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NCHRP IDEA Program

Development of a Portable Stress Measurement Instrument

Final Report for
NCHRP IDEA Project 179

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Development of a Portable Stress Measurement Instrument

IDEA Program Final Report

DRAFT

NCHRP IDEA Project 179

Prepared for the IDEA Program
Transportation Research Board
The National Academies

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EXECUTIVE SUMMARY

This report documents the results of IDEA project 179, *Development of a Portable Stress Measurement Instrument.* An ultrasonic stress measurement (USM) instrument has been developed that provides bridge engineers with quantitative measurements of the in-situ stresses in bridge members. The instrument is very unique because there are no other practical total stress measurement methods for in-service steel bridges. The *total stress* measured includes dead load, residual, and live load stresses. This new technology is a significant improvement over other stress measurement technologies such as strain gages, which are not capable of measuring the in-situ residual or dead load stresses in a bridge member. The total stress measurement provided by the USM instrument can be used to analyze the structural adequacy of bridge members in ways not possible using conventional technologies.

The USM instrument uses ultrasonic birefringence to measure the total stress in a steel bridge member. Ultrasonic birefringence is a well-established physical phenomenon that has been used as a laboratory method for decades. The technology developed through the research extends the application of the birefringence measurements to practical field applications. The USM instrumentation developed is a portable, battery-operated system designed to be suitable for practical stress measurement in the field.

The USM instrument provides a tool that helps bridge owners assess bridge safety through data previously not available. Currently, accurate safety evaluation of bridges can be difficult due to the uncertainty in knowing the actual loads carried by individual bridge members. Engineers must rely on theoretical assumptions based on design drawings to analyze load distributions. Design drawings typically do not represent the actual conditions in the field. Locked or damaged bearings, corrosion damage, impact damage, and misalignment of members can result in unanticipated load distributions. As a result, analysis to determine if a member has adequate capacity to carry the applied forces can be inaccurate, because the load distribution is uncertain. The USM instrument developed can now actually measure the in-situ forces and resulting stress directly to provide the data needed to more accurately assess structural adequacy and ensure bridge safety.

The USM instrument was developed by integrating and modifying commercially available equipment into a single portable instrument containing all components needed for the measurements. Instrument development included specialized software to automatically process birefringence data to determine the magnitude of stresses. A custom transducer fixture was designed and manufactured that supports the transducer rotation necessary for birefringence measurements. The USM instrument was tested in the laboratory and through field testing that verified the accuracy of the total stress measurement.

Laboratory testing was used to determine key acoustic properties of common bridge steels. These laboratory studies consisted of determining the natural birefringence and acoustoelastic constants for steel, which are used to relate measured ultrasonic birefringence to the total stress in the steel. Laboratory studies were also used to develop and test the integrated hardware and software developed through the research.

The operation and capabilities of the USM instrument were verified through a field test. The field test consisted of measuring the shear stresses in a gusset plate of a truss bridge under different loading conditions. The total stress measurement was verified by removing a core from the gusset plate at the same location where the USM was made. Stresses in the core were measured using a conventional strain gage rosette to determine the stresses released when the core was removed from the plate. It was found that the USM was capable of accurately determining the total stress in the gusset plate.

Future plans to promote this new technology include more experience with field measurements. Additional measurements will improve the instrument and will provide a better understanding of how and where the measurements can best be applied. This project represented a significant step in creation of a portable stress measurement instrument and a first-generation prototype was developed. Additional system integration is planned for making the system more portable and easier to use with the end-goal of providing a commercial instrument available to the highway bridge community.

1 IDEA PRODUCT

A unique ultrasonic stress measurement (USM) instrument has been developed that provides bridge engineers with quantitative measurements of the in-situ stresses in bridge members. The unique feature of the USM tool is the measurement of total stress in a steel member. The total stress measured includes dead load, residual, and live load stresses. This new technology is a significant improvement over other stress measurement technologies such as strain gages, which are not capable of measuring the in-situ residual or dead load stresses in a bridge member. The total stress measurement provided by the new USM instrument technology can be used to analyze the structural adequacy of bridge members in ways not possible using conventional technologies such as strain gages.

The portable USM instrument shown in Figure 1 consists of an ultrasonic transducer, data acquisition, and wireless computer interface that interfaces with the data acquisition system to record and process data. The integrated system measures the in-situ stress carried by a steel bridge member. This tool can be used to identify critically-stressed members, identify repair or replacement needs, and ensure bridge safety. For example, the tool can be used to assess the potential for gusset-plate buckling, evaluate the load paths in redundant structures, evaluate damage following an extreme event, or to identify load distributions in a truss bridge.

The key innovations from the research are the ability to measure total stresses in bridge members and the development a battery- operated, portable instrument that is practical for field measurements. These developments provide an important new technology for assessing bridge safety.

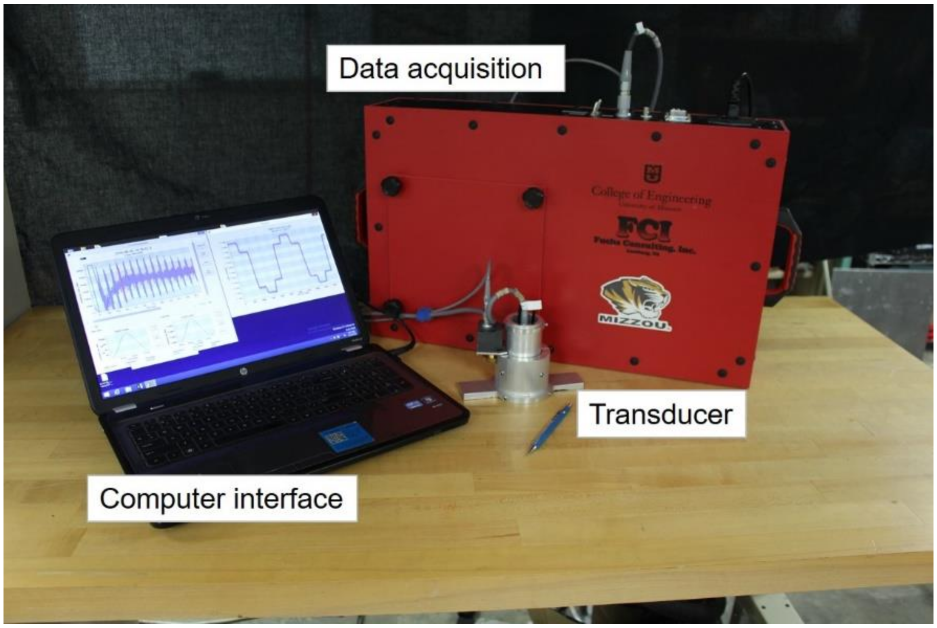
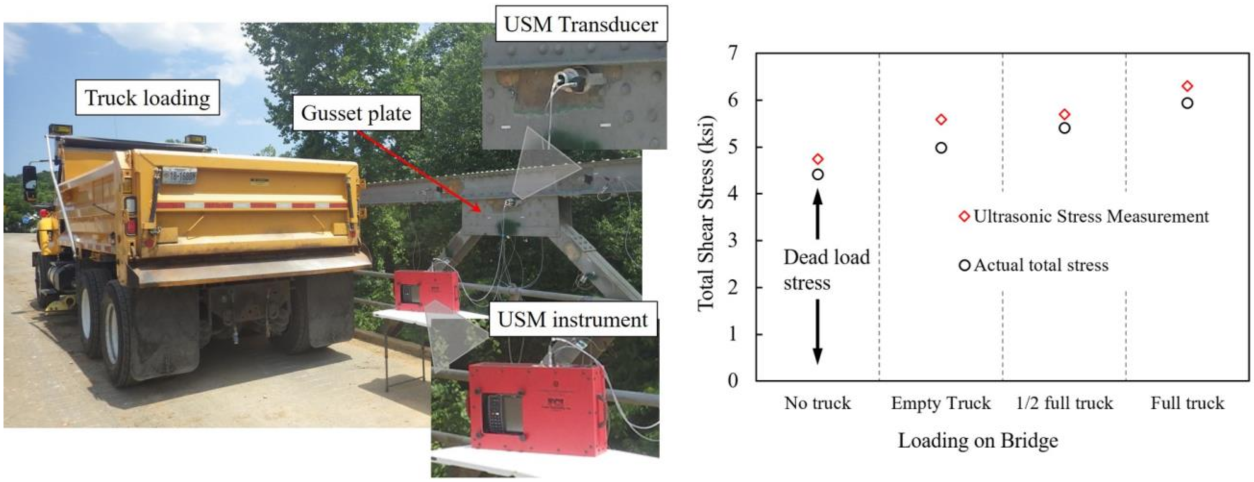


Figure 1. Photograph of the portable stress measurement technology developed through the research.

1.1 HOW DOES THE NEW TECHNOLOGY WORK?

The instrument uses ultrasonic birefringence to measure the total stress in a steel bridge member. Ultrasonic birefringence is a well-established physical phenomenon that has been used as a laboratory method for decades. The resulting USM is the through-thickness average stress carried by the member being evaluated. This measurement is unique because it includes the total stress in the material, including residual, dead load, and live-load stresses. The instrumentation developed through this research is battery operated and designed to be suitable for practical stress measurement in the field.

Figure 2 illustrates the application of the technology in the field to measure stresses carried by a gusset plate. The photograph in Figure 2A shows the instrument developed through the research with the transducer placed on a gusset plate, and a truck used to apply different loads on the bridge. The results shown in Figure 2B indicate the total shear stress measured by the USM technology as compared with the actual total shear stress. These data verify the capability of the USM developed through the research to make an accurate measurement of stress in the field.



A B

Figure 2. Photograph showing the USM technology applied to a gusset plate (A) and the resulting total stress measurement (B).

1.2 HOW DOES THE INSTRUMENT OPERATE?

The instrument operates by placing the transducer of the surface of a steel bridge member. The transducer attaches magnetically to the surface of the steel. The transducer is manually rotated to collect the ultrasonic birefringence data needed to determine the total stress carried by the member. Data is analyzed by using specialized software developed through the research. This software automatically calculates the ultrasonic birefringence data needed for analyzing the magnitude and direction of principal stresses. The USM technology developed is battery operated and portable for use in the field, and is simple to operate. A single measurement takes about 1-2 minutes to complete, with the data acquisition and analysis being largely automated through software developed as part of the research.

2 CONCEPT AND INNOVATIONS

The concept of this research was to develop a practical nondestructive technology for measuring the total stress carried in bridge members. This new technology provides a tool that helps bridge owners ensure bridge safety through better analysis of existing bridges. Effective safety evaluation of bridges can be difficult due to the uncertainty in the actual loads carried by individual bridge members. Engineers must rely on theoretical assumptions based on design drawings to analyze load distributions, and these design drawings typically do not represent the actual conditions in the field. Locked or damaged bearings, corrosion damage, impact damage, and misalignment of members can result in unanticipated load distributions. As a result, analysis to determine if a member has adequate capacity to carry the applied forces is compromised, because the load distribution is uncertain. The technology developed measures the in-situ forces and resulting stress directly to provide the data needed to assess structural adequacy and ensure bridge safety.

Conventional technologies such as strain gages are only capable of measuring the live load portion of stresses in a bridge member. Strain gages cannot measure the dead load stresses resulting from the weight of bridge materials, locked-in stresses resulting from member misalignment, or residual stresses. These stresses are often larger than the live load stresses applied by traffic loading. The safety evaluation of bridges can be greatly improved by a technology that measures the total stresses carried in a bridge member, including the live load, dead load, locked-in, and residual stresses. In fact, the measurement of total stresses in bridge members was identified as the number two research priority by a working group of state bridge engineers, industry, and academics assembled by the FHWA in 2016[1]. The concept of the research was to develop a nondestructive tool that can address the need for practical, quantitative measurement of total stress to assist bridge owners in ensuring bridge safety.

