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Highway IDEA Program

Instrumentation to Aid in Steel Bridge Fabrication

Final Report for Highway IDEA Project 127

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
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Instrumentation to Aid in Steel Bridge Fabrication

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. EXECUTIVE SUMMARY

The goal of this project was to begin development of a complete laser measurement system that will eventually *eliminate the shop assembly process of steel bridges* and will *provide a complete permanent record of the as-built condition of each girder*. This system is built around an established commercial laser scanner and can provide features not found using any other commercial instrument or collection of instruments. This system measures girders in a fabrication shop, produces documentation, and can provide data to virtually assemble girders, see FIGURE 1.

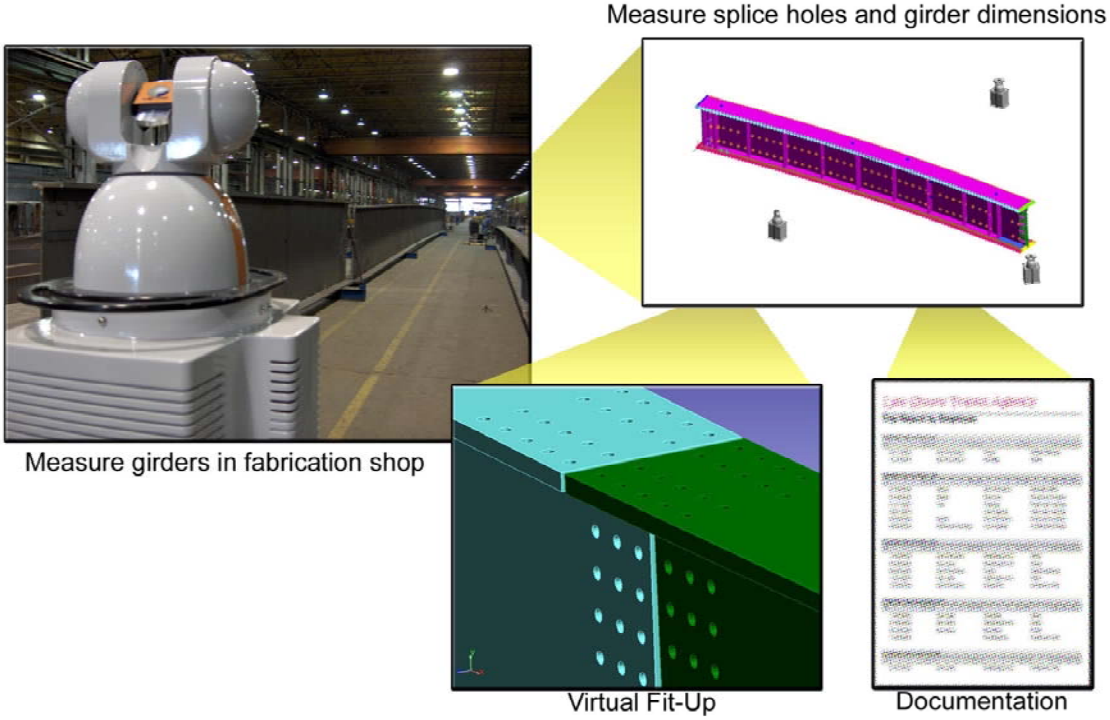

FIGURE 1 System concept for laser measurements of steel bridge girders.

The impact of this laser system is its potential to save millions of dollars on production costs of steel bridges. As a quality control tool, a written record of exactly what was manufactured would be of great value. Current practice uses manual quality control measurements (i.e. string lines and rulers) to verify the as-built condition of girders. This process is time consuming and can lead to errors not noticed until bridge erection. Automated geometric measurements of fabricated bridge girders could serve as an important documentation tool and produce a permanent record. When used as a virtual assembly tool the potential benefit to the steel bridge fabrication industry is substantial. Some estimates put the added cost of shop assembly at 10-20% of the total cost of a steel bridge. There is potential for State Departments of Transportation to save millions of dollars on steel bridges with the use of this laser system.

When this laser system is used as a virtual assembly tool the potential benefit to the steel bridge fabrication industry is substantial. The shop assembly process requires several labor intensive and time consuming steps. The elimination of shop assembly will require acceptance from bridge owners. This acceptance will only come through successful demonstration of this laser system's capabilities. This system has been shown to make measurements and produce splice plate designs for straight girders. Simple curved girders can also be measured and verified with the existing system. The virtual assembly of more complex box and other structures will require some additional work and development. The tools to perform this work exist, but must be properly implemented. Elimination of shop assembly can potentially be done right now for simpler structures. For more complex structures, additional development work is required.

The cost of shop assembly is a quantifiable cost for each bridge job. This cost, if eliminated, would be a direct payback for use of this laser system. In addition, other savings would result. Often girders are fabricated at different plants many miles apart. Shop assembly requires that these girders be transported to one common facility and erected prior to shipment to the shop site. This extra shipment could be eliminated with a virtual assembly system.

The Fuchs Consulting, Inc. (FCI) Bridge Fabrication Laser System (FCI Laser System) under development in this project is a complete turn-key system. This laser system is built around an established commercial instrument and can provide features not found using any other commercial instrument or collection of instruments. This commercial laser scanner is a key piece of the overall system, but by itself this commercial scanner does not have all of the necessary components for this application.

The FCI Laser System integrates all of the necessary components around this commercial laser scanner to provide the needed features for this application, see FIGURE 2. One of these features is additional computer systems that control added system functions and receive data from additional system sensors. System software provides a user interface and handles interaction with existing CAD systems currently in use in fabrication facilities. The FCI Laser System also includes the components that provide customized measurement automation and processing algorithms for girder dimensioning and virtual fit-up analysis. The complete system incorporates customized mounting and packaging of the existing commercial system suitable for fabrication environments. The system provides custom reports and data storage for this application.

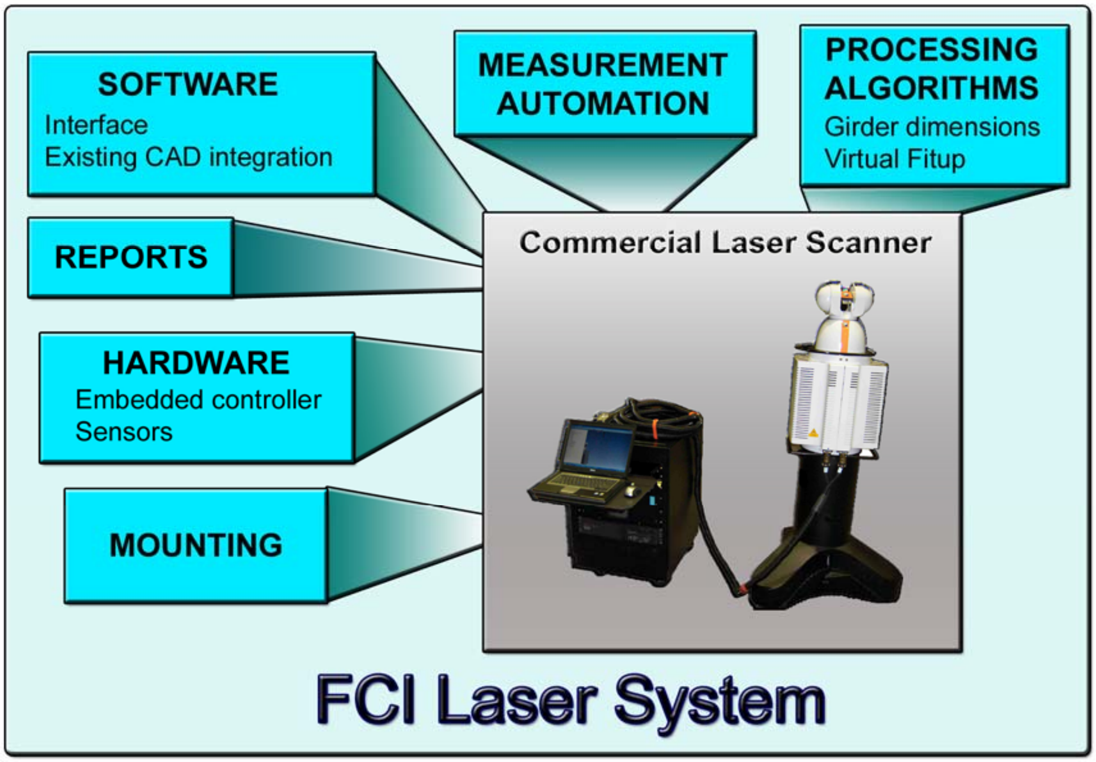

FIGURE 2 FCI Laser System main components built around commercial system.

This NCHRP-IDEA project was a first step in creating a complete laser measurement system for steel bridge fabrication applications. To get a feel for various end-user perspectives, site visits were made to two steel bridge fabricators, which were High Steel Structures, Lancaster, PA, and Egger Steel Company, Sioux Falls, SD. Five weeks of testing and development work were conducted at the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC). Here several important system concepts were demonstrated in a more controlled environment. Most importantly the measurement of splice plate holes, with no special targets, was verified. Laser system measurements were used to successfully create custom splice plates based on measurements and to demonstrate virtual girder assembly. This project testing culminated with one week of testing at an actual steel bridge fabricator. The FCI laser system was operated at High Steel Structures in Lancaster, PA. Here several straight and curved girders were measured along with other more complex geometry pieces. This fabrication shop testing was the most beneficial part of the project. Here the issues of system integration into a real-world environment were encountered. The completion of this project represents the first steps in developing a complete turn-key system for use in a fabrication shop.

2. IDEA PRODUCT: FCI LASER SYSTEM

The goal of this project was to begin development of a complete laser measurement system that will eventually *eliminate the shop assembly process of steel bridges* and will *provide a complete permanent record of the as-built condition of each girder*. This system is built around an established commercial laser scanner and can provide features not found using any other commercial instrument or collection of instruments. This system measures girders in a fabrication shop, produces documentation, and can provide data to virtually assemble girders, see FIGURE 3.

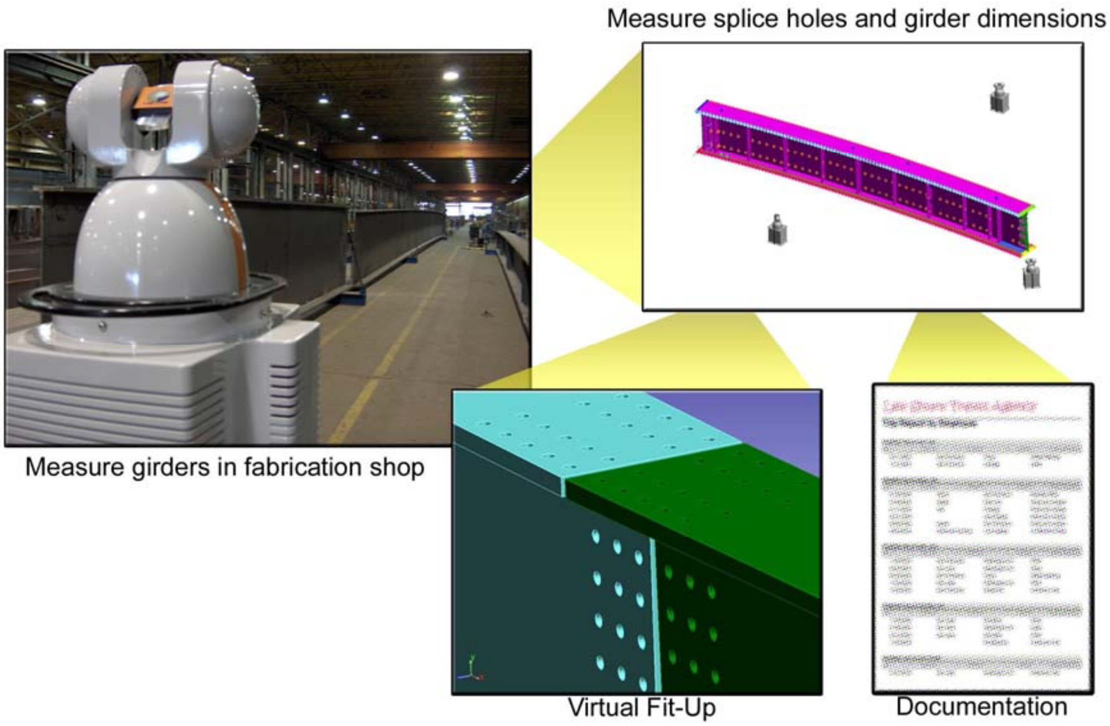

FIGURE 3 FCI Laser System concept for bridge girder measurement.

