Innovations Deserving
Exploratory Analysis Programs

Highway IDEA Program

Bridge Retrofit Laser System

Final Report for
Highway IDEA Project 153

Prepared by:
Paul A. Fuchs
Fuchs Consulting, Inc.

September 2012

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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

NCHRP-153: Bridge Retrofit Laser System

Final Report

Prepared for
NCHRP-IDEA Program
Inam Jawed
Project Manager
TRB/IDEA Program Office
500 Fifth Street NW
Washington, DC 20001

Prepared by
Fuchs Consulting, Inc.
Paul A. Fuchs, Ph.D.
502 Ayrlee Ave. NW
Leesburg, VA 20176
Phone: (703) 737-3871
Fax: (703) 737-6381
Cell: (571) 239-7139
paul.fuchs@fuchsconsultinginc.com

FCI
Fuchs Consulting, Inc.
Instrumentation / Systems Engineering
Nondestructive Evaluation Applications
Software Development

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Director, Systems Operations Bureau

Mark Dunn, P.E.
Iowa Department of Transportation
Operations Research Engineer

Ahmad Abu-Hawash, P.E.
Iowa Department of Transportation
Chief Structural Engineer

Jose Gomez, Ph.D., P.E.
Virginia Department of Transportation
Virginia Center for Transportation Innovation & Research
Director

Michael Holmes
Maryland State Highway Administration
Team Leader, Structures Remedial Engineering Division

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William Via (Materials Engineer)

Hirschfeld Industries – Bridge
John O'Quinn (Executive Vice President)

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Brian Covington (Vice President)

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1. EXECUTIVE SUMMARY

This project has developed an advanced laser measurement system to accelerate the bridge retrofit process in order to reduce the time between identification of repair needs to resumption of service for a bridge. A unique laser system precisely measures sections of a bridge structure involved in a retrofit process. Measurements are processed to produce CAD design drawings of needed retrofit parts that can be automatically sent to a fabricator. The system uses a laser measurement system with features that cannot be found in other commercially available equipment. These features allow the system to provide data that is much more accurate than conventional methods and allows completely new types of information to be collected.

The BRIDGE RETROFIT LASER SYSTEM (RLS) is driven to a bridge site in a vehicle, quickly setup, and used to make measurements on the bridge. No special targets are needed and the structure does not need to be directly accessed. Very accurate measurements can be made over very large distances. The system produces measurements with far greater accuracy than conventional methods or other advanced measurement methods. Measurement accuracy is validated in the field and procedures have been developed that allow for reliable field measurements under typical bridge conditions. The BRIDGE RLS will measure the exact dimensions and spatial location of bridge details, including splice hole locations based on measurements of bolt or rivet heads. Based on the physical laser measurements, CAD design drawings will be automatically produced. These drawings can be used by an engineering design firm and fabricator to rapidly produce retrofit parts. High accuracy measurements are essential for retrofit measurements (gusset plates, trusses) where precise locations of splice holes are needed. FIGURE 1 shows the system concept.

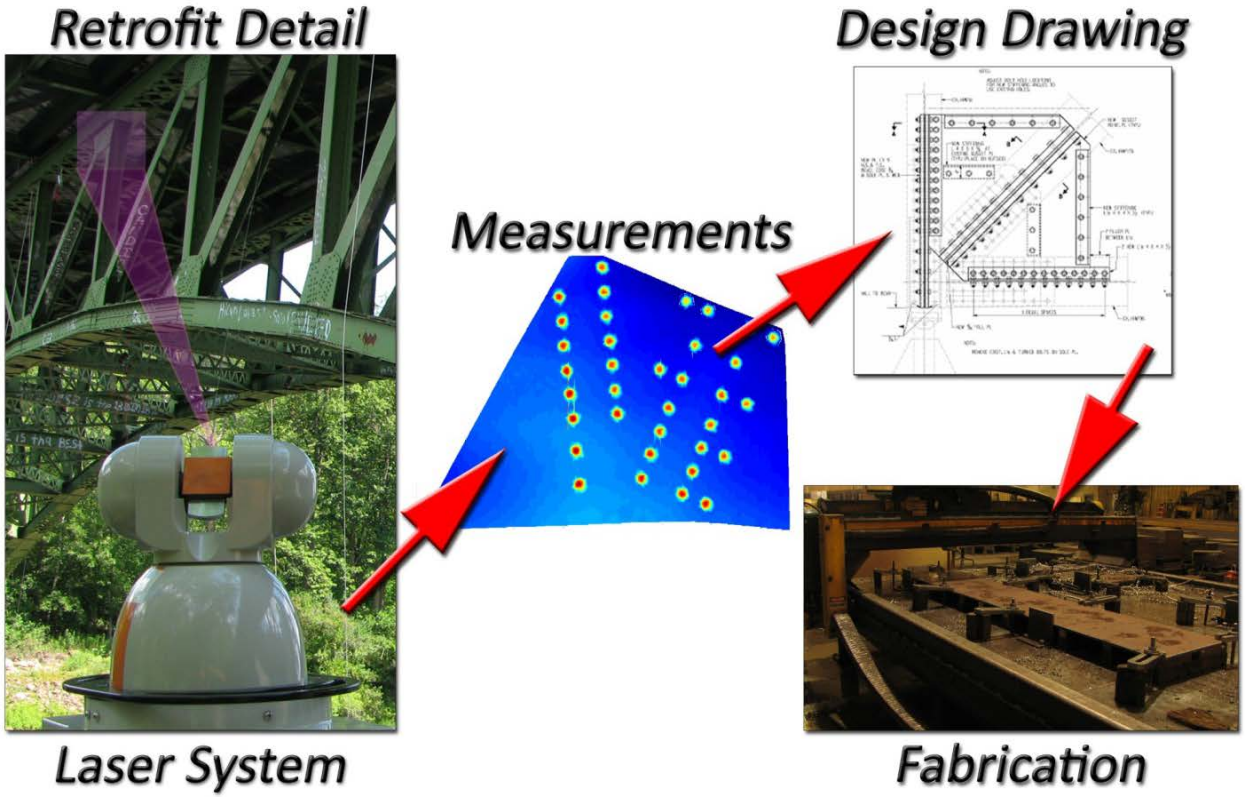

FIGURE 1 System concept for laser measurements of steel bridge girders.

The system has the potential to significantly reduce the time between the initial identification of a problem on a bridge and the repair and resumption of service of the structure. The system saves time and money by streamlining steps in the retrofit process so that field measurements can be used to automatically produce CAD drawings for fabricators. The system provides specifically processed engineering data and not just a cloud of points. The proposed system can make measurements with minimal impact at the bridge site. Measurements can typically be made without altering traffic under the structure (i.e. no lane closure). The system can make measurements over water or other difficult access conditions, such as rail lines. Minimizing the time that a bridge is out-of-service, or eliminating lane closures, can save state Departments of Transportation (DOTs) substantial amounts of money and is in the best interest of the traveling public.

The system is based on a solid understanding of bridge fabrication and retrofit processes in order to provide targeted and specific information.

2. IDEA PRODUCT: BRIDGE RETROFIT LASER SYSTEM (RLS)

The overall system concept is remote, non-contact, highly accurate laser-based measurements are made of a bridge structure undergoing retrofit work. Spatial data is obtained with full three-dimensional measurements of components. The system does not produce an extremely large cloud of points that require extensive post-processing. The system does convert the raw measurements into engineering data that can provide useful information. These engineering data, typically in the form of CAD files, can be sent to a fabricator and parts are made. The new retrofit parts are then installed on the bridge. The entire process is intended to be performed rapidly in order that the structure can be placed back in service as quickly as possible.

2.1. CURRENT PRACTICE OVERVIEW

Current practice for taking measurements for bridge retrofit work involves measurements performed by hand with tape measures and string lines. This requires direct access to a structure, at a hands-on distance to the bridge, as is shown in FIGURE 2. Getting hands-on access to a structure can be difficult and will involve ladders, man-lifts, bucket trucks, or other types of access equipment.

FIGURE 2 Current manual measurements for bridge retrofit work made by hand directly on the structure.

Not only do currently used measurement tools require hands-on access, but they have inherent accuracy limitations. For measurements over small distances these current measurement tools will typically be easier and potentially more accurate than over large distances. This is illustrated on the truss bridges that are shown in FIGURE 3. Localized measurements on a small member, such as bolt hole spacing on a gusset plate, can be more easily made by hand with tape measures and rulers. In this case a single worker can make direct measurements over a small distance, maybe a few feet, with a ruler or tape measure. In contrast, accurate measurements over longer distances can be more difficult. For example, the measurement of the length of a diagonal or vertical member in a truss can be hard to make accurately with a tape measure or a ruler. Measurements over longer distances can also require multiple people to align the ruler or string line at both ends of the measurement.

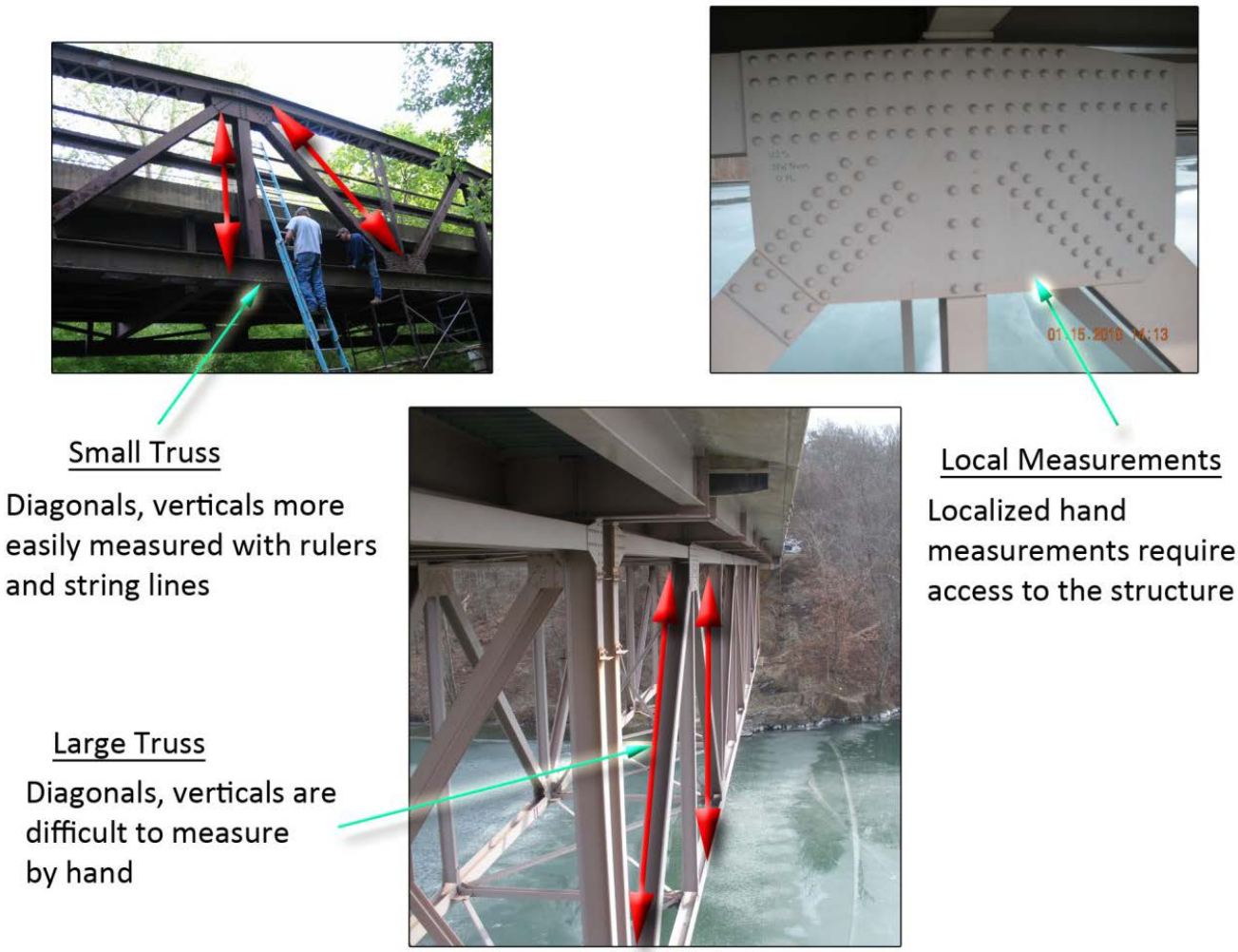

FIGURE 3 Accurate conventional measurements are more difficult on large structures.

