Nondestructive Evaluation Tools to Improve the Inspection, Fabrication and Repair of Bridges

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Abstract

This final report describes the research completed under the project entitled Nondestructive Evaluation Technologies for Highway Bridges. The goal of this research program in Nondestructive Evaluation (NDE) is to improve the safety and reliability of bridges. The objective of the research was to develop better tools for the safety condition assessment of bridges during fabrication, inspection, and repair. The research will enhance the state of good repair by developing technologies for detecting deterioration in its embryonic stages, when maintenance and preservation strategies can be implemented to ensure the state of good repair. The benefit is better, safer, and longer lasting steel and concrete bridges and related structures. Two promising areas of research were carried forward from a previous project and are reported herein. These include:

1) Develop Phases Array Ultrasonic Testing for Steel Fabrication – This research is focused on improving the quality control process for steel fabrication to improve the reliability, safety and quality of welded constructions. The research reported herein documents the assessment of key variables in the ultrasonic testing process in order to develop a better understanding of these variables to support future applications of phased array ultrasonic testing.

2) Ultrasonic Measurement of In-Situ Stress Levels in Gusset Plates

This research was focused on measuring the actual in-situ stress levels in gusset plates to ensure structural safety.

These technologies can make significant improvements in the ability of engineers and inspectors to assess the condition of bridges to improve highway safety and ensure the state of good repair. This report supplements a previous report, entitled “Nondestructive Evaluation Tools to Improve the Inspection, Fabrication and Repair of Bridges.”
Chapter 1 Evaluating Ultrasonic Testing and Phased Array Testing

1.1 Introduction

This section of the report describes the results of the task entitled “Develop Phases Array Ultrasonic Testing for Steel Fabrication.”

1.1.1 Goals and Objectives

The goal of the research was to improve the quality control process for steel fabrication to improve the reliability, safety, and quality of welded steel components. The objectives of this research were to:

- Measure key factors that influence ultrasonic testing (UT) measurements.
- Assess the influence of these factors on the American Welding Society UT procedure used to detect and characterize defects.
- Identify improvements to current UT procedures.
- Develop test procedures to assess these key factors for phased array ultrasonic testing (PAUT) measurements.

1.1.2 Motivation

All NDT technologies have unique limitations. Some technologies are unable to detect subsurface defects, while other technologies are ineffective in evaluating certain types of defects. In order to compensate for the limitations of a single technology, bridges are sometimes inspected using several different NDT technologies. While the use of multiple technologies complement each other and account for the unique limitations of each technology, the combined results from the technologies may conflict with one another [1]. It is important to use technologies that are capable of not only detecting defects throughout the entire weld volume, but are also accurate in defect characterization.
Ultrasonic testing is capable of detecting and characterizing subsurface defects within steel welds. Compared to the other technologies, UT is the preferred technology when inspecting welds for subsurface cracks. While UT is adequate for detection purposes, studies show high variability between technician reports with respect to defect characterization. PAUT is a newer technology that has been designed to improve inspection reliability in regards to defect characterization. PAUT improves upon angle beam UT by increasing the amount of information gathered from each scan. The PAUT scans provide images in the form of sectorial or S-Scans. These images are similar to the images produced in a medical sonogram. PAUT scans can be used to better determine defect characteristics. PAUT may soon be preferred to UT because defects are easier to identify using the PAUT imaging. In order to assess the effectiveness of UT and PAUT, it is important to identify the limitations of each technology and improve upon current ultrasonic procedures.

1.2 Results

1.2.1 Ultrasonic Testing

1.2.1.1 Length Measurement

The length measurement test determined the effectiveness of the 6dB drop technique described in the AWS procedure to size defects. In order to determine the beam spread effect on the measured length, each defect was measured on the first leg and then again on the second leg. The length measurements are compared to the actual defect length in figure 1.1 and figure 1.2. The length measurements in both figures are organized by the leg at which the defects were inspected.
Table 1.1 The LA1 defect length measurements

<table>
<thead>
<tr>
<th>Slot Length</th>
<th>Slot Type</th>
<th>Leg 1</th>
<th>Leg 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average Length (in)</td>
<td>Length (%)</td>
</tr>
<tr>
<td>0.0625</td>
<td>Hole</td>
<td>0.26</td>
<td>412</td>
</tr>
<tr>
<td>0.375</td>
<td>Fingernail</td>
<td>0.43</td>
<td>116</td>
</tr>
<tr>
<td>0.375</td>
<td>Slot</td>
<td>0.39</td>
<td>104</td>
</tr>
<tr>
<td>0.75</td>
<td>Fingernail</td>
<td>0.60</td>
<td>80</td>
</tr>
<tr>
<td>0.75</td>
<td>Slot</td>
<td>0.74</td>
<td>99</td>
</tr>
<tr>
<td>1.5</td>
<td>Fingernail</td>
<td>1.51</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>Slot</td>
<td>1.48</td>
<td>99</td>
</tr>
<tr>
<td>2.25</td>
<td>Slot</td>
<td>2.20</td>
<td>98</td>
</tr>
</tbody>
</table>

The data shown in figure 1.1, figure 1.2 and table 1.1 indicate that the length measurements are impacted by the defect length relative to the transducer length. Defects shorter than the 0.625” transducer length were affected by the beam spread and were initially oversized.

Figure 1.1 Length measurements vs actual length of all LA1 defects in Leg 1
The data in table 1.1 indicate that defects with larger volumes are more accurately measured. The 0.75” fingernail slot measured 0.15” shorter from both legs than the actual defect length due to the fingernail geometry of the groove. The fingernail slot represents the geometry of a fatigue crack where the length value is twice the depth value and is smaller in geometry than the slot of the same length. The loss in defect volume caused the measured length to be undersized.

![Graph showing length measurements vs actual length of all LA1 defects in Leg 2](image)

**Figure 1.2** Length measurements vs actual length of all LA1 defects in Leg 2

The results in table 1.1 show that the slots smaller than the transducer are typically oversized, while measurements of slots equal or larger than the transducer can be accurately sized or slightly undersized. In order to better understand the beam spread effect on defects smaller than the transducer, the slots shorter than the transducer were further evaluated in the beam spread test measurements.
1.2.1.2 Beam Spread

The beam spread test further investigated the impact of beam spread on sizing defects longer and shorter than the transducer length. A series of length measurements were conducted on the 1/16” diameter hole, 3/8” slot, and the 3/4” slot in the LA1 plate. These defects were chosen because the 1/16” hole and the 3/8” slot were shorter than the 0.625” transducer length, and the 3/4” slot was longer than the transducer length. Similar to the length measurement tests, the measured defect edges were associated with a 6 dB drop in maximum reflected amplitude.

