GEORGIA DOT RESEARCH PROJECT 22-02

Final Report

FIELD EVALUATION OF WIRELESS ULTRASONIC THICKNESS MEASUREMENT WITH STEEL BRIDGE MEMBERS

Georgia Department of Transportation

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16. Abstract

This report presents the field validation of wireless ultrasonic thickness measurement systems on in-service steel bridges. The objective of this implementation is to demonstrate the feasibility of long-term corrosion monitoring. The developed system utilizes *Martlet* wireless ultrasonic sensing devices with two specially designed daughterboards: the high-rate ultrasonic board and the pulser board. To ensure accurate measurements, the project first derives the calibration function of the *Martlet* ultrasonic device. Subsequently, thickness measurements are carried out on various steel members and compared with readings obtained from a commercially available handheld thickness gauge. For preliminary validation, the system is deployed on an in-service highway bridge near the city of LaGrange, GA. Following the successful operation of the installed system, this project implements the system on the target bridge located in Douglas County, GA. Visual inspection of the bridge confirms corrosion on structural members across the bridge. A solar panel and a support structure are first installed to provide continuous power for the battery and gateway computer. Four wireless ultrasonic sensing units are installed on three pile tops and the bottom flange of a beam at the Douglas County bridge. Ultrasonic data are collected at scheduled intervals and automatically uploaded to the cloud, enabling remote monitoring of the thickness values over time. This research validates the feasibility of a continuous steel thickness-monitoring solution without the need for physical presence at the bridge location.

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GDOT Research Project 22-02

Final Report

FIELD EVALUATION OF WIRELESS ULTRASONIC THICKNESS MEASUREMENT WITH STEEL BRIDGE MEMBERS

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

This report presents the field validation of a wireless ultrasonic thickness measurement system on in-service steel bridges for long-term corrosion monitoring. The developed system utilizes *Martlet* wireless ultrasonic sensing devices with two specially designed daughterboards: the high-rate ultrasonic board and the pulser board. The compact ultrasonic sensing device is capable of high-voltage pulse excitation, filtering/amplification of the received ultrasonic signal, and high-speed analog-to-digital conversions (up to 80 MHz). To ensure accurate measurements, the project first derives the calibration function of the *Martlet* ultrasonic device. Subsequently, thickness measurements are carried out on 14 steel members with various thickness values. Measurements from the *Martlet* ultrasonic device are compared with readings obtained from a commercially available handheld thickness gauge for further validation.

Field testing is first conducted on a highway bridge in LaGrange, GA. The *Martlet* ultrasonic device is confirmed to provide the accurate thickness values of the web and bottom flange of a steel girder. This bridge has electricity available, allowing convenient implementation of the long-term monitoring system. A *Martlet* wireless ultrasonic device and a 2.25 MHz dual-element transducer are installed at the web of a steel girder as a preliminary validation of the long-term monitoring system. The thickness measurements have been reliably obtained for about seven months.

Following the successful operation confirmed on the first bridge, this project proceeds to implement the system on a second bridge, which is located in Douglas County, GA. Visual inspection of the bridge confirms corrosion on structural members across the bridge. A solar panel and a support structure are installed to provide continuous power for the battery and gateway

computer. Four wireless ultrasonic sensing units are installed on three pile tops and the bottom flange of a beam on the bridge. Ultrasonic data are collected at scheduled intervals and automatically uploaded to the cloud, enabling remote monitoring of the thickness values over time. Through wireless ultrasonic sensing devices and a gateway computer installed on-site, this research validates the feasibility of continuous steel thickness measurement that can be monitored remotely.

CHAPTER 1. INTRODUCTION

Recent advancements in wireless sensing technology have provided structural health monitoring systems with a cost-effective and efficient way to collect, analyze, and store data.[1] Wireless sensors can be installed at critical locations across a structure to monitor its condition. The collected sensor data can be wirelessly transmitted to the cloud, allowing engineers to monitor the structural condition and identify potential problems in real time.

Ultrasonic thickness measurement is a technique that can measure the thickness of a metal plate, as shown in figure 1. The technique works by sending ultrasonic waves through the material and measuring the time of flight (ToF), which is the time it takes for the waves to travel back and forth. The identified ToF is then used to calculate the thickness of the specimen. A thin layer of viscous or liquid gel (known as couplant) is typically applied between the transducer and specimen to facilitate the propagation of solid waves.

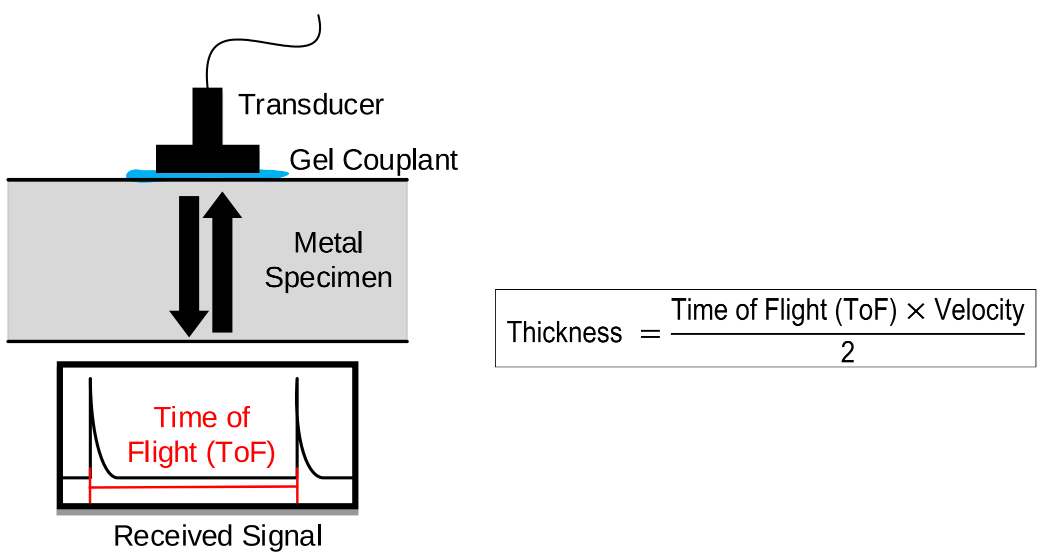


Figure 1. Diagram. Ultrasonic thickness measurement.

Regularly assessing corrosion damage on bridge structural members is crucial to making informed maintenance decisions. However, current practices primarily rely on human visual inspection, which is labor-intensive and expensive, mainly due to the difficulties in regularly accessing the underside of the bridge deck. The main goal of this project is to develop and implement long-term ultrasonic thickness measurement systems on steel members of in-service bridges using *Martlet* wireless sensing devices. The measured ultrasonic data are uploaded to the cloud through an on-site gateway computer and can be accessed remotely for decision-making.

CHAPTER 2. LABORATORY STUDIES OF *MARTLET* WIRELESS ULTRASONIC SENSING DEVICE

This chapter begins with a description of the *Martlet* wireless ultrasonic sensing device. The calibration function of the *Martlet* ultrasonic device is then derived, using a steel calibration block. Finally, laboratory experiments compare thickness measurement values between the *Martlet* ultrasonic device and a commercial handheld device.

MARTLET ULTRASONIC WIRELESS SENSING UNIT

This section describes the *Martlet* ultrasonic thickness measurement device. Figure 2 shows the functional diagram. The *Martlet* wireless sensing system is a low-cost platform for intelligent infrastructure monitoring.[2] As shown in figure 2, the *Martlet* motherboard incorporates a dual-core Texas Instruments Piccolo microcontroller, which can run up to 90 MHz. A Zigbee radio transmits data at rates up to 250 kbps. With *Martlet*'s modular design, researchers have developed a variety of stackable daughterboards to interface with various sensors used in structural health monitoring.[3-7] Recently, the authors and collaborators have developed two daughterboards for ultrasonic thickness measurement: the high-rate ultrasonic board and the pulser board.[6, 8] These two daughterboards, together with the *Martlet* motherboard, form a *Martlet* ultrasonic thickness measurement device.