2.1. CURRENT PRACTICE OVERVIEW

Most states require a steel bridge fabricator to shop assemble some or all parts of a steel bridge. This practice is intended to assure that the structure, primarily the splice plates and cross frames, will fit together at the job site as designed. In many cases during initial girder fabrication splice plate holes are sub-drilled at a dimension smaller than the final hole size needed for a splice plate bolt. To make sure all holes are aligned, the fabricated girders with sub-drilled holes are shop assembled, a splice plate is placed on the girders, and the holes are reamed to their final size. After shop assembly verifies proper fit-up of components, the bridge is disassembled and taken to the job site. This procedure is labor and time intensive and adds significant cost to a steel bridge. The application of laser-based metrology instrumentation to measure the exact size and shape of fabricated bridge girders, including splice plate hole locations, could potentially be used to aid in the fabrication of steel bridges. A laser-based instrument could be used in a fabrication shop to measure each girder after it was fabricated. Precise measurements of splice plate hole locations could be measured and documented. After all separate girders in a bridge have been measured with this laser-based instrument, this data could then be used to virtually assemble the bridge. Fabricated dimensions of the girders could be checked against shop or design drawings. The position of splice plate holes between girders could be checked to ensure proper alignment. Full sized holes could be placed in girders during fabrication, eliminating the need to sub-drill holes and shop assemble girders. All of the bridge assembly could be performed virtually, without physical shop assembly. Additionally, a complete record of the dimensions of a fabricated girder could be created. This record could be used as a quality control tool to detect fabrication errors prior to shipment to a job site.

2.2. WHAT IS THE POTENTIAL PAYOFF?

The impact of this laser system is its potential to save millions of dollars on production costs of steel bridges. As a quality control tool, a written record of exactly what was manufactured would be of great value. Current practice uses manual quality control measurements (i.e. string lines and rulers) to verify the as-built condition of girders. This process is time consuming and can lead to errors not noticed until bridge erection. Automated geometric measurements of fabricated bridge girders could serve as an important documentation tool and produce a permanent record. When used as a virtual assembly tool the potential benefit to the steel bridge fabrication industry is substantial. Some estimates put the added cost of shop assembly at 10-20% of the total cost of a steel bridge. There is potential for State Departments of Transportation to save millions of dollars on steel bridges with the use of this laser system.

2.2.1. Quality Control Tool

This laser system can be used as it exists now, without any further integration work, as a quality control tool and will have an immediate payback. The system can produce a complete permanent record where the measurements would be traceable and certifiable. Currently collected quality control data taken by hand, see FIGURE 4, and recorded in tables on paper can sometimes contain errors (i.e. wrong number written down). The permanent record produced by this laser system would eliminate this problem and could be shown to a customer in the event of a dispute. For cases where fabricated girders are erected by another party this permanent record could help protect from situations where the erector, or other contractors, were at fault and tried to blame the problem on a fabrication error. The legal expenses for one dispute of this type could more than pay for the cost of this system. In the event a fabrication error occurred, the system could identify this condition prior to painting and before the girder left the shop.

FIGURE 4 Conventional string line or other manual measurements can be eliminated.

2.2.2. Eliminate Shop Assembly

When this laser system is used as a virtual assembly tool the potential benefit to the steel bridge fabrication industry is substantial. The shop assembly process requires several labor intensive and time consuming steps, see FIGURE 5. The elimination of shop assembly will require acceptance from bridge owners. This acceptance will only come through successful demonstration of this laser system's capabilities. This system has been shown to make measurements and produce splice plate designs for straight girders. Simple curved girders can also be measured and verified with the existing system. The virtual assembly of more complex box and other structures will require some additional work and development. The tools to perform this work exist, but must be properly implemented. Elimination of shop assembly can potentially be done right now for simpler structures. For more complex structures, additional development work will be required.

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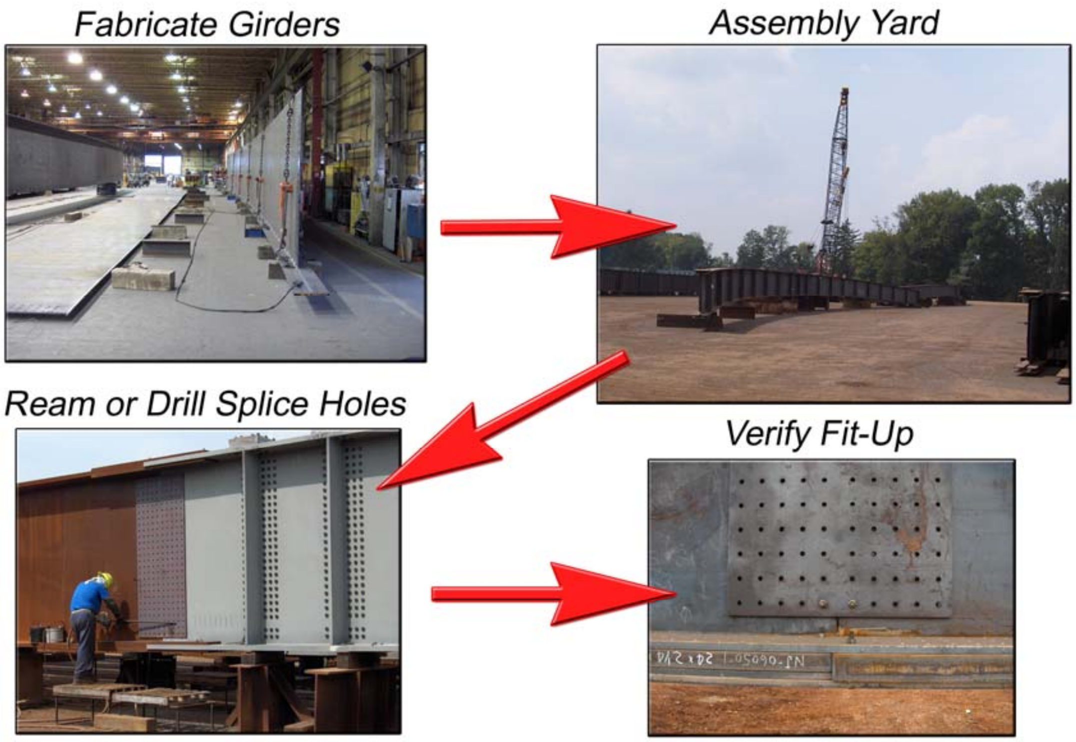

FIGURE 5 Conventional shop assembly can potentially be eliminated.

2.2.3. Other Uses

One of the biggest assets of this laser system is its flexibility. The system is very adaptable to new applications and uses. One potential other use of the system would be for retrofit applications. Here the laser system could be taken to the field and measure existing parts to be retrofitted. A custom designed part can then be designed based on these actual measurements.

2.3. HOW WILL THIS SYSTEM BE BENEFICIAL?

A completely integrated system will provide at least the following end uses.

- *Quality Control Tool*
    - Completely measure and document the as-built condition of girder: length, camber, sweep, end-kick, splice hole locations
- *Virtual Shop Assembly*
    - Eliminate shop assembly of entire bridge or girder lines
- *Splice Plate Design*
    - Measure girder splice hole locations and produce design for a matching splice plate without fit-up
- *Field retrofit measurement*
    - Make field measurements of parts to be retrofitted to produce custom design of parts
- *Web distortions*
    - Check web distortions or other geometric properties of girder difficult to measure with other instruments

2.4. HOW WILL THE MEASUREMENT PROCESS WORK?

This laser system could be implemented into an existing fabrication shop with minimal changes to the existing process. One of the strengths of this system is that the measurement system is brought to the part. As such, this laser system could be setup at the end of the shop and used to measure girders right before they are placed on a truck. This would have minimal impact on the production line and allow for any fabrication errors to be identified prior to leaving the shop. The following gives a brief description of how the measurement process will work.

- *Start with 2D or 3D CAD file*
- *Pre-define measurements*
    - Software setup of measurements
    - Once defined, standard measurement setups will exist for common girder designs
- *Set girder on shop floor at end of fabrication line*
- *Measure four (4) known locations*
    - Use targets or maybe special zinc marks on girder
- *Software orients laser measurements to CAD with four (4) known points (all other measurements are now automated)*
- ***Automatically** collect measurements (no targets, no operator)*
    - Measure points for length, sweep, camber, end-kick
- *Re-orient laser*
    - Move laser scanner to new location to measure girder end or backside splice holes
- *Automatically make output*
    - Automatically create an output CAD file compatible with existing systems
    - Automatically create a measurement report
    - Automatically highlight fabrication errors based on CAD drawings

3. CONCEPT AND INNOVATION

The FCI Bridge Fabrication Laser System (FCI Laser System) under development in this project is a complete turn-key system. This laser system is built around an established commercial instrument and can provide features not found using any other commercial instrument or collection of instruments. This commercial laser scanner is a key piece of the overall system, but by itself this commercial scanner does not have all of the necessary components for this application.

The FCI Laser System integrates all of the necessary components around this commercial laser scanner to provide the needed features for this application. One of these features is additional computer systems that control added system functions and receive data from additional system sensors. System software provides a user interface and handles interaction with existing CAD systems currently in use in fabrication facilities. The FCI Laser System also includes the components that provide customized measurement automation and processing algorithms for girder dimensioning and virtual fit-up analysis. The complete system incorporates customized mounting and packaging of the existing commercial system suitable for fabrication environments. The system provides custom reports and data storage for this application.

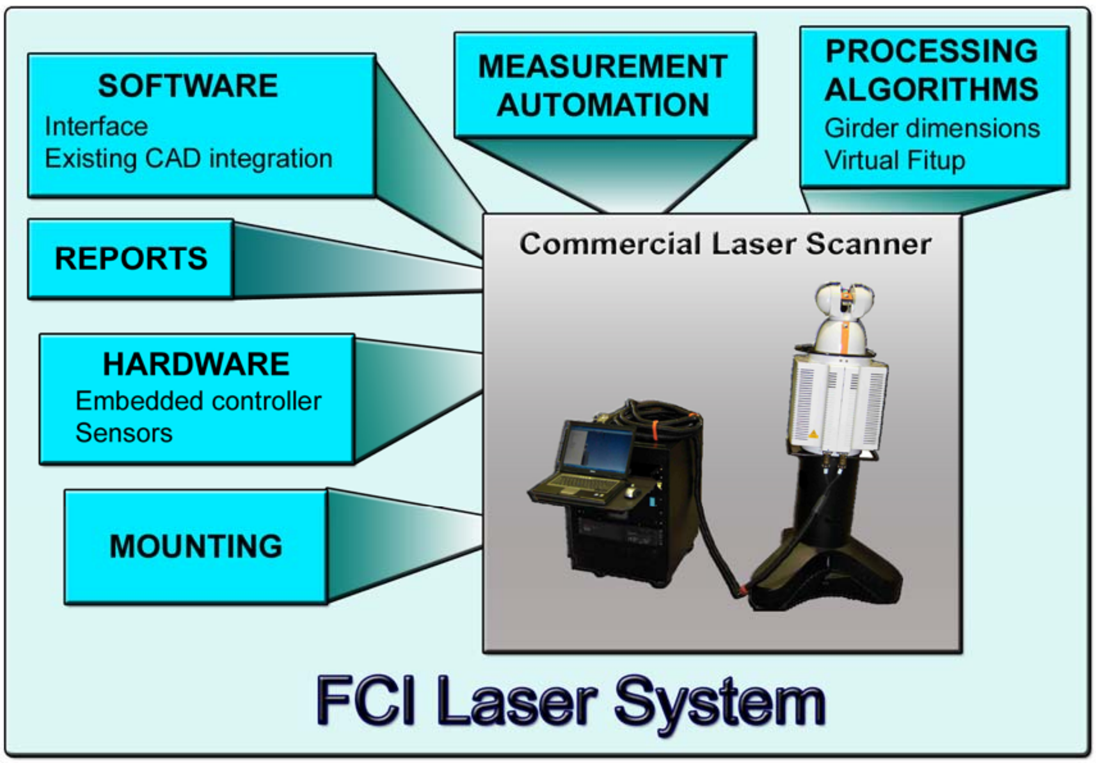

FIGURE 6 FCI Laser System block diagram.