During this test, the transducer was placed on the steel specimen’s surface at various surface distances away from the defect. Due to the near field interference calculated at 1.4 inches, the defect was initially inspected at a wave path length of 1.86” or a surface distance of 1.75” away. The wave path lengths are identified in figure 1.3, figure 1.4 and figure 1.5. This process was repeated while moving the transducer away from the defect by 0.25” increments until a 6” surface distance was attained. Figure 1.3 to figure 1.5 show two data point groups that represent the left and right measured edges of each length measurement. The thin slanted lines are trend lines representing the slope of each group of data points, and the thick slanted lines represent the calculated beam spread angle of the transducer.
Figure 1.3 Beam spread test results of 1/16" diameter hole in LA1 plate

Figure 1.4 Beam spread test results of 3/8" slot in LA1 plate
Figure 1.5 Beam spread test results of $3/4\"$ slot in LA1 plate

The defect’s maximum reflected amplitude was identified in each B-Scan to determine the $6 \text{ dB}$ drop associated with both defect edges. Figures 1.3 through 1.5 show the measured lengths versus the calculated wave path distance. The thick slanted lines represent the angle of dispersion, $\gamma$. The wavelength was calculated at $0.0569\"$ based on the $0.128 \text{ in}/\mu\text{s}$ shear velocity of the steel plate and the $2.25 \text{ Mz}$ frequency at which the transducer operates. The length of the piezoelectric transducer, $A$, was $0.625\"$, and the constant $k_{dB}$ was $0.44$ based on the desired $-6\text{dB}$ drop in the echo field. The angle of dispersion was calculated at $4.594^\circ$. The data shown in table 1.2 indicate that the length measurements are impacted by the defect size as well as the wave path length. As seen in figure 1.3 to figure 1.5, the beam spread, $\alpha$, affects the length measurement of defects smaller than the transducer as the wave path length increases.

The measured beam spread angles in table 1.2 were calculated using the average initial measured length and the average maximum measured length. The differences from the maximum and initial measured lengths were used along with the difference in wave path length of $4.52\"$
from the initial inspection to the furthest inspection. The results found in table 1.2 indicate that the beam spread angle greatly impacts the length measurement of defects smaller than the transducer.

**Table 1.2 Beam spread angle test results**

<table>
<thead>
<tr>
<th>Slot Length</th>
<th>Average Initial Measured Length</th>
<th>Average Maximum Measured Length</th>
<th>Measured Beam Spread Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/16”</td>
<td>0.34”</td>
<td>0.68”</td>
<td>4.79</td>
</tr>
<tr>
<td>3/8”</td>
<td>0.38”</td>
<td>0.59”</td>
<td>3.00</td>
</tr>
<tr>
<td>3/4”</td>
<td>0.67”</td>
<td>0.69”</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The initial length measurements were controlled by the larger of either the transducer length or the defect length. As shown in table 1.2, the ultrasonic measurement of the 1/16” slot length measurement at a wave path length of 1.81” indicated an average length of 0.34”, or 545% of the actual defect length. The 3/8” slot’s initial measurement revealed the average length measurement was 0.38”, or 102% of the actual defect length. The length measurements of defects smaller than the transducer are only 0.04” different in length, and approximately 57.8% (or slightly over half) of the transducer length. However, the 3/4” slot initial length measurement found that the average length measurement was slightly undersized at 0.668”, or 89% of the defect length.

The effect of the beam spread is related to the size of the defect. Smaller defects are impacted more significantly by beam spread, and this impact increases as the path length increases. The average initial length measurements and maximum length measurements of the 1/16” hole are 0.3407 inches and 0.6757”, respectively. The 1/16” defect yielded a 98% increase in measured length when evaluated from a longer wave path length. The average initial length
measurements and maximum length measurements of the 3/8” slot are 0.38” and 0.59”, respectively. The 3/8” defect saw a 55% increase in measured length when evaluated at a further distance from the defect. The average initial length measurements and maximum length measurements of the 3/4” slot are 0.668” and 0.6885”, respectively. The 3/4” defect only yielded a 3.1% increase in measured length.

Length measurements for defects smaller than the transducer length are inaccurate due to their echo field behaviors. The maximum reflected amplitude from the larger slots drops more severely as the acoustic wave moves off the defect. The large slot reflects a larger portion of the acoustic wave at the maximum reflected amplitude. As the transducer is moved off the slot, the reflected amplitude drops significantly, resulting in more accurate length measurements. Smaller slots reflect a smaller portion of the acoustic wave at the maximum reflected amplitude. As the defect is moved off the small slot, the reflected amplitude drops more gradually, which results in oversized length measurements.

1.2.1.3 Attenuation

The attenuation measurement test determines the decrease in reflected amplitude due to the attenuation of the material. This test analyzed the B-Scan amplitudes developed during the beam spread angle test. As the transducer was moved away from the slot or hole, the reflected amplitude peaked at two locations: the bottom corner at the end of the first leg and the top corner at the end of the second leg. These corner traps, identified in figure 1.6 to figure 1.8, were analyzed because they consist of the same geometrical defect located at two different wave path lengths.
The results in table 1.3 indicate that the 2 dB drop with each wave path inch assumed by the AWS ultrasonic code is not accurate. The wave path length increases by 2.926” between the bottom and top corner measurements. This should result in a 4 dB drop in amplitude. According to table 1.3, the average maximum reflected amplitude for the first leg of the 1/16” diameter hole was 220 mV. The measured amplitude found at 87 mV indicates an 8.06 dB change. As the defects’ sizes grew, the change in reflected amplitude dropped. This means that a single attenuation value should not be used to characterize the loss in amplitude due to attenuation for all defects. The results in table 1.3 indicate that the attenuation effect on the reflected amplitudes is underestimated. It may be necessary to incorporate a DAC curve to improve the accuracy of the indication rating.
Figure 1.6 Attenuation of the 1/16" hole

Figure 1.7 Attenuation of the 3/8" slot
An additional test inspected Side 7 on the SR1 plate at multiple distances from the wall. The transducer was placed 1.5” away from the wall and moved away from the wall in 1/4” increments until a surface distance of 4” was attained. A-Scans were taken at each distance to determine the amplitude reflecting from SR1, Side 7. The results relate each maximum reflected amplitude to the wave path length as shown in figure 1.9 and table 1.4.