The USM technology developed is based on measuring the ultrasonic birefringence in a steel plate. Birefringence is the difference in ultrasonic wave velocity between orthogonally polarized shear waves, which varies as a function of stress. Figure 3A shows a schematic diagram of the test arrangement for making the stress measurement using polarized shear waves. As shown in the figure, the transducer is placed on the surface of the steel, and a polarized shear wave is launched from the transducer. The wave propagates through the thickness of the plate, reflecting from the opposite surface and detected by the transducer. The travel time for the wave to propagate through the plate is determined as shown in Figure 3B. When the transducer is rotated, the travel time varies revealing a "fast" direction and a "slow" direction. The birefringence is the difference between the ultrasonic velocities in the "fast" and "slow" directions. As shown in the figure, the magnitude of the birefringence varies as a function of the stress. For the data shown in the figure, the birefringence is larger for a stress of 25,000 psi as compared with a stress of 0 psi.

The concept of USM based on birefringence has been the subject of study in the past, primarily utilized for research and laboratory applications. Practical instrumentation, sensor technology and software for applying USM for measuring total stress in bridge members has not been developed previously.

The research reported herein developed a practical field instrument for performing ultrasonic birefringence measurement to determine the total stress in steel plates. The key innovations from the research are the ability to measure total stresses in bridge members and the development a battery operated, portable, practical instrument for field measurements. These developments provide an important new technology for assessing bridge safety.

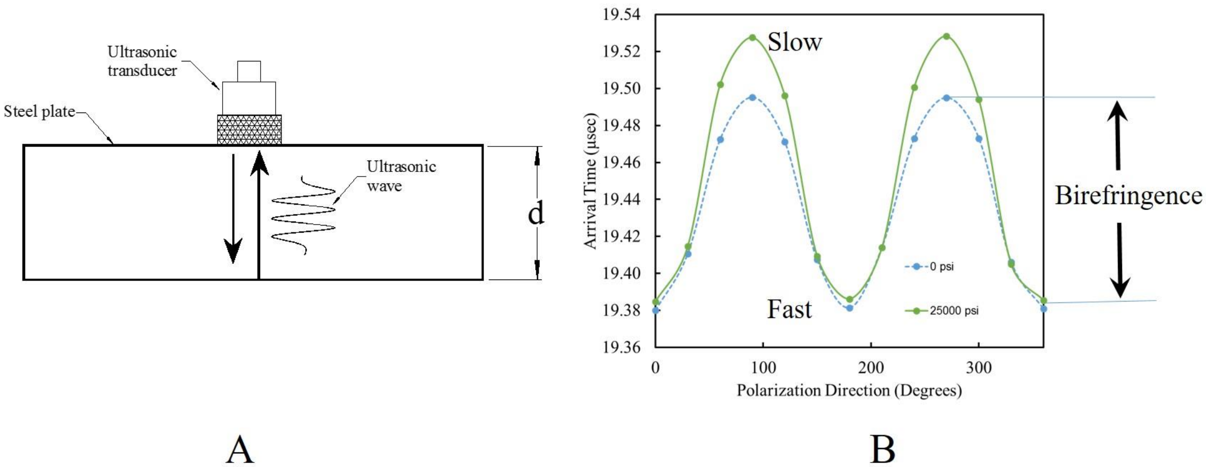


Figure 3. Schematic diagram of the test arrangement for USM (A) and ultrasonic birefringence data used to determine stress (B)

3 INVESTIGATION

This portion of the report describes the investigation and testing completed as part of the research. Section 3.1 provides background on the underlying theory governing the use of ultrasonic waves to measure total stress, and discusses the application of the technology for the evaluation of gusset plates in truss bridges. Section 3.2 describes the development of the USM instrument and supporting software. The ultrasonic measurement of stress in bridge steels has been the subject of limited previous research with only a few field applications for stress measurement in bridges. Therefore, the research included laboratory testing to assess key parameters and develop the operation of the USM technology. Section 3.3 describes the laboratory testing completed as part of the research. These testes were used to evaluate key ultrasonic properties of bridge steel such as the acoustoelastic constants needed to convert birefringence measurements to stress measurements.

To demonstrate the implementation of the technology in the field, the research included a field trial in which the new USM technology was used to evaluate shear stresses in a gusset plate of a truss bridge. This application was selected due to its relevance the 2007 collapse of the I-35W bridge over the Mississippi River in Minneapolis, in which a gusset plate failure resulted in the collapse of the entire bridge. Section 3.4 describes the field testing completed as part of the research to demonstrate field implementation of the technology and verify the stress measurements.

3.1 BACKGROUND

3.1.1 *Ultrasonic Stress Measurement with Birefringence*

Ultrasonic testing (UT) utilizes high frequency sound energy for characterization and examination of material properties of structural members in a bridge. Typical UT systems consist of a pulser/receiver, a transducer, and a display window for measurement analysis. UT inspection is currently used for flaw detection in welds, dimensional measurements (e.g. plate thickness) of materials, and material characterization (e.g. modulus).

The use of ultrasonic waves for stress measurement is a less common use of the technology. Ultrasonic stress measurement is based on the variation of wave velocity caused by applied strain. The elastic properties of a metal are a function of strain in the material; therefore, when the material undergoes strain the velocity of the wave will change [2]. This phenomenon is known as the acoustoelastic effect. For small changes in an wave velocity a relationship between the measured velocity of the acoustic waves and stress can be linearly characterized by Equation 1:

$$V = V_0 + k\sigma \tag{1}$$

where V_0 is the wave velocity in an unstressed medium, k is a material-dependent acoustoelastic constant, and σ is the stress in the material [2, 3]. This general relationship has been used in the past for applications such as determining the stress in prestressing strand, measuring fatigue loading in steel bridges, and measuring stress in railroad tracks[4-6]. In this research, ultrasonic birefringence has been applied for measuring stress in the gusset plates and other steel bridge members.

In an isotropic homogeneous material, ultrasonic shear waves propagate at a single velocity regardless of wave polarization direction. In steel, the shear wave velocity is approximately 10,500 ft/sec. However, if a material exhibits anisotropy, the velocity of the shear waves will become dependent of the polarization direction of the wave. Anisotropy in a material occurs for two reasons; texture and stress [7]. The texture effect, or the natural birefringence, is typically due to the fabrication process of the material. Mechanical process introduces a texture to the material by elongating the polycrystalline grain structure into a preferred orientation in the rolling direction. This causes a “natural” birefringence effect, B_0, in the steel when the stresses in the material are nominally zero. As a result, the fast pure – mode polarization direction is coincident with the rolling direction of the unstressed steel material, and the slow pure – mode polarization direction is transverse to the rolling direction in the same unstressed steel material.

Stresses in the material that result in strain relative to the natural positions of the atoms also cause anisotropy in the material. The ultrasonic birefringence method measures the anisotropy (as manifested through the wave velocities) caused by stress in the material to quantify the level of stress, relative to the unstressed state. In this way, the USM measurement includes any stresses causing the material to be strained. This includes residual stresses, live load stresses, and dead load stresses.

The material anisotropy results in polarization orientations where the wave velocity is at a maximum and minimum, typically termed the “fast” and “slow” wave direction. These orientations are known as pure – mode polarization directions and are orthogonal to one another. The normalized difference in velocity of the pure-mode polarization directions is the acoustic birefringence, B, defined by Equation 2:

$$B = \frac{V_f - V_s}{V_{avg}} \tag{2}$$

where V_f is the velocity of the fast wave, V_s is the velocity of the slow wave, and V_{avg} is the average velocity of the wave. These types of measurements are independent of material thickness because the wave propagates over the same material distance. Therefore, the difference between those measurements can be characterized as the transit time, or time-of-flight (TOF), of the wave through the material thickness. Acoustic birefringence can then be rewritten as follow in Equation 3:

$$B = \frac{t_f - t_s}{t_{avg}} \tag{3}$$

where t_f is the TOF of the fast wave, t_s is the TOF of the slow wave, and t_{avg} is the average TOF of the wave.

Pure – mode polarization directions are aligned with the rolling and transverse direction of a material when the material is unstressed and when the principal stress directions are coincident with the rolling and transverse directions. Under the presence of shear stress, the fast and slow polarization directions will deviate causing a rotation of the pure – mode polarization direction through an angle from the rolling direction [3, 8, 9]. Figure 4 shows a representation of this phenomenon where X_0 and Y_0 represent the rolling and transverse direction, while X and Y represent the pure – mode polarization directions rotated by an angle ϕ [9].

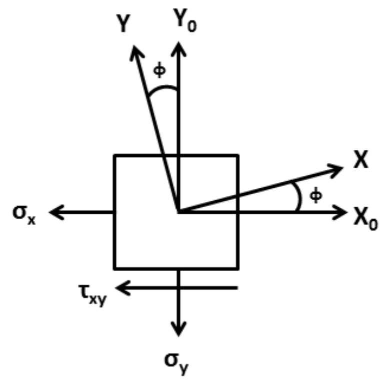


Figure 4. The pure – mode polarization direction, X and Y axis, rotated through the angle ϕ with respect to the transverse and rolling direction, X_0 and Y_0 axis, due to the presence of shear stress.

The relationship between stress and birefringence was first studied by Iwashimizu in [10]; these relationships were later simplified by Okada [11, 12] and Clark [8, 9]. The relationship between birefringence and stress as referenced to a coordinate system parallel and perpendicular to the rolling direction of the material is shown Equation 4:

$$B^2 = \left[B_0 + (m_1 + m_2)\sigma_x + (m_1 - m_2)\sigma_y\right]^2 + \left(2m_3\tau_{xy}\right)^2 \tag{4}$$

where B_0 is the natural birefringence of the material in an unstressed state, m_1, m_2, and m_3, are acoustoelastic constants, σ_x and σ_y are the in – plane principal stresses parallel and perpendicular to the rolling direction of the material, and τ_{xy} is the shear stress in the material.

As previously discussed, the pure – mode polarization directions will be aligned with the rolling and transverse direction of an unstressed material. However, shear stresses, like those experienced in gusset plates, will cause a rotation of these directions through an angle ϕ. This can be characterized by Equation 5.

$$tan2\phi = \frac{2m_3\tau_{xy}}{B_0 + (m_1 + m_2)\sigma_x + (m_1 - m_2)\sigma_y} \tag{5}$$

When the principal stresses are aligned with the texture direction in the steel, such as would be the case in most open steel shapes, rotation of the fast and slow directions does not occur. A combination of Equation 4 and Equation 5 with trigonometric identities yields Equation 6 and Equation 7 for normal and shear stress respectively:

$$m_1(\sigma_x + \sigma_y) + m_2(\sigma_x - \sigma_y) = Bcos2\phi - B_0 \tag{6}$$

and

$$\tau_{xy} = \frac{B \sin 2\phi}{2m_3} \tag{7}$$

It is notable that the final equation does not depend on the natural birefringence in the material, but rather only on the measured birefringence at a given stress level, and the appropriate stress-acoustic constant, m_3. These equations demonstrate the relationship between the stress state of a material and birefringence measurements. In this research, these relationship have been used to measure the total stress in steel gusset plates, focusing on the shear stress measurement that requires calculating both the angle of the pure mode rotations and the birefringence.