While the FCI Laser System is build around one particular commercial laser scanner, other commercial instruments or collections of instruments can be integrated into the overall system. The commercial instrument selected for the system provides the best features of any commercial system, but could be replaced as needed.

3.1. COMMERCIAL LASER SCANNER DESCRIPTION

The FCI system is built around a commercial laser metrology system that is an extremely accurate, large-volume three-dimensional coordinate mapping device. Within the field-of-view of the instrument, the three-dimensional coordinates of a point in space can be found. Three measurements are required to define this point in space. One of the measurements is obtained from a laser-based range finder. The additional two measurements are found from precise angle encoders on a mechanical scanner that positions the laser. The measurement laser can be scanned across the surface of an object and sub-millimeter accuracy measurements are easily achieved. Measurements can be made directly on a specimen surface without requiring special targets. Measurements can be made within a very large volume. The instrument is not affected by ambient lighting conditions and does not need to operate in a special environment. The system is manufactured by Metris, Model Number MV224 Laser Radar (Mobile Optical Scanning CMM), and is shown in FIGURE 7.

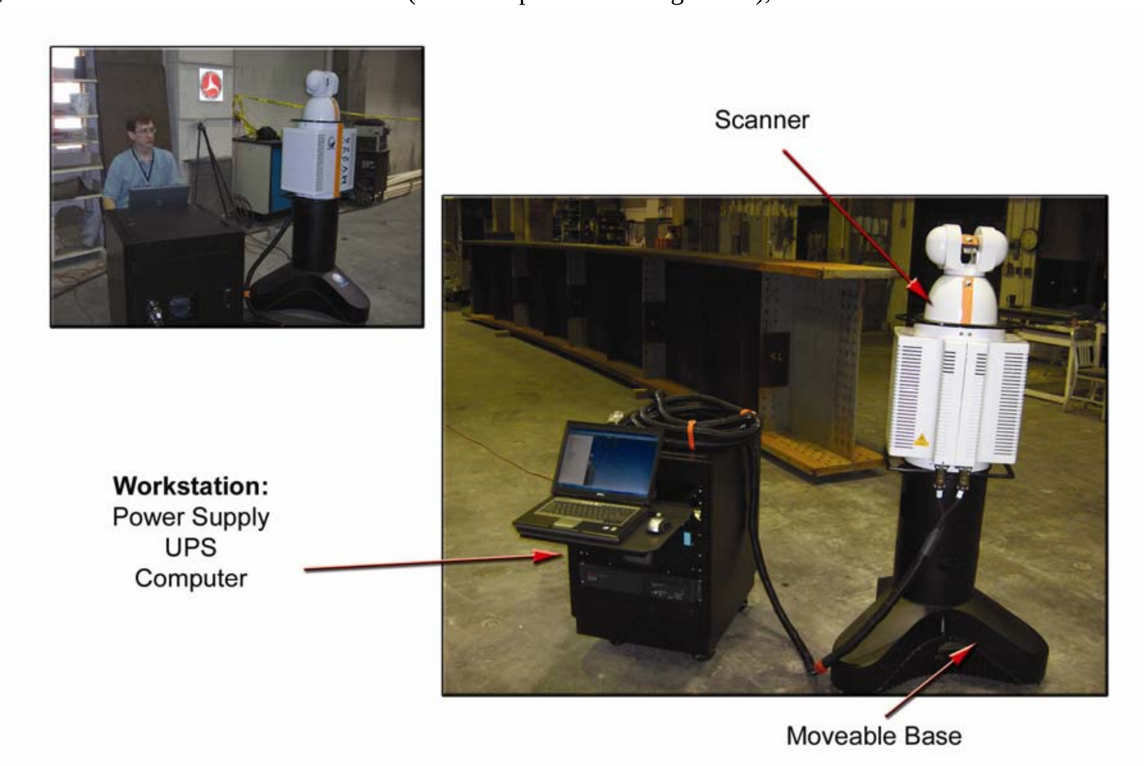

FIGURE 7 Commercial laser scanner and workstation.

This laser system does not require a special target to make a measurement but has the ability to use special targets to perform specific tasks. One of these tasks is to track or measure a known location on a specimen. Special targets can also be used as a reference to re-orient the laser system to different locations around a specimen or to check for specimen movement during testing. The most common target used is a 12.7 mm (½ in) diameter tooling ball. For this project two types of 12.7 mm (½ in) tooling ball targets were used, see FIGURE 8. The first was a magnetic mounted target that was placed on test specimens. The second was a special-made splice hole target that was used to find the center of the splice hole in a specimen.

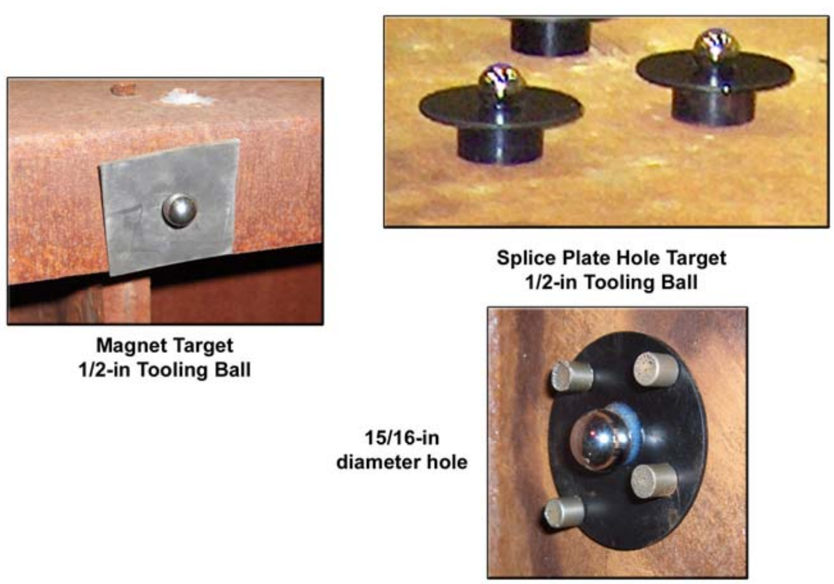

FIGURE 8 Tooling ball targets used with the laser system.

This commercial laser scanner has the following characteristics essential to this bridge fabrication application.

- *Robust and rugged enough to work in a typical fabrication plant*
  - Most fabrication facilities are environments that can be dirty and dusty. This instrument has been demonstrated to be capable of working in these types of environments.
- *Very high accuracy measurements*
  - This high accuracy is needed to measure small features of bridge girders such as splice plate hole locations. A very high accuracy measurement is required to locate and size splice plate holes.
  - This laser system can measure with an accuracy of better than 0.2 mm (0.007 in).
- *Very large measurement volume*
  - A large volume is needed because of the size of typical bridge girders. Measurements must be made over the length of girders that are typically 36 m (120 ft) in length.
  - This system can measure up to 24 m (80 ft) from the instrument in any direction (48 m [160 ft] diameter). An extended range 60 m (200 ft) option is available.
- *Ease-of-Use*
  - No special targets or measurement rooms are required to make a measurement. This instrument can make measurements on the unprepared surface of the steel girders. Special targets can be used in a limited fashion to help re-position the instrument or to track a particular point on a specimen.
- *Mobile system that can be used in various parts of fabrication plant*
  - The instrument is portable and can be moved around a fabrication facility for measurements.
- *Near full automation*
  - Customized setup and measurement algorithms can be programmed into the instrument. Specialized software can be made to automate the measurement process and eliminate complicated setup by an operator.

3.2. HOW IS THIS COMMERCIAL LASER SCANNER UNIQUE?

The specifications established for this bridge fabrication application dictate the type of metrology system selected for the project. The three key specifications are very high measurement accuracy, very large volume, and direct specimen measurement without a target. High accuracy is needed for the measurement of splice plate hole locations. A large volume measurement is needed because of the size of typical bridge girders. The direct specimen measurement is needed for full measurement automation.

In general there are three basic methods using laser systems to measure distance for larger-scale applications, which are pulsed time-of-flight, interferometric, and beam-modulation methods. Pulsed time-of-flight measurement systems transmit a short-pulse signal toward a target and measure the time elapsed until a reflected signal is received. There are a very large number of commercial laser systems in this category, such as those manufactured by Riegl USA and Leica. Applications for these systems are generally related to rapidly scanning large objects and producing very high-density point clouds. Time-of-flight systems can have accuracy on the order of 6 mm (0.24 in) to 25 mm (1.0 in). This type of low-accuracy scanning system is well-suited for large scenes where gross positions of objects are measured (i.e. measurement of a bridge collapse for forensic investigation such as the I-35W bridge collapse in Minnesota in 2008). Rapid scanning systems can measure directly off a specimen (non-cooperative target). Time-of-flight systems achieve greater accuracy by use of a special target (cooperative target). The need to use a target, probe, or retroreflector, such as is the case for a laser tracker instrument, eliminates the ability to make measurements in an automated fashion and requires an operator. Time-of-flight systems are not suitable for the bridge fabrication application because of insufficient measurement accuracy.

Interferometric laser systems provide extremely high accuracy measurements. This method measures interference patterns between a beam of light separated into two paths to determine distance and can make measurements with a resolution of less than a wavelength. This technique requires a highly stabilized laser in order to make measurements over long distances. Systems for long-range measurements are typically very expensive and are best suited for controlled laboratory conditions. Many laser system manufacturers use an interferometric laser system as a benchmark standard in order to test operation of their equipment. Interferometric systems are not practical for the bridge fabrication application due to cost and the inability to operate in a typical fabrication shop environment.

Beam modulation (or phase-based) methods use continuous-wave lasers to measure distance. In a simplified example a sinusoidal laser signal is transmitted to a specimen and the range to the specimen is determined by measuring the phase between the transmitted and received laser signals. Further improvement in operation can be achieved by modulating the transmitted laser signal. The amplitude or the frequency of the laser signal can be modulated. An example of a fixed line-of-sight beam modulation system is made by Phase Laser Systems. This system is designed to measure levels in tanks. Leica manufactures beam modulation systems, such as the Leica HDS6100. This system has an accuracy of about 3 mm (0.12 in). These commercial systems are again suited for rapid scanning of large objects and produce large point clouds of data. Similar to the time-of-flight systems, the majority of these commercial beam modulation systems (all systems except the Metris Laser Radar) are not practical for the bridge fabrication application because of insufficient measurement accuracy when used without a cooperative target. Many commercial beam modulation systems also have a large measurement spot size, 8 mm (0.31 in), and cannot measure splice holes at a distance. The Metris Laser Radar is a type of beam modulated system.

There are other classes of metrology equipment that could be used for this application. One example is a localized arm system, such as those manufactured by Faro. Here a probe attached to an arm is touched by an operator to a specimen for a measurement. These arm systems typically operate over a very small volume, typically less than 3.5 m (11.5 feet). An operator is needed to touch the probe to the measurement location and therefore automated measurements are not possible. There are specialized probe-type systems that track a remote target, such as the Metris iGPS (indoor GPS) system. This system needs stable reference equipment setup in the measurement environment, requires additional work to setup and maintain, and cannot be automated. Laser trackers, such as the Faro Laser Tracker X, have very high accuracy but require a target at the measurement location. All of these systems need direct contact with the specimen and therefore cannot be automated.