The results shown in figure 1.9 and table 1.4 indicate that the reflected amplitude does not follow the 2dB decrease in amplitude. The results in table 1.4 show the average reflected amplitude at the 2.93” wave path length is 104.6 mV, and the average reflected amplitude at 3.99” wave path length is 54.6 mV. By using the AWS estimation, the reflected amplitude at the 3.99” wave path length should be 65.998 mV. Instead of the 2 dB/in drop assumed by the AWS, a 4 dB or 4.25 dB drop better characterizes the decrease in amplitude due to attenuation.
### Table 1.4 SR1, Side 7 Attenuation Test Results

<table>
<thead>
<tr>
<th>Wave Path Length Traveled</th>
<th>Surface Distance from Wall</th>
<th>Average Amplitude</th>
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<tbody>
<tr>
<td>1.06</td>
<td>1.00</td>
<td>244.2</td>
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<tr>
<td>1.33</td>
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<td>4.26</td>
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### Figure 1.9 SR1, Side 7 Attenuation Results
1.2.1.4 Defect Roughness

The defect roughness test determines the impact that defect texture has on the reflected amplitude. A series of tests were conducted to relate the change in reflected amplitude to the surface roughness of an edge or defect. The SR1 plate consists of seven sides with various surface finishes of different patterns and roughness. The reflected amplitudes from the SR1 walls were then compared to the reflected amplitudes from a specimen containing walls that were fatigued until failure.

Two different methods were incorporated in inspecting the SR1 and Fatigue specimens. B-Scans were created to evaluate a segment of each textured side of the SR1. These B-Scans were used to develop a profile of the reflected amplitude as the transducer inspected each side. The root mean square (RMS) value from each B-Scan was then calculated to better characterize each wall’s profile. While B-Scans were the preferred method, the geometry of the fatigue specimen would not permit the use of the encoder. Instead, several A-Scans were captured at the location of the profilometer roughness measurements. Both top and bottom plate corners were present in the A-Scan waveforms due to the thinness of the fatigue specimens. The reflected amplitude due to surface roughness was assumed to be located between the two edge reflections. The reflected amplitudes from both test specimens are listed in table 1.5 and table 1.6.
### Table 1.5 Manufactured specimen test results

<table>
<thead>
<tr>
<th>Side</th>
<th>Pattern</th>
<th>Max Roughness (µin)</th>
<th>Average Amplitude (mV)</th>
<th>Maximum Reflected Amplitude</th>
<th>Minimum Reflected Amplitude</th>
<th>Range in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side 1</td>
<td>Machine Cut</td>
<td>324</td>
<td>66.60</td>
<td>79</td>
<td>50</td>
<td>3.97</td>
</tr>
<tr>
<td>Side 2</td>
<td>Fine</td>
<td>68</td>
<td>36.90</td>
<td>43</td>
<td>32</td>
<td>2.57</td>
</tr>
<tr>
<td>Side 3</td>
<td>Large Profile</td>
<td>1112</td>
<td>45.10</td>
<td>55</td>
<td>30</td>
<td>5.26</td>
</tr>
<tr>
<td>Side 4</td>
<td>Medium Profile</td>
<td>600</td>
<td>43.78</td>
<td>49</td>
<td>37</td>
<td>2.44</td>
</tr>
<tr>
<td>Side 5</td>
<td>Small Profile</td>
<td>165</td>
<td>28.60</td>
<td>35</td>
<td>24</td>
<td>3.28</td>
</tr>
<tr>
<td>Side 6</td>
<td>Large Horizontal</td>
<td>1161</td>
<td>62.40</td>
<td>75</td>
<td>54</td>
<td>2.85</td>
</tr>
<tr>
<td>Side 7</td>
<td>Small Horizontal</td>
<td>541</td>
<td>75.50</td>
<td>98</td>
<td>55</td>
<td>5.02</td>
</tr>
</tbody>
</table>

### Table 1.6 Fatigue specimen test results

<table>
<thead>
<tr>
<th>Side</th>
<th>Max Roughness (µin)</th>
<th>Average Amplitude (mV)</th>
<th>Maximum Reflected Amplitude</th>
<th>Minimum Reflected Amplitude</th>
<th>Range in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side 1</td>
<td>600</td>
<td>15.90</td>
<td>27</td>
<td>7</td>
<td>11.73</td>
</tr>
<tr>
<td>Side 2</td>
<td>875</td>
<td>23.00</td>
<td>31</td>
<td>11</td>
<td>9.00</td>
</tr>
<tr>
<td>Side 3</td>
<td>718</td>
<td>108.33</td>
<td>139</td>
<td>62</td>
<td>7.01</td>
</tr>
<tr>
<td>Side 4</td>
<td>2000</td>
<td>74.73</td>
<td>90</td>
<td>60</td>
<td>3.52</td>
</tr>
<tr>
<td>Side 5</td>
<td>377</td>
<td>116.55</td>
<td>159</td>
<td>70</td>
<td>7.13</td>
</tr>
<tr>
<td>Side 6</td>
<td>330</td>
<td>45.50</td>
<td>70</td>
<td>24</td>
<td>9.30</td>
</tr>
</tbody>
</table>

Table 1.5 and table 1.6 indicate the amount of variability in each inspection associated with the high standard deviations in the reflected amplitudes. The range in dB was calculated using the maximum and minimum reflected amplitudes from each side. The results indicate a large discrepancy between the maximum and minimum amplitude values. Table 1.5 shows that the large profile pattern received amplitudes within a 5 dB range. Side 1 in table 1.6 indicates measured reflected amplitudes almost 12 dB in range. These reflected amplitudes show trends associated with the wall texture, but also contain large amounts of variability. These results indicate that the reflected amplitude varies due to the defect’s texture, and that the AWS code
may need to include these variations in their acceptance criteria.

Figure 1.10 and figure 1.11 show the maximum reflected amplitude from each inspection vs the measured roughness. The data shown in figure 1.10 indicates that the reflected amplitude was affected by the texture pattern as well as the texture roughness.

![Surface Roughness](image)

Figure 1.10 RMS values for each surface roughness B-Scan

The SR1 contained two sides that were designed to act as references: the fine finish and the manufacturer’s cut finish. The fine finish side refers to the fabricated side containing the smallest roughness. A separate side was left unaltered from its manufacturer’s cut to replicate a typical steel surface encountered in the field. When the steel plate was purchased, the fabricator used a ban saw to cut the steel plate. The course, jagged edges from the ban saw and the rusted portions caused by exposure combined to generate larger reflected amplitudes than the fine
finish. The results in table 1.5 show that the fine finish reflected a smaller average amplitude of 36.9 mV than the manufacturer’s cut side, which reflected 66.6 mV.

The horizontal finishes in the SR1 consist of small ridges running along the inspected surface. These small grooves are oriented such that they impacted the reflected amplitude the most. The results in figure 1.10 show that the horizontal finishes reflect the greatest amount of the acoustic wave back to the transducer. Table 1.5 shows that Side 7, containing the smallest roughness with a horizontal pattern, reflected the largest average reflected amplitude of 75.5 mV. Side 6, containing the largest roughness with a horizontal pattern, reflected lower reflected amplitude of 62.4 mV. The results indicate that acoustic waves reflected high amounts of noise, resulting in high amplitudes at low wall texture roughness. As the roughness was increased and reached half the length of the transducer wavelength, the roughness impacted the acoustic wave path, resulting in less of the reflected wave traveling back to the transducer.