Another complicating factor with conventional measurements is that direct measurements between two points are not always possible with a tape measure or ruler. The geometry around a measurement area may not allow a direct measurement. This is illustrated with the measurement of a sway bracing member shown in FIGURE 4. The diagonal member is about 9 m (30 feet) in length and has connection points at the top, middle, and bottom of the member. The measurement of the length and hole patterns of this type of member can be difficult. The tape measure must be run diagonally over a very long distance using two people and must be run around the middle connection plate. Because of the presence of the middle connection plate, the tape measure cannot be run directly along the diagonal member edge in order to obtain the length.

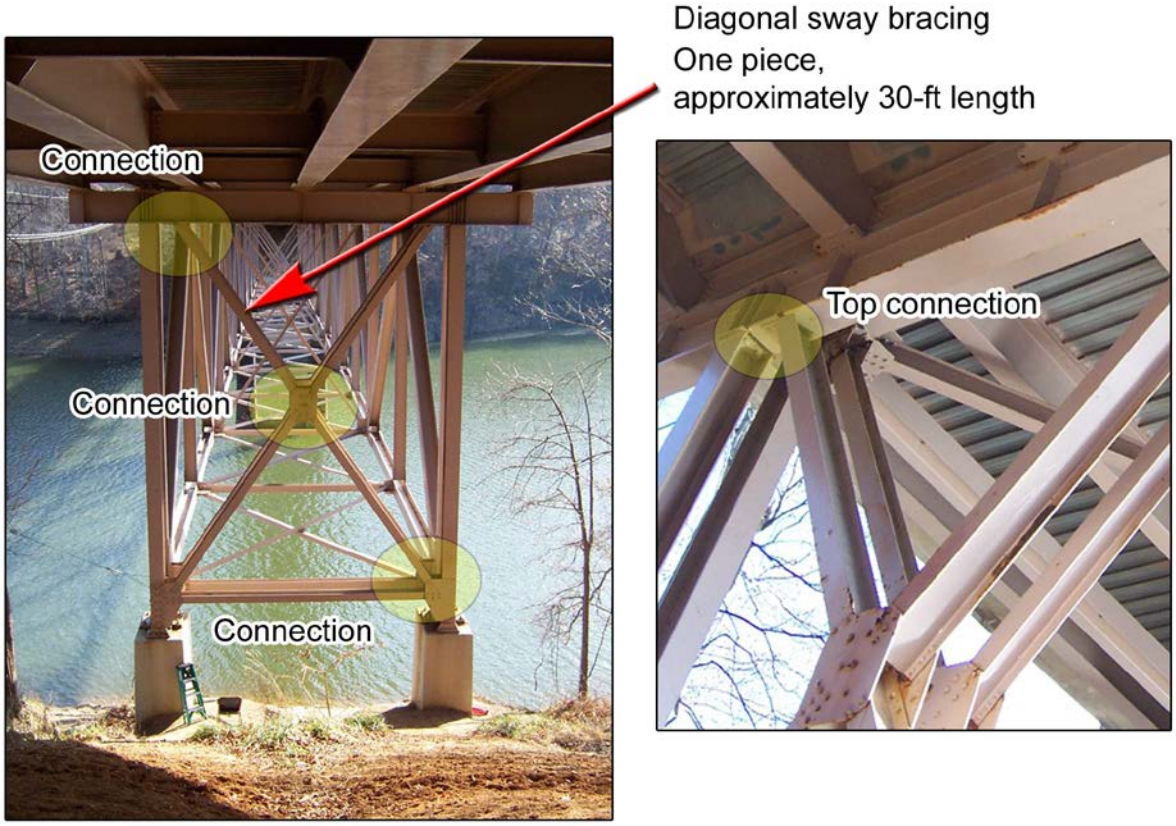

FIGURE 4 Retrofit measurement of sway bracing members showing difficulty of non-direct measurements.

Since the current practice requires hands-on access, conditions at a particular bridge will determine the level of difficulty required to obtain measurements. Bridges over roadways will require closing lanes of traffic. Bridges over rail lines may be very difficult or impossible to access, as rail traffic is extremely difficult to impede even for short-term work. Measuring bridges over a rail line often involves an extensive permitting process and can have very limited access times. These access conditions add considerable time and expense to obtaining the measurements.

2.2. HOW IS THIS SYSTEM BETTER?

The advanced measurement system developed in this project can provide more accurate measurements than those obtained currently, can collect measurements more efficiently, and can provide types of information that cannot be currently obtained. The ability to make spatial measurements remotely on a bridge without direct access can greatly improve the current retrofit process. The use of these more advanced measurement methods, as compared with tape measures and rulers, can also improve the process by providing more accurate measurements.

2.2.1. Measure Large Area

One of the primary benefits of the system developed in this project is the ability to remotely measure very large bridge structures. As demonstrated above, current methods of measurement require getting up close to a structure in order to take a measurement. By contrast, if the required measurements can be made without accessing the bridge, then the process of obtaining data can be made much more efficient. The advanced measurement system can remotely take measurements over a very large volume, essentially a sphere around the instrument with a diameter of about 100 m (328 feet). The ability to measurement very large volumes is shown in FIGURE 5, where laser measurements are shown on a very large truss bridge that is over 122 m (400 feet) in length. The center span of this truss bridge is also over water, making conventional measurements more difficult. From one measurement position on the ground on the side of the bridge, a large number of gusset plates can be measured without needing to access this bridge in any manner. Measurements are made directly on the bridge surface, without the need to place any type of target (i.e. photogrammetric marker, probe, retroreflector).

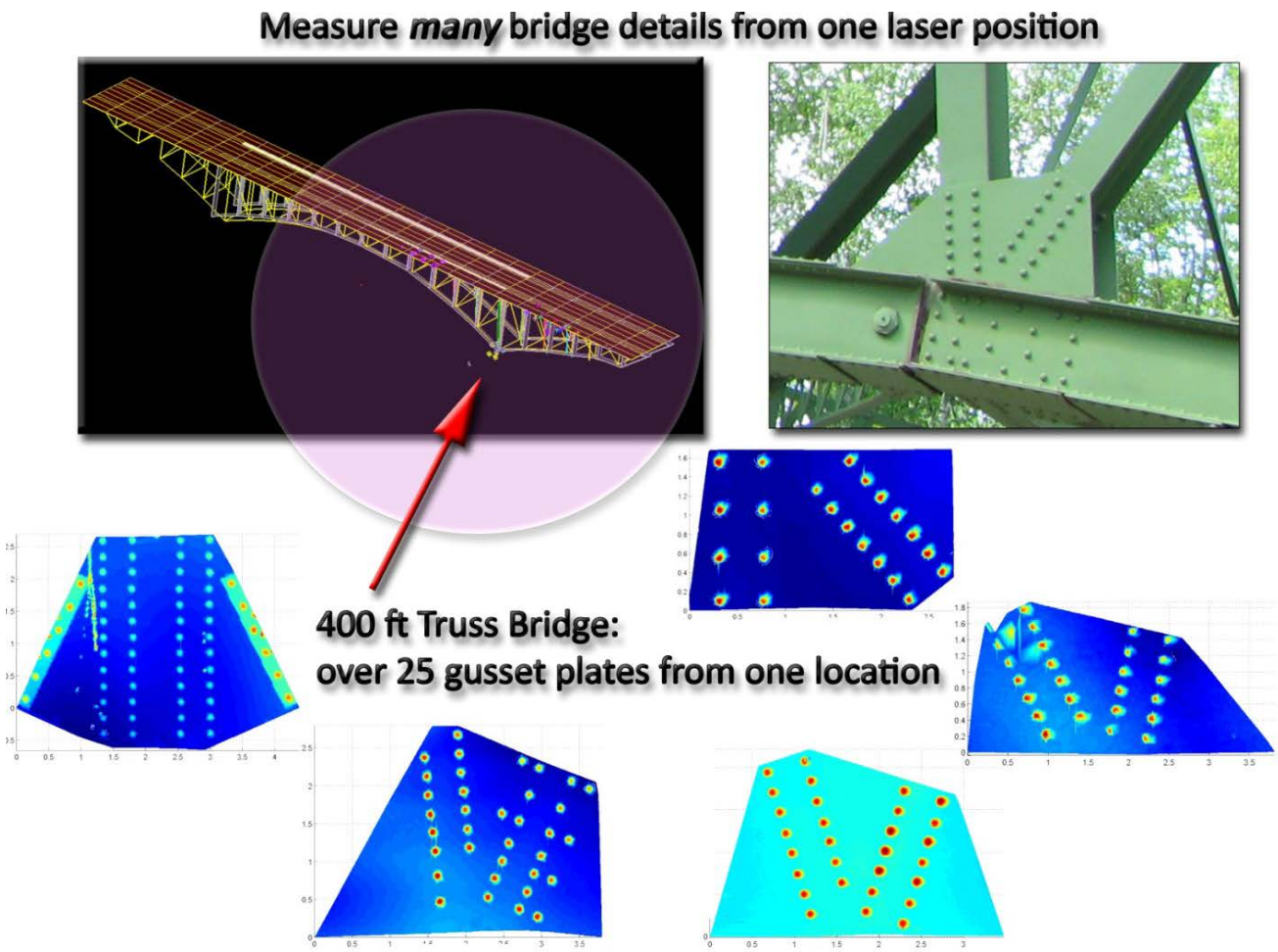

FIGURE 5 BRIDGE RLS measurements over a very large volume without access to the bridge.

2.2.2. Minimal Impact

The ability of the laser system to make measurements remotely without any type of special targets allows measurements at a bridge site to be taken much more quickly and efficiently. Since the bridge does not need to be accessed directly, measurements can be made at a distance. This includes making measurements over traffic without a lane closure. Measurements can be made over rail lines without impeding the rail traffic. Measurements can be made from the road shoulder or the median without affecting vehicular traffic under the bridge. Measurements can also be made over water. The ability to eliminate traffic control or access equipment can save considerable expense in the measurement of a bridge and eliminating lane closures is beneficial to the traveling public.

FIGURE 6 shows the BRIDGE RLS making measurements with minimal impact to the structure being measured. The system is shown making measurements over water (top left, middle). The system is shown making measurements over live traffic (top right, bottom left, bottom right). FIGURE 7 shows the BRIDGE RLS making measurements over an in-service rail line with periodic rail traffic. This example is from a previous load test using an earlier model of the laser measurement system where deflection data was collected on the bridge span over the rail line and is provided to illustrate the capabilities of the current system.

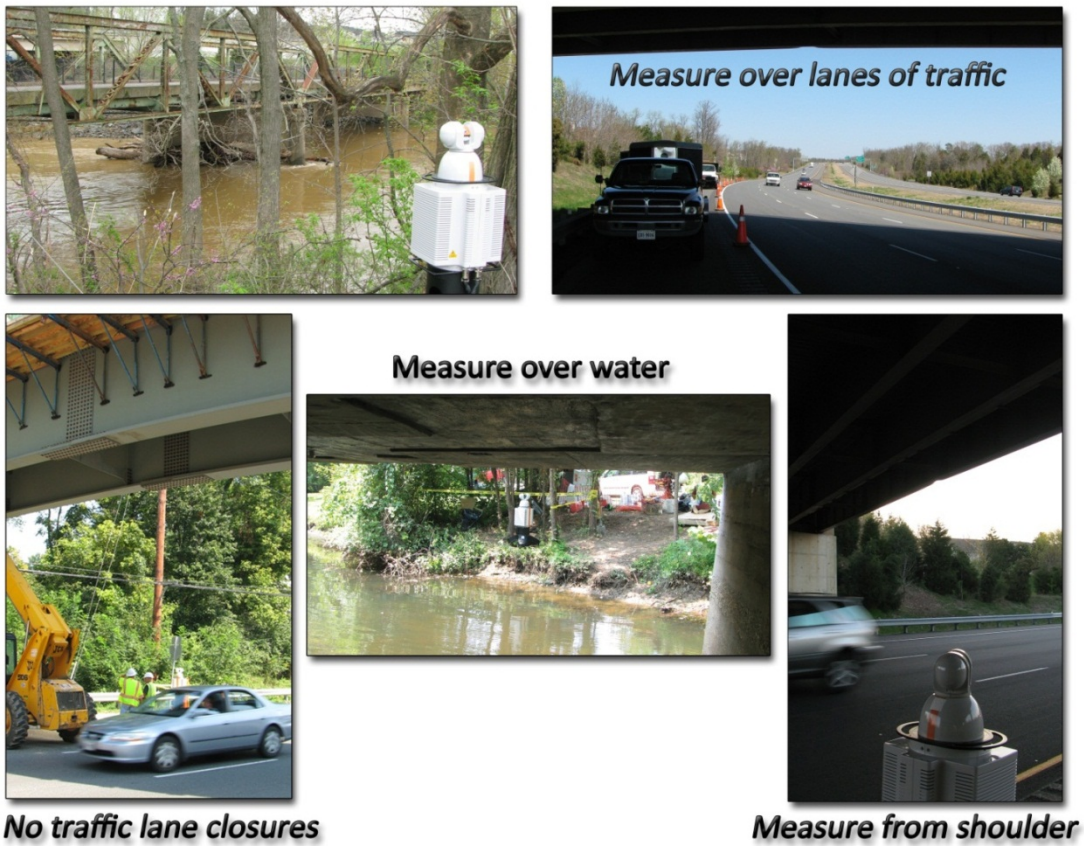

FIGURE 6 BRIDGE RLS measuring without traffic control and over water.