Another metrology solution is a combination of multiple commercial systems that can attempt to achieve the same specifications as a single Metris system and provide accurate data over large volumes. For example, a Faro arm can be combined with a laser tracker, which is used to reference the position of the arm in space. This allows high-accuracy measurements with the localized system and larger volume measurements with the laser tracker. Software exists to tie measurements from multiple instruments together into one coordinate system. The cost of multiple localized systems is comparable to or greater than the Metris Laser Radar and has the disadvantage of additional setup, maintenance, and operation requirements. Also, careful consideration of the total system measurement accuracy is required when using multiple systems, each with different accuracies and noise limitations.

The Metris laser system chosen for this project is a beam modulation system that uses a specialized frequency modulation method. The specialized measurement technique provides significantly higher accuracy than time-of-flight or other beam modulation systems. The frequency-modulation technique of the Metris system provides the ability to make measurements with very small returned signals and allows for direct measurements on a specimen surface and immunity to ambient lighting. No other commercial laser system uses the same measurement technique and therefore no other commercial system can provide the same specifications. This allows the Metris Laser Radar system the ability to combine high accuracy measurements over a very large volume with no special targets. For this reason the Metris Laser Radar system was selected for this application.

The Metris system can make measurements directly on the surface of steel girders without requiring a special target, such as a photogrammetry dot, retro-reflectors, or probes. The Metris instrument can make measurements with accuracy less than 0.2 mm (0.007 in) out of a total range of 24 m (80 ft). This is a 24 m (80 ft) radius around the instrument, so a very large volume can be measured from one position. A 60 m (200 ft) radius system is also available. The system can be used with mirrors to see areas hidden from line-of-site view of the instrument. Combining the instrument's direct surface measurements with CAD data allows for near-full automation. Here almost all measurements can be preprogrammed in CAD and automatically carried out by the instrument. This eliminates manual measurements by an operator and significantly reduces errors in measurements. Even splice holes can be defined in CAD and automatically measured by the instrument with no operator intervention.

4. INVESTIGATION

This NCHRP-IDEA project was a first step in creating a complete laser measurement system for steel bridge fabrication applications. Several important steps were accomplished in this project.

- *Steel Fabricator Site Visits*
    - Visit and met with High Steel Structures, Lancaster, PA
    - Visit and met with Egger Steel Company, Sioux Falls, SD
- *Commercial Laser System Manufacturer Tests*
    - Performed initial system work and preparations for FHWA laboratory testing
- *FHWA Laboratory Tests*
    - Demonstrated splice plate fabrication and virtual assembly
    - Demonstrated direct hole measurements with no special targets
    - Demonstrated girder dimensioning
    - Demonstrated CAD driven measurements
- *Fabrication Shop Tests*
    - Demonstrated laser system can work in a typical fabrication shop
    - Demonstrated measurements of typical girders can be made on the shop floor
    - Demonstrated manual measurements can be made in a short amount of time
    - Demonstrated CAD data can be exchanged with the laser system
    - Demonstrated splice holes can be measured without targets
- *System Development*
    - Developed many additions to the existing system for more efficient operation
    - Identified many key design features needed for a final system

This project investigation identified several of the key measurement procedures needed for a final system. This included procedures for measurement of splice plate holes without any targets. The five-week laboratory phase of testing at the Federal Highway Administration Turner-Fairbank Highway Research Center was used to prepare for the fabrication shop testing. This fabrication shop testing was the most beneficial part of the project. Here the issues of system integration into a real-world environment were encountered.

4.1. STEEL FABRICATOR SITE VISITS

To get a feel for various end-user perspectives, site visits were made to two steel bridge fabricators, which were High Steel Structures, Lancaster, PA and Egger Steel Company, Sioux Falls, SD. Here fabrication procedures were examined and implementation of the laser system into the fabrication process was discussed. Fabricators were chosen in geographically diverse areas to get a feel for various procedures and conditions in typical steel fabrication facilities.

4.2. COMMERCIAL LASER SYSTEM MANUFACTURER TESTS

Three days of tests were conducted at the laser system manufacturer, Metris, at their facility in Newington, VA. Metris provided an instrument as well as space at their facility for testing. In addition, Metris provided technical support with instrument setup and operation. The goal of these tests was to become familiar with the current version of the instrument hardware and software and to prepare for future measurements. A test splice plate was used for making measurements on splice plate holes. Here scans of the plate surface and measurements of splice plate holes were made. Tests were done on various procedures for making splice hole measurements. These initial tests helped better determine the current capabilities of the laser system for this measurement and to examine software features for splice hole measurement.

4.3. FHWA LABORATORY TESTS

Laboratory tests were conducted at the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center (TFHRC) Structures Laboratory for a total of 26 days. These tests occurred over a total of 15 days from the period from July 31st until August 10th, 2007. Additional tests occurred for a total of 11 days over the period from October 5th through October 20th, 2007. The majority of measurements were performed in the FHWA TFHRC Structures Laboratory. This laboratory, shown in FIGURE 9, is approximately 55.2 x 15.5 x 9.1 m (181 x 51 x 30 ft).

FIGURE 9 FHWA Structures Laboratory testing of the laser system.

The laboratory environment is not as harsh a working environment as a bridge fabrication facility, but it is similar in some regards. This laboratory is a good location to begin testing and work through any potential problems prior to working at a bridge fabrication facility. During the course of laboratory testing normal activities in the test area included plasma torch cutting of steel, operation of overhead cranes, movement of material with fork-trucks, and other similar work. The laboratory has two high-bay doors that were frequently opened during testing. All of these conditions helped prepare for subsequent work in an actual fabrication facility.

4.3.1. Completed Test Goals

These laboratory tests were used to define measurement capabilities and procedures for fabrication shop testing. This test period was also used to prepare the system for tests in the steel bridge fabrication facility. The following test goals were completed during the laboratory testing program.

- Tested laser system hardware and software in a laboratory environment
- Measured global girder parameters
    - Camber, Sweep, End-kick
- Measured splice plate hole locations
- Validated splice hole measurement without any special target
- Demonstrated virtual splice plate design
- Prepared the laser system and practiced procedures for future fabrication shop testing
    - Determined necessary accessories needed for fabrication shop testing
    - Developed procedures for transporting the laser scanner
- Imported CAD files of specimens and created measurements based on CAD data
- Exported CAD data for use with external systems
- Explored measurement automation

4.3.2. Splice Hole Measurement and Splice Plate Fabrication

One of the most important aspects of the laboratory tests was the measurement of splice holes. Here the laser system was used to measure two separate straight girder sections with web and top flange holes and virtually create splice plates. Several tests were done to characterize hole measurements. Measurements were made entirely without targets. A two-dimensional CAD drawing was used to form the basis of all measurements. Then the laser system was moved in four different locations and used to make measurements of 20 holes in each girder end web and 12 holes in each girder end top flange. Based on these measurements taken with the girders blocked on the laboratory floor at arbitrary locations and while sitting in arbitrary orientations, splice plates were designed and CAD files created. These CAD files were used to machine test splice plates at the TFHRC Machine Shop.

Tests were done using two straight girders each about 8.5 m (28 ft) long. These specimens had full-sized 24 mm (15/16 in) diameter splice holes in the web and top flange. Web holes were drilled with a Hougen HMD904 magnetic base drill with a Rotabroach 24 mm (15/16 in) diameter annular cutter. These holes were of good quality. Top flange holes were drilled with a larger magnetic base drill, Milwaukee 4292-1, with a 24 mm (15/16 in) diameter twist drill bit. These holes were not of good quality and many were out-of-round as the magnetic drill base appeared to wander during drilling.

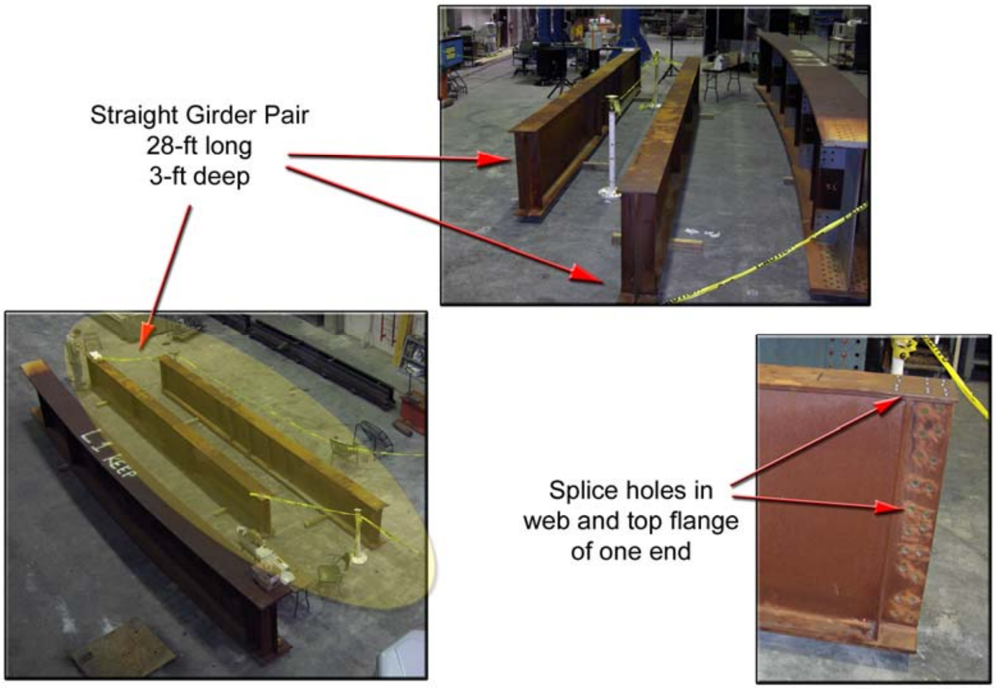

FIGURE 10 Straight girder pair used for laboratory testing.

TABLE 1 Straight Girder Properties

Length	8.5 m (28 ft)
Web Depth	0.9 (3 ft)
Top Flange Thickness	19.1 mm (¾ in)
Bottom Flange Thickness	19.1 mm (¾ in)
Web Thickness	12.7 mm (½ in)
Top Flange Width	0.3 m (12 in)
Bottom Flange Width	0.3 m (12 in)

4.3.2.1. Non-Target Hole Measurements

The goal of the splice hole measurements was to characterize direct measurement on a girder without using any special targets. Hole measurements were made primarily on the two straight girders. Hole measurements were used to perform virtual fit-up of girders and produce splice plate designs. Additional hole measurements were made on the curved girder specimen.

Hole measurements can be made directly on a specimen without a target with a measurement accuracy of less than 0.25 mm (0.01 in). Measurements can be made over a wide range of angle of incidence between the specimen and the laser system.

A wide range of tests was performed to characterize hole measurements without using any special targets (direct hole measurements). This included comparisons to a special tooling ball target plug reference. Direct hole measurements were made over multiple days and with different laser scanner positions. A summary of some of the measurements statistics is shown in TABLE 2.

TABLE 2 Statistics from comparison of actual hole locations to CAD locations

Measurement	**Mean** ***mm (in)***	**Standard Deviation** ***mm (in)***	**Maximum** ***mm (in)***
Target Plug to Direct Hole Measurements SET 1	0.127 (0.0050)	0.051 (0.0020)	0.305 (0.0120)
Target Plug to Direct Hole Measurements SET2	0.229 (0.0090)	0.102 (0.0040)	0.457 (0.0180)
Repeated Direct Hole Measurements SET 1	0.076 (0.0030)	0.025 (0.0010)	0.152 (0.0060)
Repeated Direct Hole Measurements SET 2	0.152 (0.0060)	0.076 (0.0030)	0.305 (0.0120)
Direct Hole Measurements at Different Angles of Incidence	0.102 (0.0040)	0.051 (0.0020)	0.178 (0.0070)
Compare Measurements over Multiple Days (Curved Girder)	0.284 (0.0112)	0.056 (0.0022)	0.414 (0.0163)

4.3.2.2. Splice Plate Fabrication and Virtual Fit-up

Test splice plates were fabricated to verify hole measurements and virtual fitting of girder sections. A polycarbonate splice plate was made, as opposed to steel, to make fabrication of the plate quicker. Given the short time frame for laboratory testing, splice plates needed to be fabricated quickly after laser system measurements. The polycarbonate plates are also transparent and therefore allow for easier determination of hole alignment. Here the splice plate hole and girder hole alignment can be visually observed.