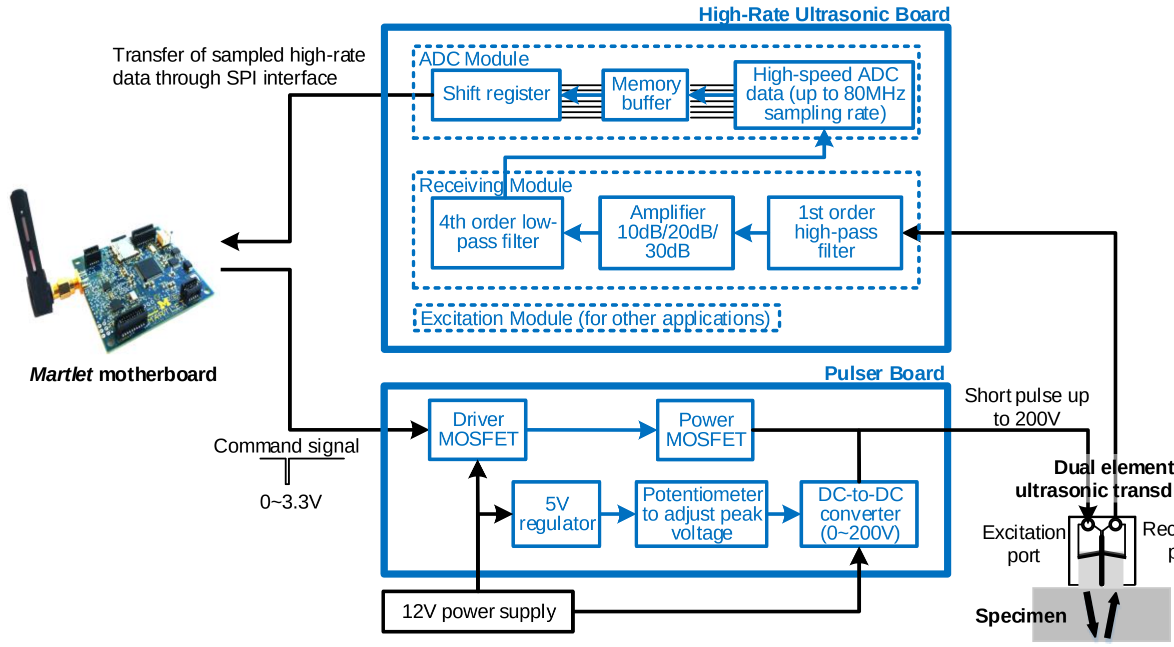


Figure 2. Diagram. Functional diagram of the *Martlet* ultrasonic thickness measurement device.

The high-rate ultrasonic board consists of three modules: the excitation module, the receiving module, and the analog-to-digital converter (ADC) module. The excitation module was designed for launching surface waves and is not utilized in this study for thickness measurement. Instead, the pulser board serves as the transducer excitation source for measuring specimen thickness. The receiving module conditions the signal from a transducer through a first-order high-pass filter, amplitude amplification (10dB/20dB/30dB), and a fourth-order low-pass filter. Among the commonly used standard filter types, Bessel is selected for the fourth-order low-pass filter that is critical for the signal conditioning performance. Bessel filters offer a linear phase performance and help maintain the signal waveform in the time domain, which assists in accurately identifying the ToF of the received signal.[9] The high-speed ADC module samples the filtered and amplified signal with a sampling frequency up to 80 MHz. The sampled data are transferred to the *Martlet* motherboard through a serial peripheral interface (SPI) connection. Ultimately, the *Martlet* motherboard wirelessly sends the data to a base station connected to a personal computer (PC).

When the ultrasonic solid wave propagates into the specimen, the amplitude of the ultrasonic signal decreases as the wave reflects multiple times between the two surfaces of the specimen. A larger signal amplitude is preferred to ensure a good signal-to-noise ratio, resulting in a more accurate thickness measurement. For this purpose, a compact pulser board has been developed to generate a short-pulse excitation at high voltage. The high-voltage direct current (DC)-to-DC converter increases the excitation voltage up to 200V. An onboard potentiometer can easily adjust the voltage. The metal-oxide semiconductor field-effect transistor (MOSFET) is a power amplifier that accepts a low-power command signal from a microcontroller on the *Martlet* and produces a high-current drive input for the gate of the MOSFET. The MOSFET initiated by the high-current drive input achieves the fast-switching time required by the pulse excitation. An example pulse excitation signal generated by the developed pulser board can provide a 200V pulse with about 1 μs duration. With this high excitation voltage, the ultrasonic signal can achieve a better signal-to-noise ratio, which helps improve the accuracy of the ultrasonic thickness measurement. Note that the pulser board requires an external 12 V power supply separated from the power supply to the motherboard and the high-rate ultrasonic board.

Figure 3 shows the printed circuit board (PCB) design of the *Martlet* ultrasonic thickness measurement device that consists of the *Martlet* motherboard, the high-rate ultrasonic board, and the pulser board. The planar dimension of the motherboard is 2.5 inch × 2.35 inch. The pulser and high-rate ultrasonic boards can stack on the *Martlet* motherboard through the four corner connectors. The device connects with a dual-element transducer (as illustrated in figure 1) with excitation and receiving ports. In this study, a 2.25 MHz dual-element transducer is selected.

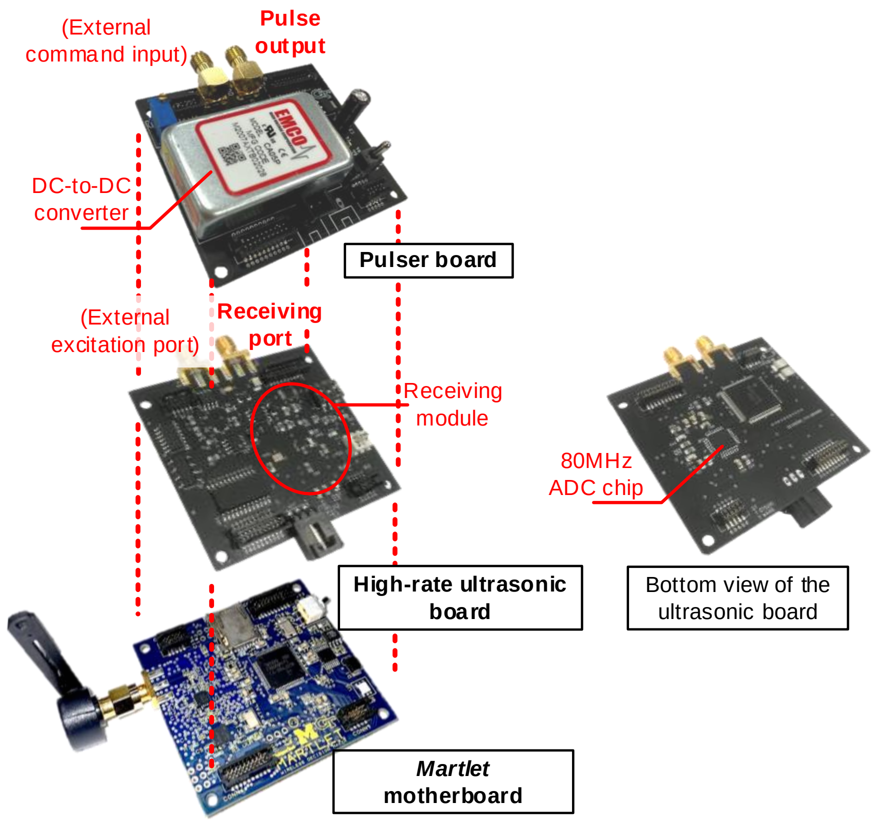


Figure 3. Photographs. Printed circuit board design of the *Martlet* wireless ultrasonic device.

DERIVATION OF CALIBRATION FUNCTION

Generally, it is necessary to calibrate thickness measurement values to identify the offset value specific to the instrument, transducer type, and ultrasonic characteristics. This procedure, known as calibration, is crucial for achieving accurate ultrasonic thickness measurements. Most commercial thickness measurement devices have built-in calibration features to improve the accuracy of measurements. To establish a calibration function for the *Martlet* ultrasonic device, we conduct thickness measurements on a 10-step steel calibration block. The block encompasses a range of thickness values from 0.1 to 1.0 inch, as shown in figure 4.

Figure 4. Photograph. Steel calibration block from 0.1- to 1.0-inch thicknesses.

The calibration block is made of 1018 steel, for which the nominal velocity is set as 0.2330 inch/μs.[10] With the fixed velocity value, the calibration function is derived for the measured ToF values. Specifically, we compare the true ToF (true thickness divided by 0.2330 inch/μs) and the ToF measured by the *Martlet* ultrasonic device. Table 1 summarizes the comparison of ToFs for each of the 10 thickness values.

Figure 5 plots error percentages obtained from table 1. It is evident that the error percentage is more significant for smaller ToFs corresponding to thinner thicknesses (less than 0.4 inch). This observation can be attributed to the 2.25 MHz frequency of the transducer. In general, higher frequency transducers offer better resolution and can lead to smaller errors. However, it is important to note that higher frequency transducers are limited in their ability to penetrate thicker specimens. Given the practical thickness range of actual bridge members, which falls between 0.4 and 1.0 inch, the transducer with a frequency of 2.25 MHz was selected for this study.

Table 1. Comparison of thickness measurements on various specimens without calibration.