The SR1 contained profile surface finishes consisting of semicircular grooves along the surface of the steel. The circular pattern scatters the reflection of the acoustic wave, resulting in lower reflected amplitudes received by the UT transducer. The RMS values, shown in figure 1.10, indicate that the low roughness profile finish reflected small amounts of the acoustic wave. As the roughness increased, the interference of the reflected wave also increased. Once the roughness increased to half wavelength, the reflected amplitude decreased.
In order to relate these surface roughness tests to real life conditions, two specimens containing edges fatigued to failure were inspected. B-Scans were unattainable due to the geometry of the weld. Instead, several A-Scan waveforms were taken at different locations on the specimen and used to characterize the roughness of the fatigued surfaces. The results shown in table 1.6 indicate the reflected amplitude from the fatigue surfaces resemble the reflected amplitude from the horizontal finishes. As the surface roughness increases, the reflected amplitude decreases from excessive scattering. Figure 1.12 compares the average reflected amplitudes of the horizontal surface textures and the fatigued specimens. The averages of both horizontal texture and fatigue crack walls increase in reflected amplitude as the roughness interferes with the reflected amplitude and decreases as the roughness interferes with the wave path reflection.

**Figure 1.11** Maximum reflected amplitudes for each fatigue specimen side
1.2.1.5 Defect Orientation

The defect orientation test determined the decrease in reflected amplitude as the transducer rotated along a circular path surrounding the defect. Since the decrease in amplitude is affected by the defect size [2, 3], the bottom corners of the 3/8” slot, 3/4” slot, and the 1.5” slot were inspected. The transducer was rotated about a focal point, which allowed the transducer to inspect the same location on the slot at multiple angles. This focal point was located on the edge of each slot to allow the transducer to inspect the defect’s bottom corner. The bottom corner was located at the end of the first leg of the wave path.

Each inspection angle was tracked by the encoder to produce unique B-Scans. The encoder tracked the location as the transducer rotated about the focal point. The inspection angles can be then calculated using the wheel diameter, the distance from the encoder to the focal point, and the encoder location points. The B-Scans were then analyzed to identify the
angle at which the maximum amplitude dropped by 50%. The 50% drop in maximum amplitude was identified in order to compare the rate of decreasing amplitude due to the defects’ size. Figure 1.13 contains the normalized B-Scans of each defect indicating the rate of decrease in amplitude as the transducer is rotated. Figure 1.14 represents the normalized B-Scan incorporating the average reflected amplitude inspected from each defect.

<table>
<thead>
<tr>
<th>Defect Size</th>
<th>Average 6 dB drop angle (°)</th>
<th>6 dB drop angle standard deviation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8” Slot</td>
<td>7.08</td>
<td>1.44</td>
</tr>
<tr>
<td>3/4” Slot</td>
<td>5.14</td>
<td>0.56</td>
</tr>
<tr>
<td>1.5” Slot</td>
<td>4.45</td>
<td>0.32</td>
</tr>
</tbody>
</table>

The angles associated with 50% maximum amplitude of each defect are listed in table 1.7. Table 1.7 also indicates the standard deviation of each angle at which 50% maximum amplitude was attained. These results demonstrated that the reflected amplitude decreases at a slower rate with smaller defects than with larger defects. The 50% drop in maximum amplitude associated with the 3/8” slot was 7.08°, and the 50% amplitude associated with the 1.5” slot was 4.45°.

The results from this test could be used to account for human error in the AWS ultrasonic testing code’s acceptance criteria. Since the reflected amplitude is an important component to the acceptance criteria, a conservative amount of rotation should be assumed in acceptable indication ratings. If a human error factor or acceptable rotation is identified at 4.5°, then the required reflected amplitude in the acceptance criteria should account for a decrease in reflected amplitude of a rejectable defect by 50%.
Figure 1.13 Normalized defect angle test B-Scans

Figure 1.14 Reflected amplitude as the transducer is rotated about the defect
1.2.1.6 Transducer Angle

The transducer angle measurement test determined the amount of reflected amplitude that was lost due to transducer rotation about a focal point located within the transducer. Unlike the defect orientation, the focal point of rotation was located on the transducer. The rotation during this test moved the ultrasonic wave over the entire defect. The transducer orientation measurements were taken by inspecting the flat surfaces of the 1/4” and 1/8” FBHs located in the FBH1 plate as well as the bottom corners of the 3/8”, 3/4”, and 2.5” slots in the LA1 plate. The 1/32” and 1/16” FBHs in the FBH1 specimen were inspected, but the holes were too small for the transducer to identify. Due to the near field interference in the first leg of the waveform, the bottom of the flat bottom holes were inspected within the second leg of the waveform.

In each of these inspections, the angle beam transducer was rotated while maintaining its location on the steel plate. An encoder was attached to the probe and was used to track the transducer’s rotation. Each test yielded a B-Scan relating the reflected amplitude to the transducer angle. Figure 1.15 shows the normalized B-Scans of each inspection relative to the calculated transducer angle.
The results in table 1.8 indicate that the amplitude decreases rapidly when evaluating large defects and decreases gradually when evaluating small defects, i.e. the length of the defect is less than the length of the transducer. The results for the 1/8” FBH indicate a 50% decrease in reflected amplitude as the transducer was rotated by an average angle of 12.8° with a standard deviation of 1.5°. The results for the 1/4” FBH indicate a 50% decrease in amplitude at an average angle of 11.1° with a standard deviation of 2.0°. These results indicate that the reflected amplitude decreases at different angles based on the diameter of the FBHs. These results show that the reflected wave drops more severely as the hole diameter increases.
Table 1.8 Transducer angle test results

<table>
<thead>
<tr>
<th>Defect Size</th>
<th>Wave Path Length</th>
<th>Average 6 dB drop angle</th>
<th>6 dB drop angle standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8” FBH</td>
<td>3.3</td>
<td>12.8</td>
<td>1.5</td>
</tr>
<tr>
<td>1/4” FBH</td>
<td>3.3</td>
<td>11.1</td>
<td>2.0</td>
</tr>
<tr>
<td>3/8” Slot</td>
<td>2.9</td>
<td>6.2</td>
<td>0.4</td>
</tr>
<tr>
<td>3/4” Slot</td>
<td>2.9</td>
<td>5.1</td>
<td>0.3</td>
</tr>
<tr>
<td>2.25” Slot</td>
<td>2.9</td>
<td>4.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Due to the relatively small size of the flat bottom holes, the 3/8”, 3/4” and 2.5” slots of the LA1 plate were also inspected; table 1.8 shows the results of these inspections. The results show that defects larger than the transducer are impacted similarly as the transducer rotates. The B-Scans for the 3/8” in table 1.8 show that the amplitude decreases to 50% when the transducer is rotated by an average angle of 6.2° with a standard deviation of 0.4°. The results for the 3/4” show that the amplitude decreases to 50% when the transducer is rotated by an average angle of 5.1° with a standard deviation of 0.3°. The results for the 2.25” show that the amplitude decreases to 50% when the transducer is rotated by an average angle of 4.6° with a standard deviation of 0.2°. These results were within 1.4° of each other, indicating that the transducer rotation does not change based on the size of the flat slots. The results indicate that the reflected amplitude drops by 50% within at least 6.2° of transducer rotation.