The laser system was used to measure splice plate holes with the girder ends in separate arbitrary positions. Measurements were also taken of the ends of each girder to define the location of the hole patterns with respect to the girder ends. Laser system software was then used to virtually align the girders using the measured data, see FIGURE 11. With the girders virtually aligned a custom splice plate CAD file was created.

A total of 5 splice plates were fabricated. The two girders were aligned and fit together for testing of splice plates. For all splice plates, each hole in each plate was in alignment when the two girders were fit together. During fit-up a bolt was placed through each hole. For both the top flange and the web this results in 64 separate splice holes. An example of web and top flange plates are shown in FIGURE 12.   The hole patterns in the girders were intentionally made in an irregular pattern in order to make the measurements and splice plate designs more challenging. The following 5 splice plates were designed and fabricated.

- A web plate based on measurements made with target plugs
- A top flange and web plate pair based on direct measurement of the holes
- A top flange and web plate pair based on direct measurement of the holes and with virtually moving the girders apart a fixed amount.

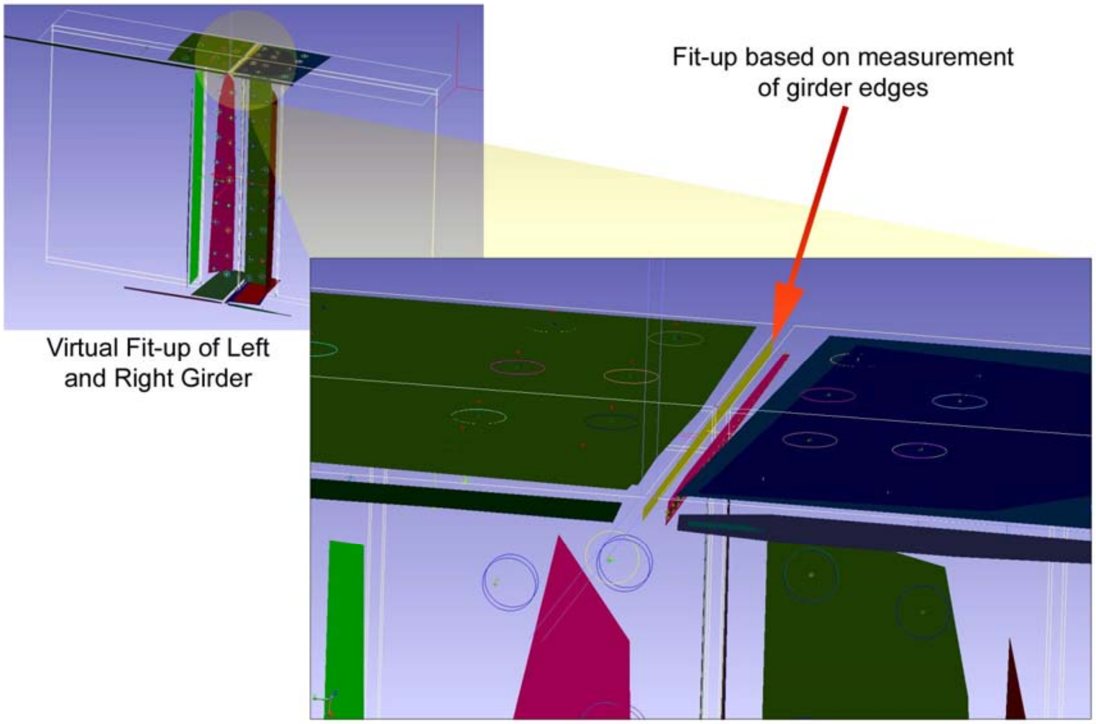

FIGURE 11 Virtual fit-up of girders for splice plate design.

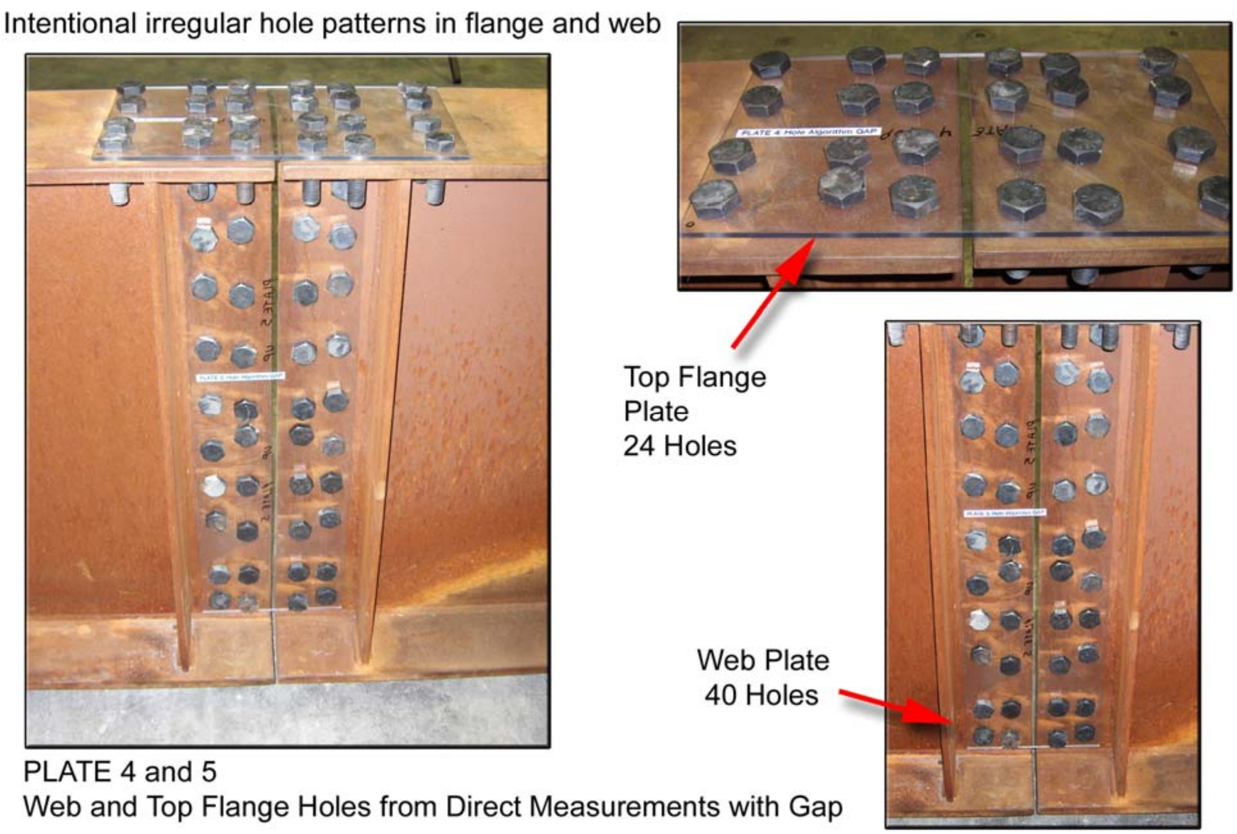

FIGURE 12 Custom splice plates designed from laser system measurements.

4.3.3. Global Girder Parameter Measurement

Another aspect of laboratory tests was girder dimensioning. For this purpose a 10.7 m (35 ft) long curved girder specimen was used. This curved girder had a splice connection on one end. It was fabricated by Williams Bridge Company in approximately 1996 as part of an FHWA curved girder bridge research project, see FIGURE 13.

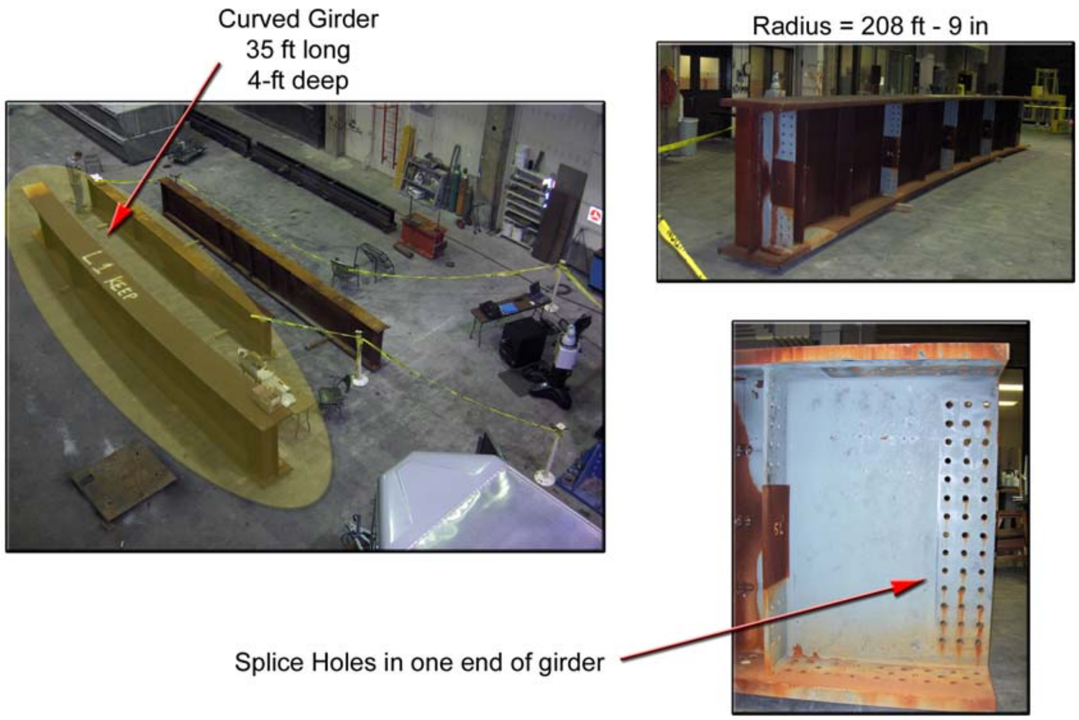

FIGURE 13 Curved girder specimen used for laboratory testing.

TABLE 3 Curved Girder Properties

Section Number	113PG11.03
Length	10.8 m (35 ft- 3-3/8 in)
Web Depth	1.2 m (4 ft)
Top Flange Thickness	57.2 mm (2-1/4 in)
Bottom Flange Thickness	57.2 mm (2-1/4 in)
Web Thickness	12.7 mm (½ in)
Top Flange Width	0.6 m (2 ft)
Bottom Flange Width	0.6 m (2 ft)
Radius of Curvature	63.6 m (208 ft – 9 in)

Global girder measurements were taken on the curved girder specimen. Here the laser system was moved around the girder to make measurements along the length and at the girder ends. Some of the measurement positions are shown in FIGURE 14.

FIGURE 14 Curved girder specimen measurements of global parameters.

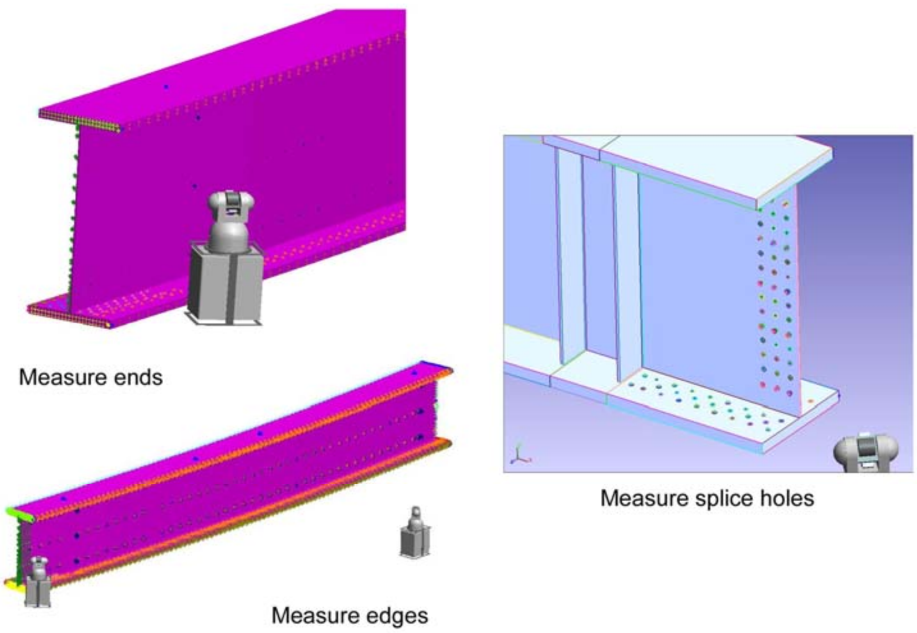

FIGURE 15 Global laser measurements on girder edges and end sections.