3.1.2 *Stress Measurement In Gusset Plates*

A key motivation for the research was the need for improved methods to evaluate the structural capacity of steel bridge members, including gusset plates in truss bridges. The need for structural evaluation of gusset plates was revealed by the collapse of the I35W bridge in 2007. This tragic accident, in which 13 motorist were killed, was caused by the failure of an over-stressed gusset plate in one of the bridge joints [13]. The gusset plates that failed were not adequately sized to properly support the large compressive forces transmitted from the primary truss members.

Previous research by Mentes indicated gusset plates fail in one of two ways. For thin gusset plates, less than 3/8 in thickness, the plate fails due to buckling, while thick gusset plates, greater than 5/8 in thickness, fail due to shear failures [14]. The work performed by Ocel with the Federal Highway Administration determined the main cause of gusset plate failure was due to the high shear stresses in the gusset plates. This work included full-scale testing of 13 gusset plate members using experimental and analytical methods. The results from these investigations determined that half of the test specimens failed due to buckling and the other half failed due to shear yielding [15]. Ocel concluded that:

> *Although it may seem odd to use a shear formulation to predict buckling, the research showed that once a partial shear plane in the gusset plate along a compression member yields, its elastic modulus decreases and thus reduces the out-of-plane rotational restraint the plate can provide to the idealized column [15].*

The work performed by Ocel is further reiterated in a study of in-service gusset plates in bridges performed by the University of Washington for the Washington State Department of Transportation. This study concluded that buckling in gusset plates did not occur prior to yielding of the gusset plate in any of the connections studied. The interaction of the complex stresses generated in the gusset plate members, as previously described by Whitmore, initiated the yielding of the members [16]. Therefore, it is of the upmost importance to assess the magnitude of shear stresses in gusset plates to identify members potentially at risk of failure.

This previous research indicates that the analysis of shear stresses in the gusset plates is key to assessing the risk of failure. However, analytical determination of the forces and stresses in the gusset plate is complicated by the need to estimate the load induced from the axial-force members joined by the gusset plate. As previously discussed, determining the force carried in these members and transferred by the gusset plate is complicated by the uncertain load distribution in truss bridges. An additional complication for gusset plates is that the plates commonly have corrosion damage resulting in section loss. Therefore, even if the forces were known, the total section of the plate carrying those loads may be uncertain. A direct measurement of total stress, such as offered by the USM technology developed through this research, overcomes these challenges. Since the USM instrument measures total stress, the effect of any section loss is measured directly in the stress measurement. The unknown distribution of forces is also mitigated, since the total stress measurement assesses the effect of those loads, even if the loads themselves are unknown. For these reasons, the research focused on the measurement of shear stresses in gusset plates to demonstrate the unique characteristics and utility of the USM technology.

It should be noted that there are other more conventional applications for the USM, some of which have been developed in the past. For example, Lozev et. al. [3] explored measuring the locked-in forces in an I-shaped member of a jointless bridge. Clark et. al. [8] implemented USM as a tool to determine if a pin and hanger connection were locked by measuring the bending stresses in the hanger plate. Fuchs et. al. [5] developed USM for monitoring applied live loads for the purpose of measuring stress ranges for analyzing remaining fatigue life. Axial stresses in truss members and bending stresses in open and closed steel bridge members are additional applications where the ability of USM to measure normal stresses could be applied. USM in this research focused on the unique application of gusset plates as described above, although much of the developmental laboratory testing that will be described illustrates the measurement of axial stresses that could be applied to primary bridge members.

3.2 DEVELOPMENT OF THE USM INSTRUMENT

A field-ready instrument was developed through modification of commercially-available hardware and integration into a practical system suitable for field implementation. The primary components of the system consisted of the following:

1. A pulser-reciever for launching and detecting polarized shear waves
2. Computer software for signal analysis
3. Wireless link for communication
4. Rotational ransducer fixture with encoder

The design of the system is intended to create a small, portable system that is easy to use in the field. This system contains a minimum number of components and operates in a near – automatic mode. Figure 5 shows a block diagram of the instrument developed through the research. The design incorporates a self-contained data acquisition system, a wireless router, battery and signal conditioning module. Each of these components was mounted in a suitable field-ready enclosure. A specialized rotational transducer fixture was designed and manufactured that allowed the transducer to be rotated in a circular fashion to support the birefringence measurement. A laptop computer was used for data collection and signal processing of the data. The synchronized data collection is triggered by the transducer position, and processed via the remote laptop computer that communicates with the system through a wireless router or via a USB connection. The following section describes each of the components of the USM instrument developed through the research.

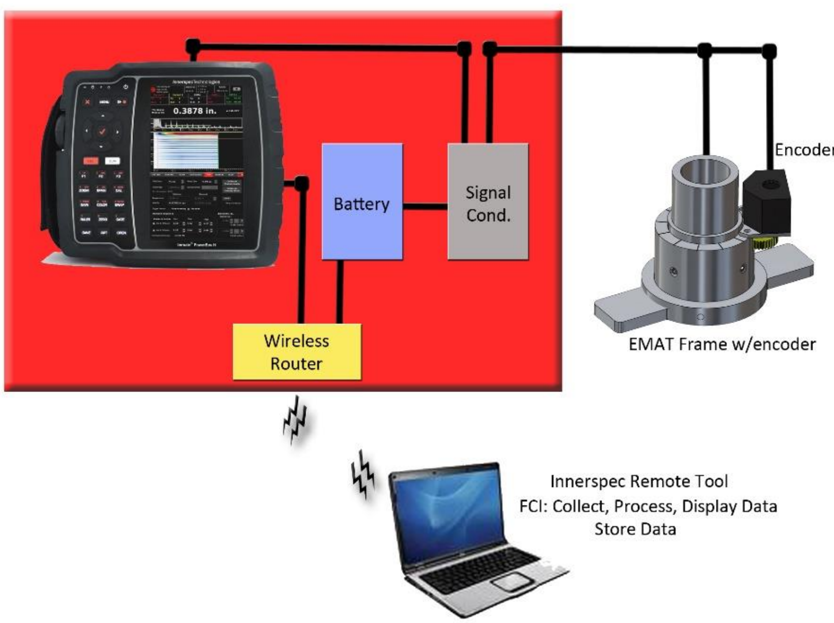


Figure 5 Block diagram of the field portable instrument design concept (FCI).

3.2.1 *Ultrasonic Pulser- Receiver*

A commercially available ultrasonic instrument (Innerspec Temate® Powerbox H (PBH)) was used to provide the pulser-receiver for launching and receiving ultrasonic waves. The commercial instrument was used to because it integrated several key components necessary for USM such as an ultrasonic pulser, high speed ultrasonic receiver, and a transducer for launching and receiving ultrasonic waves. The transducer is an Electromagnetic Acoustic

Transducer (EMAT) that launches and receives ultrasonic waves through electromagnetic interactions with the specimen under test. The PBH provides the high-power pulser characteristics necessary for use of an EMAT sensor. The EMAT provided with the commercial PBH instrument was used for launching and receiving polarized shear waves. A signal conditioner module containing a multiplexer and tuning module provided the first stage of amplification for the low-level signals generated from the transducer. The multiplexer permits the use of the pulse – echo technique by merging the transmitted and received signals onto a single line.

3.2.2 *Transducer*

EMATs were used in the research to generate and detect ultrasonic shear waves in the steel plate. EMATs were used because no coupling medium is required to transmit the ultrasonic wave between the transducer and the steel plate. Waves are generated through electromagnetic interactions within the steel plate itself. In contrast, conventional ultrasonic transducers consist of a piezoelectric sensor element that produces acoustic waves in the transducer. The acoustic waves are transmitted from the transducer into the material using a coupling medium. The coupling of the waves between the transducer and the material can be inconsistent, resulting in variations in the signal amplitude. For USM, the variation in the coupling can make it difficult to achieve the timing accuracy required to make repeatable measurements. For this reason, the use of an EMAT is desirable, since an EMAT does not require mechanical coupling and consequently produces more consistent signals.

Figure 6 shows photograph of the 1.88 in. diameter EMAT used in the research to produce polarized shear waves. A marker placed on the transducer housing indicates the shear wave polarization direction; the polarization direction is adjusted by rotating the transducers to the desired orientation on the steel specimen during testing. The magnetic force from the permanent magnet inside the EMAT holds the transducer onto the surface of the steel; this allows for rotation of the transducer while it is still in contact with the surface of the steel by the application of sufficient rotational force. A specialized transducer fixture was designed to allow for rotation of the transducers and integration of an encoder device for determining the polarization orientation during testing, as described in the following section.

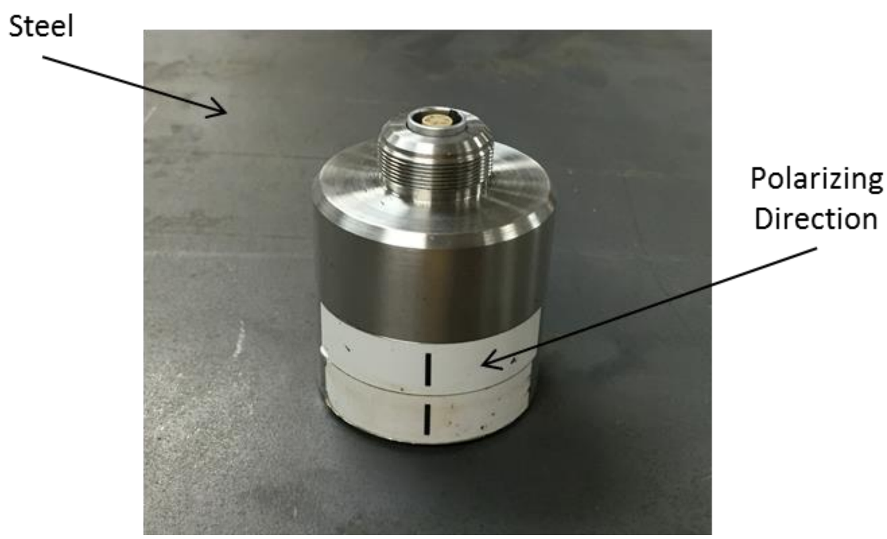


Figure 6. EMAT fixed to the surface of a steel specimen.

3.2.3 *Transducer Fixture Design*

Birefringence measurements require the detection of ultrasonic waves at different polarization directions as the transducer is rotated. A special transducer fixture was designed and manufactured that allowed for data collection at specific transducer orientations. This fixture allows rotation of the EMAT sensor and for automated collection of the ultrasonic data at known rotational positions. Figure 7A shows a 3D CAD rendering of the transducer fixture design. Figure 7B is an image of the final fixture after fabrication. The transducer is housed in an outer tube with a rotation handle that allows for easy rotation of the transducer. An encoder is attached to the outer tube with its own encoder housing. The encoder is used to synchronize data collection with the rotational angle of the transducer. The whole fixture attaches to magnetic materials via a plate with embedded magnets allowing for the fixture to remain stationary while the transducer is allowed to rotate. Several different attachment plates were designed to allow for a variety of different mounting options to address different possible geometric restraints. For example, for large plates where there are few spatial constraints, an attachment plate with four magnetic-arm plates was designed that provides for maximum stability of the transducer. For situations where spatial constraints are significant, such as where connected members intersect, a ring-shaped magnetic attachment without magnetic-arm plates was designed.

