

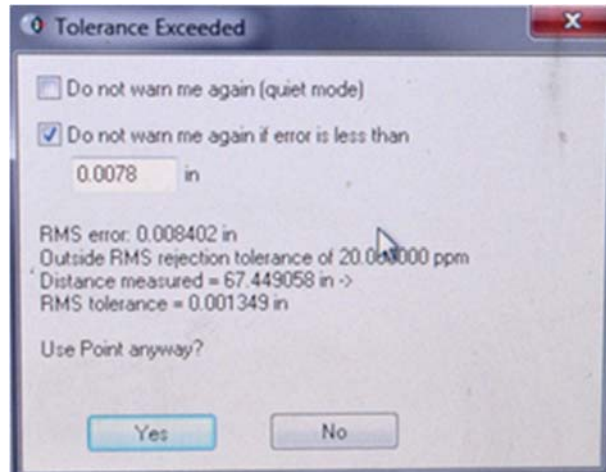


Figure 32: Tolerance exceeded warning

Examples of the results from the jumping and hammering tests are shown in Table 2 and Table 3. These figures show the resulting comparison of tracking measurements of the girder holes when the jumping/hammering is being performed vs. the normal measurements. In these tests the tolerance exceedance warnings were ignored, but the vibrations were meant to stay within the tolerance when possible. The test results show the largest error was 0.017", which occurred on the jumping on girder test. Even though the average errors of 0.0062" for jumping and 0.0035" for hammering on the girders are not significantly large due to the tolerances established on each measurement, it is best to perform measurements in an area where the girders will not be subject to a substantial amount of vibration or interference. The accuracy of the virtual scan is extremely important for the splice plate fit and step should be taken to minimize any unnecessary errors and avoid a potential misfit.

Table 2: Jumping test results

Summary: Group to Group Relationship Groups: 56C-LD Holes to 56C2-LD JUMPING				
Statistic	dX (in)	dY (in)	dZ (in)	Mag (in)
Min	0.0050	0.0034	-0.0153	0.0064
Max	0.0104	0.0057	0.0001	0.0177
Average	0.0062	0.0044	-0.0029	0.0087
StdDev from Avg	0.0013	0.0006	0.0043	0.0032
StdDev from Zero	0.0065	0.0046	0.0052	0.0095
RMS	0.0063	0.0045	0.0051	0.0093
Tol Range				
In Tol				
Out Tol				
Count	19			

Table 3: Hammering test results

Summary: Group to Group Relationship Groups: 56C2-LD Hammer to 56C-LD Holes				
Statistic	dX (in)	dY (in)	dZ (in)	Mag (in)
Min	-0.0081	-0.0044	-0.0018	0.0032
Max	-0.0024	-0.0004	0.0037	0.0092
Average	-0.0035	-0.0021	0.0016	0.0046
StdDev from Avg	0.0009	0.0008	0.0013	0.001
StdDev from Zero	0.0036	0.0022	0.0021	0.0047
RMS	0.0036	0.0022	0.002	0.0047
Tol Range				
In Tol				
Out Tol				
Count	42			

Large angle/distance of target

The final example error test performed with the tracker was to measure the locations of holes in a splice plate at different distances and a substantially larger angle. A diagram of the scan locations can be seen in Figure 33.

