Accelerated Innovation Deployment of Laser Metrology for Steel Bridge Fabrication

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16. Abstract

This report documents the use of a laser metrology technique in the production of splice connection 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 custom 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 from the Tennessee Department of Transportation thru the Federal Highway Administration'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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ABSTRACT

This report documents the use of a laser metrology technique in the production of splice connection 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 custom 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 from the Tennessee Department of Transportation thru the Federal Highway Administration'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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INTRODUCTION

Accelerated Innovation Deployment (AID) Demonstration grants

The Accelerated Innovation Deployment (AID) program is one aspect of the multi-faceted Technology and Innovation Deployment Program (TIDP) approach, which provides funding and other resources to offset the risk of trying an innovation. The AID Demonstration funds are available for any project eligible for assistance under title 23, United States Code. Projects eligible for funding shall include proven innovative practices or technologies such as those included in the Every Day Counts (EDC) initiative. Innovations may include infrastructure and non-infrastructure strategies or activities, which the award recipient intends to implement and adopt as a significant improvement from their conventional practice.

The Federal Highway Administration (FHWA) Accelerated Innovation Deployment (AID) Demonstration grant program, which is administered through the FHWA Center for Accelerating Innovation (CAI), provides incentive funding and other resources for eligible entities to offset the risk of trying an innovation and to accelerate the implementation and adoption of that innovation in highway transportation.

Projects deemed eligible for funding included proven innovative practices or technologies, including infrastructure and non-infrastructure strategies or activities, which the applicant or subrecipient intends to implement and adopt as a significant improvement from their conventional practice. The AID Demonstration funds were available for any project eligible for assistance under title 23, United States Code.

Entities eligible to apply included State departments of transportation (DOT), Federal Land Management Agencies, and tribal governments as well as metropolitan planning organizations (MPOs) and local governments which applied through the State DOT as subrecipients.

REPORT SCOPE AND ORGANIZATION

This report documents the Tennessee Department of Transportation (TDOT) demonstration grant award for accelerating fabrication of steel bridge girders on the State Route 92 construction project in Jefferson County using advanced laser-based metrology and 3D modeling. The report presents details relevant to the employed project innovation, the overarching TIDP goals, performance metrics measurement and analysis, lessons learned, and the status of activities related to adoption of accelerated steel girder fabrication using advanced laser metrology as conventional practice by TDOT. Technology transfer activities that took place to disseminate the project results are also discussed.

PROJECT OVERVIEW

Project Overview

The Tennessee Department of Transportation (TDOT) was selected to receive an AID Demonstration grant in the amount of $221,984 to promote the utilization of Advanced Laser-Based Metrology and 3D Modeling. The AID Demonstration fund award was based on the cost of the innovation in this project, not the total project cost. The awarded AID Demonstration funds were used in place of other Federal program funds and did not otherwise modify the Federal fund match requirements.

TDOT developed specifications for the contractor to accelerate fabrication of the steel bridge girders through the use of advanced 3D laser based metrology.

The utilization of this technology met the TIDP/AID goals of improving highway efficiency and quality.

Lessons Learned

Through this project, the TDOT gained valuable insights with regard to the innovative laser metrology and 3-D modeling used in the fabrication of steel bridge girder splice connections. The following were some of the lessons learned:

1. The 3-D modeling and laser metrology can be successfully implemented in order to increase efficiency and save time and money during the fabrication of steel bridge girder splice connections.
2. The virtual comparisons of splice plates holes and girder holes, which is done as part of the application of this innovation, can be used to effectively identify errors during the splice connection fabrication process.
3. No negative impact on the erection process for steel bridges related to the application of this innovation was identified. Rather, this innovation has the potential to speed the erection process by quantitatively identifying and eliminating any misfits in the girder slice connections.
4. The considered laser metrology and 3-D modeling technology and methods have the potential to be utilized to accelerate other parts of the steel bridge girder fabrication process beyond what was considered in the scope of this innovation, including virtual erection of girders, and cross-frame fit-up, and a wide array of quality control checks.