FIGURE 7 BRIDGE RLS measuring over a rail line.

2.3. HOW WILL THIS SYSTEM BE BENEFICIAL?

An example of how the BRIDGE RLS can be useful in the retrofit process is a bridge that requires replacement of a girder. A common retrofit situation is a bridge struck by an over-height load where the fascia girder is damaged and requires replacement. In order to design a replacement girder, the placement of the cross frame stiffeners in the new girder must match those in the original girder. The normal retrofit process would be to manually measure the girder cross frame stiffener locations with a tape measure prior to fabrication of the replacement girder. Shop drawings may or may not exist for a bridge. Even if drawings are available, it is possible that the actual as-built girder would differ from the drawings and measurements would still be required. FIGURE 8 shows a bridge with a fascia girder damaged by an over-height load and shows the measurement locations of some cross frame stiffeners.

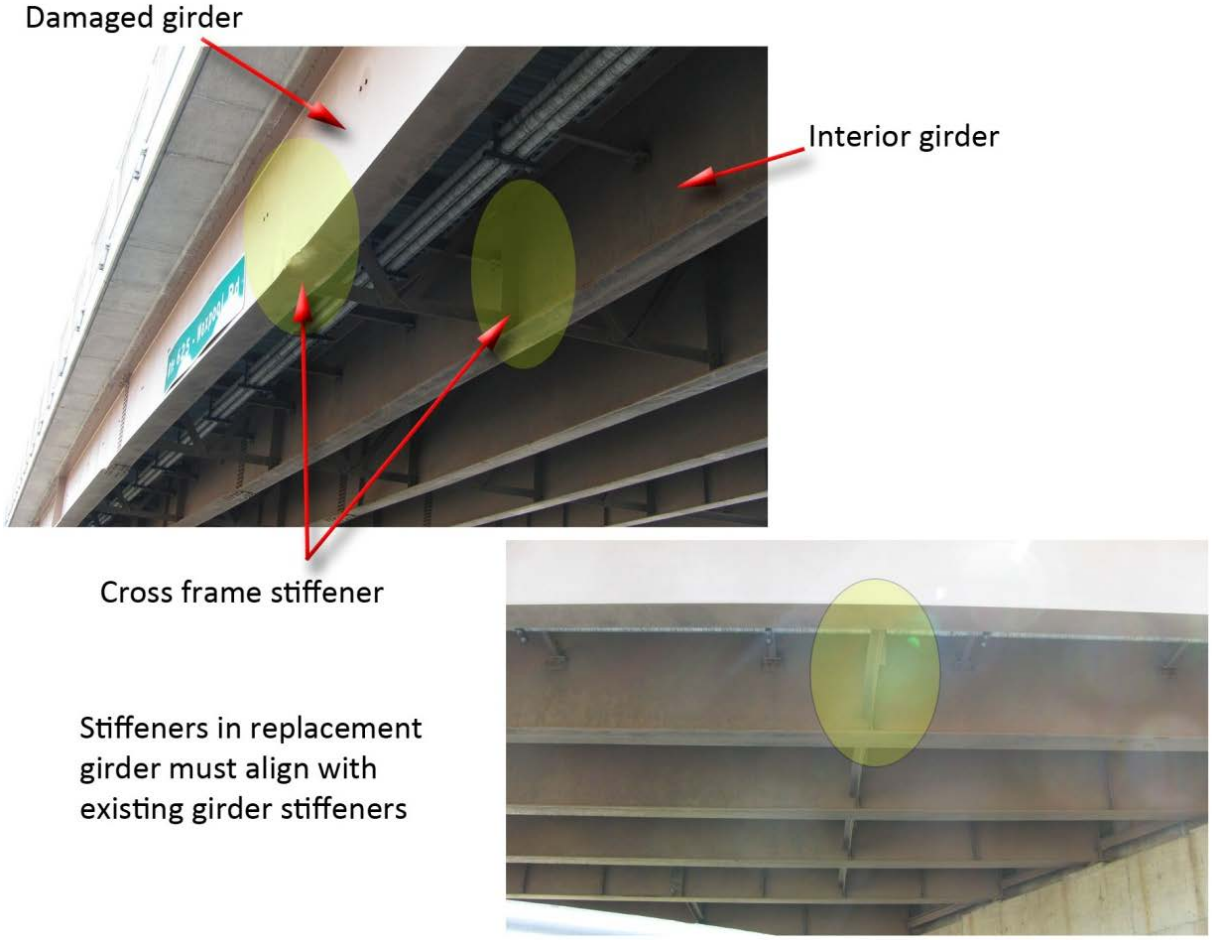

FIGURE 8 Retrofit girder replacement cross frame stiffener measurement locations.

The Maryland Transportation Authority experienced this exact type of retrofit problem with a bridge over I-95, north of Baltimore, MD. For this particular structure, the bridge carries traffic over I-95 and traffic would need to be shut-down on a major interstate road in order to make these measurements using a conventional tape measure. This conventional measurement procedure would require multiple lane closures in order to collect all of the necessary data (i.e. close left-hand lanes and measure left side of girders, close right-hand lanes and measure right side of girders).

In this example the BRIDGE RLS could make measurements of the girder and cross frame stiffener locations from the road shoulder without requiring any lane closures. The use of the BRIDGE RLS in this case could significantly speed up the measurement process and reduce cost (traffic control, measurement time). Only a shoulder lane closure would be necessary. The traveling public would not be impeded in order to collect these measurements as lane closures (including shifting lane closures) could be eliminated. As important, the laser measurements are much more accurate than with conventional manual measurements with tape measures.

2.4.

3. CONCEPT AND INNOVATION

The system developed uses advanced laser measurement equipment combined with specialized mounts and fixtures combined with specialized software tools to create an overall system. Remote, non-contact measurements are taken with a unique laser metrology instrument. Custom software tools interact with conventional shop drawings and with three-dimensional data produced by the measurement system.

3.1. SYSTEM DESCRIPTION

An overall system has been designed that provides all of the necessary components to make measurements in the field on bridge structures and to provide useful information in a form that is beneficial to the end-user. FIGURE 9 shows a block diagram of the main system components. The system takes as input engineering specifications and requirements for measurements as defined by discussions and interaction with the engineers in charge of the retrofit work. This may include as-built drawings or shop drawings for components being measured. The overall system consists of all components needed for measurements in the field. This includes the methods to transport and operate the system at a bridge site. While the system can measure without any targets directly on the girder, the system includes special targets for custom measurements (See Section 3.4) and specialized mounts and fixtures to setup and position the laser measurement equipment for measurements. The system also includes software components that define measurement procedures, operate the system, and post-process measurements. System output is engineering data in the form of customized reports and CAD drawings.

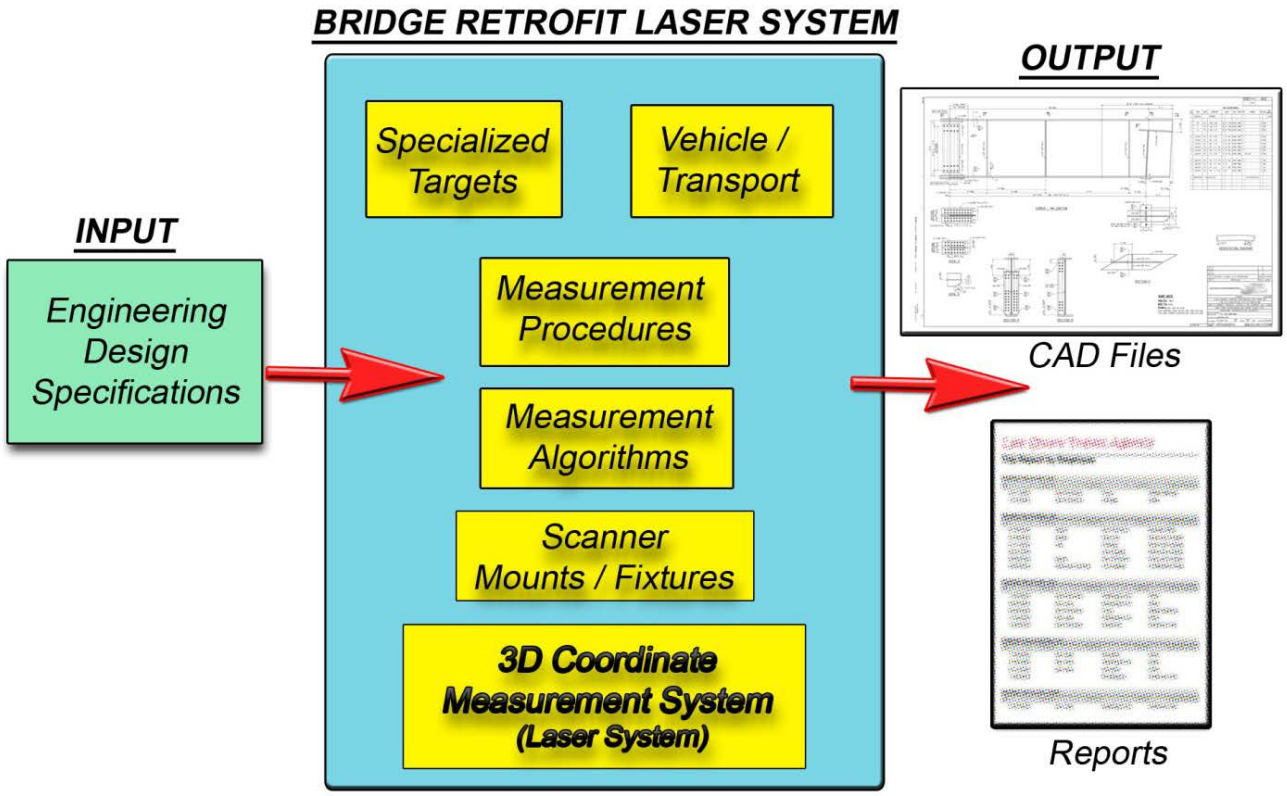

FIGURE 9 BRIDGE RLS block diagram.

3.2. MEASUREMENT SYSTEM DESCRIPTION

The main measurement component of the system is a laser-based system that has unique features that are well-suited to this application. FIGURE 10 summarizes the main instrument specifications that are described in more detail below. The combination of these main instrument features allows the system to make measurements that cannot be made by other types of instruments and that are superior to conventional methods.

3.2.1. Direct Surface Measurements

The BRIDGE RLS can make measurements directly on a specimen surface *without* requiring a special target. The system can measure on steel, concrete, and even on timber. This is a very important attribute as it allows measurements to be made on bridges without having to first access the bridge in any manner. There are a wide variety of commercial metrology instruments with an equally wide variety of specifications. Systems that provide very high measurement accuracy typically require some form of a target. This can be a retroreflector, photogrammetric marker, or some other form of a special target. Use of these types of systems requires direct access to a structure in order to place each target.

3.2.2. High Accuracy Measurements

The BRIDGE RLS can also make extremely accurate measurements. Measurements can be made with full three-dimensional accuracy in the thousandths of an inch over the working volume of the instrument. At a distance of 98 feet the system can make measurements with a full three-dimensional accuracy of 0.30 mm (0.0118 inches). There are again a wide variety of commercial laser-based measurement systems that can measure without targets over a large distance, but they generally provide low accuracy measurements (maybe 13 – 50 mm (½ - 2 inches)). Course, low-accuracy measurements would not, in general, be useful in this retrofit application.