Calibration Block		*Martlet* Ultrasonic Device		
True thickness (inch)	**True ToF (µs)**	**Measured thickness (inch)**	**Measured ToF (µs)**	**Error (%)**
0.10	0.858	0.0961	0.825	−3.888
0.20	1.717	0.1937	1.663	−3.159
0.30	2.575	0.2913	2.500	−2.917
0.40	3.433	0.3903	3.350	−2.431
0.50	4.292	0.4908	4.213	−1.849
0.60	5.150	0.5912	5.075	−1.460
0.70	6.009	0.6903	5.925	−1.391
0.80	6.867	0.7893	6.775	−1.339
0.90	7.725	0.8898	7.638	−1.137
1.00	8.584	0.9904	8.500	−0.975

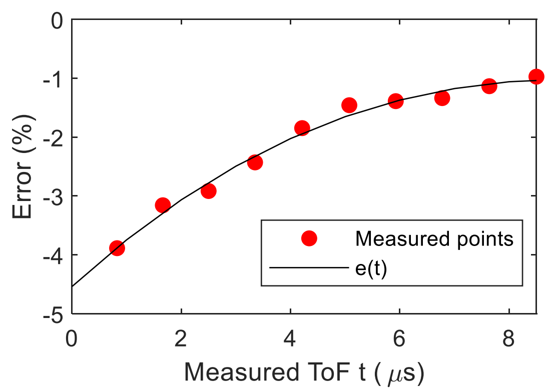


Figure 5. Graph. Measured ToF vs error (without calibration).

Based on data in figure 5, the error percentage function is assumed to be a third-degree polynomial. The coefficients of the polynomial function are determined by linear regression using the least squares method:

$$e(t) = 0.00094t^3 - 0.0597t^2 + 0.8519t - 4.539 \qquad (1)$$

where $e(t)$ is the error percentage function and t is the uncalibrated measured ToF (unit: μs). Finally, the calibrated thickness (unit: inch) is obtained as follows:

$$\text{Calibrated Thickness} = \frac{\text{ToF} \times \text{Nominal Velocity}}{2}(1 - e(t)/100) \qquad (2)$$

Using equation 2, calibrated thickness values of the calibration steel block are obtained, as shown in table 2. The maximum absolute error in calibrated thickness measurements is effectively reduced to 0.233 percent. The following section validates the calibrated thickness measurements using different steel specimens.

Table 2. Comparison of thickness measurements on various specimens after calibration.

Calibration Block		***Martlet* Ultrasonic Device**		
True thickness (inch)	**True ToF (μs)**	**Calibrated thickness (inch)**	**Calibrated ToF (μs)**	**Error (%)**
0.10	0.858	0.0998	0.8570	−0.200
0.20	1.717	0.2000	1.7171	0
0.30	2.575	0..2993	2.5692	−0.233
0.40	3.433	0.3993	3.4277	−0.175
0.50	4.292	0.5003	4.2942	0.060
0.60	5.150	0.6009	5.1577	0.150
0.70	6.009	0.6999	6.0074	−0.014
0.80	6.867	0.7989	6.8573	−0.138
0.90	7.725	0.8995	7.7211	−0.056
1.00	8.584	1.0005	8.5877	0.050

COMPARISON WITH A HANDHELD THICKNESS MEASUREMENT GAUGE

This section compares the measurements obtained by the *Martlet* ultrasonic device with a handheld thickness gauge currently on the market (table 3). Considering its price range ($1000), which is comparable to the *Martlet* ultrasonic device, we purchased a commercial handheld thickness-measurement device. Although the two devices show similar specifications, a key difference lies in the measurement mode. The commercial handheld device can only measure in the pulse-echo mode, whereas the *Martlet* device is designed to measure in the echo-to-echo mode. Pulse-echo mode utilizes the time interval between the excitation pulse to the first arriving ultrasonic echo signal. In contrast, the echo-to-echo mode utilizes the time interval between the neighboring ultrasonic echoes. In general, a device that can perform echo-to-echo measurement costs between $2000 and $3000 on the market, as echo-to-echo measurement usually provides greater accuracy and can ignore the effect of paints on the thickness measurement of steel members.

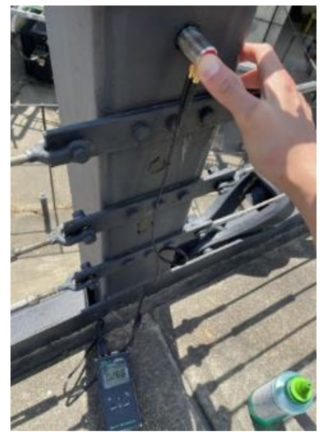
Table 3. Comparison of two thickness measurement devices.

	***Martlet* Wireless Ultrasonic Device**	**Commercial Handheld Device**
Overview		
Sampling frequency	80 MHz	120 MHz
Excitation	200V pulse wave	150V square wave
Transducer	2.25 MHz dual	2.25 MHz dual
Measurement mode	Echo-to-echo	Pulse-echo

Measurements obtained from the two devices were compared using steel plates with various thickness values. We prepared 14 different sizes of structural steel at the Georgia Institute of Technology (Georgia Tech) Structural Engineering and Materials Laboratory (Structures Lab) (figure 6). All the specimens are made of carbon steel, with a nominal velocity of 0.2339 inch/μs and thicknesses ranging 0.175 to 0.1027 inch.[11] Before conducting measurements, we sanded the measurement surface to ensure smoothness. Each thickness was first measured using a caliper to obtain a reference value for the true thickness. Subsequently, thickness measurements were performed using the *Martlet* ultrasonic device with the calibrated ToF and the handheld device.

a. Specimen 1

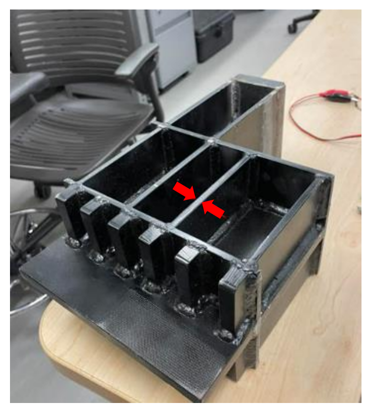
b. Specimen 2



c. Specimen 3

d. Specimen 4

e. Specimen 5

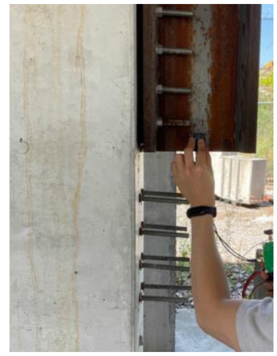


f. Specimen 6

Figure 6. Photographs. Steel specimens collected from the Structures Lab at Georgia Tech.
(Continued on the next page)

g. Specimen 7

h. Specimen 8



i. Specimen 9

j. Specimen 10

k. Specimen 11

l. Specimen 12

m. Specimen 13

n. Specimen 14

Figure 6. (Continued.)

Table 4 summarizes the thickness measurement results from the caliper (“True” column), *Martlet* ultrasonic device, and the commercial handheld device. For 10 of 14 specimens, the *Martlet* ultrasonic device produced better accuracy than the handheld device. This result demonstrates the effectiveness of the calibration function derived in the previous section and the echo-to-echo measurement mode implemented by the *Martlet* device, which, in general, produces better accuracy than the pulse-echo measurement mode used by the commercial handheld device.

Table 4. Comparison of measurement results.

Specimen	True (inch)	*Martlet* Ultrasonic Device		Commercial Handheld Device	
		Measured (inch)	Error* (%)	Measured (inch)	Error* (%)
1	0.175	0.1739	**0.63**	0.172	1.71
2	0.239	0.2361	**1.21**	0.229	4.18
3	0.240	0.2391	**0.37**	0.266	10.83
4	0.275	0.2768	**0.65**	0.280	1.82
5	0.325	0.3183	2.06	0.328	**0.92**
6	0.505	0.5066	**0.32**	0.502	0.59
7	0.548	0.5446	0.62	0.547	**0.18**
8	0.549	0.5446	**0.80**	0.543	1.09
9	0.571	0.5667	**0.75**	0.565	1.05
10	0.623	0.6197	**0.53**	0.617	0.96
11	0.767	0.7656	0.18	0.768	**0.13**
12	0.950	0.953	0.32	0.948	**0.21**
13	1.000	1.0012	**0.12**	0.995	0.50
14	1.027	1.0244	**0.25**	1.037	0.97

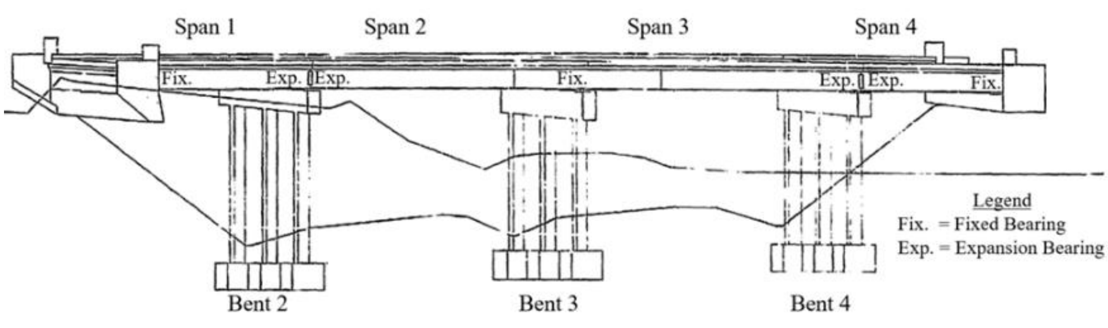
* Bold indicates the smaller error value for the specimen.