PROJECT DETAILS

Background

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 American Society of Civil Engineers (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 how priority is given to projects deemed absolutely necessary and projects that are undertaken in response to emergencies, many worthy projects are 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 laid down in a line can easily take up hundreds of feet. Furthermore, specifications often require lay downs of three girders in a line, which takes up even more space (TDOT 2015).

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.

Project Description

The innovation investigated in this report is the utilization of laser-tracking technology in order to take measurements of the splice connection hole configuration of girders. These measurements are used to produce the splice plates hole configurations virtually and cut and drill the plates using more efficient automated equipment. This innovation significantly reduces the time needed for laydowns of adjacent girders and eliminates match drilling. Match drilling of the splice connections is a long and labor intensive task; therefore, the switch to drilling all of the splice connection holes with the Computer Numerical Control (CNC) machine made possible by this innovation is extremely valuable for bringing down the labor costs and time required for splice connection fabrication. In the below paragraphs, the steps involved with utilizing this innovation are laid out and compared with the traditional method. The related costs and resulting quality of the splice connections are discussed in the data collection and analysis section of this report. Furthermore, the steps taken to spur the widespread implementation of this innovation and the effort taken to disseminate the results of this study are found in the recommendations and technology transfer sections, respectively.

The procedure to produce bridge girders and their splice connections using the innovation discussed in this report is as follows:

1. Steel plates are 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, drilled, and welded together, the girder is placed into a laydown. In this configuration, the locations of the holes predrilled in the girders web and flange plates are measured using a laser tracker system. Hirschfeld uses a FARO brand 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 tracker's 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 1.

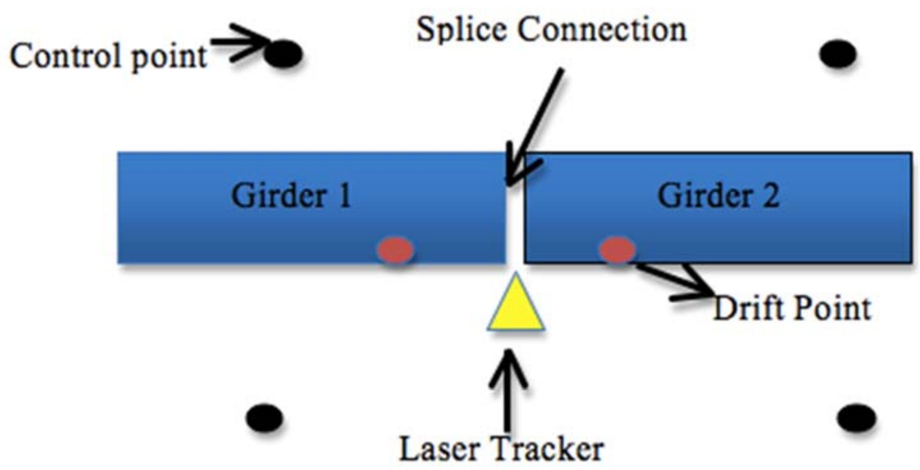

Figure 1: Diagram of laser tracker set up

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. 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 Spherically Mounted Retroreflector (SMR), to each point being measured. For the drift and control points, the SMR is placed within a magnetic fixture 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 2.

Figure 2: 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 3. 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 4.

Figure 3: CNC machine drilling a splice plate


Figure 4: 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 to ensure the fit is within the tolerance set by Hirschfeld, which limited the error in any single set of holes to 0.125 inches. A report of the virtual stacked comparisons is created and checked by the QC staff and the person performing the stack comparison. This comparison is discussed more in the quality sub-section of this report's data collection section.

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 staff person then verifies that the holes are accurate through a visual inspection. Portions of a test fit are shown in Figure 5 and Figure 6. When a test fit is not completed, only the virtual check of the completed splice plate and the girder holes is performed.