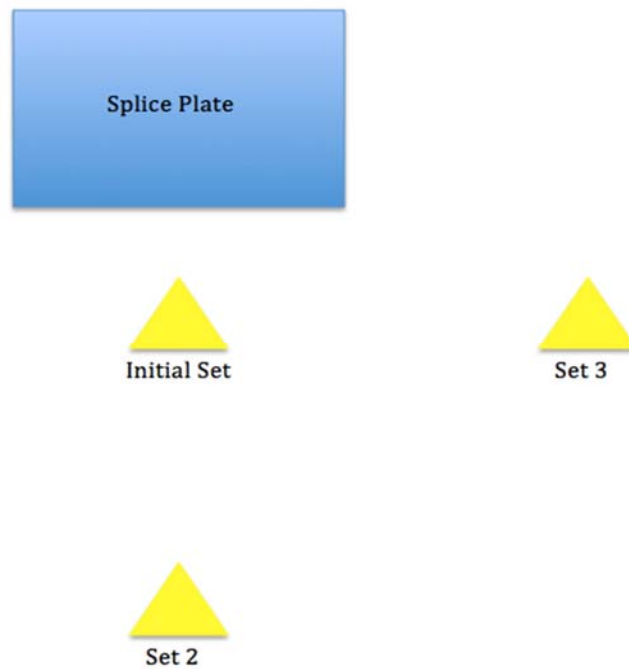


Figure 33: Diagram of test scan locations

The initial set of measurements that were used as a baseline for comparison were taken at a measurement angle normal to the splice plate and approximately five feet away from it. The next set of measurements, referred to as Set 2 in Figure 33, were taken at the same normal measurement angle and approximately 30 feet from the splice plate. This 30-foot distance is the largest measurement distance that was possible in the Bristol Virginia Hirschfeld fabrication plant due to the limitations of the experiment's set up. Although this distance is not on the extreme end of the

tracker's range, it was performed at a significantly longer distance than the typical set of tracker measurements taken at this fabrication plant. Upon completion of the measurements, a best-fit comparison was completed in order to compare the scans. This comparison is shown below in Table 4. These results show no significant differences between the two sets of measurements and that the maximum error in the comparison is 0.003 inch in the three dimensional coordinate system, which is well within the tolerance Hirschfeld uses as its standard.

Table 4: Comparison of measurements made at 5 ft (near) and 30 ft (far) from the plate

NEAR TO FAR (Summary)				
NEAR SCAN - HOLES to FAR				
Result	X	Y	Z	Mag
Coun	24	24	24	24
Max	0.001	0.002	0.003	0.0036
RMS	0.001	0.001	0.001	0.0020
StdDev	0.001	0.001	0.001	0.0020
Max Error	0.001	0.002	0.003	0.0036
RMS Error	0.001	0.001	0.001	0.0020
	Unknown	6	Equation	72
Transformati				
Translation				
Rotation				
Fixed	0.000	0.000	0.000	
Euler	0.000	0.000	0.000	
Axis-	0.00000	0.00000	1.00000	0.0000
Matri				
x	0.00000	1.00000	-	0.00000
	-	0.00000	1.00000	-
	0.00000	0.00000	0.00000	1.00000

The next set of measurements, referred to as Set 3 in Figure 33, were taken to compare the initial set of measurements with a set taken from a large measurement angle (as close to 90° as possible), relative to the surface being measured. In both Set 1 and Set 3, the laser tracker is approximately five feet away from the center of the plate; however due to the differences in the measurement angle, the distance from the tracker to the holes in Set 3 varies by almost the width

of the plate, while the distance from the holes to the tracker in Set 1 are all about the same. As a consequence of this, errors related to the distance of the tracker from the target are more likely in Set 3 than Set 1. A summary of this comparison is shown in Table 5. Similar to the previous results, the results of this comparison show no significant differences between the two sets of measurements and that the maximum error in the comparison is 0.0046 inches.

While the tests of this system were not comprehensive, it appears that with the correct tolerances set and maintenance performed, the equipment can provide extremely accurate tracking measurements. Therefore, it is of the utmost importance to routinely perform maintenance checks on the system (most of which are automated) and ensure the proper procedure is followed during the use of the equipment.