CHAPTER 3. PRELIMINARY VALIDATION OF CONTINUOUS WIRELESS THICKNESS MEASUREMENTS ON THE LAGRANGE BRIDGE

This chapter reports field thickness measurements and preliminary instrumentation of the long-term monitoring system on the first testbed bridge in LaGrange, GA. The chapter begins with a description of the bridge, followed by results of thickness measurements taken from the web and the flange of a girder, and finally, provides long-term thickness monitoring results obtained from the web of a steel girder over about seven months.

TESTBED BRIDGE IN LAGRANGE, GA

a. Overview



b. Elevation

Figure 7. Photograph and diagram. Overview of the bridge in LaGrange, GA.

Figure 7 shows the overview (figure 7a), and the elevation (figure 7b) of the first testbed bridge (Structure ID – 285-0067-0) investigated in this study. The bridge was built in 1977 and is located in LaGrange, GA. The condition rating by the National Bridge Inventory for this bridge is 7 – Good Condition. The bridge superstructure consists of six steel beams and a reinforced concrete deck. The bridge has four spans: two simply supported end spans and two continuous middle spans.

FIELD THICKNESS MEASUREMENTS

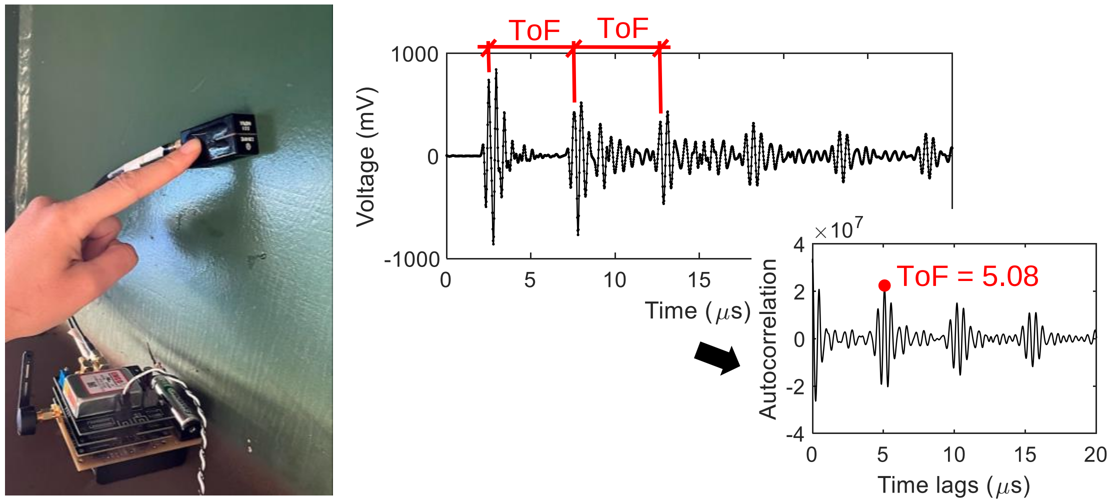
Ultrasonic thickness measurements were first conducted on the web and bottom flange of a steel girder located at Span 4. A 2.25 MHz dual element transducer was employed and connected to the *Martlet* ultrasonic device. The structural design documents show that Span 4 utilizes ASTM A36 carbon steel with a W36×135 section. The nominal thickness of the W36×135 section is 0.80 inch for the bottom flange and 0.60 inch for the web. Sand and dust have accumulated on the surface of the bottom flange, as is often the case in practice, and make the thickness measurement more challenging compared to the clean surface of the web.[12] The entire girder has paint coatings. Due to the presence of coatings, the apparent thickness is larger than the nominal thickness of the steel itself. Therefore, instead of conducting velocity calibration by caliper measurements, this study uses the nominal velocity 0.2339 inch/μs for carbon steel.[13]

Figure 8a shows the received signals of the 2.25 MHz dual-element transducer sampled by the high-rate ultrasonic board for the 0.60-inch-thick web with a clean surface. The received signal includes a sequence of echoes, which are the reflections of the ultrasonic waves created by the transducer. The time interval between the neighboring echoes is the ToF. To accurately obtain the ToF, we calculate the autocorrelation function of the received signal using the following equation:

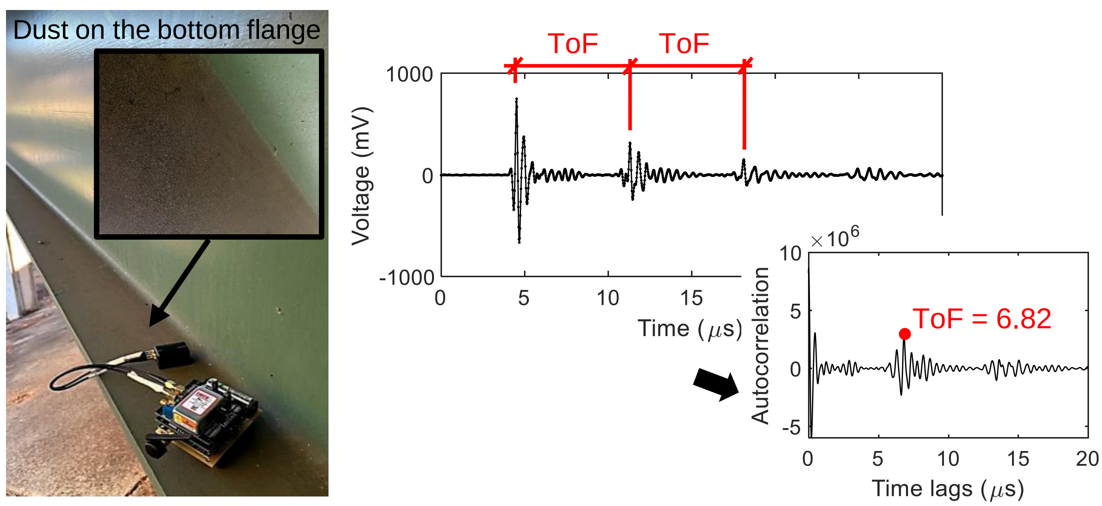
$$a[k] = \sum_{l=0}^{N-k} v[k+l]v[l], \quad k = 0, \ldots, N \tag{3}$$

where $a[k]$ is the autocorrelation function at discrete-time lag k; $v[l]$ is the received voltage signal at the time step l; and N is the total number of data points. Based on the peak value of the autocorrelation function, the uncalibrated ToF is identified as 5.08 μs for the web. Although alternatively one could estimate the ToF using the time difference between the first and second peaks in the received ultrasonic signal, the autocorrelation function is generally more robust against noise and with rough surface conditions.

Similarly, figure 8b shows the received signals and autocorrelation function for the 0.80-inch-thick bottom flange with a dusty surface. Note that we did not clean the dust on the bottom flange. Therefore, autocorrelation waveforms are slightly distorted compared to the web due to the layer of dust. However, the peak is clearly identified at 6.82 μs.



a. 0.60-inch-thick web with clean surface



b. 0.80-inch-thick bottom flange with dusty surface

Figure 8. Photographs. Received ultrasonic signals and autocorrelation function.

The thickness of each specimen is calculated by equation 2 and summarized in table 5. For the 0.60-inch-thick web, the estimated thickness is 0.6037 inch. The difference from the nominal thickness of 0.60 inch is only 0.0037 inch (0.62 percent). For the 0.80-inch-thick bottom flange, the estimated thickness is 0.8071 inch, only 0.0071 inch (0.89 percent) different from the nominal thickness of 0.80 inch. In general, actual thickness values may vary from the nominal value within an allowable tolerance, as specified by ASTM-A6/A6M-14.[11] The measurements obtained both on the dusty web and the clean flange are well within their allowable tolerance of 0.03 inch from the corresponding nominal thickness. Therefore, this field test validates the performance of the developed *Martlet* ultrasonic device in the presence of coatings and accumulated dust on the steel surface.

Table 5. Thickness measurement results on a steel girder bridge in Span 4.