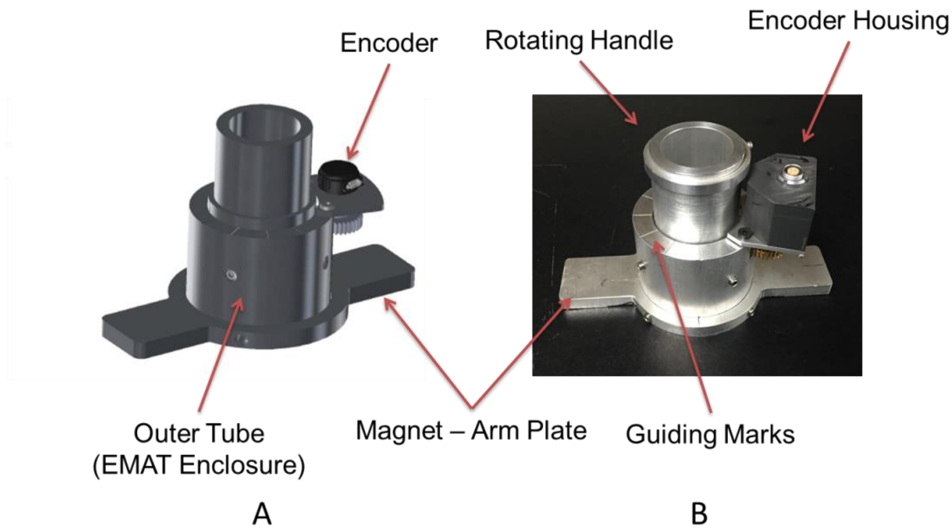


Figure 7. (A) EMAT fixture 3D solid model. (B) Fabricated EMAT fixture.

3.2.4 *Custom Enclosure*

A custom enclosure was constructed for the field portable system as shown in Figure 8. This custom enclosure houses the PBH and all of its necessary components for operation. It features a removable front panel for access to the PBH control panel and display. It also has easy access to external connections for connectivity with the EMAT sensor and to allow for hardwiring to the remote laptop computer via USB connection, if desired. The enclosure was fabricated using 80/20 aluminum extrusions with red and black expanded polyvinyl chloride (PVC) panels. The materials used for the custom enclosure were selected because of their low weight, durability, and weather resistance. These materials were used to form an enclosure with suitable durability for field operations.

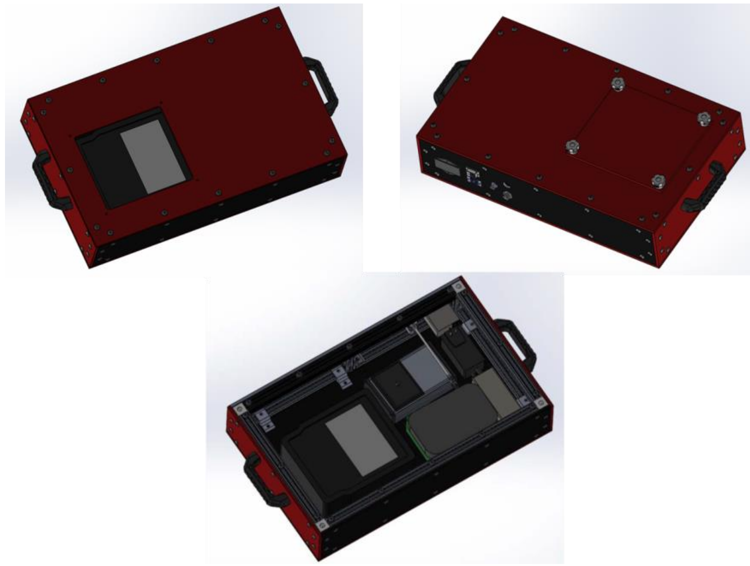


Figure 8. 3D solid model of the custom enclosure used to house the field portable instrument.

3.2.5 *Final System Design*

Figure 9 is an image of the final field-portable system developed during this research. The final system is comprised of a custom enclosure, specifically fabricated for the housing of the pulser – receiver (PBH) system and signal conditioner; a transducer fixture that retains and allows for rotation of the EMAT transducer during testing; and a laptop computer for collecting and processing data. Software developed by Fuchs Consulting, Inc. (FCI) for data processing. All components of the system can be operated by battery for field operations.

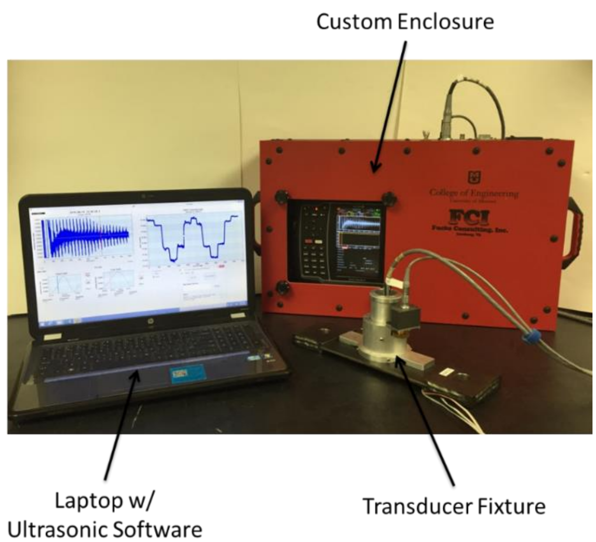


Figure 9. Image of the final portable ultrasonic stress measurement instrument.

3.2.6 *Data Processing Software*

Special software was developed to analyze the unique data generated for the birefringence measurement, which consists of multiple ultrasonic wave timing measurements as the transducer is rotated through 360 degrees. Software was developed by FCI to provide the necessary timing measurements to determine stress.

Figure 10 shows an example signal produced by the polarized shear waves generated by the EMAT transducer propagating through the thickness of a steel plate. The wave reflects multiple times through the thickness of the plate, producing multiple echoes as shown in the figure. Figure 10A shows a sample A – scan obtained from shear wave propagation through the thickness of a specimen with an individual wave packet displayed in Figure 10B. As shown in the figure, a three cycle pulse was typically used for to generate the ultrasonic wave in the material under test.

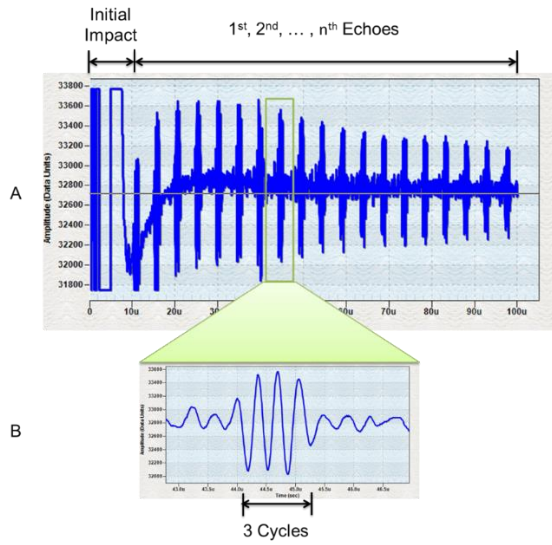


Figure 10. (A) Sample A – scan of shear waves propagating through the thickness of a material. (B) Individual wave packet showing the three-cycle pulse.

Signals such as those shown in Figure 10 were collected at appropriate polarization directions, and then processed to determine the birefringence. Figure 11 shows the graphical user interface of the software developed to automatically perform the necessary data processing. Selected start and end gates are used to identify the limits of the timing interval to be analyzed. Five or six "echoes" were typically included between the gates. After setting the gates for timing measurements, all of the A – scans obtained during one test are processed to obtain timing measurements. For example, if the test consisted of rotating the transducer through 360° of rotation with measurements at 1° intervals, then the software would batch process all 360 signals to produce the timing measurements and associated polarization directions.

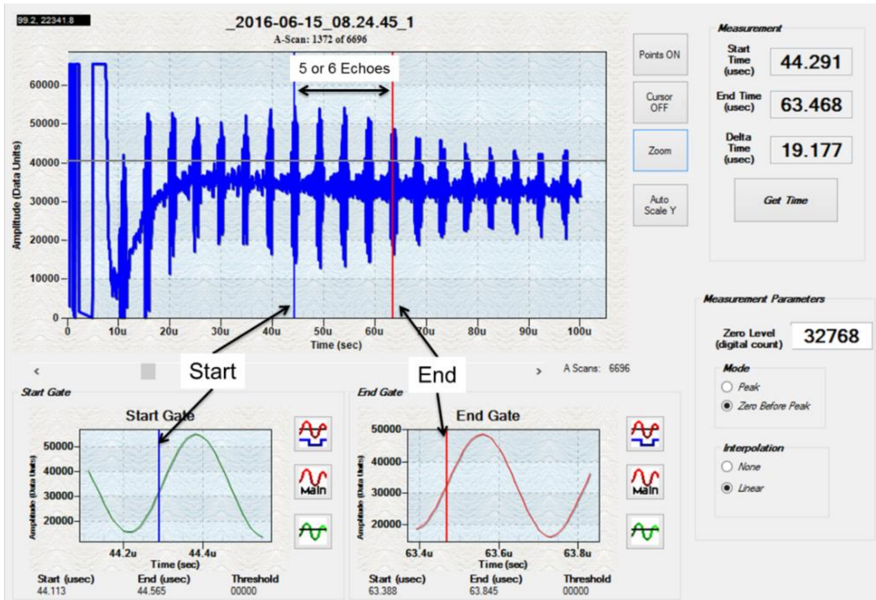


Figure 11. Graphical user interface of the software developed for timing measurements.

The software supports the data processing for a full 360° rotation of the transducer if necessary to achieve a stress measurement. For plates where the rolling direction and principle stress directions are known, as few as two measurements at 90° to each other could be used to make the stress measurement. For the case of gusset plates, where the stress field in more complex and the direction of principal stresses is not known, a full rotation of the transducer is used to identify both the magnitude and direction of principal stresses.

3.3 LABORATORY TESTING

Laboratory testing was performed to test the operation of the USM instrument developed through the research and to analyze the ultrasonic properties of the different steel specimens. Steel specimens were fabricated to investigate the acoustic properties of different types of steel used in bridge construction. Testing was also performed to determine the variation in acoustoelastic properties between different types of steel.

3.3.1 *Experimental*

This section describes the experimental details of the laboratory testing. This includes a description of the test specimens, the test setup, and data collection.

3.3.1.1 Specimens

Steel plate specimens were manufactured to analyze the variations in acoustoelastic properties of typical materials. Specimens were manufactured with their rolling direction in different orientations to allow for acoustoelastic measurements when principle stresses are not aligned with rolling direction. For example, specimen A is a 90° specimen with the rolling direction aligned with the specimen axis, while specimen B is a 0° specimen oriented with the rolling direction perpendicular to the specimen axis. These specimens were fabricated using different types of steel grades used in typical bridge construction: A7, A36, and A588. The A7 steel in representative of steel common in older bridges (pre-1960’s), A36 and A588 specimens represented contemporary steels that might be used for bridge construction. The steel for the A7 steel specimen originated from steel angle on a MoDOT truss bridge over the Lake of the Ozarks in Missouri, which had recently been removed from service. This type of steel is similar to the steel of the bridge used in the field testing of the ultrasonic system and is still readily found in older truss bridges. Specimens of different thickness were tested, as described in Table 1. Specimens were cut from different plates to provide some information regarding the potential scatter of acoustoelastic properties in the base materials. The surface of the steel specimens was typical mill scale as delivered by the local provider with the exception of the A7 steel specimen, which had typical steel coatings that were removed by grinding.