Table 5: Comparison of error tests with normal and large angle measurements

SIDE TO NEAR (Summary)				
SIDE SCAN-HOLES to NEAR				
Result	X	Y	Z	Mag
Coun	24	24	24	24
Max	0.001	0.003	0.003	0.0046
RMS	0.000	0.000	0.001	0.0015
StdDev	0.000	0.000	0.001	0.0015
Max Error	0.001	0.003	0.003	0.0046
RMS Error	0.000	0.000	0.001	0.0015
	Unknown	6	Equation	72
Transformati				
Translation				
Rotation				
Fixed	0.000	0.000	0.000	
Euler	0.000	0.000	0.000	
Axis-	0.00000	0.00000	1.00000	0.0000
Matri				
x	0.00000	1.00000	-	0.00000
	-	0.00000	1.00000	-
	0.00000	0.00000	0.00000	1.00000

9. Cost and Benefits

In this section, the costs and benefits of the adoption of the new bridge girder splice connection procedure featuring laser tracking is discussed. Any company would likely undertake a detailed cost analysis before making the large capital expenditure that a laser tracker system would necessitate. This section does not aim to replicate this detailed analysis; rather, the aim of this section is to identify and discuss the major costs and benefits related to the implementation of a laser tracking system for bridge girder splice connection fabrication.

Costs

The major sources of costs related to the implementation of the new bridge girder splice connection fabrication procedure introduced in this report are the capital costs of the equipment, the specialized training needed for workers, and an increased reliance on technology.

The capital investment required to implement this laser tracking method is significant. While dependent on the specific manufacturer and options chosen, a good estimate for the cost of the laser tracker and SMRs is at least \$100,000 with an estimated additional \$50,000 for the software required to run it and virtually build the splice plates from the resulting data. Additionally, it may make sense to purchase multiple laser trackers to increase the efficiency of the girder hole tracking process. The reason for this is that multiple data sets need to be collected at different tracker positions to obtain the locations of all of the splice connection holes in a girder. Using multiple trackers would eliminate the need to move, setup, and reinitialize the laser tracker system. Furthermore, an additional laser tracker dedicated to measurements of the splice plates themselves, which may be produced in a completely different area of the fabrication shop, may be justified to improve the efficiency by eliminating the need to move equipment and save time.

The human side of the capital cost of implementing this procedure is the specialized training needed to operate the laser tracking equipment. When the laser tracker system was brought to the Bristol Virginia fabrication shop, Hirschfeld sent two employees to a plant in Texas for about two weeks in order to train the employees from Bristol on how to run the equipment and use it correctly to measure splice connections. Even after those two weeks of training, there was still a steep learning curve when collecting measurements with the laser tracker without the supervision of the trainer. Because of this, one of the main virtual assembly workers from Texas was brought in to the plant in Bristol, Virginia so that the employees could run the laser tracking equipment under supervision until they understood the process better. In the first month, the laser tracker measurement of the splice connection holes started out taking up to four hours to complete; however, this was eventually brought down to 1.5 to 2 hours for the girders considered in this report.

Another cost to implementing this procedure is that it increases the fabrication shop's reliance on technology. This is a problem because a laser tracker that breaks, or otherwise is inoperable, may shut down work on splice connections for an indeterminate amount of time and slow down productivity for the entire fabrication shop. While the FARO laser tracker system examined in this report at the Hirschfeld fabrication shop in Bristol Virginia has proven to be durable and has, thus far, experienced no malfunctions or downtime, most equipment can typically be expected to break down at some point in its lifespan. Because of this, it might be beneficial to have a back-up laser tracker or someone on hand knowledgeable of the basic problems that may be common in the equipment, how to trouble shoot it, and how to repair it.

Benefits

The benefits of using the new technology and procedure introduced in this report include time and space savings, both of which save money.

The traditional method of match drilling the splice connections generally takes at least six to eight hours per splice connection. This time is dependent on many factors such as the amount of holes needed to be drilled, proper functioning of equipment, and the thickness of the steel; consequently, a larger than normal girder can take much longer to match drill. For example, a girder for the new Tappan Zee Bridge, which is also being fabricated by Hirschfeld and will “be the widest cable-stay (bridge) in the world” upon completion (Nordrum 2015), can take nearly 16 hours to finish match drilling the splice connections.