The combined results from the FBH and LA1 holes indicated that the reflected amplitude decreases due to the size of the defect. Small defects, such as the 1/8” diameter FBH, may see a 6 dB decrease in amplitude after 13° of rotation, but larger defects such as the LA1 slots see a 6 dB decrease in amplitude after 5° of rotation. As the defect sizes increase, the reflected amplitude decreases at a faster rate. This discrepancy is consistent with the beam spread effect seen in the length amplitude and beam spread tests.
Similar to the defect orientation tests, the transducer angle tests could be used to quantify human error during inspection. These tests show that the reflected amplitude will drop by 50% within at least 4.6°. If an acceptable rotation of 4.6° is assumed, then the acceptance code should be adjusted to account for 50% decrease in reflected amplitude of a rejectable defect.

1.2.1.7 Wedge Angle Test

The wedge angle test determined the decrease in reflected amplitude due to the incidence angle of each wedge angle. Two procedures were used to determine the impact that the incidence angle of each angled wedge has on the reflected amplitude. The first procedure inspected the large horizontal pattern texture of the SR1 plate, Side 7, using each angled probe to relate the reflected amplitude of a vertical defect to the incidence angle. The second procedure inspected the bottom corners of the 1/16” diameter hole, the 3/8” slot, and the 3/4” slot in the LA1 test specimen using each of the three angle beam probes.

The AWS code adjusts the allowable reflected amplitude in the acceptance criteria based on the angle of incidence for the probe used during the inspection. The code assumes each indication represents a vertical crack within the steel because a vertical orientation is the most severe crack alignment. In order to replicate a vertical crack, the horizontal texture of SR1, Side 7, was inspected using each angle beam probe. Each probe was placed at the appropriate distance to inspect the same wall area located 1.25” deep on the SR1, Side 7.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Average Amplitude</th>
<th>dB Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>29.4</td>
<td>8.4</td>
</tr>
<tr>
<td>60°</td>
<td>58.8</td>
<td>2.4</td>
</tr>
<tr>
<td>70°</td>
<td>77.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>
The results in figure 1.16 and table 1.9 identify the average reflected amplitude and the decibel adjustment required to translate the average amplitude to the 70° amplitude. These results do not agree with what was expected. The AWS code requires a 3 dB increase in sensitivity to relate an indication from a 60° probe to an indication using a 70° probe. It also shows a 5 dB increase in sensitivity to relate an indication from a 45° probe to an indication using a 70° probe. The results from this test indicate that 8.4 dB and 2.4 dB are required to adjust the 45° and 60° probe indications, respectively.

Figure 1.16 Maximum amplitudes from the SR1, Side 7 using the 45°, 60°, and 70° wedges

The second procedure inspected the bottom corners of the 1/16” diameter hole, the 3/8” slot, and the 3/4” slot in the LA1 test specimen using each of the three angle beam probes. While the AWS assumes all cracks are vertically oriented, this is not always the case. The bottom corners were chosen to demonstrate the effect that the defect orientation has on all three transducer wedge results.
The results shown in figure 1.17 and table 1.10 indicate that a smaller angle of incident is associated with larger reflected amplitudes when inspecting the slot corner. Figure 1.17 and table 1.10 relate all measured reflected amplitudes to the smallest reflected amplitude measured at 81 mV at a gain measurement of 62. The 45° probe reflected an average amplitude 14.3 dB, 14.9 dB, and 13.3 dB larger than the reflected amplitude of the 60° probe. The 60° probe reflected an average amplitude 3.1 dB, 1 dB, and 2.5 dB larger than the 70° probe.

Table 1.10 Wedge angle test results from the slot corner inspections

<table>
<thead>
<tr>
<th>Wedge Angle</th>
<th>Average Reflected Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/16” Hole</td>
</tr>
<tr>
<td>45°</td>
<td>18.1</td>
</tr>
<tr>
<td>60°</td>
<td>3.8</td>
</tr>
<tr>
<td>70°</td>
<td>0.7</td>
</tr>
</tbody>
</table>
These test results indicate that the most efficient inspection angle is not the horizontal beam assumed in the AWS code. Defects with similar orientations may have been rejected using a 45° probe, but not rejected using the other two angle beam probes. It may be more effective to inspect the weld with multiple angles and establish a single amplitude threshold for acceptance or rejection.

1.2.1.8 Defect Length Measurement

The defect length measurement tests determine the effectiveness of the current AWS length measurement technique when inspecting realistic flaws. The SMB 11 plate was inspected to identify and characterize the three defects embedded within the weld. B-Scans were developed during the inspection of each SMB-11 defect and used to determine each defect’s length. The encoder tracked the movement of the probe as the transducer acquired waveforms. The locations at which the amplitude dropped by 50% represent the defect edges and are used to establish the measured length.

The AWS code requires that each weld is inspected from multiple sides and the largest amplitude and length measurements are recorded. For this research, each defect was inspected from all four sides of the weld: side A+, side A-, side B+, and side B-. Side A+ refers to the initial face (A) of inspection and the initial side (+) of the weld. Side B- refers to the opposite face (B) of inspection and on the opposite side (-) of the weld. Due to Defect 3’s location at the bottom of the weld, the defect was inspected within the second leg of the wave path; the remaining defects were inspected within the first leg of the wave path.

The results in table 1.11 display the length measurements for all three defects inspected at all four sides of the weld. The length measurements for all defects vary between each inspection side. For example, Defect 3 consists of a 0.4” toe crack extending across the bottom of the plate.
The defect was measured on the first leg from Face A+ and Face A-. These inspections yielded length measurements near or slightly undersized compared to the actual length. The defect had to be inspected at the end of the second leg during the Face B+ and Face B- inspections due to the position of the defect within the weld. These inspections yielded overestimated length values. This length overestimation is due to the effect of beam spread on a defect smaller than the transducer as seen in the length measurement tests.