Figure 5: Test fit (side view)

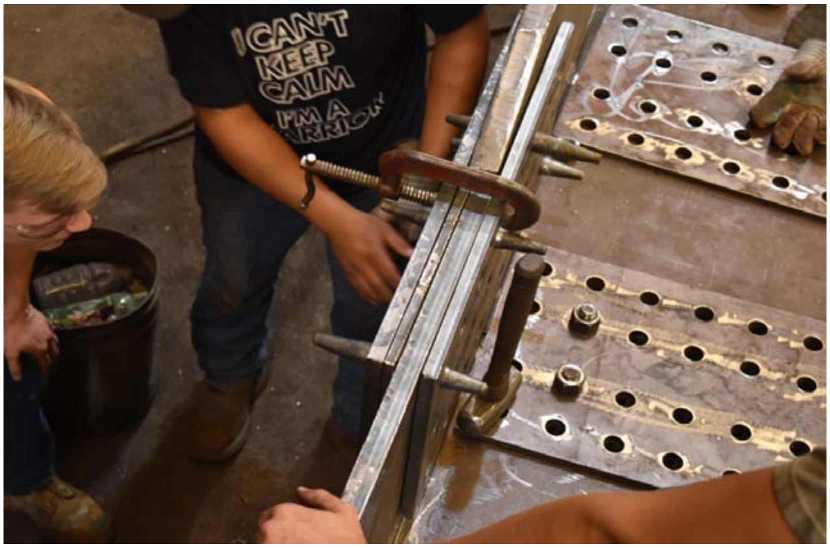

Figure 6: Test fit (top view)

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.

DATA COLLECTION AND ANALYSIS

Performance measures consistent with the project goals were jointly established for this project by TDOT and FHWA to qualify, not to quantify, the effectiveness of the innovation to inform the AID Demonstration program in working toward best practices, programmatic performance measures, and future decision making guidelines

Data was collected to determine the impact of using advanced laser-based metrology and 3D modeling on schedule, cost, quality, and user impacts before, during, and after construction and demonstrate the ability to:

- Reduce overall project delivery time and associated costs
- Reduce life cycle costs through producing a high-quality project
- Satisfy the needs and desires of our customers

This section discusses how the TDOT established baseline criteria, monitored and recorded data during the implementation of the innovation, and analyzed and assessed the results for each of the performance measures related to these focus areas.

Safety

The TDOT is always concerned with the safety of both the workers delivering the project and the users of our infrastructure during construction. The construction workers should see no difference in products properly fabricated using traditional methods of match drilling the splice plates versus products fabricated using advanced laser-based metrology. Furthermore, the higher level of precision in the splice connections fabricated with the technology considered in this report would likely decrease the chances of a misfit in the erection process. This is beneficial from a safety perspective as this would avoid any accidents while the construction workers fix a misfit in the splice connection. As a matter of fact, the erection contractor noted in an interview that he thought the final product was very good quality as he had no problems erecting the girders.

The public should see no noticeable difference between bridges constructed with traditional fabrication processes and advanced laser-based metrology methods.

Schedule

Streamlining the project delivery process results in earlier overall project completion. This in turn provides greater service to our end users sooner. The use of this innovation is expected to decrease the cost of the project by decreasing the overall time for the fabrication of the steel bridge girders due to the decreased time required to fabricate the splice connections between girders. Additionally, implementation of this innovation allows for the elimination of the majority of the test fits of the splice connections. This reduction in test fits is important because, in addition to the related time saved not performing a test fit, there is the space saved in the fabrication shop by eliminating the need to leave girders in laydown as frequently. This is important because the space occupied by the girders during a test fit, and the wait for the required quality control checks, effects and limits the flow of work on other jobs that are in a fabrication shop.

Once the girders are in their laydown position, 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 on a pair of girders already in their laydown position 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 the paper, 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 at the laydown very long. This available shop space can then be used 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 may need to remain at the laydown until complete. 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.