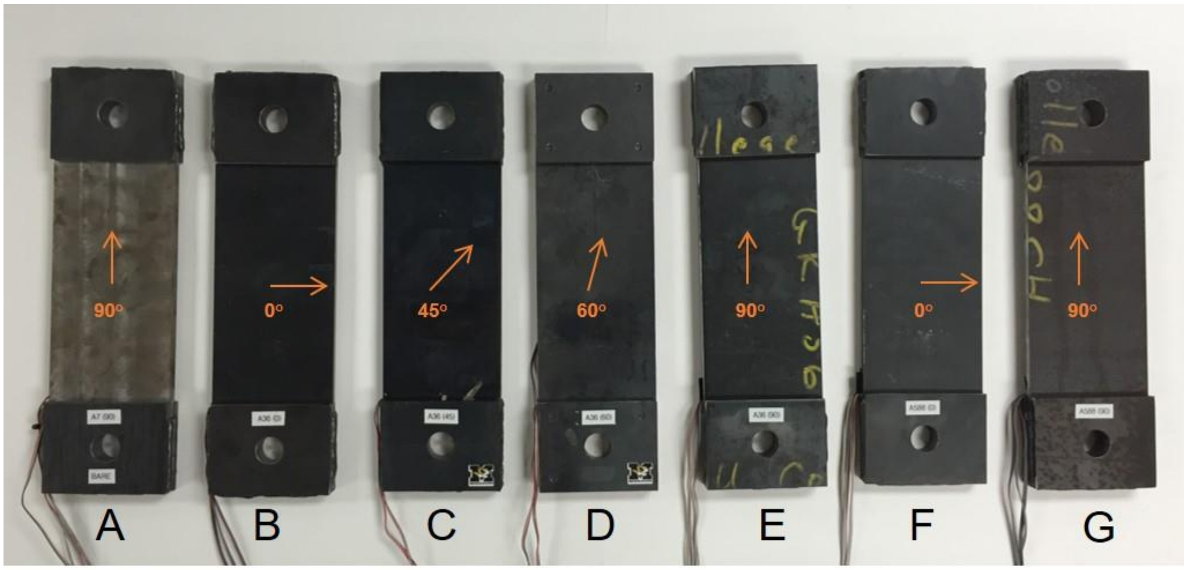


Figure 12. Photograph of the steel specimens fabricated to determine the texture and stress acoustic constants. The red arrows represent the rolling direction of the steel material.

The specimens were fabricated with a reinforcement plate and a hole at each end to accommodate a pin through which the loads are applied. Loads were applied using a Materials Testing Systems (MTS) loading machine during testing.

Table 1. Summary of the characteristics of the fabricated test specimens.

Plate Specimen	Steel Grade	Plate Angle (°)	Plate Thickness (in.)
A	A7	90	5/16
B	A36	0	1/4
C	A36	45	1/4
D	A36	60	1/4
E	A36	90	5/16
F	A588	0	1/4
G	A588	90	5/16

3.3.1.2 Test Setup

Figure 13 shows a picture of the basic uniaxial tension experimental setup. The setup consisted of an individual test specimen fixed via pin – and – clevis connections on the top and bottom of the specimen. The plate was loaded in tension in a uniaxial stress condition. The testing was load – controlled by a computer program created in LabView, which controlled the displacement of the hydraulic ram in the MTS machine until the desired level of loading was achieved.

The resulting strains induced in the specimens were measured using typical 350Ω strain gages. The USM were compared with the strain gage measurements for verification of the birefringence stress measurement and to determine the acoustoelastic constants needed for stress calculations.

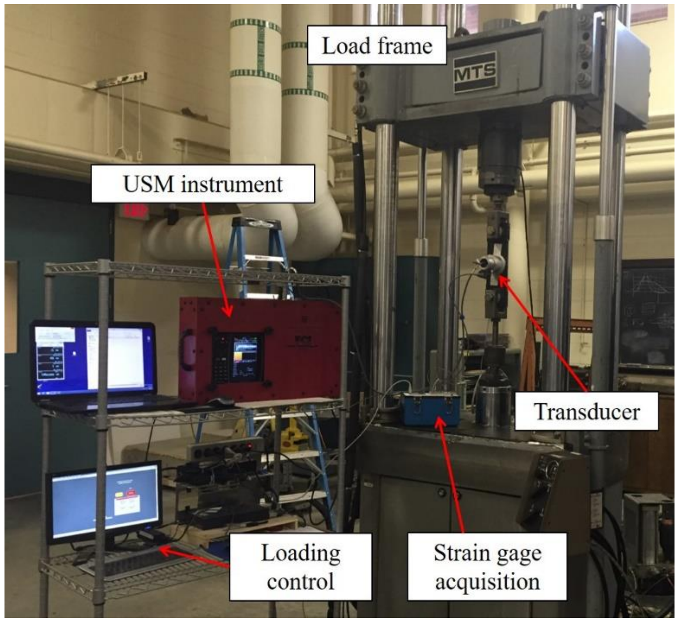


Figure 13. Basic test setup consisting of the loading apparatus, strain gage acquisition system, and portable ultrasonic instrumentation.

3.3.1.3 Data Collection

The laboratory testing was completed using two different procedures depending on the orientation of the rolling directions with respect to the axis of loading. For specimens where the rolling direction was parallel or orthogonal to the loading direction, such that the principal stresses align with the rolling direction, there is no rotation of the pure-mode polarization angles. As a result, less data is necessary to achieve the stress measurement. For these specimens, waveforms were collected at 30° intervals while the transducer was rotated from 0° through 360°. For specimens where the rolling direction is off-axis with the principal stress directions, rotation of the pure mode polarization angles is expected. These specimens simulate the conditions that are found for a gusset plate, where complex stress may exist due the interaction of forces from different truss members being joined by the plate. For these specimens, waveforms were collected at 1° intervals from 0° to 360°.

Each test consisted of a texture measurement at 0 psi loading to determine the natural birefringence in the specimen, followed by USM at different load steps. Load steps of 5,000 psi were applied, ranging from unloaded up to approximately 70% of the yield strength of the steel grade that was being tested. A summary of the load steps for different steel grade types can be seen in Table 2. The ultrasonic measurements were analyzed to determine the pure-mode polarization orientation, the natural birefringence value due to texture, and the birefringence at each load increment. These birefringence values were compared with the measured stresses to obtain the acoustoelastic properties of each material.

Table 2. Loading steps for the different types of grades tested (0.7Fy = 25,200 psi for A7 and A36 and 0.7Fy = 35,000 psi for A588).

Load Step	Stress (psi)		
	A7	A36	A588
0	0	0	0
1	5,000	5,000	5,000
2	10,000	10,000	10,000
3	15,000	15,000	15,000
4	20,000	20,000	20,000
5	25,000	25,000	25,000
6	N/A	N/A	30,000
7	N/A	N/A	35,000

3.3.2 *Results*

This portion of the report documents the results of the laboratory testing. Results are reported in several sections. First, the results of texture testing are reported. These tests were used to determine the typical anisotropic behavior of the different materials tested. The second section reports results on specimens where the applied tensile loading was coincident with the rolling direction of the steel plates. These results are useful, for example, for stress measurement in open steel shapes in bending or axially loaded, where the principal stresses are aligned with the rolling direction of the plate. In this case, there is no rotation of the polarization orientations, and the determination of stress is simplified. Finally, results are reported for specimens where that applied tensile loading is not coincident with the rolling direction of the plate. For this orientation, both birefringence time measurements and rotation of the fast and slow directions are necessary for determining the applied stress.

3.3.2.1 Texture Results

Figure 14 illustrates typical time-of-flight (TOF) curves for an axially loaded specimen of A36 steel with ultrasonic waveforms captured at 30° intervals. The data in figure shows the actual TOF for the shear wave at each position. A fitted curve has been applied for illustration purposes. Data collection for one test rotation from 0° to 360° was initiated at the horizontal and the transducer was rotated in a clockwise direction. Figure 14 shows a 0° specimen in which the rolling direction in orthogonal to the direction of the applied load. As shown in this figure, the fast direction (smallest time) is aligned with the rolling direction (i.e. 0° and 180°). TOF varies as the polarization angle is rotated, with the maximum TOF occurring at 90° and 270°. For the 0° specimens, the difference between the maximum and minimum TOF increased as the tensile loading of the specimens was increased. As shown in the figure, the application of tensile loading results in a slowing of the wave with applied stress. This signified a positive rate of change of the birefringence values. The natural birefringence (i.e. texture effect) was determined from specimen in the unstressed state (0 psi in Figure 14).

Table 3 shows the results of the natural birefringence measurements determined by experiment. The values represent the texture effect in the materials, i.e., the anisotropy caused by rolling. These data indicate that the natural birefringence ranged from approximately 0.002 to 0.006 among the different steel plates tested. The measurement were repeatable, exhibiting standard deviations of less than 1% for all of the plates. These data indicate that there is variation in the natural birefringence resulting from the rolling process. These data are significant for the measurement of axial stresses in bridge members, where the natural (unstressed) birefringence needs to be known in order to make a quantitative measurement of stress. The data suggests that it may necessary to establish the natural birefringence for a given steel plate by either identifying a portion of the plate that where stresses are zero, or by physically removing a core to establish the natural birefringence.

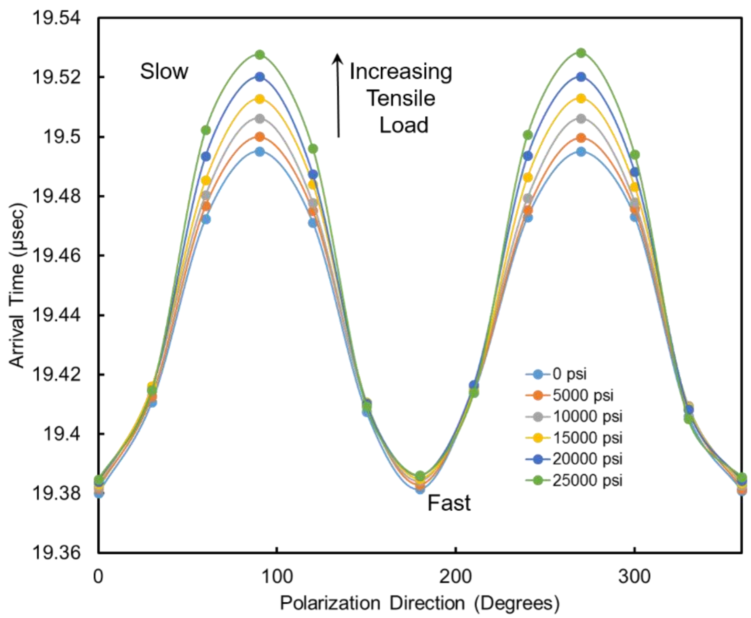


Figure 14. Time-of-flight measurements showing variation in arrival time as the transducer is rotated through 360° at different levels of applied stress.

Table 3. Natural birefringence measurements for steel specimens.

Test #	A7	A36				A588	
	90°	0°	45°	60°	90°	0°	90°
1	0.006188	0.005929			0.003118	0.005977	0.003039
2	0.006176	0.005927	0.002474	0.001967	0.003067	0.005952	0.002988
3	0.006174	0.005892			0.003141	0.005963	0.003036
Avg.	0.006179	0.005916	0.002474	0.001967	0.003109	0.005964	0.003021
Stdev.	0.000006	0.000017	0	0	0.000031	0.000011	0.000024

3.3.3 *Stress Relationship*

This portion of the report describes the results of laboratory testing to evaluate the relationship between ultrasonic birefringence and applied stresses for common bridge steels. The specimens shown in Figure 12 and listed in Table 1 were tested in an MTS load frame as described in section 3.3.1.2. The data processing for each test consisted of collecting ultrasonic data at each load and then processing the ultrasonic data to measure the birefringence. Results are presented for on-axis stresses. For these specimens, the rolling direction is aligned with either the fast or the slow wave velocity orientation. Consequently, there is no rotation of fast and slow orientations, since the anisotropy from rolling is aligned with the anisotropy induced by the application of stresses. Results are also presented for the off-axis specimens (45° and 60° specimens) where the material anisotropy is not aligned with the stress-induced anisotropy such that rotation of the fast and slow directions occurs with stress-induced anisotropy.