Table 1.11 Defect length test results

<table>
<thead>
<tr>
<th>Defect Size</th>
<th>Average Measured Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Face A+</td>
</tr>
<tr>
<td>0.3”</td>
<td>0.62</td>
</tr>
<tr>
<td>0.4”</td>
<td>0.38</td>
</tr>
<tr>
<td>0.5”</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Figure 1.18 SMB 11 length measurements from Face A+ and Face A-
1.2.2 Phased Array Ultrasonic Testing

This section describes the use of PAUT and demonstrates its unique defect characterization features. PAUT incorporates multiple element arrays to rapidly generate waves of constructive interference at multiple angles. The reflected waves are organized and displayed in S-Scan similar to the image in figure 1.22.
The phased array IIW block shown in figure 1.20 was inspected using a Phasor XS, PAUT pulser receiver. The phased array IIW block contains two curved walls of different radices whose focal point is identified in figure 1.20. Three flat bottom holes are located on the interior curved wall. These flat bottom holes are difficult to identify using a standard UT A-Scan; however, the PAUT S-Scan clearly identifies the three circular holes as seen in figure 1.22.
This scan incorporated a 32 element PAUT transducer to create a 40°-75° S-Scan. In order to identify both curved walls and all three flat bottom holes, the transducer was placed at the focal point of both curved walls on the IIW block, as seen in figure 1.21.

The Phasor XS receiver is capable of generating an A-Scan at any angle within the current angle range. The S-Scan in figure 1.22 displays the A-Scan at 60° to the left of the S-Scan. The A-Scan angle is associated with the thin slanted line extending from the upper left-hand corner to the bottom right-hand corner of the S-Scan. The A-Scan at 60° shows three spikes in amplitude: (1) the flat bottom hole, (2) the first curved wall, (3) and the second curved wall. Using the range of angles in a single inspection, each indication can be identified as a hole or a curved wall.
These characterization features provided in an S-Scan may entice inspectors to use PAUT rather than UT. Defects similar to the flaws located in the SMB11 may be easier to identify as well as characterize. Planar defects similar to the cracks in the SMB 11 may be oriented at less than optimal orientations for a single A-Scan angle; however, the PAUT incorporates a large range of angles that encompass the other optimal inspection angles. Volumetric defects such as porosity resemble regions of reflected amplitude in an S-Scan. Depending on the significance of these amplitudes, the defect may be overlooked using a traditional A-Scan. The test procedures in Appendix C are to be performed to identify and compare the common limitations of both UT and PAUT. These limitations should be considered when developing a PAUT procedure for bridge and building inspection.

1.3 Conclusions

The objectives of this research were to measure the impact of variables that affect the ultrasonic response, to evaluate the current UT procedure, to improve upon the UT procedure based on the measured results, and to develop test procedures that measure the variables that
impact PAUT measurements for future research. Data analysis from the experimental measurements has yielded the following results:

- The defect orientation test found that the reflected amplitude dropped by 6 dB within a minimum transducer rotation of 4.45° about the defect.
- The wedge angle measurements found that the amplitude decreased as the beam incidence angle decreased. The results do not agree with the AWS acceptance criteria assumptions, and indicate that maximum reflected amplitude is determined by the defect orientation within the weld and the beam’s incidence angle.
- The results from the length measurement tests indicated that defects larger than the transducer were accurately sized, but that defects smaller than the transducer were oversized. The extent to which these smaller defects were oversized increased as the path length increased due to beam spread.
- The beam spread measurements found that the length measurements for slots smaller than the transducer increased as the measured wave path length increased due to the effect of beam spread. The beam spread effect increased as the slot length decreased for slots smaller than the transducer. The length measurements for slots larger than the transducer were not influenced by beam spread.
- The attenuation measurements found that the amplitudes decreased by a maximum of 8.06 dB over an increase in wave path length of 2.926”. The amplitude decreased more for smaller defects than for larger defects. An additional test was conducted that inspected the SR1, Side 7, wall at different wave path lengths. The results found that the reflected amplitude dropped by 4.25 dB/in rather than the 2 dB/in assumed by the AWS ultrasonic testing code.
- The defect texture measurements indicated that the reflected amplitudes from the fatigue
specimens were best represented by the horizontal patterns of the SR1 plate. The results also show that the maximum reflected amplitude varied greatly for each texture inspection.

- The transducer orientation measurements identified the amount of amplitude lost as the transducer was rotated while remaining at the same x-y coordinates. The results indicated that the reflected amplitude decreased by 6 dB with a minimum rotation of 4.6°.

The results from these UT tests indicate that the current AWS ultrasonic testing procedure may need to be adjusted to better represent the behavior of the UT technology. The reflected amplitude is a critical component used to indicate the severity of the defect; however, these tests indicate that the reflected amplitude is affected by the beam angle, defect texture, transducer orientation, and the attenuation by the material. The length measurement is the other key component in ultrasonic inspection, but it is limited by factors which include transducer oscillator length, beam spread, and defect position within the weld.
Chapter 2 Ultrasonic Biaxial Stress Measurement for Evaluating the Adequacy of Gusset Plates

2.1 Introduction

2.1.1 Goals and Objectives

The goal of the research was to improve the safety of steel truss highway bridges. The objectives of this research were to:

- Develop an ultrasonic stress measurement methodology for determining total stress in steel gusset plates in-situ
- Evaluate the accuracy and precision of ultrasonic stress measurements for a biaxial stress condition
  - Assess the effect of texture direction on ultrasonic shear wave velocities

2.1.2 Motivation

This study explored the application of ultrasonic stress measurement technologies to measure stress levels in gusset plates as a potential tool for condition assessment. The need for improved condition assessment technology became evident as a result of the investigation of the I-35W Bridge collapse in Minneapolis, Minnesota; this bridge collapsed on the evening of August 1, 2007, resulting in the deaths of 13 people [4]. An investigation of the collapse by the National Transportation Safety Board (NTSB) indicated that the cause of the collapse was an overloaded gusset plate that connected key members of the structure. The gusset plate was not of adequate thickness to carry the applied loads given its configuration, despite an adequate performance of the bridge since the construction of the bridge in 1967. Additional dead load applied to the structure over time due to rehabilitation activities, as well as construction loading due to ongoing operations, were identified as factors that may have contributed to the failure of the gusset plate [4].