With the new process, the setup of the tracking equipment and a complete measurement of the girder holes takes 1.5 to 2 hours. Then the only time left on the splices is the amount of time it takes to cut out and drill the splice plates on the CNC machine. One splice connection can be done in around 30 minutes if set up of the plates goes smoothly. However, there is also the option to wait until multiple measurements of splice connections are completed and then use the CNC equipment to cut out multiple splice plates at once on one sheet of steel. This is beneficial because it saves on the amount of steel scrap left over from the completed job and it reduces the overhead time that would be required for the CNC machine to fabricate the splice plates for each connection individually. However, the major time saved from the newer method of steel splice plate fabrication is from the predrilling of the girders with the splice connection holes. As mentioned earlier in this report, the traditional method involving the magnetic and custom drills can take a significant amount of time to complete. Now, the girders that have the holes predrilled by the CNC machine can be completed in a significantly reduced time as the CNC machine is capable of

drilling holes much more quickly and accurately. Furthermore, as it is automated, the addition time needed for the CNC machine to cut and drill the girder plates, as opposed to just cut them, occurs without a significant increase in labor costs.

In addition to directly saving time, the use of the new procedure also saves shop space because the girders do not need to be left in the laydown position for very long. This available shop space can then be used to for other projects and accelerate their completion. As soon as the scans are completed, the girders can be prepped and readied for shipment, moved to a holding yard, and shipped once a positive virtual comparison of the plates and the girders are made. This will save space because the girders do not need to be parked in the primary sections of the shop for as long and the area used for laydowns can be used for another activity once the girders are moved. However, if a girder is required to have a test fit, then the girders will need to remain in the laydown position until the splice plates are complete and the test fit has been performed. Once the new method of splice connection fabrication is proven to be reliable, it is expected that the required number of test fits will decrease.

Comments On Timing

It is important to take note that it was not possible to track the complete time taken to create an individual splice connection using the virtual method, and therefore not completely accurate to compare the individual timings of the virtual assembly method to the old process. The reason for this is that the complete process of laydown, laser tracker equipment setup, hole measurement, splice plate design, splice plate fabrication, and a possible test fit was never completed as one continuous effort. For the virtual method we were able to record how long it takes to set up the equipment and record the measurements as well as record a few timings of the splice plate fabrications from the CNC equipment. These recordings are separate because the fabrication plant

optimizes their time by measuring multiple splice connections over time and then fabricating the plates in batches. This is possible because it is assumed that the recordings are accurate, thus no changes in the drilled holes or repeated measurements are required, and the test fit is not often required. During the time spent at the fabrication plant, two to three batches of plates were fabricated and only a handful of plates had a test fit. The fabrication plant ended up completing more of the work after the on-site observation period ended and the authors were no longer at the site for all of the test fits and splice plate fabrication. As for the older process, timings of the match drilling of splice plates are recorded for the comparison. For the final comparison of timings we are able to compare the time it takes to record the measurements of a girder versus the time it takes to complete the match drilling process. In addition to this time, more time is required for the standardized plates to be fabricated in the traditional method before the laydown and for the custom plates to be fabricated in the virtual method in a batch after the laser tracker hole measurements are collected.

10. Provisions, possible improvements, and future plans

In this section, provisions to enable the more widespread implementation of this method are discussed as well as possible improvements and extensions.

To enable the use of the steel bridge girder splice connection fabrication technique examine this report, provisions governing its implementation must be created. Consequently, one of the goals of this project is to establish a set of provisions for TDOT and for TDOT to include these specifications as an official special provision. These provisions will enable other interested fabricators in the state of Tennessee to adopt this technique and will encourage the spread of similar provisions to other states. The resulting draft provisions can be found in their entirety in Appendix

A. In this appendix, alongside the provisions, is the justification for each of the rules. This set of justifications was developed based on the observations and results of the demonstration study.

To increase the benefits of the utilization of laser tracking technology in this new bridge girder splice connection fabrication procedure, multiple potential improvements to the process could be implemented. These potential improvements include some relatively incremental steps as well as some more advanced and challenging ideas for improvement.