	0.60-inch-thick Web (clean)	**0.80-inch-thick Bottom Flange (dusty)**
Uncalibrated time of flight (ToF)	5.08 μs	6.82 μs
Calibrated time of flight (ToF)	5.16 μs	6.90 μs
Nominal velocity	0.2339 inch/μs	0.2339 inch/μs
Estimated thickness	0.6037 inch	0.8071 inch
Difference from nominal thickness	0.62%	0.89%

LONG-TERM ULTRASONIC THICKNESS MEASUREMENTS

The bridge happens to have electricity available, allowing convenient implementation of the long-term monitoring system in this preliminary investigation. A *Martlet* ultrasonic device is installed on the web of a girder located in Span 2.[14] Note that Span 2 utilizes a W135×150 steel section with a nominal web thickness of 0.625 inch. The *Martlet* unit establishes Zigbee wireless communication with the gateway computer installed at the edge of Span 1 of the bridge. The gateway is connected to a 4G LTE network, enabling the collected data to be uploaded to the cloud for subsequent analysis.

Figure 9 shows the installed *Martlet* wireless ultrasonic device in Span 2. A 2.25 MHz dual-element ultrasonic transducer is installed together with a magnet mount to ensure firm contact between the transducer and the steel surface. A wireless antenna and a 12V battery are placed next to the wireless unit. The 12V battery is connected to a pulser board via a relay switch, ensuring battery power is only consumed during brief measurement intervals that last a few seconds. Consequently, the battery lifespan is significantly extended. Between the measurement surface and the transducer, we applied a paste-like couplant (more viscous than commonly used gel) suitable for long-term monitoring.

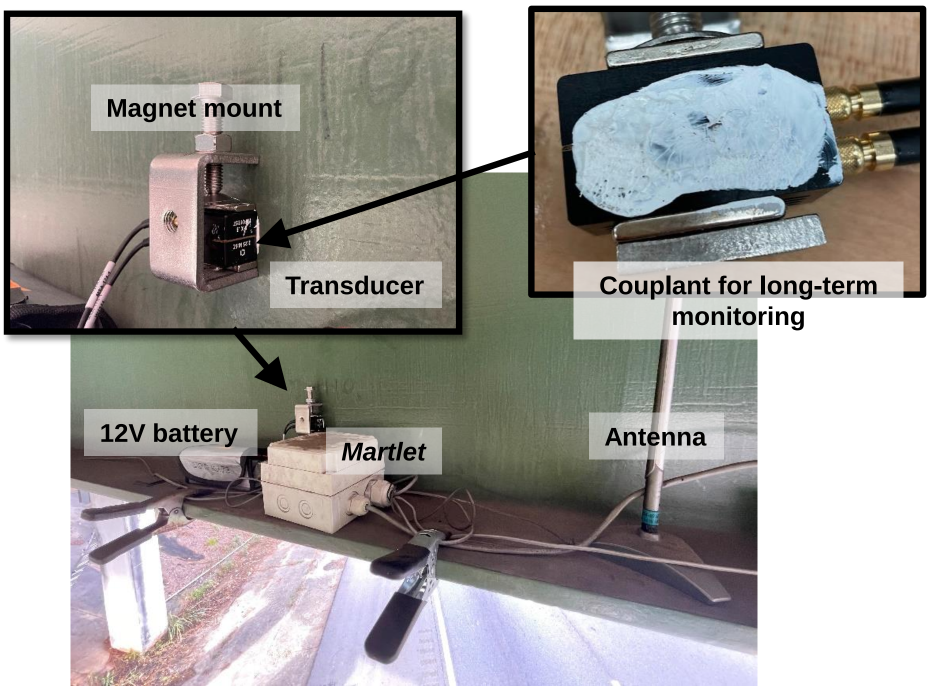


Figure 9. Photographs. Installation of a *Martlet* wireless ultrasonic device for long-term thickness monitoring.

The thickness measurements are taken at scheduled time intervals for long-term monitoring. Figure 10 shows the daily thickness values recorded from November 21, 2022, to June 13, 2023. Overall, stable measurements are obtained around 0.64 inch, close to the 0.625-inch nominal thickness. The ultrasonic measurement system has a resolution of 0.0015 inch. Minor fluctuations in the measured thickness values, either slightly higher or lower by 0.0015 inch, are observed from December 2022 to February 2023. These variations could be attributed to the influence of cold weather conditions on the couplant during the winter months or the couplant material taking time to reach a stable state until February 2023. Over the subsequent three months, the measurement values have remained stable, indicating the successful operation of the long-term thickness measurement system. This field testing validates the long-term ultrasonic thickness measurement system on a regular highway bridge and serves as the preliminary validation. Chapter 4 describes installation of the system to a second testbed bridge with corrosion.

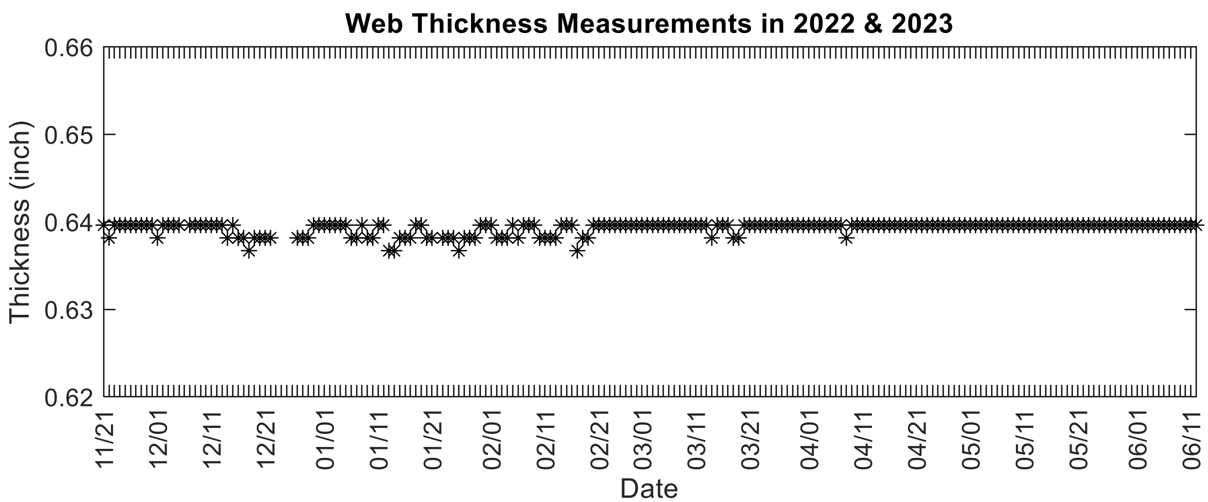


Figure 10. Plot. Daily history of the web thickness measurements on the bridge in LaGrange, GA

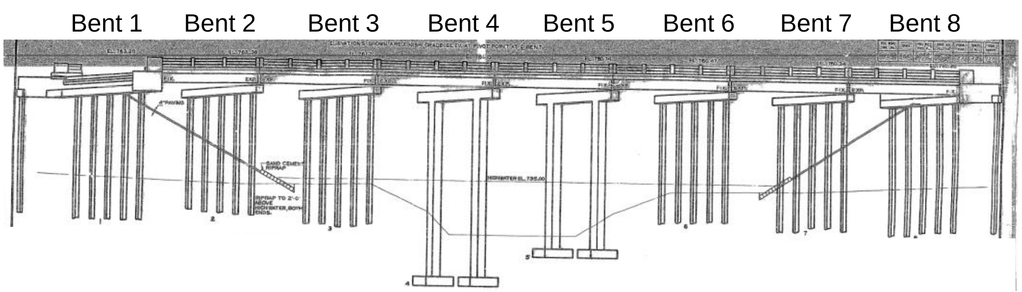
CHAPTER 4. LONG-TERM WIRELESS THICKNESS MEASUREMENTS ON THE DOUGLAS COUNTY BRIDGE

Chapter 3 confirmed the successful operation of long-term thickness measurement on a bridge in good condition. This chapter presents the implementation of the long-term thickness measurement system on another testbed bridge with corrosion. The chapter first describes the testbed bridge in Douglas County, GA, and then provides the installation details followed by the long-term thickness measurement results from four installed wireless sensing units.

TESTBED BRIDGE IN DOUGLAS COUNTY

Figure 11 provides an overview of the bridge located in Douglas County, GA. The bridge consists of eight bents and five beams, forming a composite structure with a reinforced concrete deck. The middle two bents, Bents 4 and 5, are positioned above the river from the Bear Creek Reservoir, close to the bridge. These two middle columns (supporting Bents 4 and 5) are made of concrete, whereas other columns are made of wide flange steel sections. The bridge (Structure ID # 097-0013-0) was constructed in 1957, making it 20 years older than the bridge investigated in chapter 3. The National Bridge Inventory condition rating for this bridge is 5 – Fair Condition.

a. Overview



b. Elevation

Figure 11. Photograph and drawing. Overview of the bridge in Douglas County, GA.

INSTALLATION

Figure 12 shows four wireless sensing units (U152, U156, U164, and U166) installed on this bridge. The long-term thickness monitoring system also includes a gateway enclosure with a rechargeable battery powered by a solar panel. The details of each of these components are explained in the following subsections.