There is also a financial component of time. With few exceptions the purchasing power of today’s money is greater than the purchasing power of the same amount in the future. This is due to the effects of inflation; materials, fuel, labor, equipment, and supplies will generally cost more in the future than they do today. Therefore, when the widespread adoption of this innovation occurs, the accumulated cost savings realized will allow some infrastructure projects to be started earlier; thus, realizing savings due to greater purchasing power.

Cost

The cost savings realized from the implementation of this innovation is primarily related to the resulting reduction of manual labor hours. The time required to match drill each girder splice connection is at least 6 hours for a typical girder with a two-person crew, but can be considerably higher if the splice connection is being made in a thicker girder or if the connection includes a larger amount of bolts. As discussed above, with this innovation, match drilling is eliminated and instead, while the girder is in laydown, the laser tracker is used to measure the locations of the pre-drilled bolt holes in the girder. The time required to perform this measurement is significantly less than the match drilling time, about 1.5 hours with a two-person crew per splice connection. A considerable amount of this time is related to setup, thus additional bolt holes in a girder does not greatly change the time required to measure the connection's hole locations. Furthermore, the setup time for a measurement can be reduced with the use of multiple trackers (see the below paragraphs for a discussion related to this). With this innovation, additional time is required during the cutting of the girder flange and web plates such that the splice connection holes can be drilled at the same time; however, as these holes are drilled with the numerical controlled machine, they do not require additional manual labor and can be drilled much faster than using a match drilling process. An additional cost savings is realized via a reduction in manual labor required for test fits. With this innovation, the number of test fits is dramatically reduced.

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 targets 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 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 very 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 for this demonstration, two employees were sent away for two weeks of training 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.

Quality

As previously discussed, using traditional techniques, the quality of the splice connection would be assessed using a hands-on quality control inspection of the splice connection via a test fit at the end of the laydown. However, through the use of the laser metrology innovation considered in this report, this hands-on quality control inspection was largely eliminated. With the innovation, this quality control assessment was largely replaced by an assessment of the quality of the connection via comparison of the splice plate and girder hole layouts obtained through laser metrology. In addition to largely eliminating the more time-consuming hands-on inspection, this innovation allows for a quantitative and recorded measurement of the quality of each pair of holes in the splice connection in terms of their ability to align properly. Furthermore, the quality of the splice connection hole layouts themselves will be increased. With this innovation, the holes in both the girders and the splice plates will be drilled using the numerically controlled machine; in comparison, with the traditional technique the splice plates holes were drilled with the numerically controlled machine, but the girder holes were match drilled. From a quality perspective, drilling all of the splice connection holes is advantageous because the precision and consistency of the holes drilled with the numerically controlled machine will be much higher.

The resulting improvements in the quality of the connection holes and the quality control technique used to assess the connections provide benefits beyond the fabrication of the girders. Because of these improvements, the girders connections produced with this innovation will have less misfits. Misfits are a serious issue when erecting a bridge and require corrective action such as reaming out holes, re-drilling, or re-fabrication of the splice plate. These corrective actions can be time-consuming, thus the reduction of misfits will improve the quality and scheduling of the erection process.

Figure 7 shows the error magnitude measured from every hole comparison made for the girder splice connections of the SR 92 bridge, which was used to demonstrate this innovation. This figure includes the error magnitudes from 16,245 hole comparisons taken from 370 splice plates across 37 splice connections. These error magnitudes are computed based on the X and Y measurement comparisons. As shown in Figure 7, 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”.