The skill set needed to efficiently operate the laser tracker and perform measurements with it is different than the skill set needed for the traditional bridge splicing process. This issue has been identified by Hirschfeld and they are currently adapting the computer system for the laser tracker to be more user friendly. The update of the laser tracker software that they have proposed will lead the workers through the measurement process step by step. While nowhere near a complete automation of the laser tracking process, with this update, the measurement process will be even easier to understand and execute. This update should also serve as a source of continuous training for employees and help those who are not as familiar with this technology to be more efficient.

The laser tracker can also be used to improve the QC/QA checks performed in the fabrication plant. The Hirschfeld plant in Bristol, VA currently uses plumb bobs and tape measurements to record the data needed for checks on the girders. The tracker is a surveying tool that can record the measurements very precisely and potentially be integrated with computer software that saves and shares the data for anyone who may need it. With the high price tag on the laser tracking equipment, fabricators could potentially get better value for their investment dollars by also utilizing this system for some of these checks.

Incremental improvements are important to enhance the new procedure examined in this report; however, laser-tracking systems could, in the future, be utilized much more aggressively in the manufacturing of these bridge girder splice connections. With the use of the laser tracking system, it is possible that the entire current laydown procedure could be eliminated. It is hopeful that the technology may be used in order to scan essential points on each individual girder for the needed information for QC checks without ever needing to laydown girders next to each other. Adjacent girders could then be “virtually assembled” to design the splice plates for the splice connection between the girders. This would potentially save a tremendous amount of hours in labor, time, space, and money. In addition to eliminating match drilling of splice connections (which was examined with the new procedure primarily studied in this report), there would be no need for people to move the girders around and set up laydowns that take up hundreds of feet. This would all be beneficial, save money, and would allow for more productivity from fabrication shops without the need for additional floor space.

11. Conclusions

This report documents the use of a laser metrology technique in the production of splice connections for steel bridge girders which was successfully implemented at the Hirschfeld Industries steel bridge fabrication plant in Bristol, VA. As part of this report, the traditional method of splice connection fabrication was presented and compared alongside a newer method involving the use of laser metrology to enable the use of pre-drilled girder splice connection holes and custom splice plates fabricated using a numerically controlled machine. The primary benefit of this new method is that the time consuming match drilling of girder splice connections was replaced with automated drilling methods. This new technique was demonstrated on girders that

were fabricated for use as part of the new Tennessee SR 92 bridge being built in Dandridge, Tennessee. In addition to documenting the technique and its implementation, this report examines various aspects of the technology used, costs and benefits, possible sources of error, and potential uses and extensions of the technique in the future. Based on feedback provided by the erectors of the SR 92 bridge, no misfits in the splice connections resulted from the implementation of this technique utilizing laser metrology. Furthermore, the measured errors present in the splice connections were found to be well within the limitations outlined in the Tennessee Department of Transportation specifications. These results, as well as an analysis of the cost of the benefits of implementation, suggest that this technique has great potential to provide significant time, money, and space savings in the girder fabrication process. To aid in the more widespread implementation of this process, draft provisions governing its usage were developed and presented to the Tennessee Department of Transportation.

12. References

- "2013 Report Card for America's Infrastructure". ASCE. <http://www.infrastructurereportcard.org>.
- Azimi, Reza, et al. "A framework for an automated and integrated project monitoring and control system for steel fabrication projects." *Automation in Construction* 20.1 (2011): 88-97.
- Bong, William. "Electroslag welding makes comeback for fabricating bridges." *Welding journal* 84.2 (2005): 48-51.
- FHWA, "Steel Bridge Fabrication". *Steel Bridge Design Handbook*, Publication No. FHWA-HIF-16-002 - Vol. 2, December 2015.
- Fuchs, Paul A. "Instrumentation to Aid in Steel Bridge Fabrication." (2009).
- Fuchs, P., and R. Medlock. "FUTURE FABRICATION." *Modern Steel Construction* 53.4 (2013): 44-48.
- Lubowiecka, Izabela, et al. "Historic bridge modeling using laser scanning, ground penetrating radar and finite element methods in the context of structural dynamics." *Engineering Structures* 31.11 (2009): 2667-2676.
- Minehane, M. J., et al. "The Use of 3D Laser Scanning Technology for Bridge Inspection and Assessment." *Structural Health Monitoring (SHM)* 13: 14. 2014
- Nordrum, Amy. "The Rise of the Cable-Stayed Bridge." *Scientific American* 312.2 (2015): 15-19.
- Pegels, G., S. H. R. Eslimy-Isfahany, and H. Azadnia. "A proposal for best practice in design, detailing and fabrication of steel structures in developing countries based on worldwide experience." *Asian Journal of Civil Engineering (Building and Housing)* 4.2-4 (2003): 87-99.