3.2.3. Measure over Large Distances

The BRIDGE RLS can measure over a very large volume. The maximum instrument range is 50 m (164 feet) from the instrument. This means that measurements can be made over a diameter of 100 m (328 feet) around the instrument. There is a wide variety of commercial systems that can make high accuracy measurements, but only over a very short range (typically a few feet).

Non-contact measurements
No targets needed

Measure directly on girders

Highly accurate
0.0040 inch at 33 feet
0.0118 inch at 98 feet
0.0197 inch at 164 feet

Huge working volume
Up to 50 m (164 ft) radius

FIGURE 10 BRIDGE RLS uses a laser measurement system that provides unique specifications.

3.3. SOFTWARE TOOLS

Work was completed on efficiently creating three-dimensional (3D) models of bridge components to be measured. The 3D model creation is essential for two parts of the process. The first use is measurement planning. Measurements are pre-planned based on the 3D model for a bridge detail. This pre-planning simplifies the measurement process and allows for better visualization of the data in the field. FIGURE 11 shows a three-dimensional CAD model for a concrete slab bridge.

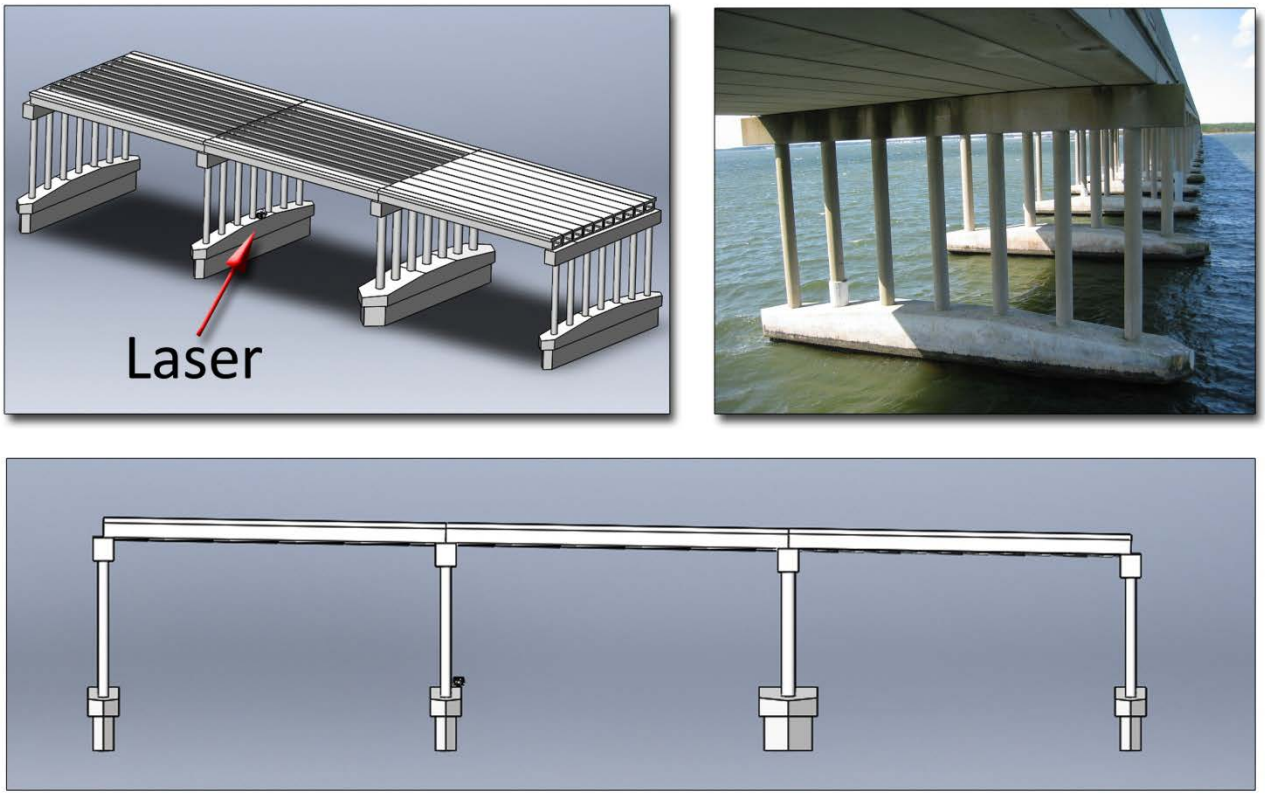

FIGURE 11 Three dimensional CAD model for a concrete slab bridge.

Three-dimensional models do not, in general, exist for bridges. If engineering data exists it will be in the form of a design or shop drawing. These existing drawings are two-dimensional (2D) and must be converted into a 3D model. To assist in 3D model creation, the project has been leveraging work from a current pooled-fund project related to measurement of bridge components in the fabrication shop, TPF-5(226). For this pooled-fund project, a set of tools were developed to quickly and efficiently turn a 2D shop drawing into a 3D CAD model. FIGURE 12 shows a 3D model for a bridge girder that was created using these tools from conventional 2D shop drawings. These tools are being adapted and expanded to included ranges of bridge details encountered in the retrofit process.

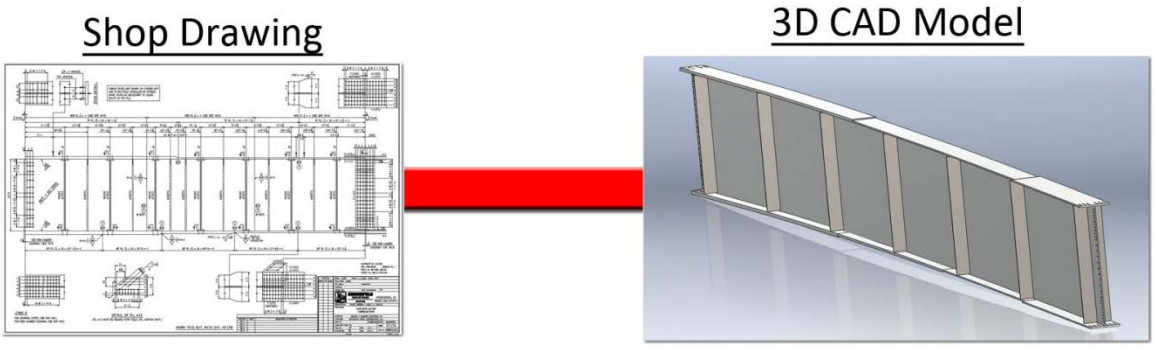

FIGURE 12 Conversion of a 2D shop drawing to a 3D model.

In many retrofit cases, engineering drawings will not exist. The BRIDGE RLS can still be applied to the bridge components, with measurements being defined on-site at the bridge. The field tests for this project, described in the sections below, were conducted with all measurement made on-site without any pre-planned CAD models. The trade-off in this case is the time needed to collect measurements at the bridge. Pre-planned measurements will be more efficient. In addition to the measurement planning use, 3D models are used in the creation of output engineering drawings.

3.4. TARGETS

While the system can measure without any targets directly on a girder, special targets can be used in certain applications. A number of special targets have been designed for custom applications, some of which are shown in FIGURE 13. Each target design is extremely robust and works well on bridges under typical field conditions. Targets are very low cost (a few dollars) and can be left in place for extended period of time. Targets are used for such functions as monitoring of long-term structural movement and instrument readjustment references.

FIGURE 13 Various target designs for specialized measurements.

3.5. VALIDATOR TARGET

The characteristics of the measurement system and how the measurement system is used in the field allow for much greater accuracy than with other methods. As discussed in detail earlier in the report, this includes a much greater accuracy than conventional string lines and rulers, as well as greater accuracy than other types of more advanced measurement systems. For example, other commercial LIDAR systems typically produce measurements with significantly lower accuracy. Experience in field measurement of bridges has produced many validation tools to provide a level of confidence in measurements. One of these tools is a special validator target that is placed on the bridge being measured. This special target is fabricated with precisely known geometric features, which include holes of known size and location and steps of known and very small changes in height. Measurement of this special validator target, which is embedded in the bridge data set, can demonstrate measurement accuracy under the same conditions as measurements on the bridge. One example of a special validator target being used while taking measurements on a truss bridge is shown in FIGURE 14.

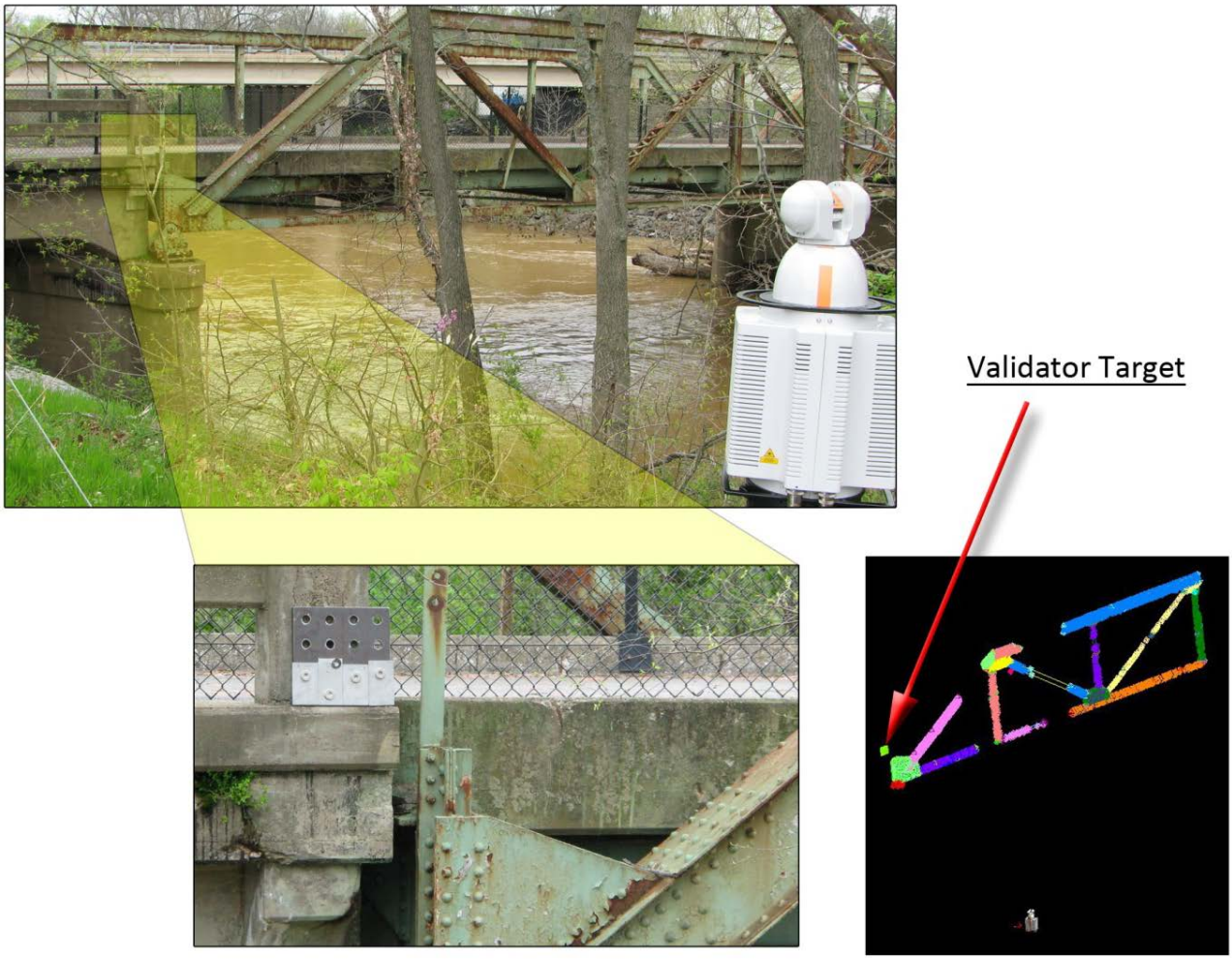

FIGURE 14 Validator target being used during the measurement of a truss bridge.

4. INVESTIGATION

This project focused on identifying the measurement and system design needs of the bridge retrofit process and on implementing and demonstrating the system on bridge structures. The specific needs of typical bridge retrofit work were analyzed by working with State DOTs and bridge fabricators. Specialized hardware and software components were prepared to implement the system. The system was implemented on typical bridge retrofit applications to illustrate how the system can be used.