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Since the time of the collapse, State Departments of Transportation and other bridge owners have struggled to determine if existing gusset plates are adequate to carry applied loading and ensure bridge safety. To assess the adequacy of a given plate to carry required loads, the actual forces acting on the plate are needed to compare with the calculated capacity of the plate. The complex nature of force distributions in large truss bridges results in significant uncertainty in the level of stress carried by individual bridge members and, consequently, the required stresses in the gusset plates connecting the members. Previous research has indicted that the magnitude of shear stress is the best predictor of gusset plate failure. In this research, an ultrasonic stress measurement methodology is being developed to evaluate the total shear stress level in a gusset plate. The approach used ultrasonic birefringence as a means of assessing the maximum shear stress carried in the plate. Measurements from the ultrasonic birefringence approach can determine the total shear stress level resulting from dead load, live load, and residual stresses. It is expected that the developed methodology will have a significant impact on the current state-of-the-art for evaluating bridge capacities and enable more reliable assessments to ensure bridge safety nationwide.

2.2 Background and Theory

2.2.1 Ultrasonic Waves

When an ultrasonic shear wave propagates through an isotropic, homogeneous medium, it propagates at a single velocity regardless of the wave polarization direction, as shown in figure 2.1A. However, when a material is anisotropic, the velocity of the shear waves will become dependent on the polarization orientation of the wave. As illustrated in figures 2.1B and 2.1C, anisotropy in a material can occur for two reasons – texture and stress.
2.2.2 The Acoustoelastic Effect

Anisotropy in steel can result from a texture effect, which is caused by the rolling process during fabrication. This process gives a texture to the material by elongating all of the polycrystalline steel grains in a preferred orientation (i.e., the direction of rolling). Ultrasonic wave velocity becomes dependent on the polarization direction of the shear wave as a result of this texture effect. Another form of anisotropy in steel is strain (or stress) and is referred to as the acoustoelastic effect. The acoustoelastic effect expresses variations in the elastic properties of the material resulting from applied strains through the effect on the velocity of an acoustic wave. The relationship between wave velocity and wave polarization is a combination of the texture and stress effects.

2.2.3 Acoustic Birefringence and Natural Birefringence

Since the velocity of a shear wave in an anisotropic material is dependent on polarization direction, orientations must exist in which the wave velocity is at a maximum and minimum (i.e.,
a fast wave direction and a slow wave direction). The normalized velocity difference between the fast and slow waves is defined as acoustic birefringence, $B$:

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

where $V_f$ is the fast wave velocity, $V_s$ is the slow wave velocity, and $V_{avg}$ is the average of $V_f$ and $V_s$ [5, 6].

The steel texture causes a birefringence effect when stresses are nominally zero, referred to as natural birefringence, $B_0$. The presence of shear stress, in the direction of texture will cause a rotation of the fast and slow wave directions through the angle $\phi$. The rotation causes a phase shift of $\phi$ to the sinusoidal plot of wave velocity versus polarization direction, as shown in figure 2.2 [5]. The phase shift may have a significant outcome on the ultrasonic stress measurement and must be accounted for in order to avoid large errors.

**Figure 2.2** The effect of shear stress on the wave velocity versus polarization angle plot

Since the fast and slow wave directions rotate in the presence of shear stress, $B$ is not measured with respect to a single set of orthogonal directions over a range of stresses. The
detection of stress-induced velocity changes are simplified using a single point of reference because $B$ and $\phi$ are both accounted for simultaneously using a single parameter. For convenience, a separate birefringence parameter was implemented that utilized velocity measurements with polarization angles in reference to the same set of orthogonal directions – the principal stress directions. As shown in figure 2.3, the principal stress birefringence is defined as:

$$B_\sigma = \frac{V_{\sigma_1} - V_{\sigma_2}}{V_{\text{avg}}}$$

where $V_{\sigma_1}$ is the velocity of a wave polarized in the major principal stress direction, $V_{\sigma_2}$ is the velocity of a wave polarized in the minor principal stress direction, and $V_{\text{avg}}$ is the average of $V_{\sigma_1}$ and $V_{\sigma_2}$.

**Figure 2.3** Wave velocities $V_{\sigma_1}$ and $V_{\sigma_2}$, measured at the major and minor principal stress axes, which were used to calculate the principal stress birefringence, $B_\sigma$. 
2.3 Experimental Testing

2.3.1 Experimental Setup

Figure 2.4 is a photograph of the basic experimental setup. The setup consisted of a 14” x 4” x 0.25” steel plate fixed to a Material Testing Systems (MTS) loading machine via pin-and-clevis connections. The plate was loaded vertically in tension by the loading machine and horizontally in compression by a steel load frame to provide a static biaxial stress condition. The resulting strains were measured using resistance-type strain gages. Ultrasonic stress measurements were compared to the strain gage readings to assess the accuracy and precision of the applied technique.

![Figure 2.4](image)

**Figure 2.4** The basic test setup consisting of loading apparatuses and ultrasonic instrumentation

2.3.2 Steel Specimens

Three A36 hot rolled steel plate specimens were fabricated for testing, as shown in figure
2.5. Each specimen had a rolling direction that made a unique angle (45°, 60°, and 90°) with respect to the horizontal. The purpose of differing grain directions (i.e., texture) was to demonstrate the relationship between texture and principal stress directions for birefringence measurements. For all specimens, the loading condition applied during testing was such that the major principal stress direction was located at 90° (vertical) and the minor principal stress direction was located at 0° (horizontal). Based on the test configuration, the 90° plate had the rolling and transverse directions aligned with the principal stress directions; this means that no shear stress was present in the direction of texture. In contrast, the 45° plate and 60° plate had shear stress present in the direction of rolling because the rolling direction did not coincide with a principal stress direction.

![Figure 2.5](image)

**Figure 2.5** Photograph of the (A) 90° plate, (B) 60° plate, and (C) 45° Plate. The arrows represent the direction of rolling.

2.3.3 Ultrasonic Testing Instrumentation

An electromagnetic acoustic transducer (EMAT), shown in figure 2.6, was used to transmit and receive ultrasonic bulk shear waves through the thickness of the plate. The EMAT
was used in a pulse-echo configuration in which the transducer both transmits and receives signals. The shear waves were created from the interaction of electronic current flowing through a conductive wire and a magnetic field produced by a permanent magnet. During testing, shear waves with a frequency of 3 MHz were transmitted. The permanent magnet inside the EMAT bonded the transducer to the surface of the steel. No coupling is required because the shear waves were produced inside the steel, making it possible to operate through thin coatings such as paint or rust.

Figure 2.6 The EMAT fixed to the surface of a steel specimen

The received ultrasonic signals were subsequently displayed and stored on a high-speed digital oscilloscope operating at a sampling rate of 100 Msa/s. The stored waveforms were post-processed to obtain the ultrasonic wave velocity using specially designed software that enabled sub-interval timing of the digital signal. After the wave velocities were determined using the timing software, the data was further processed to calculate the desired birefringence parameters.
This was done using a sine regression analysis technique in which a sine regression curve was fit to the wave velocity data for a given state of stress (see fig. 2.7). For a single test, the shear wave polarization direction was rotated to specific angles; measurements were recorded at 22.5° increments from 0° through 360° with respect to the horizontal (a total of 17 measurements per test).