- Pires, J. Norberto, et al. "Welding robots." *IEEE robotics & automation magazine* 10.2 (2003): 45-55.
- Tamai, Shoji, Yosiaki Yagata, and Tomohide Hosoya. "New technologies in fabrication of steel bridges in Japan." *Journal of Constructional Steel Research* 58.1 (2002): 151-192.
- Tennessee Department of Transportation (TDOT), Standard *Specifications for Road and Bridge Construction*. January 2015.
- Want, Roy. "An introduction to RFID technology." *IEEE Pervasive Computing* 5.1 (2006): 25-33.
- Wire, E. D. M., and E. D. M. Sinker. "Computer Numerical Control."
- Yabuki, Nobuyoshi, Tomoaki Shitani, and Hiroki Machinaka. "A cooperative system environment for design, construction and maintenance of bridges." *International Conference on Cooperative Design, Visualization and Engineering*. Springer Berlin Heidelberg, 2005.

Appendix A

Proposed SPECIAL PROVISION REGARDING Section 602 Steel Structures

The following is a (specification/special provision) for the use of laser metrology equipment in the fabrication of steel bridge girder splice connections. Following these guidelines is recommended and has been demonstrated to yield successful results.

a) Location of girder laydown must be out of direct sunlight.

Justification:

- i. *While in direct sunlight, the girders will be more susceptible to heating and cooling cycles. Temperature induced deformations will affect the layout of the holes in the girder splice connection during the measurement process.*
- ii. *While the drift points can measure the overall result of temperature on the girder, it would be difficult to adjust the localized hole measurements. Consequently, sources of heating and cooling should be avoided as best as possible.*

b) During measurement of the girder hole locations with the laser tracker, disturbances, such as the vibration of the girder, should be avoided. Furthermore, the laser tracker and software utilized must be able to detect excessive vibration during a hole measurement and reject that measurement. A variation in the measurement of over 1/128" detected over a 0.5 sec measurement is considered excessive.

Justification:

- i. *Vibration of the girder during measurements increases the resulting error during those measurements; therefore, vibration and other disturbances should be minimized.*
- ii. *In order to detect vibrations, the tracking system cannot take an instantons measurement of a hole location. Rather, the tracking system needs have a built-in automated way to take a measurement over a set amount of time. If that measurement includes an excessive amount of drift, it indicates that the girder is vibrating or the laser's target is not being applied properly; thus, the measurement should be automatically rejected.*

c) The location of the laser tracker must be established with the use of control points, fixed points which serve a reference for the measurements. The location of these control points

must be measured before and after the measurement of the girder or splice plate holes. If a deviation of more than $1/128''$ is detected in the comparison of the location of the control points before and after hole location measurement, the set of measurements must be repeated. Additionally, at least 5 separate control points must be utilized. These control points must be all visible and tracked from every location the laser tracker is positioned in during the measurement of the holes in the girder splice connection.

Justification:

- i. Control points are required for this technique to work. A minimum of 3 are needed to establish a location in three-dimensional space, however, the specifications require more than that in order to more accurately and robustly establish the laser tracker location.
 - ii. Measurement of the control points before and after measurement of the hole locations, will allow the user to assess if the control points or the laser tracker have moved during that set of measurements. If they there has been movement, the set of measurements must be repeated in order to prevent introducing large amounts of error into the process.
- d) In order to track the overall temperature effects on the girder during measurement of the location of the splice connection holes in the girders, fixed reference points placed on the girders, known as drift points, must be utilized. At least two drift points must be used; one on each of the two girders that make up the splice connection being measured. These drift points are to be positioned on girders approximately 5' away from the splice connection. The location of the drift points must be measured before and after the measurement of the girder splice connection holes. If a deviation of more than $1/128''$ is detected in the comparison of the location of the drift points before and after the connection hole locations are measured, the set of measurements must be repeated. The drift points must be all visible and tracked from every location of the laser tracker during the measurement of the holes in the girder splice connection.