The system was able to easily measure the curved girder specimen from multiple vantage points and automatically fit together data using four reference targets. Scan lines and measurement points were defined on the girder flanges, web, and end sections. These measurements were all taken directly on the girder surface without any special targets. Direct girder measurements were used to determine girder length, camber, and sweep. Also measurements were used to define the end characteristics of the girders. An example of measurement data is shown in FIGURE 15. Starting from a three dimensional CAD drawing of a curved specimen, the system was able to setup and collect data with a minimal amount of physical targets on the structure. Here four tooling ball targets were used placed by eye at locations identified in the CAD drawings. All other measurements were made without targets and were defined prior to the actual measurements based on the CAD data. The advantage here is that if a CAD drawing of a specimen exists, then all measurements steps can be planned and defined prior to actual measurements on a girder. This leads to a quicker data collection time for a girder and will eventually lead to a fully or near-fully automated system.

4.4. FABRICATION SHOP TESTING

Testing was conducted at High Steel Structures in Lancaster, PA from October 22nd through October 26th, 2007.

4.4.1. Completed Test Goals

The purpose of the tests was to demonstrate operation in a real bridge fabricator shop environment and to begin to work through system integration issues. This testing demonstrated the following.

- *The laser system can work in a typical fabrication shop*
  - Dust, debris, vibrations, and other work in the facility do not impact measurements
- *Measurements of typical girders can be made on the shop floor*
  - A girder pair, 9.1 m (30 ft) and 36.6 m (120 ft) lengths, with one field splice were measured within an area of about 48.8 by 6.1 m (160 by 20 ft)
  - The laser system was moved on the shop floor around the girders to make measurements
  - Other work around the girders (movement of parts on the overhead cranes, welding, grinding) was not affected
- *Manual measurements can be made in a short amount of time*
  - Complete manual measurements on both girders could be completed in about 90 minutes
  - These measurements were done manually **with moving the laser system** to three measurement locations for each girder
  - *This time can be greatly reduced with a fully automated measurement process. For example, since this testing fully automated hole measurements, driven from a CAD file, is now operational and greatly speeds up measurement time.*
- *Data can be exchanged with the laser system*
  - CAD data can be imported into the laser system
  - The laser system can export CAD data into existing CAD systems

4.4.2. Measurement Details

The laser system was moved around the girders on the shop floor for measurements. Here measurements were taken at the ends of each girder and near the middle, as shown in FIGURE 16. Various laser system positions were used to capture necessary data and to work around other activities in the shop.

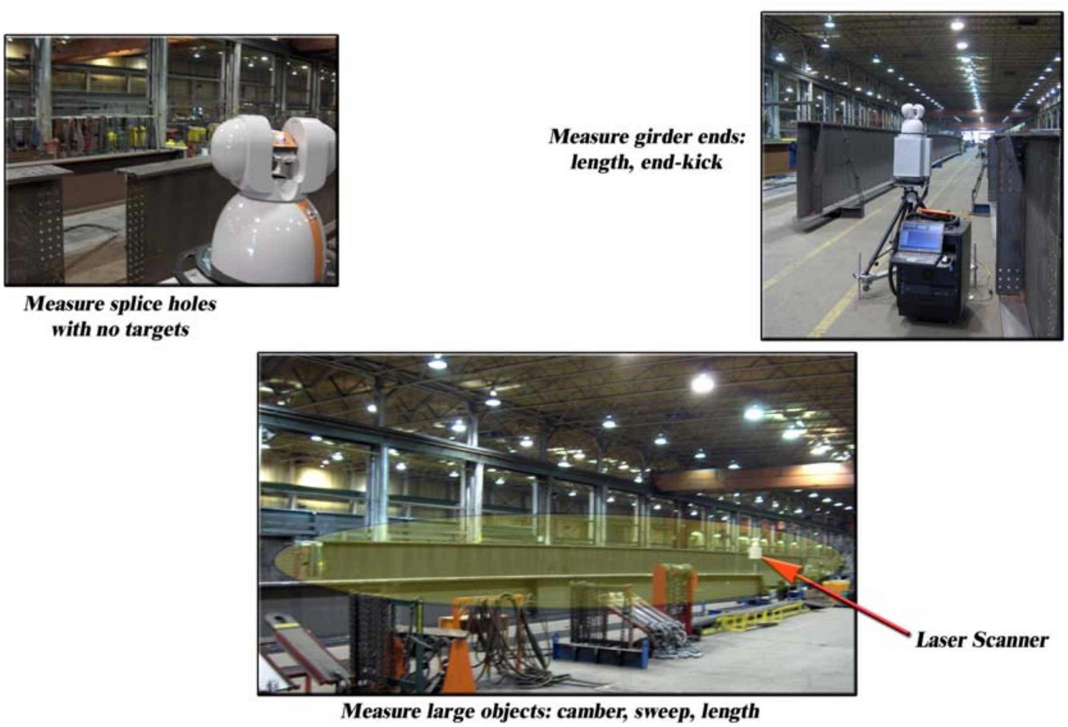

FIGURE 16 Measurement position on girder in the fabrication shop.

The laser system was able to operate in a typical bridge fabrication shop environment without any observed problems. The normal operations of the shop were not impeded for testing. This included movement of plates and girders with overhead cranes, welding, cutting, and vibrations from other shop activities, see FIGURE 17.

FIGURE 17 Laser system operating in a fabrication shop environment.

4.4.3. CAD Data

CAD data was provided prior to testing for a pair of straight girders joined with one field splice. This CAD data was used to setup measurements and plan testing. The initial CAD data from a pair of girders to be connected with a field splice was fit together in the laser system software. Prior to testing, laser system position requirements, such as field-of-view, could be defined. FIGURE 18 shows fitting of the girders at the field splice and some measurement positioning used to plan testing.

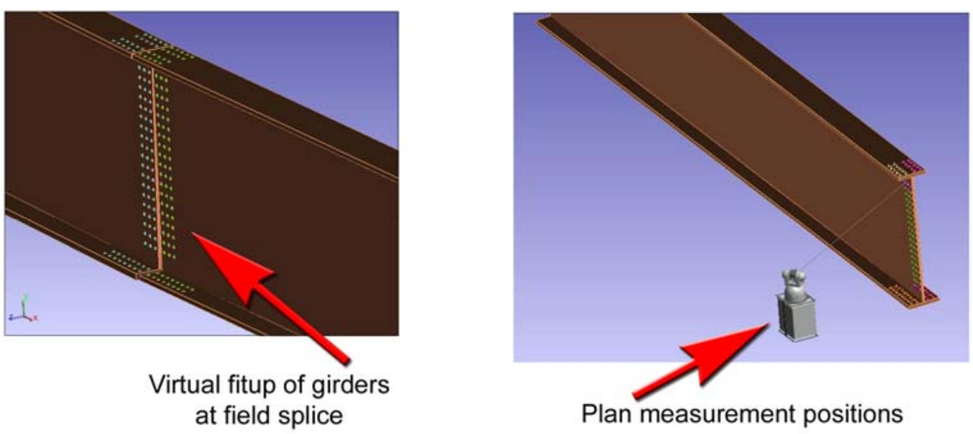

FIGURE 18 Pre-test measurement setup and planning based on CAD data.

After testing all measurements were exported to standard CAD file formats for use in the fabrication shop CAD system. Comparisons were made between the CAD nominal and measured data. FIGURE 19 illustrates the ability of the laser system to both import and export CAD data.

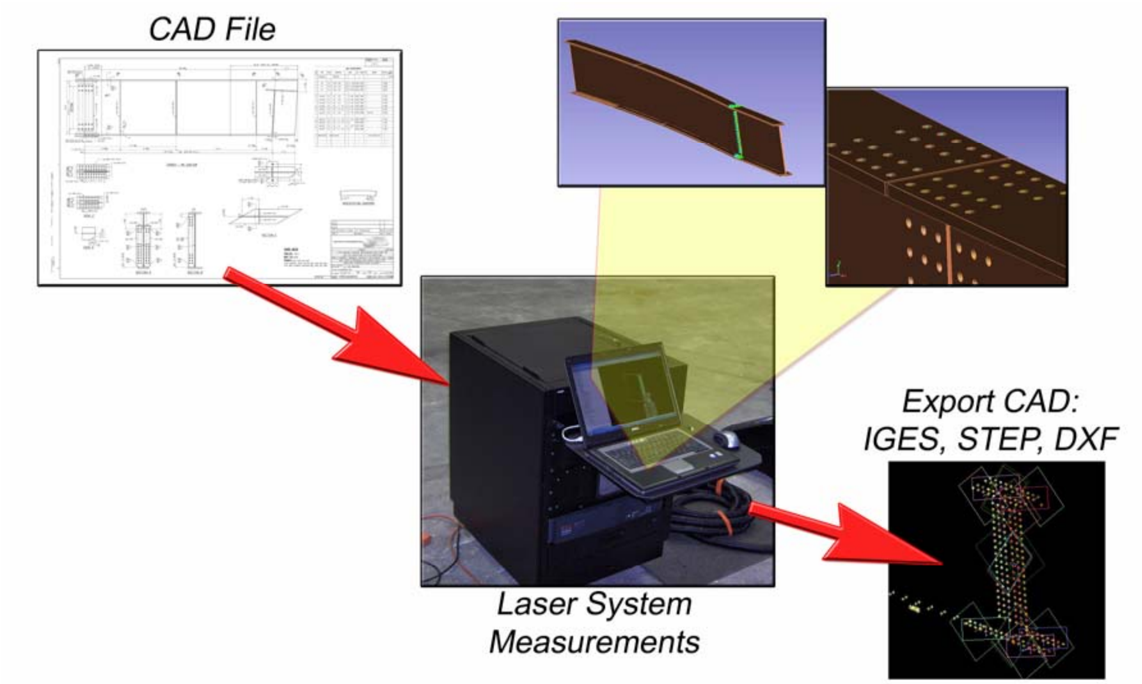

FIGURE 19 Laser system integration with CAD.

4.4.4. Measured Specimens

The main goal of fabrication shop testing was measurements on a pair of straight girders with one field splice. CAD data for these girders was available prior to testing and measurements were defined based on this CAD data. During the course of testing, other specimens were measured. This included a curved girder and a more complex specimen.

4.4.4.1. Straight Girder Pair

A pair of straight girders from a Maryland State Highway Administration (MD SHA) job was measured. This girder pair included one 9.1 m (30 ft) section and one 36.6 m (120 ft) section joined with a field splice, see FIGURE 20. No targets were used to make the measurements. Three measurement positions for the laser scanner were used on each girder.