4.1. PROCESS IDENTIFICATION

The project intended to develop targeted, specific procedures based on needs identified in the current processes. Meetings were held with fabricators and end-users in order to better define the existing retrofit process. Input from end-users provided a better understanding of the necessary measurements needed and helped develop processes for the final system. The types of organizations involved in this collaboration include engineering firms, fabricators, and State DOTs.

Input was received from multiple engineering firms involved with bridge retrofit work. URS Corporation is an engineering firm that performs work in the bridge retrofit design process. Whiting-Turner is another engineering firm that performs bridge field retrofit work. Discussions were held with these engineering firms to identify bridge retrofit projects and to define types of previous work. Applications reviewed included a range of techniques, from more conventional measurements with string lines and rulers to more specialized measurements and design work.

Input was also received from State DOTs. DOTs (State or local) are typically owners of structures and as such are directly responsible for the maintenance and repair. Meetings were held with various State DOTs that included Maryland State Highway Administration (MD SHA) and the Virginia Department of Transportation (VDOT). The purpose of the meetings was to understand the needs of the bridge owner and see how retrofit work is coordinated. In addition, this collaboration was intended to make the State DOTs more aware of this project and illustrate how it may be beneficial for future work.

The final group from which input was received was bridge fabricators. This included a large-scale bridge fabricator, Hirschfeld Industries – Bridge. Another fabricator, Covington Machine, specializes in customized retrofit work. Covington Machine, located in Annapolis, Maryland, performs many of the more difficult retrofit jobs for the MD SHA. Discussions were held to determine how conventional retrofit work is currently performed and to identify how these methods may be improved.

4.2. FIELD TEST EXAMPLES

The laser measurement system was implemented on multiple applications in order to develop procedures and demonstrate system capabilities. Details of these implementation examples are provided below.

4.2.1. Impact Damage

A large number of bridges have suffered impact damage and repair of these structures is a common retrofit application. The use of the BRIDGE RLS on impact damaged girders was presented in Section 2.3, where measurements are needed for replacement of a girder. To illustrate this application, two different bridges are presented that were measured with the BRIDGE RLS. The first example was performed for Virginia Department of Transportation (VDOT), but is a good illustration for this application. The structure carries I-66 traffic over Virginia State Route 29 near Washington D.C. This bridge has twelve lines of steel girders and ten of these twelve girders were impacted with an over-height load. VDOT wanted to perform a detailed analysis of the bridge to plan potential repair work. To aid in the analysis the BRIDGE RLS was used to measure and quantify the magnitude of the deformation caused by the impact. This laser data was used by VDOT to create a detailed finite element model of the structure. Localized sections of four girders (bottom flanges and webs) were measured and are shown in FIGURE 15. Measurements were made remotely, with no direct access to the structure.

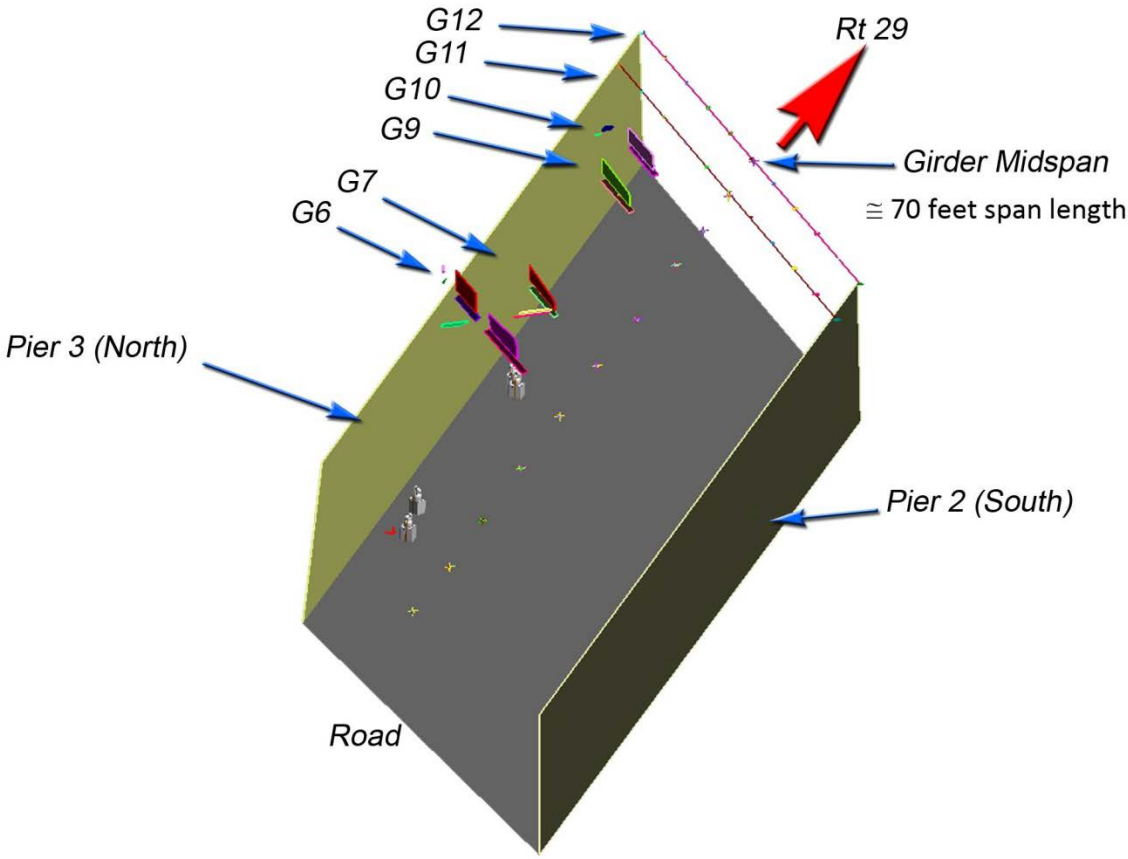

FIGURE 15 Localized impact damage measurements on four girders.

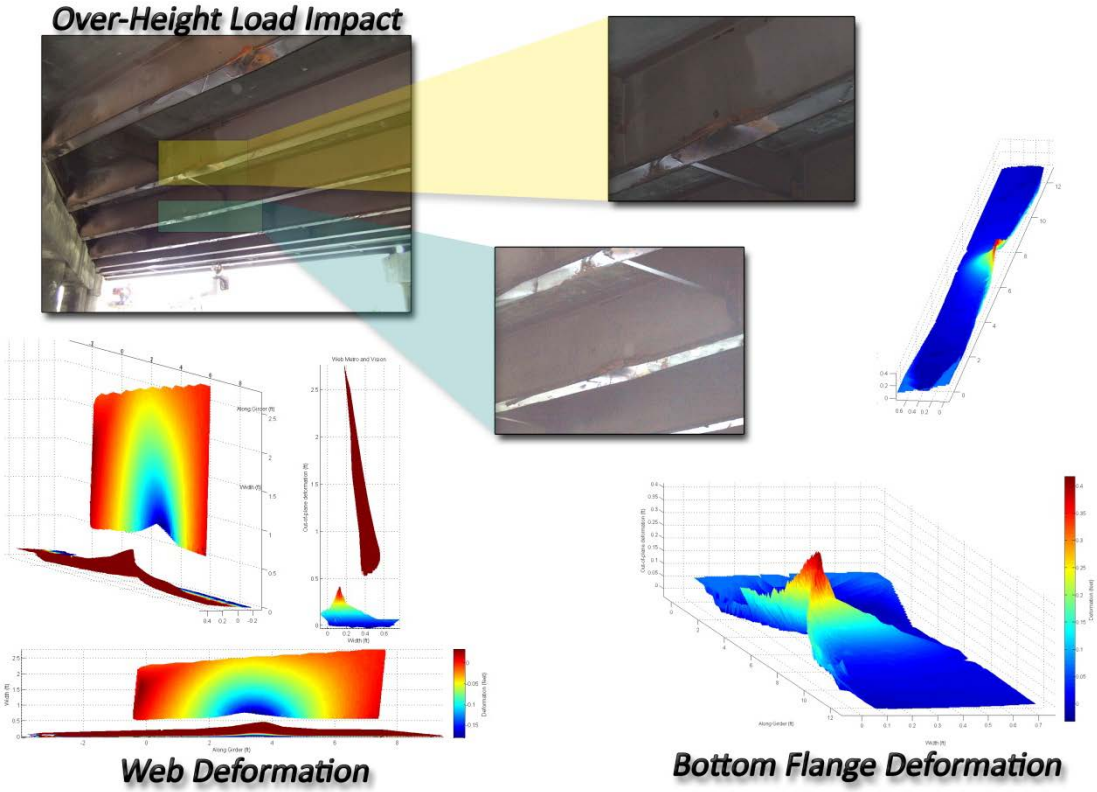

FIGURE 16 Web and bottom flange deformation measurements.

Localized deformation measurements on the web and bottom flange are shown in FIGURE 16. Measurements were made on localized sections of the girder, about 3.0 – 3.7 m (10 – 12 feet), around the impact damage. The color in these images is proportional to the out-of-plane deformation.

The previous example is a good illustration of high accuracy measurements on smaller sections of multiple girders. The following example more fully illustrates the power of the BRIDGE RLS in measuring impact damaged girders. This test shows measurements can be made on a bridge over a major roadway without any lane closures. Testing was completed on a multi-girder steel structure located on the Dulles Toll Road east of Leesburg, VA. The fascia girder had been struck by an over-height load and the bridge had sustained visible impact damage. The BRIDGE RLS was setup in the shoulder of the road for measurements, and no traffic on the heavily trafficked three-lane toll road was altered, see FIGURE 17.

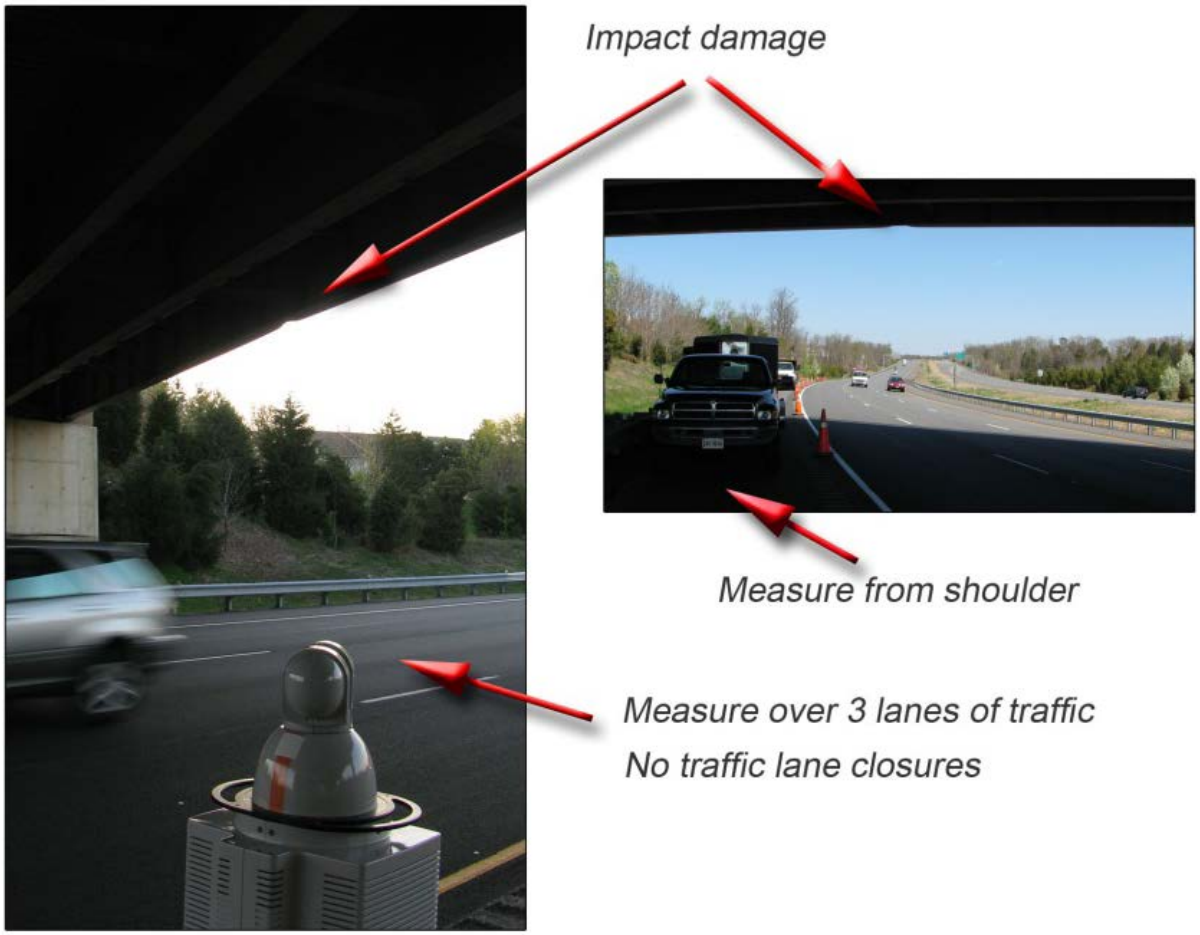

FIGURE 17 Measurement of impact damage on Virginia Bridge 4021.