![Sine regression analysis performed for a single test](image)

**Figure 2.7** Sine regression analysis performed for a single test

2.4 Experimental Results

2.4.1 Texture Tests

To establish texture direction and natural birefringence, five 360° velocity tests (or texture tests) were performed on the plate specimens in an unstressed state. Based on the test results, the texture direction ($\theta_f$) was identified as the location of maximum wave velocity (i.e., the location of the maximum of the sine regression curve). The natural birefringence ($B_0$) was calculated using the maximum and minimum values of the sine regression curve. The values obtained for natural birefringence and texture location for all five tests were averaged and used
in the analysis of the biaxial loading tests to separate the effects of texture from the effects of stress. Table 2.1 is a summary of the texture test results.

**Table 2.1** Summary of the texture testing results for the three steel plate specimens

<table>
<thead>
<tr>
<th>Test Number</th>
<th>90° Plate</th>
<th>60° Plate</th>
<th>45° Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( B_0 )</td>
<td>( \theta_f )</td>
<td>( R^2 )</td>
</tr>
<tr>
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<td>0.002000</td>
<td>89.4</td>
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</tr>
<tr>
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<td>0.989</td>
</tr>
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<td>0.995</td>
</tr>
<tr>
<td>4</td>
<td>0.001988</td>
<td>87.8</td>
<td>0.982</td>
</tr>
<tr>
<td>5</td>
<td>0.002005</td>
<td>87.8</td>
<td>0.977</td>
</tr>
<tr>
<td>Average</td>
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<td>88.6</td>
<td>0.985</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.000013</td>
<td>0.8</td>
<td>0.007</td>
</tr>
</tbody>
</table>

2.4.2 Biaxial Load Tests

The plates were subjected to biaxial loading to evaluate the accuracy and precision of acoustic birefringence measurements. Biaxial loading best represents the loading experienced by a highway bridge gusset plate. Three “rounds” of testing were performed on each specimen, with each round consisting of five different tensile loading steps (4,000lb-20,000lb in 4,000lb increments). The lateral compressive load was held relatively constant (~3,000-4,500lb) as the tensile force was increased. Figure 2.8, figure 2.9, and figure 2.10 illustrate the response of the regression curves for one round of loading for the 90°, 60°, and 45° plates, respectively.
Figure 2.8 Sine regression velocity curves produced from one round of loading for the 90° plate

Figure 2.9 Sine regression velocity curves produced from one round of loading for the 60° plate

Figure 2.10 Sine regression velocity curves produced from one round of loading for the 45° plate
Figure 2.11 demonstrates the relationship between acoustic birefringence, $B$, and the phase shift of the velocity curve, $\phi$, for the three unique rolling directions. The $B$ versus $\phi$ relationship was proven to be dependent on the texture direction relative to the principal stress directions. Figure 2.12 illustrates the correlation between the principal stress birefringence, $B_\sigma$, and the magnitude of the maximum shear stress, $\tau_{max}$, obtained from strain gage measurements. The figure shows a very strong and consistent linear correlation between stress and birefringence.

**Figure 2.11** The relationship between $B$ and $\phi$ for the unique texture directions
2.5 Conclusions

Experimental testing for this study has been completed. The purpose of the research was to evaluate the use of ultrasonic acoustic birefringence as a stress measurement technique to evaluate the adequacy of steel gusset plates. Experimental measurements discussed in this paper include the effects of texture and applied biaxial loading on the ultrasonic wave velocity of polarized shear waves. The production of accurate and repeatable experimental measurements, which strongly correlate with the state of stress, demonstrate the effectiveness of the birefringence technique.

2.5.1 Test Results

Experimental testing led to the following conclusions:

- Texture Tests

Figure 2.12 Correlation between the principal stress birefringence and the maximum shear stress determined from strain gage measurements
o The average natural birefringence for A36 steel was 0.001926 with a standard deviation of 0.000166. The measured values ranged from 0.001592 to 0.002158.

o The data showed consistency between the three plate specimens, obtaining average wave shear wave velocities of 3159.2 m/s, 3155.8 m/s, and 3157.6 m/s for the 90°, 60°, and 45° plates, respectively.

o The average velocity difference between the “fast” and “slow” waves for unstressed state was approximately 6 m/s.

o The testing demonstrated repeatability in determining the texture direction for an unstressed state. The average standard deviation of the measured “fast” wave orientation (i.e., the texture direction) was 0.8°.

• Biaxial Load Tests

  o For the ultrasonic measurement of maximum shear stress, the average uncertainty was 681 psi (3.3% of the shear yield strength) using the natural data correlation (i.e., different stress-acoustic constants) for each specimen. Uncertainties ranged from 5 psi to 1,731 psi.

    ▪ The average stress-acoustic constant between the three plate specimens was $-8.290 \times 10^{-8}$ psi$^{-1}$.

  o For the ultrasonic measurement of maximum shear stress, the average uncertainty was 799 psi (3.8% of the shear yield strength) using the average stress-acoustic constant for all specimens. Uncertainties ranged from 11 psi to 2,577 psi.

  o The pure-mode polarization directions tended to rotate toward compressive force (i.e., the minor principal stress direction).

  o The minimum birefringence for a material occurs when the “fast” wave coincides
with the maximum shear plane; this information can be used to identify the principal stress directions with respect to the texture direction.

- For texture directions within 45 degrees of the minor principal stress axis, the birefringence will increase as load is applied. For texture directions greater than 45 degrees from the minor principal stress axis, the birefringence will decrease as load is applied. This effect occurs because wave velocity increases when the wave is oriented closer to the compressive stress and decreases when the wave is oriented closer to the tensile stress.

Using sine regression analysis to measure birefringence parameters was successful for this study. The sine regression curves correlated very strongly with the wave velocity data, yielding an average coefficient of determination ($R^2$) of 0.961 for the entirety of the testing. Based on the texture test results, the average natural birefringence for A36 steel was 0.001926 with a standard deviation of 0.000166. The testing also demonstrated repeatability in determining the texture direction for an unstressed state. Based on the biaxial load test results, the average ultrasonic shear stress measurement uncertainty was determined to be 681 psi (3.3% of the shear yield strength for A36 steel). Laboratory test results have demonstrated enough accuracy and repeatability to be potentially applied as a stress measurement tool for evaluating the adequacy of steel gusset plates. Future work includes the transition of the birefringence technique utilized during this research from the laboratory into the field to determine the accuracy and repeatability of measurements obtained from in-situ gusset plates.
References