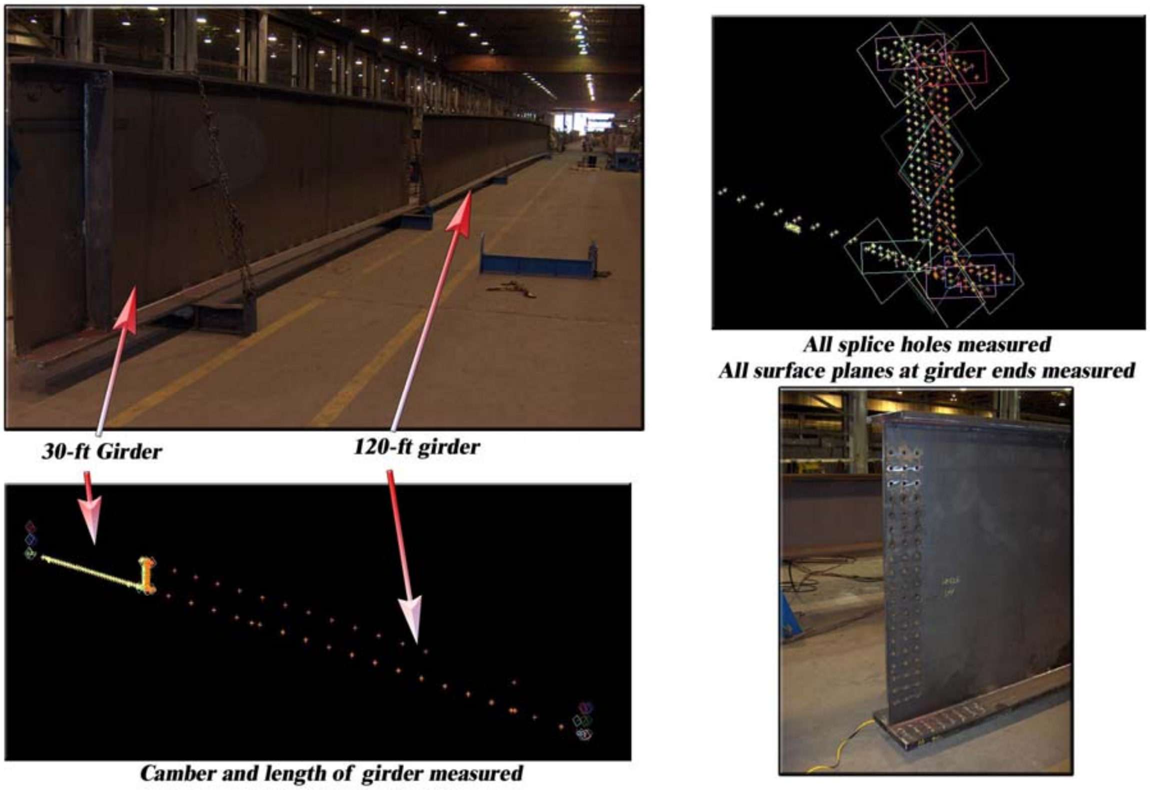

FIGURE 20 Straight girder specimens showing test data, including splice plate holes.

In addition to the length, end-kick, camber, and splice hole locations, the distortion of the web was measured. This measurement was made by comparing the splice hole location measurements to the ideal CAD locations and looking at the deviations. FIGURE 21 shows the error between the CAD nominal and the measured hole locations for one half of the field splice. Here the length of vectors in the figure is proportional to the error, with the maximum error of about 2.5 mm (0.1 in). This error is only present in the direction normal to the web plate, not in the two-dimensional location of the holes in the web plate, and represents distortions in the web plate.

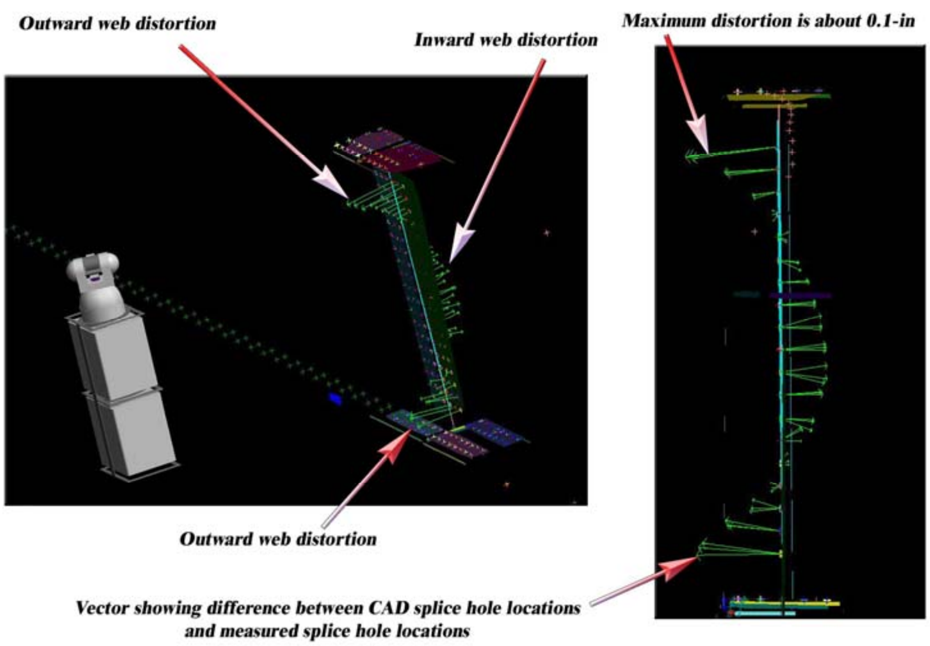

FIGURE 21 Web distortions at splice.

4.4.4.2. Curved Girder

A single slightly curved girder was measured. The ends of this girder were measured to define length and splice hole locations. Measurements were also made along the length of the girder to measure camber and sweep. There was no initial CAD data for this girder and all measurements were setup and collected manually. FIGURE 22 shows some of the measurement data from this curved girder. Data taken along the girder length shows both the camber and sweep of the girder.

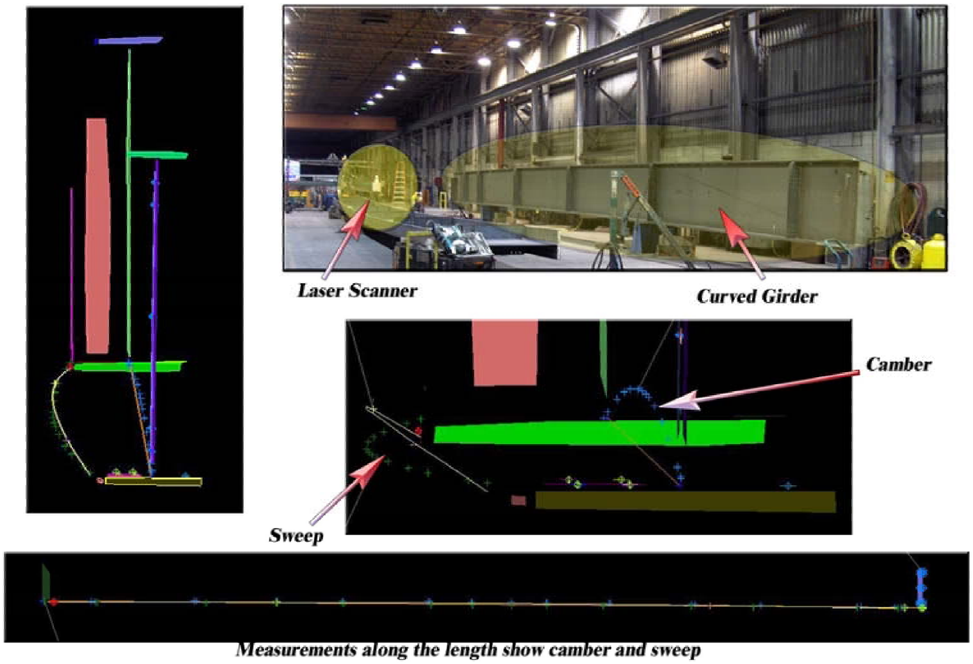

FIGURE 22 Curved girder specimen with data showing camber and sweep.

4.4.4.3. Other Specimen

Measurements were made on a more complex specimen. Here multiple plane surfaces, holes, and slots were measured. Two measurement positions were used to characterize the entire specimen. This particular specimen demonstrates the ability of the instrument to easily measure non-standard and more complex objects.

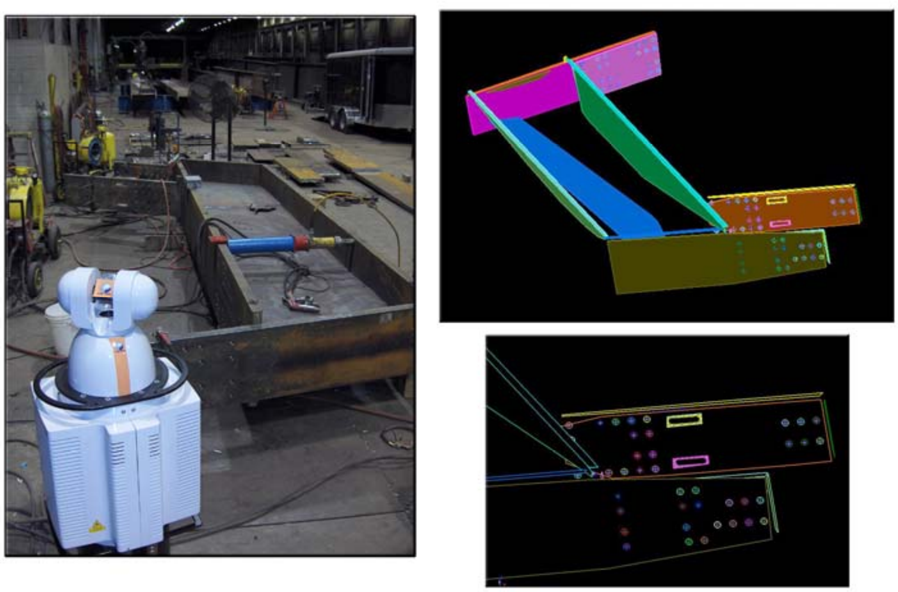

FIGURE 23 Complex geometry specimen showing hole and slot measurements.

4.5. SYSTEM MODIFICATIONS

During the laboratory test period system modifications were made to make the laser system work better in a steel bridge fabrication environment. A brief summary of some of the modifications is given below.

- *System tripod*
  - A special tripod and movement fixture was built for better placement of the laser scanner in the steel bridge fabrication plant, see FIGURE 24. Here the scanner can be raised up and down to better measure larger objects. This extra height was needed to measure selected girders in the fabrication plant. Special wheels and stabilization feet allow the laser scanner to be easily moved.
- *Backup power supply for extended operation*
  - A specialized backup power supply was developed for providing conditioned AC power to the laser system during testing.
- *User cart power*
  - Power outlets were installed on the laser user cart for system accessories.
- *Cable strain relief*
  - Additional strain relief was provided on the main power cable and the input AC power cable to allow the system to be more easily moved.
- *Main power cable cover*
  - A protective cover was placed over the main power cable between the user cart and the laser scanner to prevent damage.
- *Audio notes*
  - Hardware and software were added for collecting audio test notes.
- *Measurement validation fixture*
  - A special measurement validation fixture was fabricated for use during testing.

All of the system modifications were made and tested prior to taking the laser system to the steel bridge fabrication shop. Additional laboratory tests were done to verify measurement accuracy using the modifications. Of main concern was the affect of the new extended-height tripod on measurement accuracy.

Tripod at Minimum Height   **Tripod at Maximum Height**

FIGURE 24 System tripod for measuring larger objects.

5. PLANS FOR IMPLEMENTATION

5.1. FUTURE WORK AND CONTINUED DEVELOPMENT

The system can be implemented immediately and will provide benefits to the existing fabrication procedure. The steps that remain to be completed involve integration of the laser system into the fabrication process. These final integration steps will require additional on-site work with fabricators and will vary from location to location. This project helped identify many of the initial steps necessary to begin this integration work. However, additional system development work is needed.

One of the most significant steps that need additional development and testing is the virtual fit-up procedure. This part of the system will require more measurements in a fabrication shop in conjunction with actual fit-up of structures. Additional work will be required to establish procedures for complex structures (arches, complex tub girders, …) that can be developed once a final system is making measurements on actual girders in a fabrication shop.

Some of the future system integration steps needed are as follows.

- Development of custom system mounts for work in the shop
- Measurement automation
- Measurement algorithms for key girder dimensions
- Software for virtual assembly
- Optimize measurement locations

The steps that remain to be completed involve integration of the laser system into the fabrication process and would exist with any commercial measurement system. Most if not all of these steps cannot be completed without direct work in a fabrication shop. This project helped identify many of the initial steps necessary to begin this work. Virtual assembly of complex structures is not considered part of the steps needed for initial integration. Additional work will be required to establish procedures for complex structures that can be developed once a final system is making measurements on actual girders in a fabrication shop.