Testing was conducted entirely from the shoulder with no lane closure and traffic was not impacted. The BRIDGE RLS could measure the impact damage and the precise location of the impact damage with respect to the ends of the girders, see FIGURE 18. The BRIDGE RLS could also precisely locate each cross frame stiffener location on the damaged girder and on the adjacent girder. These cross frame locations could be used to verify shop drawings and to design a replacement girder if necessary. While the first impact damaged girder example showed measurements of a girder length of about 3.0 – 3.7 m (10 – 12 feet), this example shows measurement of the entire length of the girder. FIGURE 18 (top middle) shows the girder web out-of-plane deformation over a length of 26 m (85 feet). Not only can localized deformation be measured, but large-scale global bends or kinks that occur over very large distances can be measured. Measurements of large-scale bends are very difficult or impossible to make with conventional techniques.

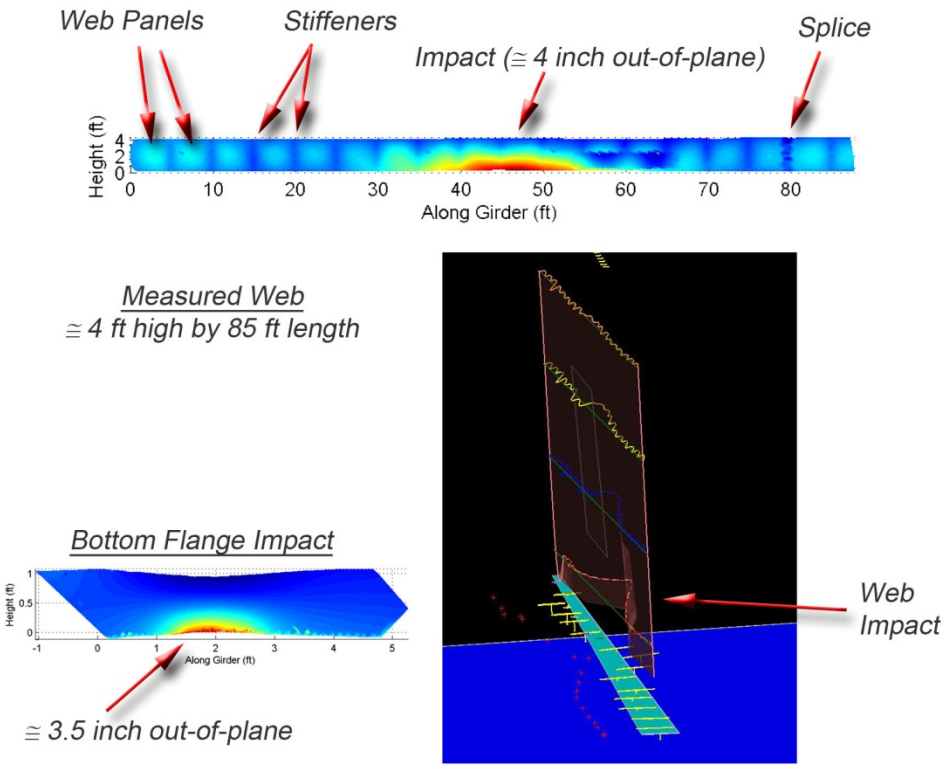

FIGURE 18 Measurement of girder web and bottom flange impact damage.

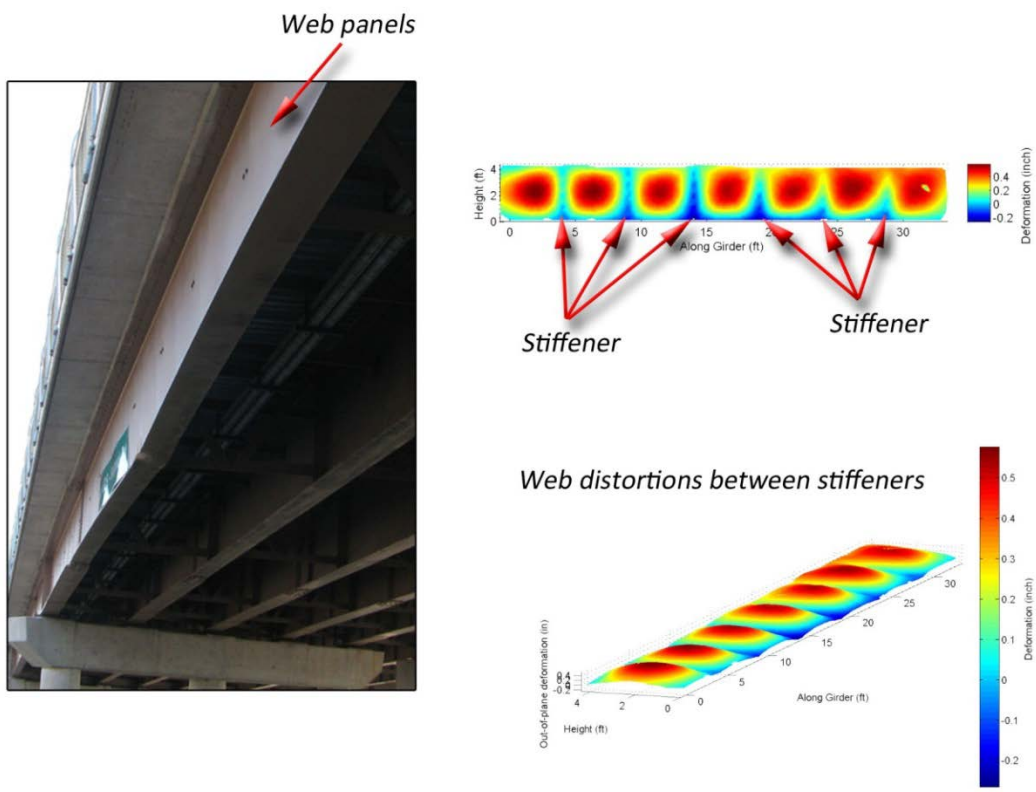

FIGURE 19 Web panel distortion measurement.

The system can also measure web panel distortions, as shown in FIGURE 19, present from the normal fabrication process. This web panel measurement may be used as a quality assurance tool for newly erected bridges. FIGURE 20 shows the system in operation at a bridge site.

FIGURE 20 Instrument setup and operation for impact damage measurements.

4.2.1.1. What can be measured?

The example on the Dulles Toll Road demonstrated how measurements can be quickly and easily made over a major roadway without any lane closures. Detailed measurements can be made of girder deformations. The location of stiffeners can be measured. The system can measure web panel distortions. Using current measurement methods with tape measures, the measurement of this bridge would have been much more time consuming, potentially more dangerous to the workers and public, and would have required one or more lane closures (and probably a lane closure switch).

4.2.2. Detail Measurements: Gusset / Splice Plates

Measurements were made on a historic steel truss bridge, currently not in service, near Leesburg, VA, see FIGURE 21. This bridge was chosen because it was a representative truss bridge, so that gusset plates and truss members could be measured. Measurements were made over a creek and from one measurement location multiple gusset plates and truss members could be measured. No direct access to the structure was required. Manual measurements on this bridge would have been very time consuming and would have required access equipment, such as man-lifts or snooper trucks.

FIGURE 21 BRIDGE RLS measuring the Goose Creek Truss Bridge.

The BRIDGE RLS, from a remote distance, very accurately measured features of the gusset plates and truss members. This included rivet head locations and the flatness (i.e. out-of-plane deformation) of the plate. The BRIDGE RLS can measure global gusset plate positions with respect to one another. Accurate global measurement is often very difficult or impossible in the field with manual measurements. FIGURE 22 shows the measurements from two of the gusset plates on the bridge. Measurements were taken at a range of about 20 m (64 feet) at a section of the bridge over the creek. The color in the gusset plate plots is proportional to the out-of-plane deformation. Surface irregularities (flaking paint, dirt) can be seen in the data sets. FIGURE 22 also shows more global measurements of the truss vertical and diagonal members. FIGURE 23 shows the system in operation for measurements on the truss bridge.

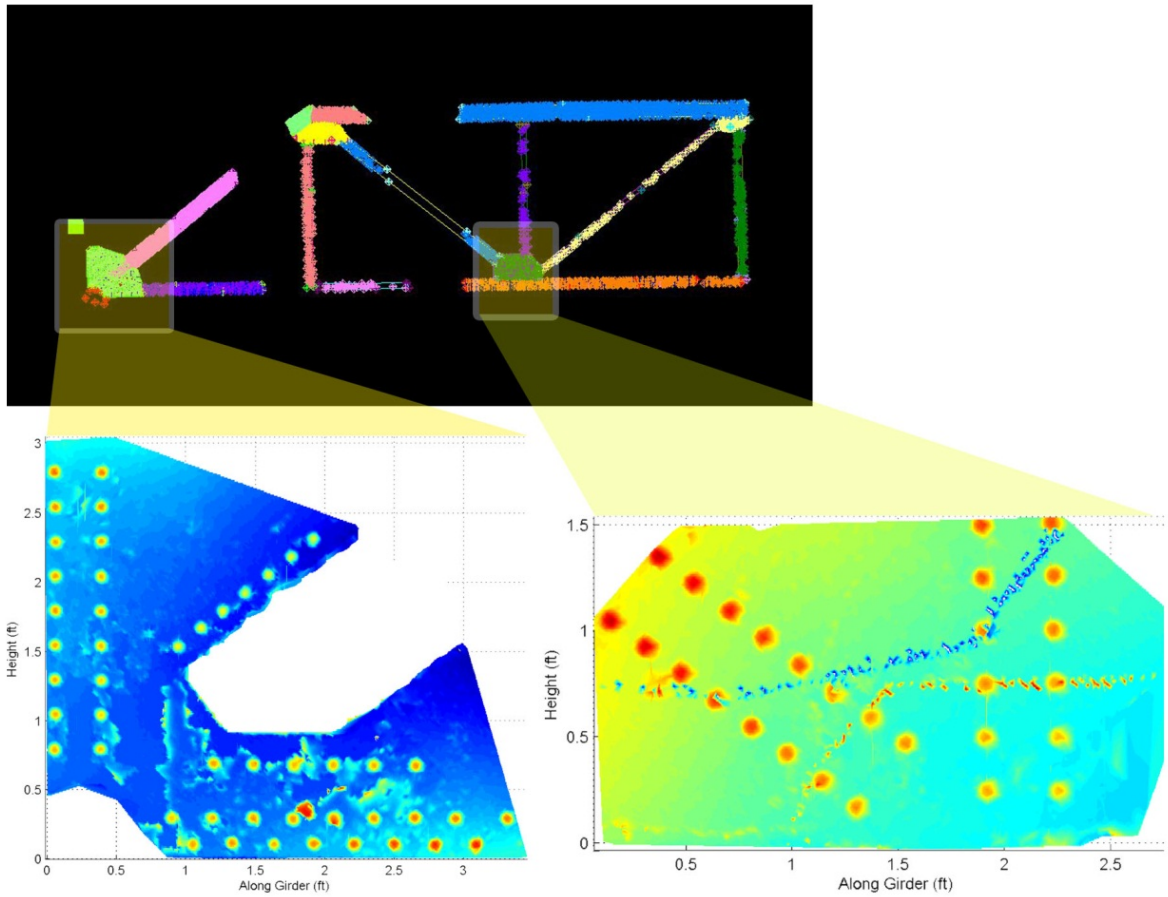

FIGURE 22 Measurements of Goose Creek Truss Bridge.

FIGURE 23 Instrumentation setup and operation for measurements on truss bridge.