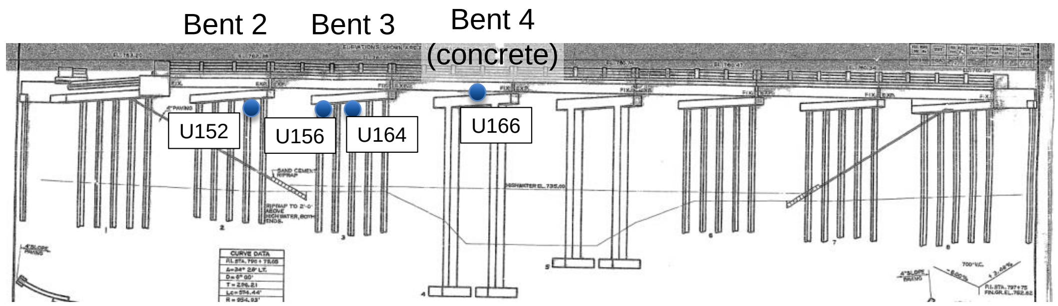


Figure 12. Diagrams. Location of four wireless sensing units.

Solar Panel and Support Structure

The long-term thickness monitoring system requires a continuous power supply for the operation of the gateway computer. However, unlike the previous bridge in LaGrange, which had electricity available, the bridge in Dougals County lacks such a power source. Consequently, a solar panel and solar charging battery system are installed on this bridge as part of the current project. We select a 200W solar panel to meet the power requirements for the continuous operation of the system. A solar panel support structure is designed to mount the solar panel in the middle of the bridge. Figure 13 shows the installed solar panel and support structure in the middle of the bridge between Bents 4 and 5. This location provides an unobstructed view for the panel, ensuring optimal exposure to sunlight. The solar panel is oriented in the south direction for maximum charging efficiency.

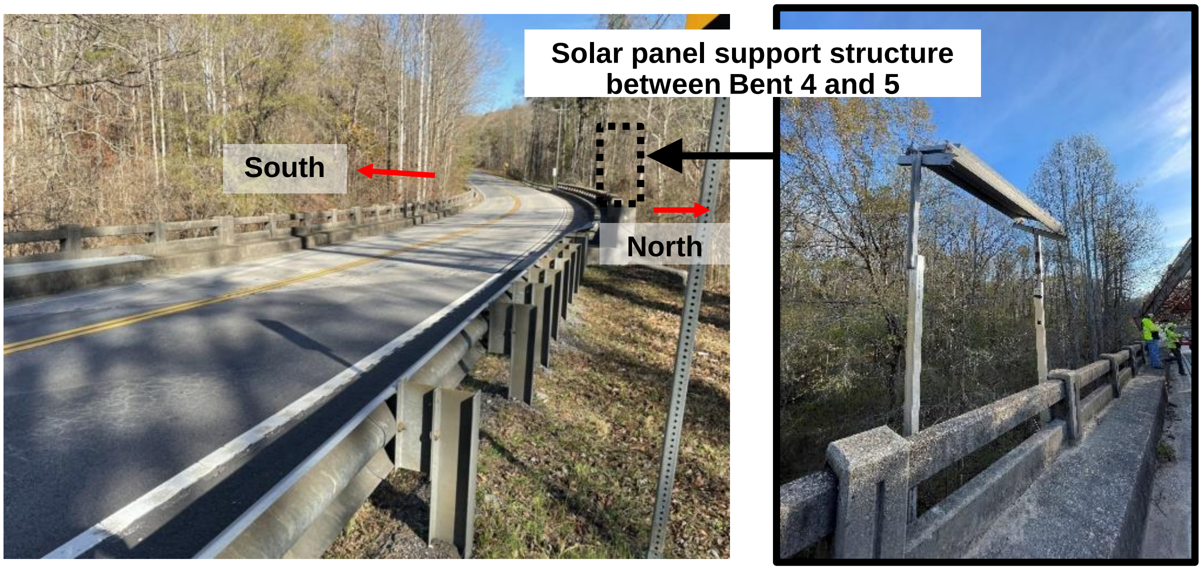


Figure 13. Photographs and diagrams. Design and installation of a solar panel and its support structure.

Enclosure and Devices

As shown in figure 12, a steel enclosure has been installed at the west end of the bridge. Figure 14 shows photographs of the enclosure securely attached to the pole sign, housing various devices inside. A modem is housed in a waterproof case and attached to the pole outside to receive a reliable 4G LTE network for uploading collected ultrasonic data to the cloud. Within the enclosure is a large 2400Wh battery that is charged by the solar panel during the daytime. A charging controller is connected between the panel and the battery to manually monitor charging efficiency and protect the panel from electrical damage. The gateway PC is powered by the battery through an inverter. The enclosure is equipped with a built-in lock and an external padlock for security purposes.

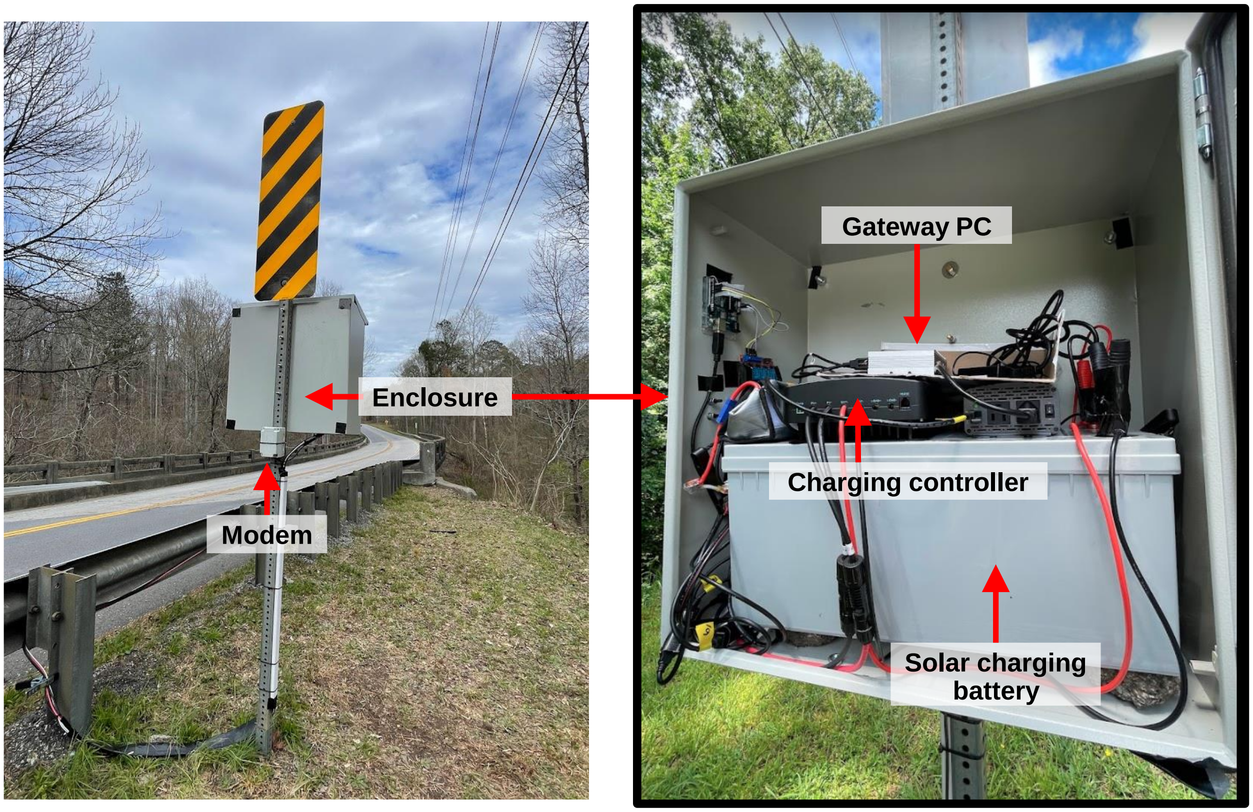


Figure 14. Photograph. Enclosure with the gateway computer and solar charging battery.