3.3.3.1 Acoustoelastic Measurement of On-axis Stresses

Figure 15 shows the relationship between birefringence and uniaxial tensile stress for specimens with 0° and 90° orientations. Birefringence showed a linear relationship between stress for both the 0° and 90° specimens. The relationship has a positive rate of change for the 0° specimens while a negative rate of change is observed for the 90° specimens. In other words, the sign of the slope depends on whether the tensile stress aligns with the rolling direction or is perpendicular to the rolling direction. When the tensile stress is aligned with the rolling direction, the slope is negative.

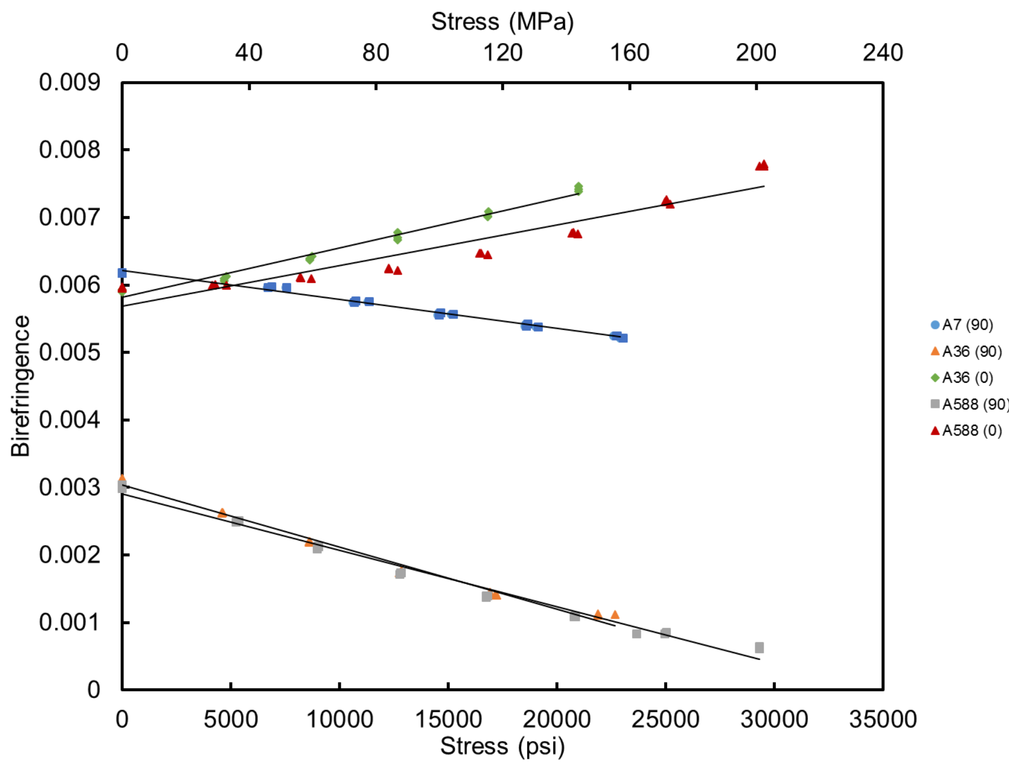


Figure 15. Stress-acoustic relationship for 0° and 90° specimens.

Table 4 summarizes the rate of change of the birefringence for the 0° and 90° specimens. The average rate of change for the 0° specimens is 6.5x10^{-8} psi^{-1} while for the 90° specimens it is -7.0 x10^{-8} psi^{-1}. These data indicate that for the different types of steel tested, the acoustoelastic constants were similar in magnitude. It should be noted that the modern steels (A36 and A588) had very similar results, with an average acoustoelastic constant of 7.5 x 10^{-8} psi^{-1}. The historic A7 steel tested had a different slope than the modern steel. This results is probably associated with the different manufacturing methods used at the time the steel was produced.

Table 4. Summary of the acoustoelastic constants for the 0° and 90° specimens.

Material	0°		90°	
	x10^{-8} psi^{-1}	(x10^{-5} Mpa^{-1})	x10^{-8} psi^{-1}	(x10^{-5} Mpa^{-1})
A7	N/A	(N/A)	-4	(-0.6)
A36	7	(1)	-9	(-1)
A588	6	(0.9)	-8	(-1)
Average	6.5	(1.0)	-7.0	(-0.9)

3.3.3.2 Acoustoelastic Measurement of Off-Axis Stresses

For specimens with off-axis rolling directions, the anisotropy induced by rolling is not aligned with the stress-induced anisotropy. This results in a rotation of the fast and slow orientations of the polarized shear wave when stress is applied. Figure 16 shows the TOF curves for the specimens fabricated with the rolling direction at an angle of 45° relative to the specimen axis. Notice that the minimum TOF corresponding to the rolling direction (fast direction) of the 45° specimen corresponds to 135°. This is due to the testing of one rotation from 0° to 360° that was started at the horizontal with a clockwise rotation of the transducer. A sine-regression was applied to the data to obtain the TOF curves in Figure 16B to reduce noise. As the loading increases a noticeable phase shift can be observe. This phase shift corresponds to the rotation through an angle φ of the pure-mode polarization direction.

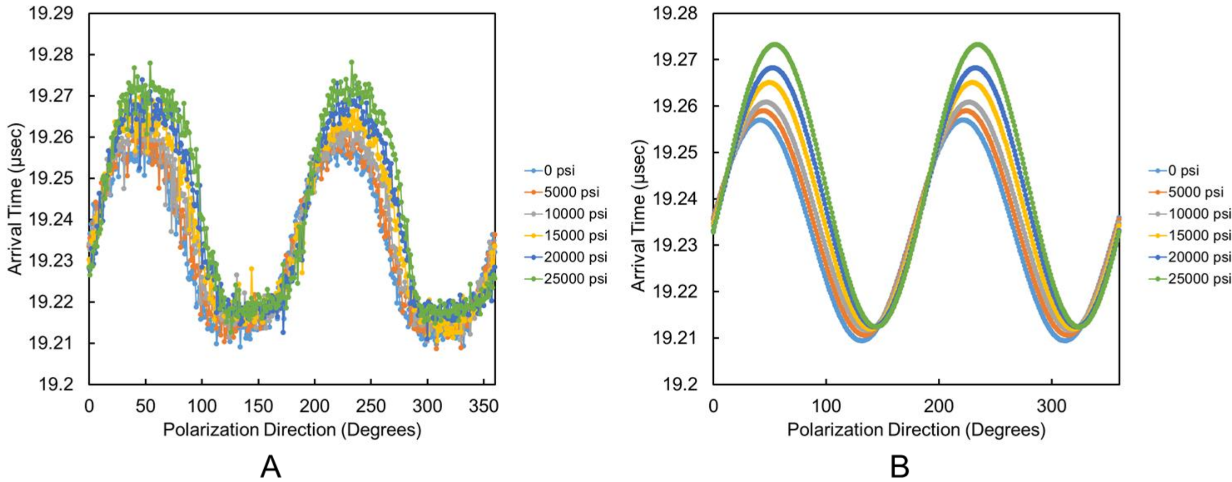


Figure 16. Time-of-flight measurements of the 45° specimen. (A) the average data of two rotations from three tests. (B) sine regression obtained from the average data.

Figure 17 illustrates the relationship between birefringence and stress for the 0°, 45°, 60°, and 90° specimens fabricated out of A36 steel. As previously explained, the 0° and 90° specimens have a linear relationship. Meanwhile, the 45° and 60° specimens are not linear, and data was fit with a 2^{nd} order polynomial line. This means that the specimens have a slight nonlinear relationship between birefringence and stress associated with the rotation of the pure-mode polarization direction. The relationship between the pure-mode polarization rotation through the angle φ can be seen in Figure 18. From the figure, it can be seen that the pure-mode polarization rotation increases as stress increases in the both the 45° and 60° specimens. The 45° specimen, however, has a lower rate of change than the 60° specimen.

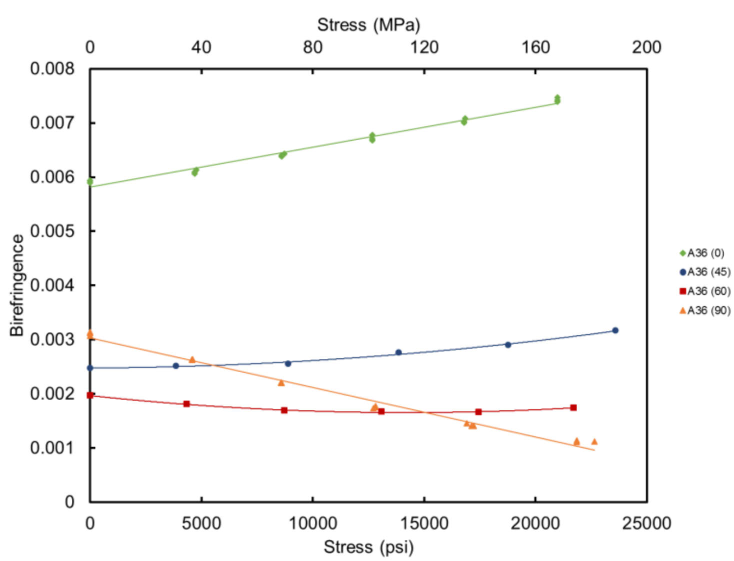


Figure 17. Relationship between birefringence and uniaxial tensile stress for the specimens fabricated out of A36 steel.

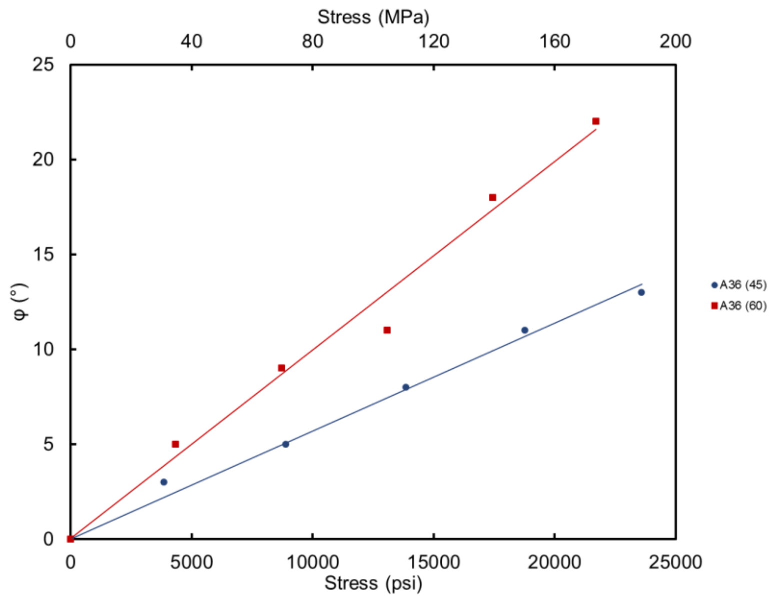


Figure 18. Relationship between the pure-mode polarization rotation φ and uniaxial tensile stress for the 45° and 60° specimens.