Justification:

- i. The girder will expand and contract in response to changes in temperature; thus, small changes in the hole pattern and gap between adjacent girders will result from temperature changes. If the temperature changes are large enough, the changes in the hole pattern might be a concern during the fit up of the girder.
- ii. To minimize these concerns, a limit has been set on acceptable amount of temperature related deformation, as measured by the change in location of the drift points.
- iii. At least two drift points are needed, one on each of the girders, to measure the general presence of temperature related deformation. The use of more than two drift points is acceptable, but not necessary. The drift points are intended to detect drift, but not necessarily give a complete picture of the local temperature related deformation; thus, two points provides the necessary information.

- e) At least two locations of the laser tracker must be used to complete the measurements of the girder hole locations. All of the control points and drift points utilized for the measurements must be visible for each laser tracker locations used.**

Justification:

- i. Due to viewing angles, it is nearly impossible to record the measurements of every hole from one location. Consequently, this requirement will prevent users from utilizing questionable techniques to attempt this.*
- f) The use of an adhesive, mechanical connector, or magnetic connector is required to secure the laser tracker, control points, and drift points. It is advised that other measures, such as cones, hazard tape, and training of personnel in the shop, also be undertaken to help prevent disruptions to the equipment.**

Justification:

- ii. This requirement is intended to help prevent minor distributions from moving the equipment, which would cause irreconcilable errors in the measurement process or corrupt the resulting data.*
- g) Before beginning the measurement process, any maintenance, calibration, or performance checks that are recommended by the equipment manufacturer must be performed. Furthermore, a record of these activities must be maintained and reviewed by management and onsite quality control personnel weekly.**

Justification:

- i. These maintenance, calibration, and performance checks can help prevent and detect any malfunctioning equipment.*
 - ii. Requiring a record of these actions helps ensure that they will be done.*
- h) Two workers should always work together during the measurement process.**

Justification:

- i. Working together ensures that human errors during the process are less likely to occur.*

- i) **After production of the splice plates, laser tracker measurements of the locations of the holes in the every splice plate must be obtained. The overall accuracy of hole layout, as measured from a comparison of the measured locations of the holes in the girder and the holes in the splice plates, should satisfy TDOT specification 602.11 regarding steel structures or any other guidelines specified.**

Justification:

- i. *The inclusion of this will make the required check of the splice plates after production mandatory.*
 - ii. *The standard referred to is set to avoid misfits when erecting the girders; thus, this new technique should adhere to this standard at a minimum.*
 - iii. *It is expected that the accuracy of this technique will far exceed this standard.*
- j) **Test fits should be performed on the first two connections fabricated for each project and a minimum of 10% of the remaining connections.**

Justification:

- i. *Test fits are necessary in the beginning to ensure accurate initial implementation of the technique; however, after the process has started up, test fits are done periodically to provide physical evidence that the virtual comparisons of the plates and girders are accurate.*
 - ii. *Theoretically test fits could be removed completely because any errors should be caught by the virtual comparisons; however, this would require a level of confidence that likely isn't present from all of the stakeholders yet.*
- k) **Workers involved in laser tracking are required to be formally trained on the laser tracking hardware, laser tracking software, and any of the associated software that they will utilize. Furthermore, after this formal training process, a newly trained individual must shadow a previously trained individual during the execution of this technique for at least 20 hours.**

Justification:

- i. *Formal training is required such that workers using this technique are trained on the proper way to use the hardware and software.*
- ii. *Even after training, there is still a learning curve to implementing this technology successfully; therefore, shadowing experienced personnel is required.*