5.2. SYSTEM DEVELOPMENT FOR RELIABILITY

One of the key steps in final system integration is taking the necessary steps to make the entire system have very high reliability. The key to this reliability is working with the commercial laser scanner embedded within the FCI laser system.

FCI has much experience in this area and has produced commercial instruments for industrial environments. In particular, FCI has designed and maintained instrumentation for use in the chemical industry where systems were expected to operate in extremely harsh environments with near 100% reliability. While the bridge fabrication environment is not as rugged, similar system design features are needed to ensure desired ease-of-operation and reliability for the end-user.

Since 1996 FCI has experience working with a Metris laser scanner prototype, which is a very early version of the current Metris laser scanner. This prototype as delivered to FHWA was not suitable for reliable work in the laboratory or field tests on bridges. FCI performed extensive system development and integration work with this prototype instrument for the FHWA for the purpose of making the system more reliable. The end result was that the prototype laser system was taken all over the United States performing field tests on bridges. The prototype system was also used extensively for laboratory tests within FHWA and the system was a key asset for structural testing.

The current commercial laser scanner used in this project is much more developed than the above mentioned FHWA prototype. This commercial instrument is an established instrument and is used in industrial environments. However, the fabrication shop environment is more rugged than other current application areas for this scanner. Use of this commercial instrument by itself without modifications does not have the needed reliability for this bridge fabrication application.

This project demonstrated that this commercial instrument can work in a typical bridge fabrication shop environment. The initial tests in this project helped identify many areas to help improve instrument reliability. Several of the additions made during the project help in this regard. The goal of the final system integration is to bring together all pieces needed to make the commercial laser system function as needed in a fabrication shop environment.

5.3. WHAT IS READY FOR USE NOW?

The system can be implemented immediately and provide benefits to the existing fabrication procedure. Currently the FCI Laser System can make measurements of fabricated girders in a fabrication shop. CAD data can be imported and exported with existing systems. Laser system measurements can be defined and planned based on CAD data. System measurements can be checked against CAD nominal values and differences can be reported. Custom reports can be generated. Measurement data can determine girder dimensions and splice hole locations. Measurements can be made without any targets on the girders (with the exception of 3-4 reference targets to initially tie measurements to CAD data). Currently the laser system has a special tripod mount for operation on the shop floor. The system can be easily moved around the shop floor as needed. A specialized backup power system is available for operation of the system. A block diagram of current system capabilities are shown in FIGURE 25.

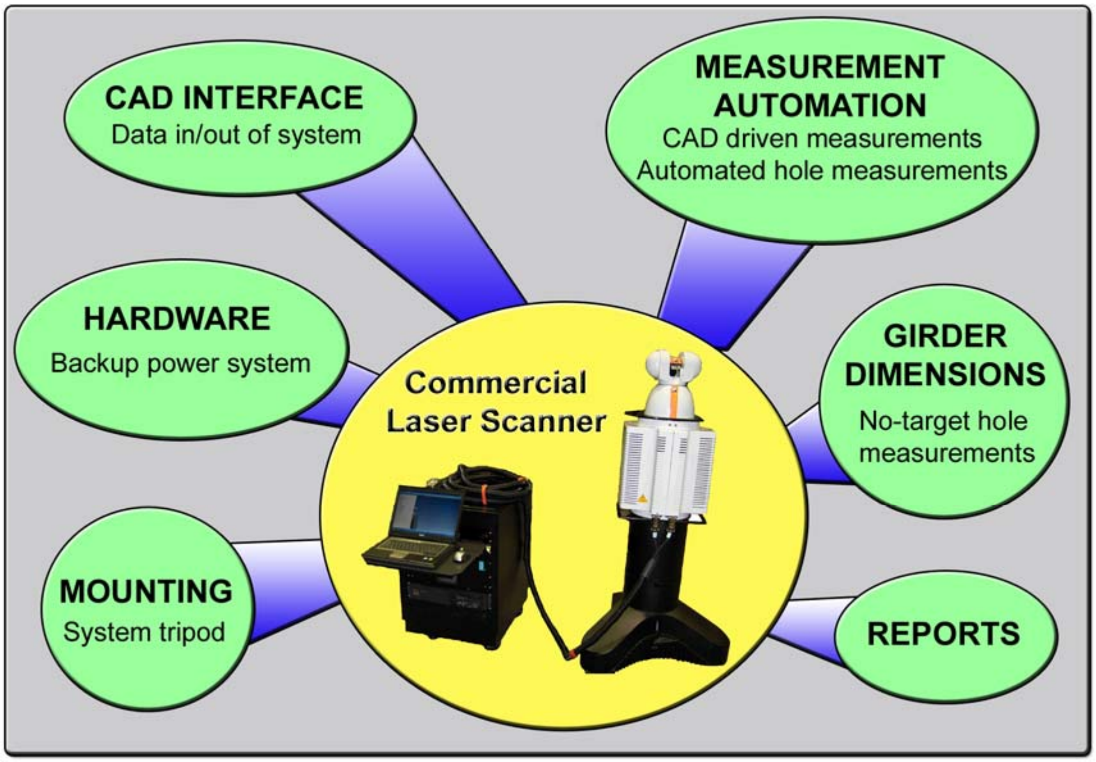

FIGURE 25 Current state of FCI Laser System features.

5.4. CONTINUED DEVELOPMENT

Since this project has been completed system development has been continuing and another key step has been automated. Now multiple splice hole measurements can be performed automatically. Nominal hole locations from an initial CAD file can now be used to measure splice holes without any manual laser instrument operation. The process is now fully automated.

All other FCI Laser System development is continuing. Additional work and tests are being planned at bridge fabrication facilities. FCI is seeking to produce a commercial system customized for the bridge fabrication industry. This NCHRP IDEA project was an essential first step toward this goal.

6. CONCLUSIONS

This NCHRP-IDEA project was a first step in creating a complete laser measurement system for steel bridge fabrication applications. To get a feel for various end-user perspectives, site visits were made to two steel bridge fabricators, which were High Steel Structures, Lancaster, PA, and Egger Steel Company, Sioux Falls, SD. Five weeks of testing and development work were conducted at the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC). Here several important system concepts were demonstrated in a more controlled environment. Most importantly the measurement of splice plate holes, with no special targets, was verified. Laser system measurements were used to successfully create custom splice plates based on measurements and to demonstrate virtual girder assembly. This project testing culminated with one week of testing within an actual steel bridge fabricator. The FCI laser system was operated at High Steel Structures in Lancaster, PA. Here several straight and curved girders were measured along with other more complex geometry pieces. This fabrication shop testing was the most beneficial part of the project. Here the issues of system integration into a real-world environment were encountered. This project investigation identified several of the key measurement procedures needed for a final system. Several laser system modifications were made. This includes development of customized scanner tripods and shop mounts, power systems, reference targets, and other features specific to this application. In addition, future work was identified, including development of customized measurement procedures. The first steps of measurement automation have been demonstrated and all key measurements, including splice plate holes, can be fully automated. This measurement automation is a key component to this system and sets this laser measurement system apart from other measurement approaches. The completion of this project demonstrated that this laser system can function in a typical bridge fabrication shop environment and represents the first steps in developing a complete turn-key system for use in a fabrication shop.

7. INVESTIGATOR PROFILE

The bridge fabrication application discussed in this project began prior to 2000. In 2000 FCI performed initial proof-of-concept testing on the virtual assembly of steel bridges for FHWA. Two tests were conducted with High Steel Structures in Lancaster, PA (1, 2). The goal of the testing was to look at using the prototype FHWA laser system to measure splice hole locations in girders.

Measuring Splice Plate Hole Locations

Measuring Blocked Position of Girder in Assembly Yard

FIGURE 26 Prototype FHWA laser system making proof-of-concept measurements in a bridge fabrication yard.

In one of the tests the laser system was used to measure splice plate hole locations in two adjacent girders that were to be joined with a splice plate. The splice plate hole locations in both girders were measured and processed with software to determine the design of a splice plate. The splice plate was then fabricated and placed successfully on the girders. Since these tests with High Steel Structures, FHWA has not pursued this project and has not conducted further testing primarily due to funding reasons. At the time of the initial testing, there was much support from the steel fabrication industry and FHWA and the results indicated that there was merit to the technology for this application. FIGURE 26 shows the prototype system being used at High Steel Structures in Lancaster, PA.

Since this initial work in 2000 for FHWA, FCI has been working to revive this concept. This current NCHRP-IDEA project is the next step in reaching the goal of a full-time dedicated system in a fabrication shop. The commercial laser instrument currently used is several generations removed from the FHWA prototype and provides greater capabilities. The particular commercial instrument is well-suited to large-scale structural applications and can make measurements that are not possible with other instruments or sensors.

FCI has a long history of work on structural applications with laser metrology instrumentation. Since 1996 FCI has completed a wide variety of tests and measurements on civil structures, both in laboratory and field environments. Field tests have been conducted on bridges all over the United States, see FIGURE 27. This includes load tests on bridges and a multi-year FHWA curved girder bridge study, see FIGURE 28. FCI is uniquely qualified in applying laser metrology instrumentation to bridge and other civil infrastructure applications.

FIGURE 27 Measurements of civil structures in the field

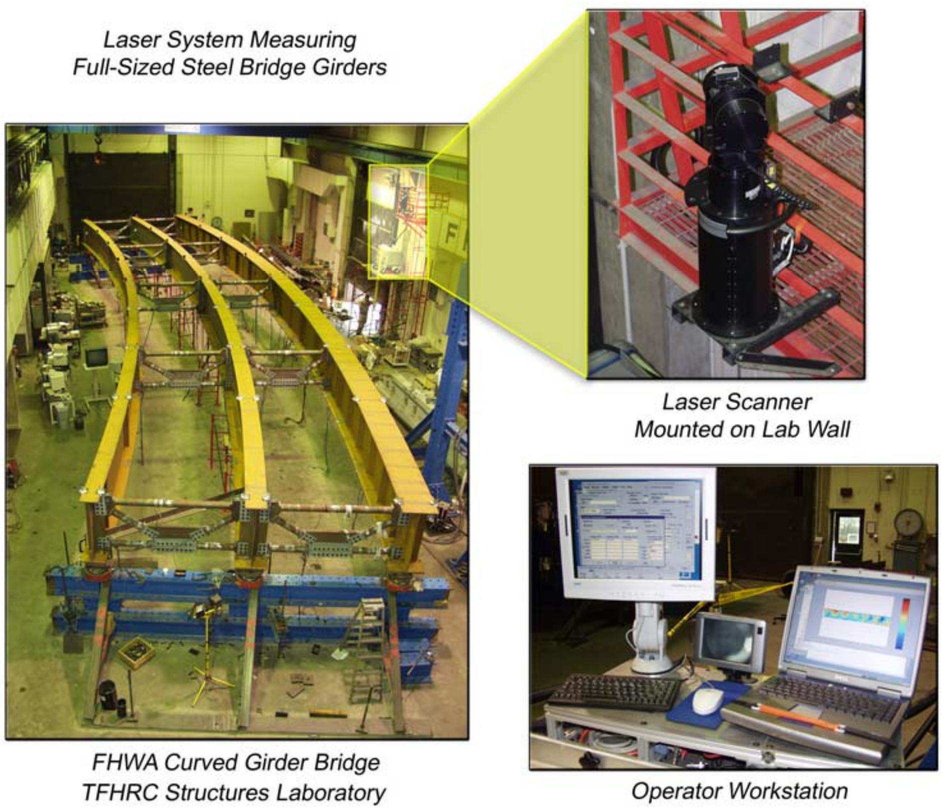

FIGURE 28 Laboratory measurements of a full-scale bridge

8. REFERENCES

1. P.A. Fuchs, B.A. Graybeal. *Steel Bridge Fabrication Tests with High Steel Structures, Inc.* Federal Highway Administration Nondestructive Evaluation Center Instrumentation Test and Evaluation Report (internal), May 2000.

2. P.A. Fuchs, B.A. Graybeal, S.B. Chase. *Steel Bridge Fabrication Tests with High Steel Structures, Inc. Test 2*. Federal Highway Administration Nondestructive Evaluation Center Instrumentation Test and Evaluation Report (internal), November 2000.