Table 5 is a summary of the birefringence, pure-mode polarization direction rotation angle φ, and shear stress obtained during testing of the 45° specimen. These data were used to determine the acoustoelastic constant $m_3$using Equation 7, this constant was calculated for each loading step. The average of all the values calculated was determined to be the stress acoustic constant m_3= 5.79x10^{-8} psi^{-1}. The calculated value of m_3 was then used to calculate the shear stress of the 45° and 60° specimen. Figure 19 shows the relationship shear stress measured with USM and shear stress measured with a conventional strain gage rosette. It can be observed from this figure that the USM determines values close to those measured using a conventional strain gage rosette. The error was calculated by assuming the strain gage value as the true value. The absolute average percent error of the 45° specimen was 7.6%, while the absolute average error of the 60° specimen was 10.5%.

Table 5. Summary of the birefringence, φ, shear stress, and calculated stress acoustic constant for the 45° specimen.

Load Step	B	ϕ (°)	τ_{xy}		m_3	
			psi	(MPa)	x10^{-8} psi^{-1}	(x10^{-8} MPa^{-1})
0	0.002474	0	0.0	(0.0)	N/A	(N/A)
1	0.002513	3	1928.5	(13.3)	6.81	(9.88)
2	0.002557	5	4441.8	(30.6)	4.99	(7.25)
3	0.002762	8	6926.2	(47.8)	5.5	(7.97)
4	0.002902	11	9386.3	(64.7)	5.79	(8.4)
5	0.003163	13	11798.2	(81.3)	5.88	(8.52)
			Average		5.79	(8.40)

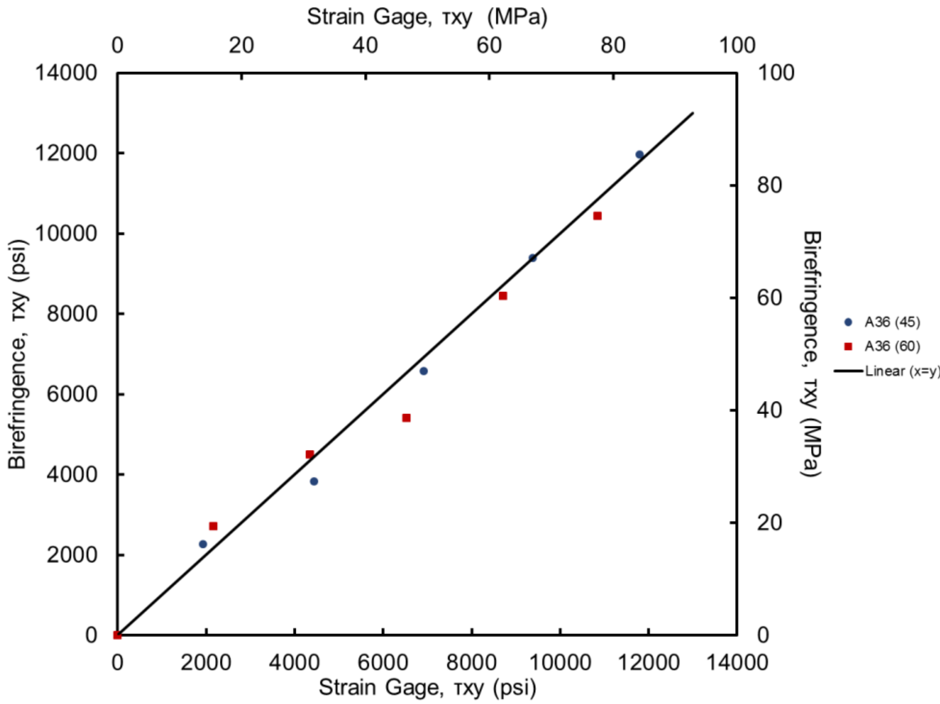


Figure 19. Birefringence shear stress versus strain gage shear stress for the 45° and 60° specimens.

These data show good correlation between the theoretical birefringence predictions and the actual test results under laboratory conditions. These data also showed that the rotation of the polarization angles results from the presence of shear stress could be measured and related to the actual shear stresses. The results are significant for demonstrating the birefringence measurements needed to assess that shear stresses in gusset plates.

3.3.3.3 Surface Conditions

Measurements were made in the laboratory to evaluate the effect of different surface conditions on the ultrasonic waves generated and received by the EMAT. Ultrasonic shear wave propagation through typical bridge components may experience signal degradation. Prior research activities performed by FCI have noted significant signal loss under certain types of surface coatings, particularly on the opposite face of the measured surface. Degradation in the signal appears to mainly come from the back side of the specimen.

Laboratory specimens were fabricated to test the surface condition effect on ultrasonic characteristics. The specimens consist of bare steel, primed steel, and painted steel. These parameters were chosen to test the effects of each type of surface with the generation/reception of ultrasonic waves using the EMAT. The test specimens were unstressed (zero loading) during testing. The purpose of this test was to observe the quality of the waves generated under specific surface conditions typically observed in steel bridge members.

Figure 20 are the waveforms obtained from testing specimens with different surface conditions. The paint on the specimens was from the original paint on an out-of-service truss bridge. From the resultant waveforms, strong waveforms were observed with the bare surface condition, but weaker signals for the painted and primer surface condition. From these tests it was shown that the EMAT was sensitive to the surface conditions, and worked best when surfaces were bare. These data indicated that improved sensor technology to increase the signal to noise ratios for the EMATs may be required for implementation of the technology in the future.

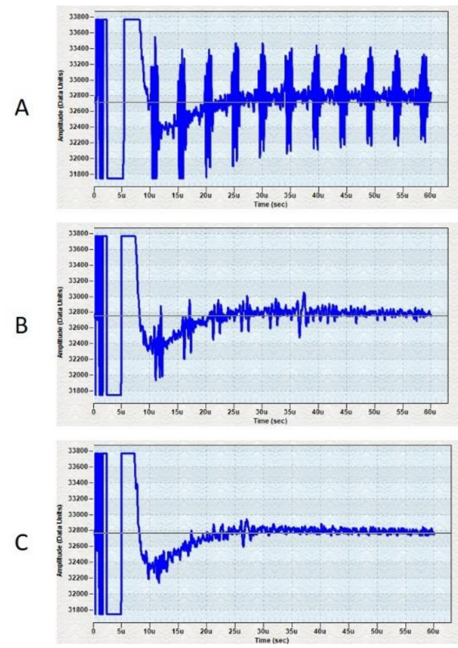


Figure 20. Images of the waveforms obtained from testing varying surface conditions including (A) bare, (B) primer, and (C) painted.

3.4 FIELD TESTING

The USM technology developed through the research was field-tested to evaluate its capability for measuring total stress in gusset plates. The field testing consisted of performing USMs on a gusset plate of a truss bridge in the field. The field testing provided an opportunity to evaluate the field performance of the technology, and also validate the total stress measurement provided by the birefringence measurement approach. The field test included removing cores from the gusset plate to evaluate the total stress present in the gusset plate using a conventional strain gage. These data were then compared with the quantitative stress measurements made with the USM technology. The field test demonstrated the successful operation of the portable USM technology developed through the research, and helped verify the accuracy of the shear stress measurements obtained under field conditions. The following section of the report describe the field testing of the technology.

3.4.1 *Test Description*

An 80 ft long pony truss bridge that was scheduled to be demolished was selected for the field testing. The through-truss design of the bridge provided good access to the gusset plates on the bridge for testing. Figure 21 is a photograph of the truss bridge with the gusset plate testing location marked.

A dump truck containing different amounts of gravel was used to load the bridge. The dump truck was stationary on the bridge deck while the ultrasonic data was collected. Data was collected without the truck, with the truck empty, ½ full, and full of gravel. In this way, different stress levels were obtained in the gusset plate and measured ultrasonically.

Data on the load induced in the gusset plate was documented by strain gage rossettes mounted to the gusset plate. The strain gauge rosettes were mounted on the back side of the gusset plate at the location where USM data was collected. A 0°/45°/90° planar strain gage rosette from Omega Engineering was used to measure shear stresses. This rosette incorporates 6 mm grids with 350Ω resistance gages and pre-attached leads. Paint was removed from the front and back of the gusset plate to enable placement of the strain gages and ensure sufficient signal strength to perform ultrasonic measurements. The axial members connected by the gusset plate were also measured. For axial members the strain gages were installed on the same side of the member as where the USMs were made. Access to the back side of the members was not possible due to the geometry of the built-up members. Consequently, paint could not be removed from the back side of the plates, which presented difficulties in acquiring data of adequate quality to perform USM.

Measurements with the new ultrasonic technology were made by attaching the EMAT sensor onto the selected gusset plate and recording data while the transducer was rotated manually through 360° of rotation. In this way the magnitude and direction of the birefringence could be measured. Data from the ultrasonic testing was processed using the software developed through the research. The magnitude and direction of the birefringence was used to determine the shear stresses in the gusset plate using the acoustoelastic constants determined for A7 steel determined through the laboratory testing. To verify the accuracy of the stress, strain gage measurements were obtained as described below.

Figure 21. Side view photograph of the pony truss bridge used for field testing.

3.4.2 *Verification of Total Stress Measurements*

The USM technology developed is unique from other measurement technologies because it measures total stress, as previously described. Strain gages are only capable of measuring the stresses that occur <u>after</u> the strain gage has been installed, and therefore cannot measure the dead-load and residual stresses already present at the time the gage is installed. To overcome this limitation, the research implemented a unique plan to remove a core of material surrounding the strain gage rosette to release any dead load or residual stresses. In this way, the stresses that were present when the strain gage was installed are released when the core is cut from the parent material, and the resulting strains were then be detected by the strain gage. The strain gage measurements including the released stresses could then be compared with the USM measurement directly. The sum of the dead load and live load stresses determined via the strain gage measurement was the total stress measurement obtained with the strain gages and was subsequently compared with the total stress measurements obtain with the new USM technology.

A magnetic drill with a 3 in. core drill bit was used for coring of the steel specimens. Figure 22 shows the removal of the core from the gusset plate. As described previously, the strain gages were mounted on the back side of the plate, and the USM were made on the front side of the plate in the same location. The strain gages remained attached and data was collected throughout the removal process. The strains were measured continuously until the removed core had completely cooled following the extraction. These date were then used to measure the total stress present in the gusset plate in-situ for comparison with the measurement made by the USM.

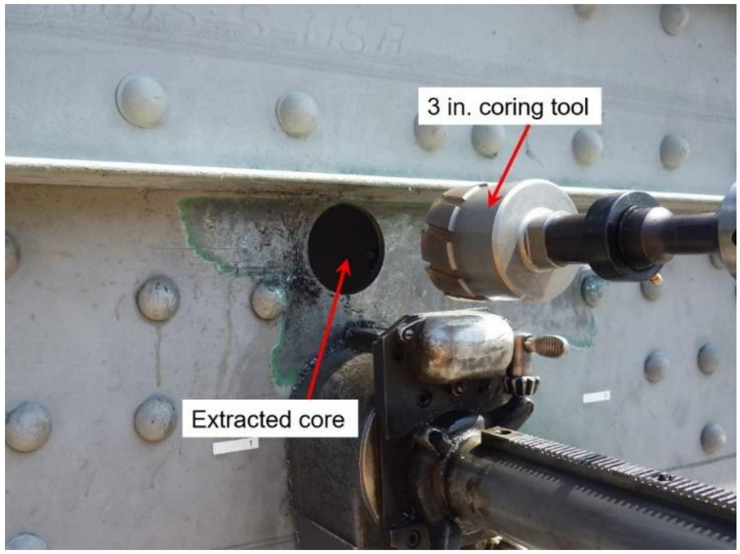


Figure 22. Photograph of extracted core and coring tool.