4.2.2.1. What can be measured?

Localized details can be measured remotely without direct access to the bridge. In this example, multiple (at least six to seven) gusset plates can be measured from one instrument location. Both smaller localized measurements (rivet head spacing, gusset plate dimensions) and global measurements can be made. Dimensions of the larger diagonal and vertical members (length, hole patterns) can be found. All laser measurements can be made much more quickly and accurately than conventional measurements. The need to have workers access the bridge can be eliminated.

4.2.3. Splice Plates

Similar to the gusset plate example, the measurement of a steel girder splice plate is shown in FIGURE 24. Measurements in FIGURE 24 were taken over live traffic without any lane closure. The BRIDGE RLS was setup on a sidewalk adjacent to the roadway for measurements.

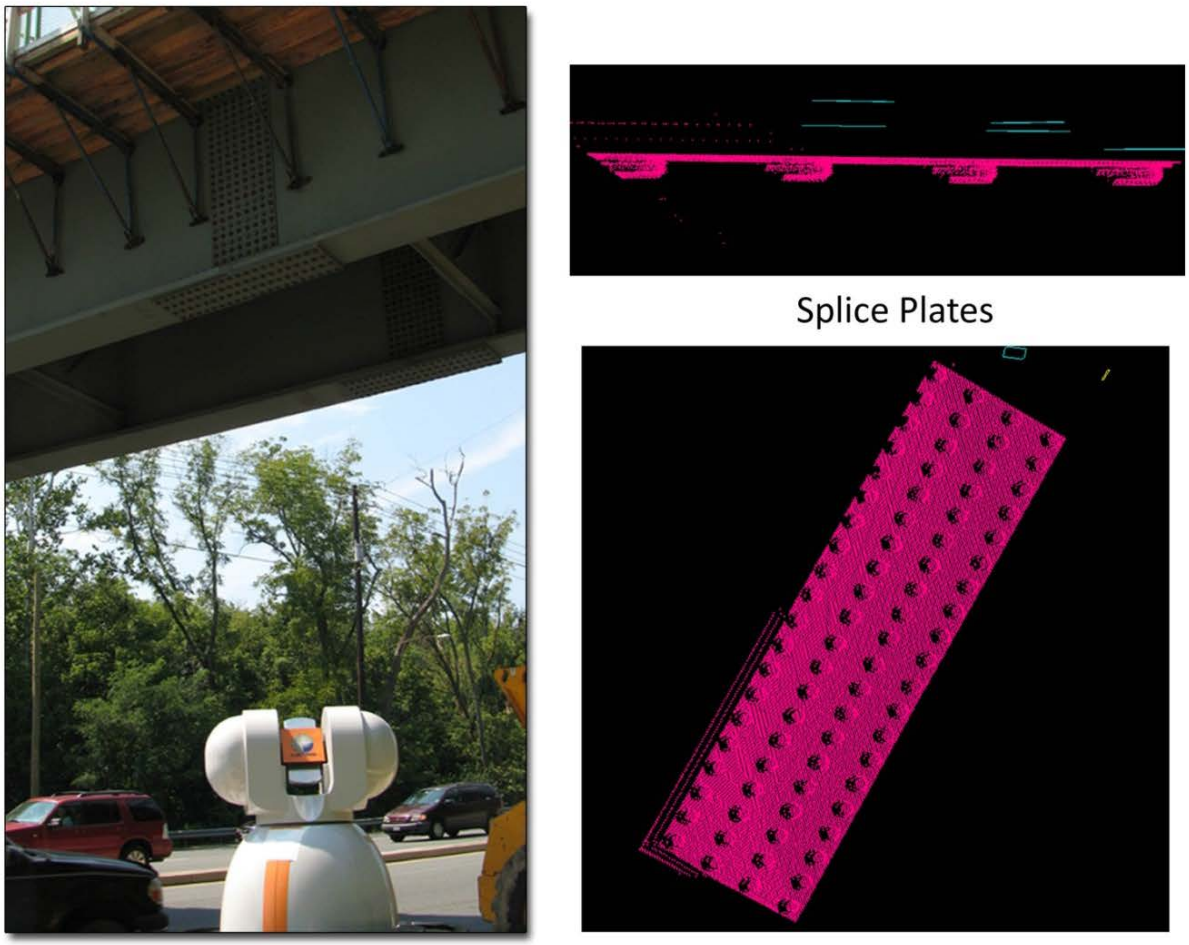

FIGURE 24 Measurement of a steel girder splice plate over live traffic.

4.3. GUIDELINES FOR IMPLEMENTATION

4.3.1. Gusset Plate Assessment

On August 1, 2007, the I-35W Bridge carrying traffic over the Mississippi River in Minneapolis, Minnesota collapsed killing 13 people and injuring 145 others (***1***, ***2***). An investigation into the cause of the collapse was done by the National Transportation Safety Board (NTSB) with assistance from the Federal Highway Administration (FHWA). It was determined that the failure of gusset plates in node U10 in the river span of the bridge led to the catastrophe (***1***, ***3***). The NTSB study concluded that the gusset plates that failed were not adequately sized to properly support the load from the bridge. The large compressive forces carried in the primary truss members and transmitted into the gusset plate caused a buckling failure of the plate resulting in translation of the primary members and eventually bridge collapse.

In the case of the I-35W bridge collapse, the gusset plates that buckled had inadequate thickness to carry the applied loading due to an error at the time of the design of the bridge. Inspection photographs taken prior to the collapse indicated a distortion in the gusset plate. Similar gusset plates in Ohio had buckled due to loss-of-section resulting from corrosion. Section loss from corrosion was undetected or inadequately assessed during visual inspections of the gusset plates, and the loss-of-section led to buckling similar to that shown in FIGURE 25 (***4***). Deformation (bowing) of gusset plates was also documented that suggested the onset or high potential for buckling failure of the gusset plate.

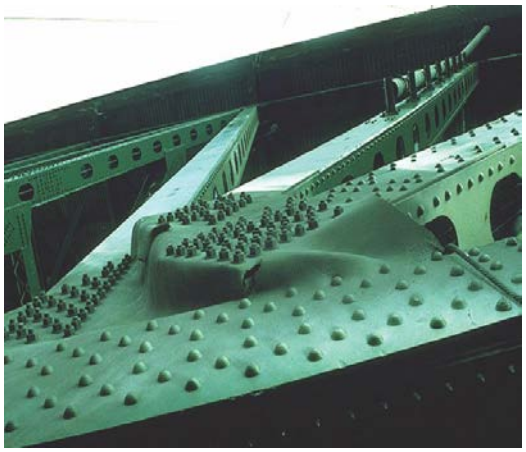

FIGURE 25 Photograph of a buckled gusset plate (4).

Inspection photographs taken prior to the I-35W bridge collapse indicated a distortion in the gusset plate, see FIGURE 26. This plate deformation was not noted prior to the collapse. In many cases, deformations in plates are very hard to observe visually. Current inspection strategies are comprised of using a straight–edge to assess bowing in the plate. This requires direct, hands-on access to the surface of the plate, which is often not possible without excessive cost for gaining access. Additionally, fasteners and attachments on the gusset are interferences that limit the plate area that can be assessed effectively with a straight edge, and the extent over which the straight-edge assessment can be made is limited by the reach of the inspector. The result depends entirely on the reliability of the inspector; typically, no quantitative data is collected except when the inspector, in his/her judgment, finds "significant" bowing and photographs the deflection with respect to the straight-edge tool. By contrast, a laser measurement is made on gusset plates without having to gain access to the plate. This BRIDGE RLS has the capability to detect out-of-plane distortions of the plate (bowing) and is not hindered by many of the access challenges faced in straight-edge measurements.

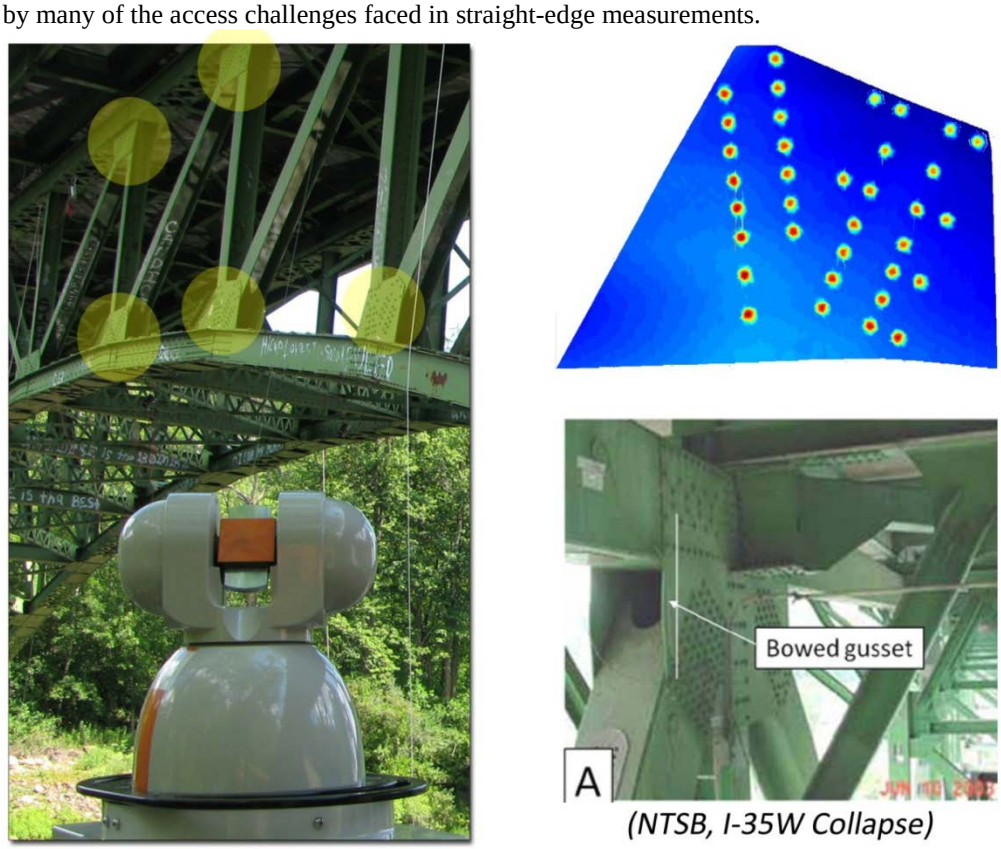

FIGURE 26 BRIDGE RLS gusset plate assessment, buckling failure of the I-35 W bridge in Minneapolis, MN (lower right).

5. PLANS FOR IMPLEMENTATION

5.1. FUTURE WORK AND CONTINUED DEVELOPMENT

Future implementation will focus on continued work with State Departments of Transportation to deploy the system on bridge retrofit applications. The system will continue to be refined with further usage in realistic applications. One specific area of future development will be in system software. The currently developed software tools will be extended to encompass a broader range of specific measurements. Tools will also be further developed to decrease operator intervention and to increase useful data to the end-user.

This system can be implemented in at least two ways. The first is as a service to an end-user. The advantage to a customer is lower investment cost in terms of equipment and maintaining trained operators. Typically, services for one to two days of measurements, including test planning and reporting, can be offered for less than $10,000. The other way to implement would be for end-users to own and operate the equipment. This implementation option would present some challenges for an agency in terms of maintaining expertise needed to operate the equipment. It is envisioned that these challenges can be managed. In this regard this field measurement system overlaps with a related Fuchs Consulting, Inc. (FCI) project for steel bridge fabrication. Here similar equipment is used in a shop environment and fabricator operator training and experience issues are being addressed. The level of expertise needed to effectively operate the system is reasonable and can be accomplished through FCI training. Test and training facilities are currently being setup with full sized bridge girders and bridge components (see below). Initial investment costs of the system are significantly higher than the service option, but the system can easily pay for itself with the benefits provided (eliminating traffic control, reducing time bridges are out of service). The design of the equipment and software is centered on creating an easy-to-use system, making this agency-owned implementation option feasible. The advantage to an agency is a potentially more rapid response time by not needing to coordinate work through a third-party vendor.

5.2. WORK WITH END-USERS

Work will continue to expose State Departments of Transportation to this technology and to look for opportunities for implementation on specific bridge retrofit projects.

Additional work will also continue with fabricators. This will include work to streamline the process of transforming measurements into useable engineering data. Work from other related efforts in development of a system for bridge fabrication shops will be leveraged to incorporate hardware and software developments into the field system.