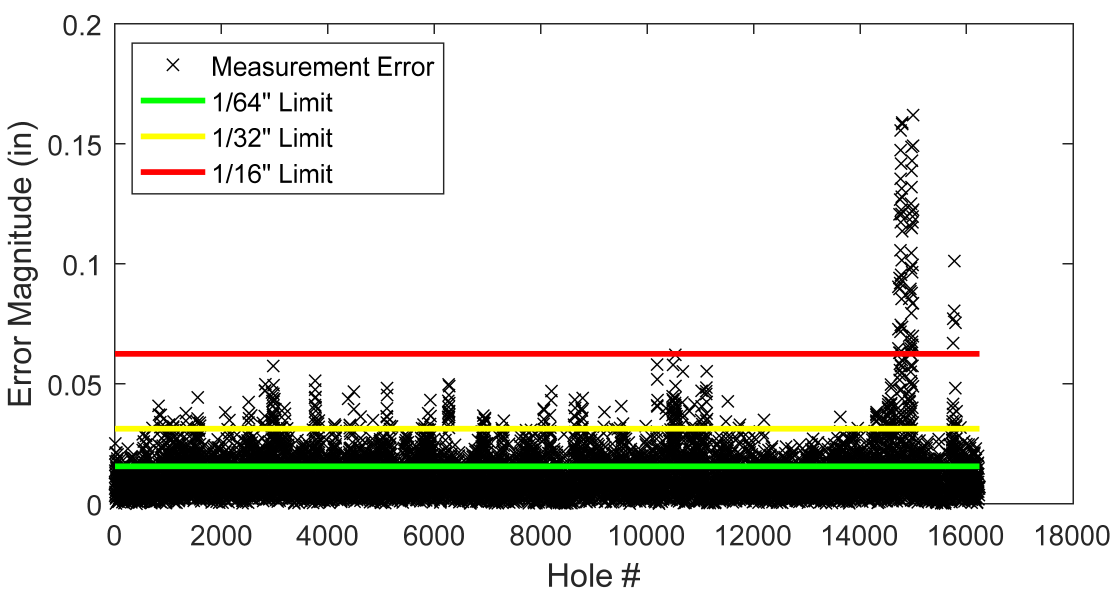

Figure 7: Magnitude of error for each hole comparison

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. While the cause of these large errors was not reported, possible causes include a bad drill bit or bearing on the drill requiring replacement, a faulty measurement set, or an error made during the design of the final layout of the splice plate. Possible sources of error, including human errors, are further 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 8). 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 8 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 this innovation is able to produce high-quality connections that are accurate and reliable enough for the intended application.