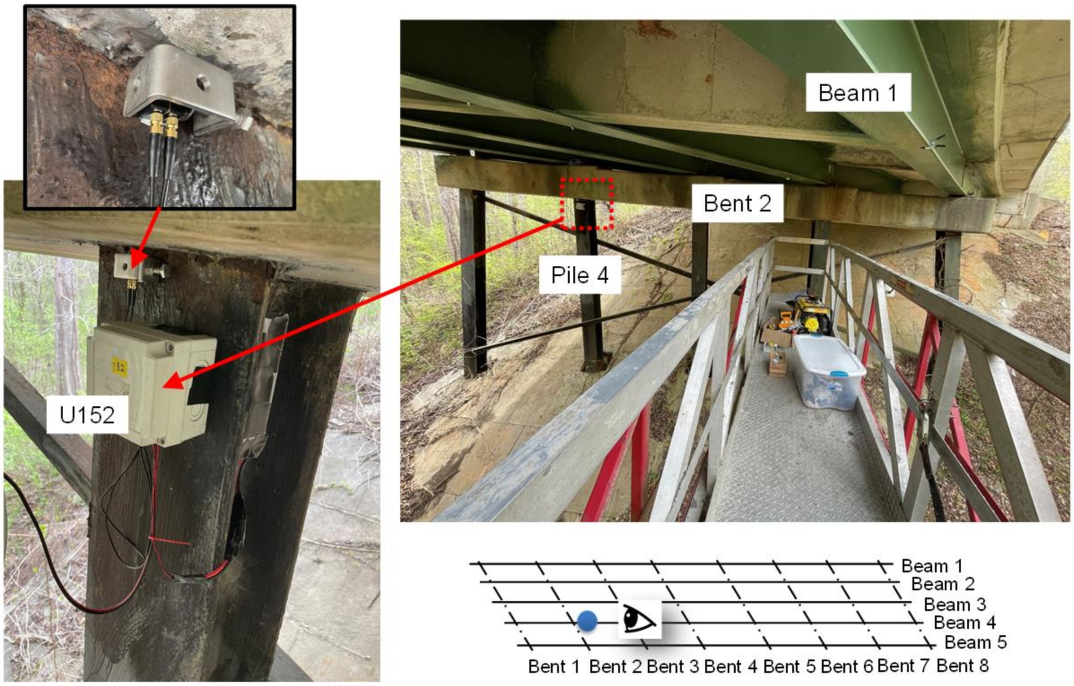
Wireless Ultrasonic Sensing Units

Prior to the installation in April 2023, the Georgia Tech and Georgia Department of Transportation (GDOT) team conduct a visual inspection in October 2022 to evaluate the level of corrosion on structural members throughout the bridge. During the inspection, corrosion was observed on the west part of the bridge. In response to these findings, four wireless sensing units, namely U152, U156, U164, and U166, are installed across Bent 2 to Bent 4, as illustrated in figure 12. This subsection provides a summary of the installation locations, pictures, collected ultrasonic waveforms, and thickness measurement values for each sensor unit upon installation.

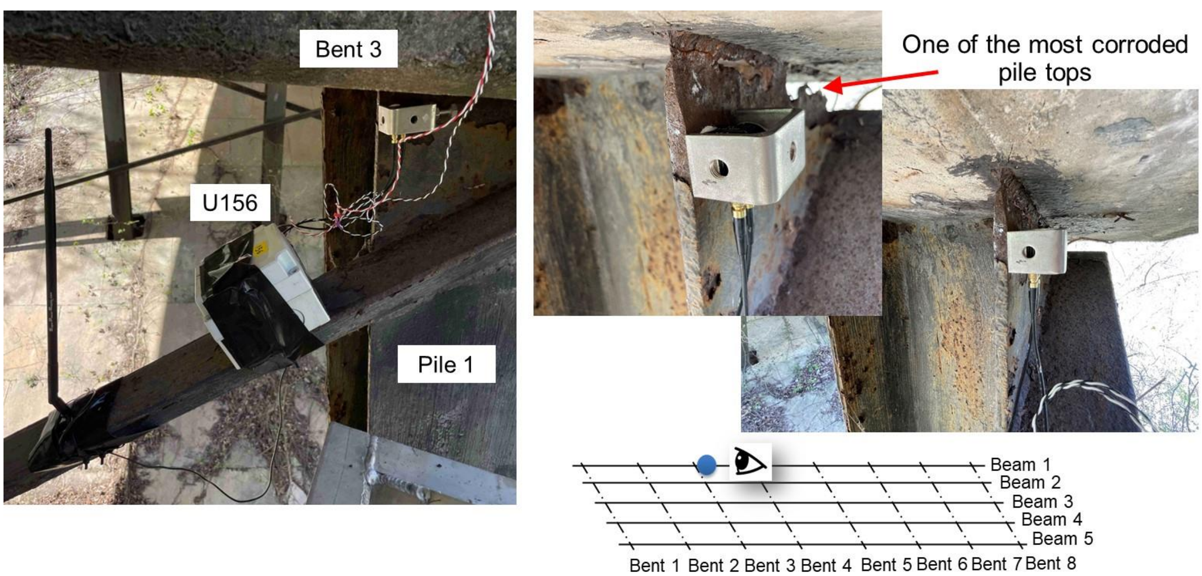
Figure 15 shows photographs of the four installed wireless ultrasonic sensing units. Wireless unit U152 is installed on the top of Pile 4 on Bent 2, as shown in figure 15a. The installed location exhibits relatively healthy conditions.

In the meantime, unit U156 is installed on the top of Pile 1 on Bent 3 (figure 15b), which is one of the more corroded pile tops on the bridge, as we can confirm a through-hole on its top. The motivation of installation at this location is to monitor the rate of corrosion on this corroded pile over time.

Figure 15c illustrates unit U164 installed on the top of Pile 3 on Bent 3. Finally, unit U166 is installed on the bottom flange of Beam 3 on Bent 4 (figure 15d), as this bottom flange is one of the more corroded flanges on the bridge.