5.3. TEST FACILITIES

Fuchs Consulting Inc. (FCI) is currently assembling a series of realistic test specimens for future measurement algorithm development and operator training. Specimens include gusset plates from decommissioned bridges, as shown in FIGURE 27 and other bridge girder sections. Training facilities are being developed to assist with implementation efforts for State Department of Transportation personnel.

FIGURE 27 Test pieces from decommissioned bridges.

6. CONCLUSIONS

An advanced laser-based measurement system has been developed and demonstrated to be applicable to the bridge retrofit process. The system is designed to provide specific, targeted information. Engineering data is output in a form that is directly useable, not just a cloud of points that need to be extensively post-processed.

The project system is designed to operate effectively under conditions found at typical bridge sites. Making high-accuracy measurements at a bridge site is not trivial and extensive effort has been expended in all design aspects to make these measurements possible. From the metrology systems to associated mounts and fixtures, all components of the system hardware, software, and measurement procedures are specifically designed for measurement of bridges.

Replacing conventional measurement tools with this advanced measurement system will improve measurement accuracy, resulting in higher quality retrofit work. Current measurements made with ruler and string-lines have inherent inaccuracies. They require hands-on access to structures and require manual documentation of measurements. The system developed in the project vastly improves measurement accuracy and can make measurements that are not currently possible.

The ability to make measurements over live traffic, water, rail lines, or other difficult access conditions is an important attribute of the system. Eliminating or reducing traffic control saves significant resources for retrofit work. In addition, remote measurements, especially in difficult access conditions, can potentially be made to a higher accuracy than with conventional methods. Measurement accuracy is validated in the field and procedures have been developed to allow for reliable field measurements.

It is believed that through continued exposure end-users will realize the advantages provided by this system in terms of better quality information and in reduced cost in the collection of information to aid in retrofit work. It is envisioned that the more applications the system is exposed to, the more ways to implement and uses for the system not currently envisioned will be found.

7. INVESTIGATOR PROFILE

Fuchs Consulting, Inc. (FCI) has a long history of developing advanced metrology systems for the assessment of bridge structures (*5, 6)*. Beginning in 1998, systems and techniques have been developed for both field and fabrication shop measurements.

7.1. FIELD MEASUREMENT OF BRIDGES

This current NCHRP IDEA project has focused on the bridge retrofit process and is a direct extension of previous FCI work related to field measurement of bridges. FCI has been developing and implementing a number of field metrology applications specifically targeted to bridges. Some of these applications shown in FIGURE 29 include measurement of arch bridges, pavements, and girder erection.

One of the first application areas developed is load testing of bridges. The main features of the BRIDGE RLS used in this project can be used to collect data on a bridge in a manner that is superior to conventional data collection methods. Using the BRIDGE RLS, deflection data can be taken on bridges without traffic control over live traffic, over water, or over rail lines. This makes obtaining load test data quicker and more efficient. Deflection data can be obtained for multiple points on multiple girders from one measurement location. Laser data can measure high-density deflection profiles along an entire girder length as compared to a single mid-span deflection measurement typically made with conventional instrumentation. FIGURE 28 shows the BRIDGE RLS being used to load test a bridge in Maryland.

FIGURE 28 Example of the BRIDGE RLS being used to load test a bridge over water.

FIGURE 29 Examples of other field measurement applications.

7.2. FABRICATION SHOP MEASUREMENT SYSTEM

FCI has developed the BRIDGE VIRTUAL ASSEMBLY SYSTEM (VAS) based on laser metrology instrumentation that is used to aid in steel bridge fabrication. This concept was the subject of an NCHRP IDEA project, NCHRP-127, in 2007. Subsequent to the NCHRP IDEA project a Transportation Pooled Fund Study was established to further develop this concept. This pooled fund project, TFP-5(226) was led by the Virginia Department of Transportation and included multiple State Departments of Transportation and the Federal Highway Administration.

A complete system was developed that is integrated into a steel bridge plant that improves the manner in which steel bridges are fabricated. This system can lower the cost to make a steel bridge and provides a quantifiable, certifiable record of what is fabricated. This system can make measurements that are far superior to conventional methods and can provide measurements that are not possible with conventional methods.

This system is conceptually simple (see FIGURE 30): a laser-based measurement system measures key aspects of a completely fabricated girder, these measurements are stored as a permanent record of the girder, and these measurements are combined with measurements from other girders to virtually assemble girders.

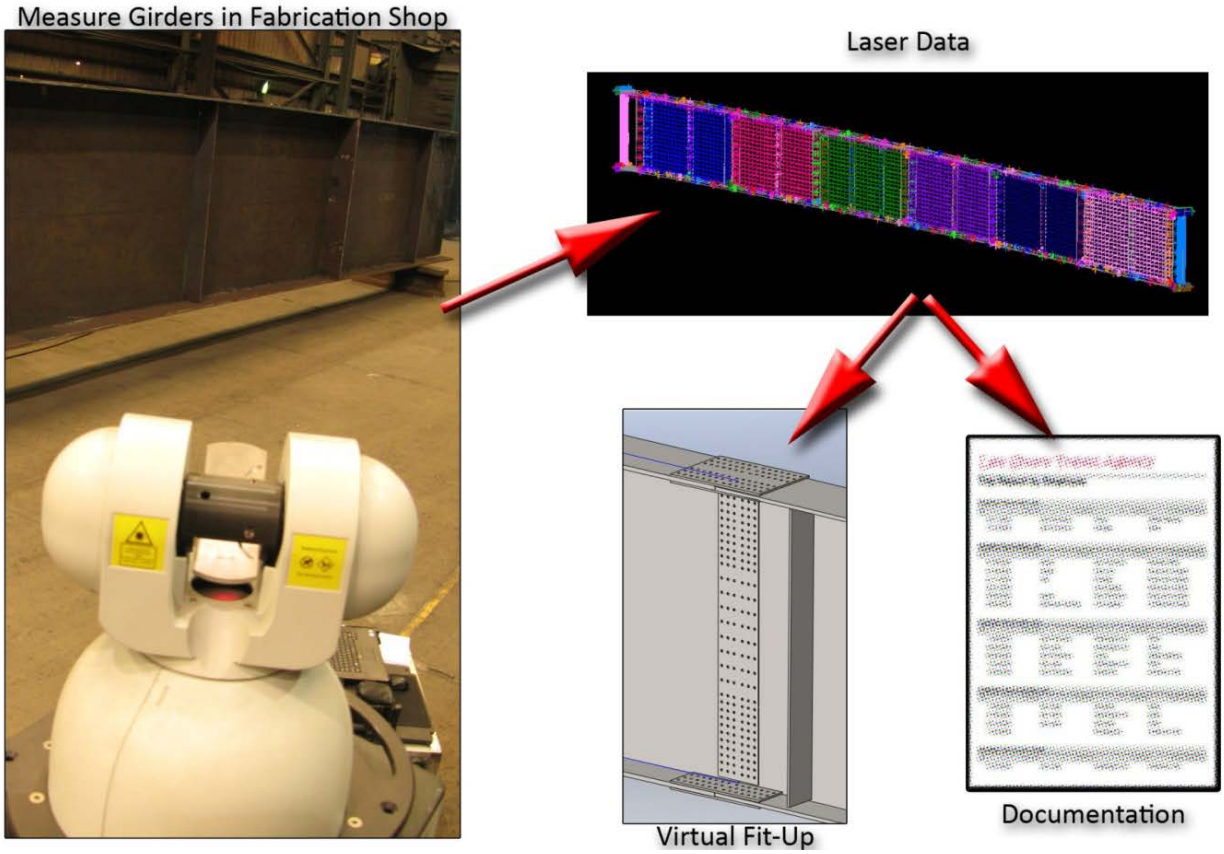

FIGURE 30 BRIDGE VAS system concept.

The BRIDGE VAS can eliminate the most time and labor intensive part of the fabrication process, the lay down process that currently match-drills girder splices. This lay down process is time consuming, cost intensive, and requires considerable amounts of floor space. The BRIDGE VAS eliminates conventional measurement methods. These conventional measurement methods are currently based on string lines and tape measures and records are kept by hand. Current records can lack detail and can be challenged easily if there are issues. The complete digital record provided by the BRIDGE VAS is certifiable, traceable, and provides full documentation of the as-built condition of each girder.

The State of Tennessee allowed use of the BRIDGE VAS on the first ever production bridge job. This is the first time that girders have been measured in a production setting using laser data for girder fit-up. This is the first time that entire lines of girders have been measured, and the first time that large, complex girders have been measured. Virtual assembly of a girder pair from this Tennessee bridge job is shown in FIGURE 31 (top), with BRIDGE VAS designed splice plates shown in FIGURE 31 (middle right). The large size of the girders measured and fit up in the job is shown in FIGURE 31 (bottom).

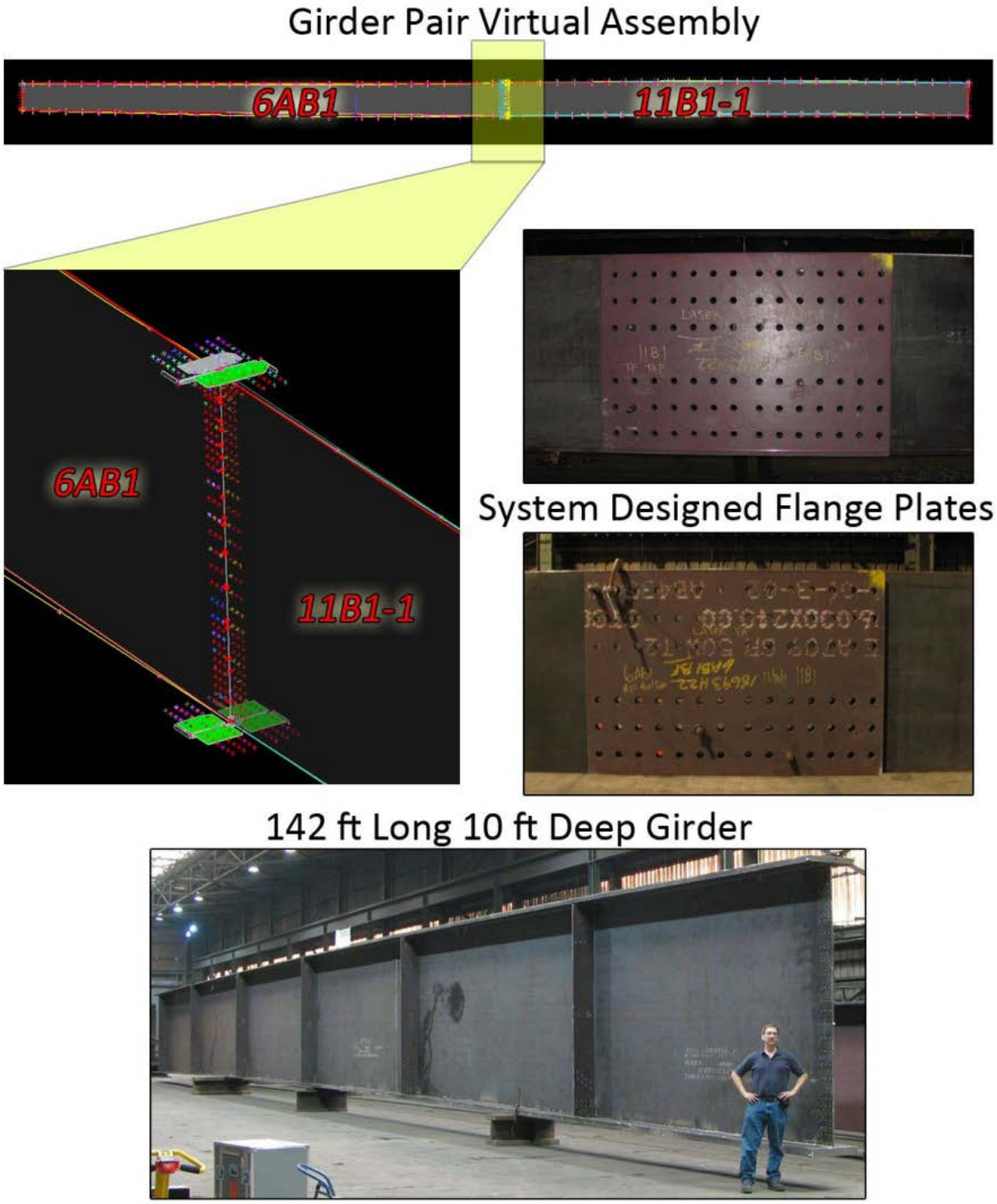

FIGURE 31 BRIDGE VAS implementation on a production bridge job.

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