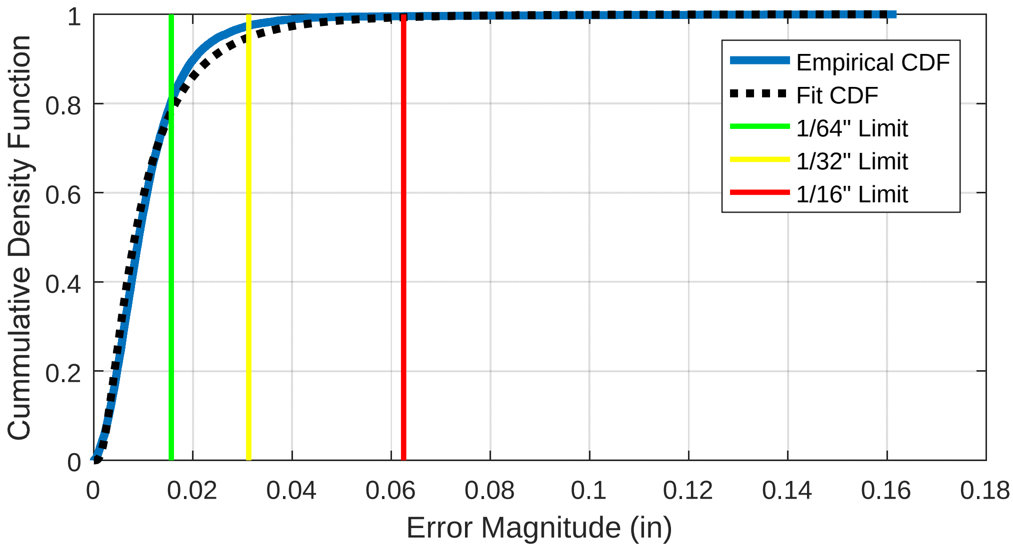

Figure 8: Empirical and fit cumulative density functions

User Satisfaction

Based on the results described in the ‘Quality’ section above, Hirschfeld, the bridge fabricator, was satisfied with the performance of this technology. In fact, Hirschfeld has plans to expand the implementation of this technology and use it on more projects. Furthermore, Hirschfeld is researching possible ways to utilize this technology to allow for a virtual laydown, which would eliminate the need for a physical laydown of multiple inline girders together. The satisfaction of Hirschfeld with this technology, and its desire to expand its implementation, gives good cause to expect the implementation of this technology by other fabricators.

The erector of the bridge also reported being satisfied with the results of this project. The reason for this satisfaction is that no misfits were encountered by the erector and the fabrication process studied does not complicate the erection process.

The owner of the bridge, the Tennessee Department of Transportation, was satisfied with the results of the performance of the metrology process as it has the potential to lower fabrication costs without complicating the erection process or compromising safety or product quality.

RECOMMENDATIONS AND IMPLEMENTATION

Recommendations

TDOT determined from the results of the presented data analysis and sense of satisfaction from the facility users that 3-D modeling and laser metrology can be successfully implemented in order to increase efficiency and save time and money during the fabrication of steel bridge girder splice connections. TDOT has proposed adopting laser-based metrology and 3D modeling for girder splice connections into the operating procedures.

However, the following areas that could be improved upon in future applications of this innovation have also been identified:

- Using multiple laser trackers to reduce equipment set up time, for use on more than one project at a time, and for increased reliability in case of down time for one of the laser trackers.
- Possibility of implementing the laser tracker to more accurately and efficiently perform QC/QA other checks that are currently performed by hand.
- Utilizing technology to eventually make the entire laydown procedure completed virtually. This advancement would eliminate the need for the physical laydowns of adjacent girders; thus, large amounts of space in the fabrication shop would be freed up for other uses.

Status of implementation and adoption

Since the completion of the project "Accelerated Innovation Deployment (AID) Demonstration Project: Advanced Laser-based Metrology and 3D Modeling", TDOT has undertaken the following activities to implement laser-based metrology and 3D modeling for girder splice connections into the operating procedures as a significant improvement from our traditional practice for similar type projects:

A draft of a special provisions allowing this innovation has been written and is currently under review.

APPENDICIES

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 <u>two</u> 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 <u>5'</u> 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 <u>1/128"</u> 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.

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:

i. 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 qualify 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 <u>two</u> connections fabricated for each project and a minimum of <u>10%</u> 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.

TECHNOLOGY TRANSFER

Presentations on this innovation were made by Dr. Wierschem at the following venues:

- 2017 Tennessee Engineers' Conference, September 27 – 29, 2017, Nashville, TN
- AASHTO Summer Bridge Task Force and T-14 Technical Committee Meeting, August 1 – 4, 2017, Denver, CO
- TDOT Steel Bridge Fabricator Meeting Committee Meeting, Tennessee Department of Transportation, April 19, 2017, Nashville, TN
- Knoxville Branch Professional Development Seminar, American Society of Civil Engineers, March 31, 2017, Knoxville, TN

The presentations that were given on this innovation were well attended and were given a good reception. The audience at the TDOT Steel Bridge Fabricator Meeting and the Bridge Task Force / T14 Committee Meeting are particularly important for the dissemination of this work. The attendees at the TDOT Steel Bridge Fabricator Meeting primarily represent regional fabricators working with TDOT. For wider adoption of this innovation in Tennessee and the larger Southeast region, these fabricators will need to make the required capital expenditures for the related equipment and training. The audience at the Bridge Task Force / T14 Committee Meeting represents the wider national steel bridge community. In addition to fabricators, this group included representatives from state transportation departments. For this innovation to be adopted wider, these people will need to setup the regulatory framework at the state level to allow its use as well as encourage its use among fabricators.

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