3.4.3 *Results*

The field test resulted in measurements of the shear stress in the gusset plate. The measurement of shear stress was successful as shown in Figure 23. In this figure, the shear stresses calculated from the USM and the corresponding strain gage measurements are both shown. The strain gage measurements were adjusted to include those strains measured when the core was removed from the gusset plate. The USM measurement were direct measurements of stress made in-situ. The figure shows the stresses measured in the field for different truck loading conditions, as indicated on the horizontal axis. The USM instrument was able to detect the changes in stress of ~500 psi that resulted from different trucks loads. Quantitatively the magnitude of the total stress was very close to actual total stress.

Table 6 shows the quantitative stress measurements made at location 1 using the USM as compared with the strain gage measurements. These data illustrate that that measurements made by the USM were accurate, with an absolute average error of 7.7%. The data indicate that the birefringence measurement was effective for estimating the shear stresses in the gusset plate.

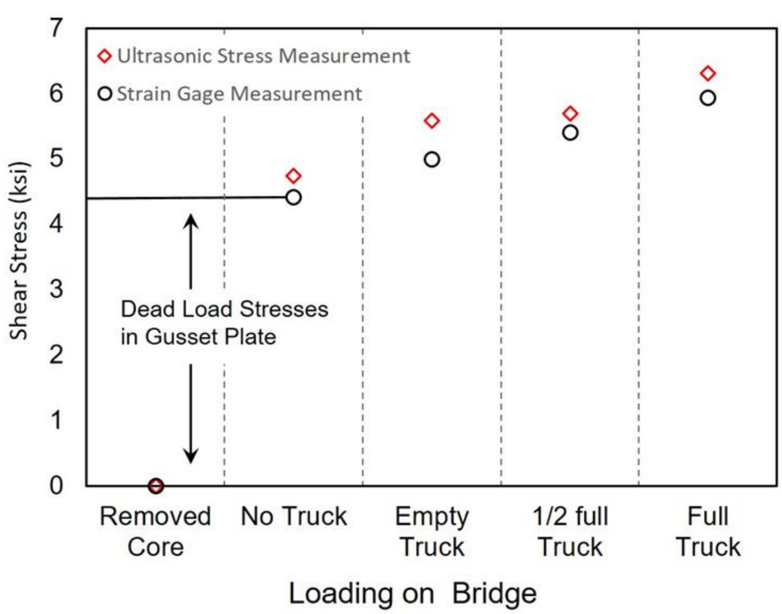


Figure 23. Results of field testing showing shear stress measurement made with USM as compared with strain gage measurements of stress.

Table 6. Shear stresses measured with USM and strain gages at location 1.

Loading	Birefringence, τ_{max}		Strain Gage, τ_{max}		% Error
	psi	(MPa)	psi	(MPa)	
Removed	0	(0)	0	(0)	N/A
Zero	4744.73	(32.7)	4415.2	(30.4)	7.5
Empty	5585.69	(38.5)	4990.5	(34.4)	11.9
Half-Full	5695.78	(39.3)	5410.1	(37.3)	5.3
Full	6306.29	(43.4)	5937.3	(40.9)	6.2
			Average		7.7

A second location on the gusset plate where measurements were made did not produce signals of adequate quality to determine the stress at that location. This is thought to be due to the location of the strain gage on the back side of the plate, which interfered with the reflection of the ultrasonic wave. The measurements on axial members was also not successful due to the paint on the back side of the members, which could not be removed due to the closed geometry of the members. Laboratory tested confirmed that the surface conditions on the back side of the plate affected the ultrasonic signal quality, as discussed in section 3.3.3.3. A sensor with improved signal-to-noise characteristics is needed to overcome this limitation.

4 CONCLUSIONS

The objective of the research was to develop a portable instrument for measuring the total stress in steel bridge members. A portable USM instrument was developed that was capable of measuring total stress. The USM instrument was demonstrated in a field test. During the field test, the results of the USM total stress measurement were compared with total stress as determined by removing a core instrumented with strain gages. To the knowledge of the research team, this approach to verifying the performance of the USM is unique. The results of this field test demonstrated that the technology was implementable under field conditions, and was capable of making a total stress measurement of shear stresses in gusset plates. USM results compared well with the total stress measured by the strain gage on the removed core, with an average error of only 7.7%. The field test also indicated the surface conditions affected ultrasonic signal quality at some locations tested.

Laboratory testing showed that the different bridge steels tested had different ultrasonic properties that need to be considered in the performing stress measurements with the USM technology. Both the natural birefringence (texture effect) and acoustoelastic constants varied somewhat between different steel specimens tested in the laboratory. For specimens with principal stresses aligned with the rolling direction, it was found that there was a linear relationship between the birefringence and the applied stresses. For specimens loaded with principal stresses unaligned with the rolling direction, the relationship was nonlinear and rotation of the polarization angle was observed as expected.

This project represented a significant step toward creation of a portable stress measurement instrument and a first-generation prototype was developed. The prototype was utilized both in the laboratory and during field test the demonstrated the capabilities of the technology.

4.1.1 *Future research needs*

Future research needs include obtaining addition measurements and experience with the prototype instrument, as describe below in the implementation plans. Further testing will help prove-out the technology, demonstrated its utility, and help develop methodologies for more wide-spread implementation.

Ultrasonic sensor performance needs to be improved to reduce the effect of surface preparation such that coatings do not need to be removed to make measurements. The EMAT sensors used during the research a capable of generating and receiving ultrasonic waves without the removal of coatings. For birefringence measurements, the precise timing control requires high-quality ultrasonic signals. Improvements to the signal to noise characteristics of these sensors is needed to produce USM without requiring removal of coatings.

5 PLANS FOR IMPLEMENTATION

The USM instrument developed through the research created a first-generation prototype that was able to make measurements of total stress on a bridge in the field. Future implementation plans are as follows:

1. Instrument refinement

   The instrument developed in the project was significant in that it was a field-portable total stress system that was demonstration to operation under typical field conditions. Further refinement would improve the ease with at which the instrument can be used. The instrument will be further integrated to make a smaller and even more portable package. Software functions that now operate on a separate field laptop computer will be integrated directly into the instrument.
2. Additional field and laboratory work

   The research completed under this project produced and tested a technology for total stress measurement. Additional testing and implementation of the prototype and the USM methodology is needed to further develop and prove the technology under realistic field conditions. The research team is currently performing additional testing of the USM technology in the laboratory and the field. Laboratory testing is being used to measure the natural birefringence and acoustoelastic constants of different bridge steels. Field measurements are focused on further developing the technology, improving data processing, and developing a larger database of experiences that can be used to promote implementation of the technology by bridge owners.
3. Commercialization

   The research team is further developing the technology toward inclusion of the USM instrument as another tool available from the commercial company Thermalstare, LLC (see investigator's profile). Discussions are on-going with commercial partners to facilitate instrument commercialization.
4. Exposing highway bridge community to this new technology.

   The USM instrument represents a very new measurement to bridge engineers and it will require some effort to expose the community to this new tool. Some of this effort has already been conducted. Research results have already been published in topical conference proceeding sponsored by the FHWA and attended by bridge owners. The research team has also made presentations are regional meetings of maintenance and inspection personnel. A journal article in an archival journal is planned.

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6 INVESTIGATORS' PROFILE

Dr. **Glenn Washer** is a Professor at the University of Missouri – Columbia (MU). Before joining the University, Dr. Washer was with the Federal Highway Administration (FHWA) at the Turner Fairbank Research Center (TFHRC) where he served as the director of the FHWA Nondestructive Evaluation (NDE) program. Dr. Washer has expertise in a wide variety of NDE technologies for the condition assessment of highway bridges, including ultrasonics, thermography, ground penetrating radar, radiography and the visual inspection of bridges.

Dr. **Paul Fuchs** is a private consultant and business owner. He develops commercial technology to assess civil structures, including laser measurement technologies, infrared imaging instrumentation and systems, and ultrasonics. Dr. Fuchs received his Ph.D. in Electrical Engineering from West Virginia University in 1995. Dr. Fuchs has over nineteen years of experience as an entrepreneur and business owner. This includes experience developing, managing, and conducting research projects and related activities for an engineering consulting, instrumentation design and development company.

Drs. Fuchs and Washer began the company ThermalStare, LLC in 2015 to commercialize products developed through their research. The products ThermalStare is commercializing were developed under funding programs such as the FHWA Small Business Innovative Research (SBIR) program, the National Pooled Fund Program, and the NCHRP IDEA program. A suite of technologies that were initiated as research projects are now commercially available from Thermalstare. Applications include, but are not limited to, bridge deck and soffit inspection, thermal stress measurement, coating assessment, and long-term bridge monitoring systems. ThermalStare clients include the US Navy, state Departments of Transportation, and engineering consulting companies.

NCHRP IDEA Project 179
Development of a Portable Stress Measurement Instrument

A new technology for total stress measurement in steel bridge members to improve the safety evaluation of bridges.

Program Steering Committee:
NCHRP IDEA Program Committee
Project Title:
Development of a Portable Stress Measurement Instrument
Project No.: 179
Start Date: August 8, 2014
Completion Date: August 8, 2016

Principal Investigator: Glenn Washer, PhD
washerg@missouri.edu
(573)884-0320

WHAT WAS THE NEED?

Structural evaluation of in-service bridges can be difficult due to the uncertainty in knowing the actual in-situ forces carried in individual bridge members. Engineers must rely on theoretical assumptions and original design drawings to analyze the forces carried in members. Design drawings sometimes do not accurately represent the actual conditions in the field. Individual members may become overloaded when bridges are damaged or deteriorated, or if the bridge joints are not operating properly. Knowledge of the in-situ forces carried in a bridge member and the resulting stresses is needed to effectively analyze structural adequacy and ensure bridge safety. Currently, there are no technologies that are capable of in-situ measurement of stresses in bridge members.

WHAT WAS OUR GOAL?

To develop a portable total stress measurement technology that enables engineers to determine the in-situ forces in bridge members to allow for improved condition assessment and ensure bridge safety.

WHAT DID WE DO?

The research developed a nondestructive test method and instrumentation for determining the total stress in steel bridge members. The technology is based on the measurement of ultrasonic waves propagating through the steel. The velocity of the ultrasonic wave varies as a function of the stresses in the steel. We developed relationships between these wave velocities and the total stress in the steel through laboratory testing. We also developed a compact battery-operated instrument and supporting software to perform measurements in the field. The technology was field-tested to verify the operation and capabilities of the technology in real-world conditions.

New portable stress measurement instrument

WHAT WAS THE OUTCOME?

An ultrasonic stress measurement (USM) instrument has been developed that provides bridge engineers with quantitative measurements of the in-situ stresses in bridge members. The instrument is very unique because there are no other practical total stress measurement methods for in-service steel bridges. The *total stress* measured includes dead load, residual, and live load stresses. This new technology is a significant improvement over other stress measurement technologies such as strain gages, which are not capable of measuring the in-situ residual or dead load stresses in a bridge member. The total stress measurement provided by the USM instrument can be used to analyze the structural adequacy of bridge members in ways not possible using any conventional technologies.

Special sensor used for stress measurement

WHAT IS THE BENEFIT?

The primary benefit of the research is a new technology for ensuring the safety of bridges. The technology measures the actual in-situ forces in bridge members to allow engineers to more accurately analyze their load carrying capacity. This technology can provide key data for identifying at-risk members and evaluating the safety of bridges.

LEARN MORE:

To view the complete report:

XXX.Xxx.xxx

If you are interested in use of this technology or need further information regarding applications, please contact ThermalStare.

www.thermalstare.com