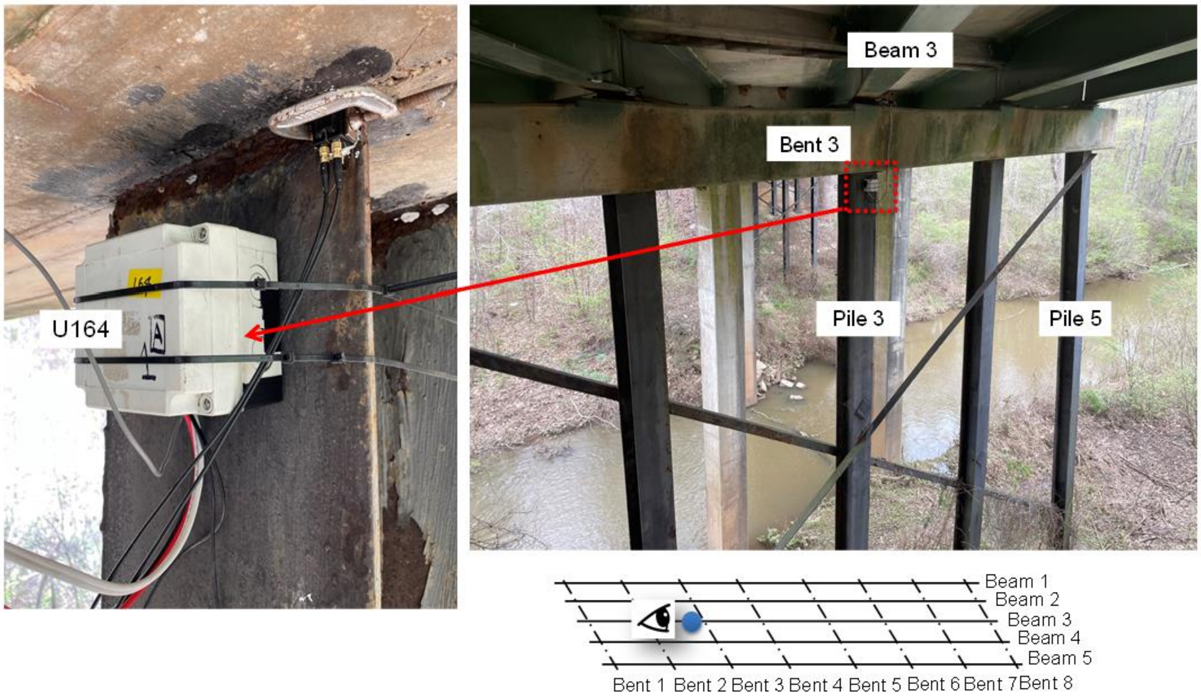


a. U152 installed on the top of Pile 4 on Bent 2

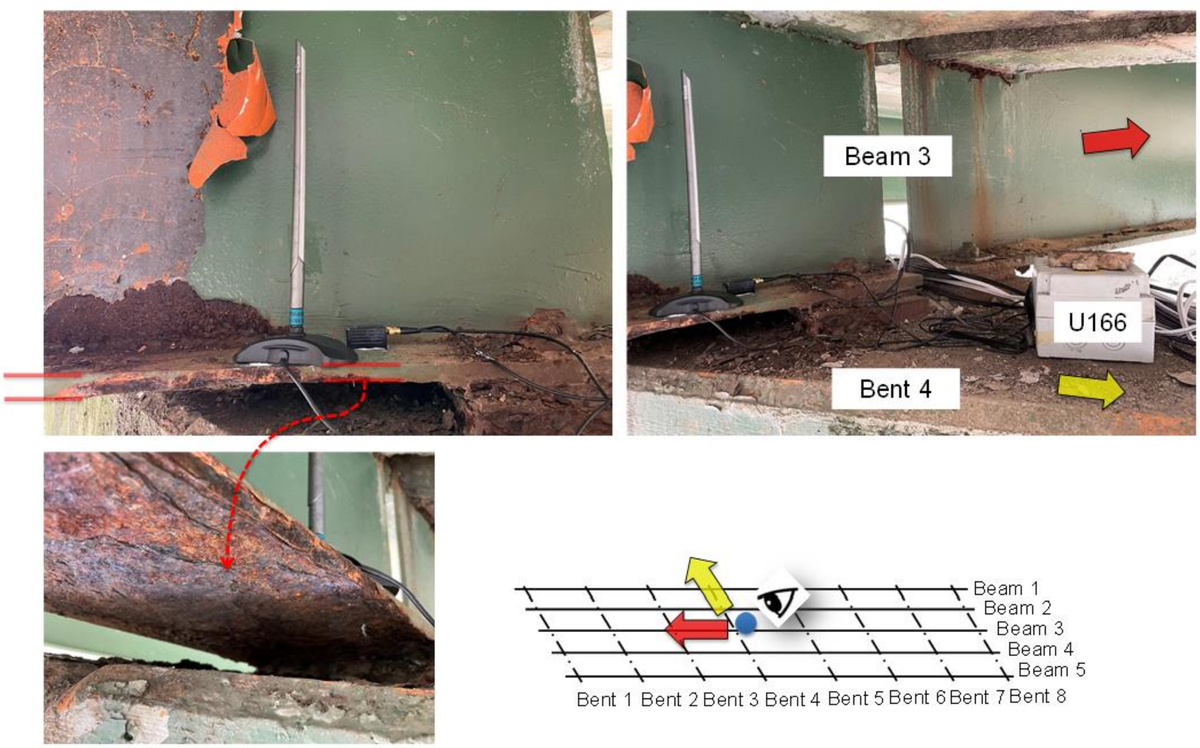


b. U156 installed on the top of Pile 1 on Bent 3

Figure 15. Photographs. Installation of four wireless ultrasonic units.
(Continued on the next page)

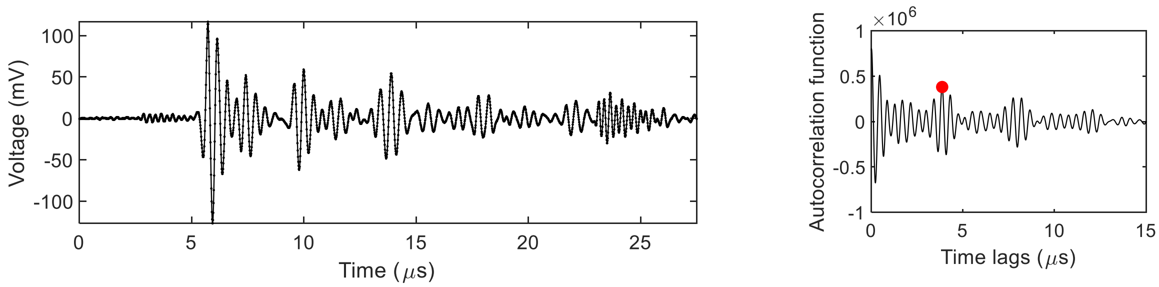


c. U164 installed on the top of Pile 3 on Bent 3

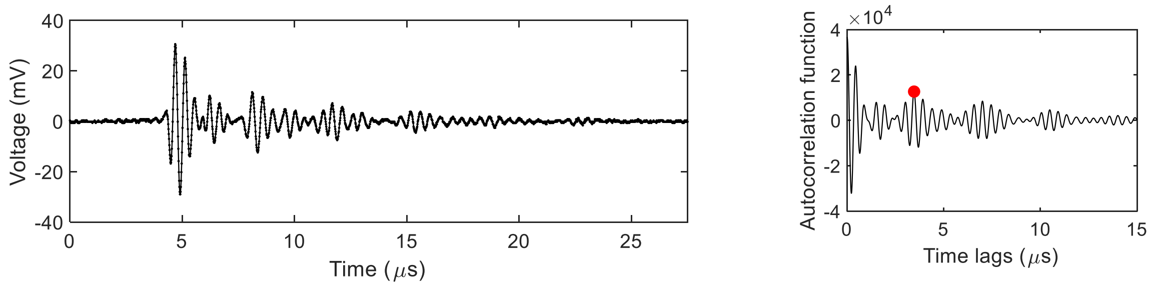


d. U166 installed on the bottom flange of Beam 3 on Bent 4

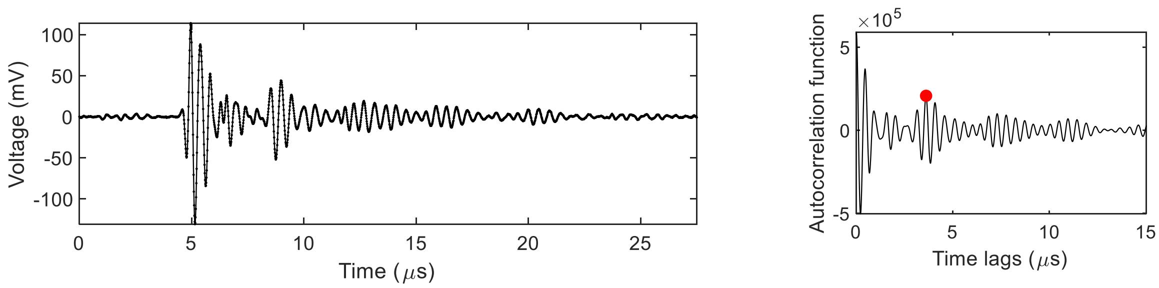
Figure 15. (Continued).



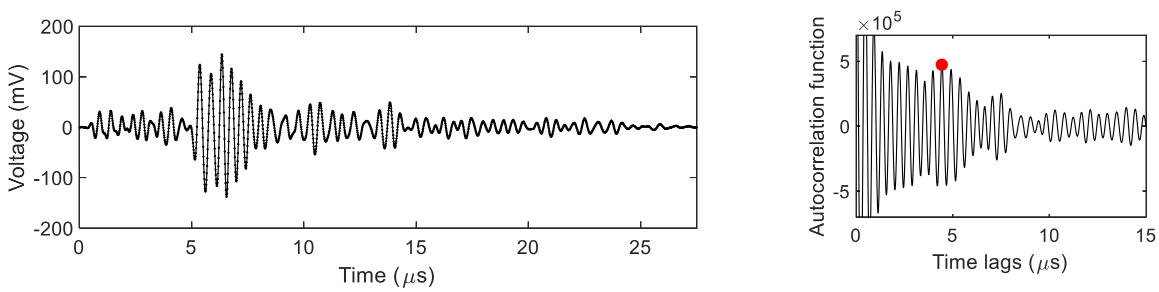
a. U152 installed on the top of Pile 4 on Bent 2



b. U156 installed on the top of Pile 1 on Bent 3



c. U164 installed on the top of Pile 3 on Bent 3



d. U166 installed on the bottom flange of Beam 3 on Bent 4

Figure 16. Plots. Ultrasonic waveforms and autocorrelation function obtained from four wireless sensing units.

Upon installation, ultrasonic waveforms are collected to validate the measurements, as shown in figure 16. The autocorrelation function is calculated to automatically identify the peak, which corresponds to the uncalibrated ToF. We confirm that ultrasonic signals are reliably obtained from the installed four units. The waveforms obtained from U166 are slightly distorted due to the rough surface conditions at the bottom flange.

Corresponding to ultrasonic waveforms in figure 16, thickness values are calculated using equation 1 and the nominal velocity 0.2339 inch/μs. Table 6 provides a summary of the thickness measurement values from the four wireless ultrasonic sensing units. As the pile tops exhibit relatively healthy conditions, the thickness values measured by U152, U156, and U164 closely match the nominal thickness of 0.435 inch. The differences between the measured and nominal thicknesses are confirmed to be within the manufacturer's tolerance of 0.03 inch. On the other hand, for the corroded bottom flange measured by U166, the remaining thickness is reduced by nearly 30%, which can also be visually confirmed from figure 16d.

Table 6. Summary of thickness measurement results from four wireless sensing units.

Unit Number	Calibrated ToF (μs)	Measured Thickness (inch)	Nominal Thickness (inch)	Difference from the Nominal Thickness (inch)
U152	3.943	0.4611	0.4350	0.026 (6.0%)
U156	3.541	0.4140	0.4350	−0.021 (−4.8%)
U164	3.692	0.4317	0.4350	−0.013 (−0.8%)
U166	4.507	0.5270	0.7450	−0.198 (−29.3%)

LONG-TERM THICKNESS MEASUREMENT RESULTS

In this section, we present the long-term thickness measurement results obtained from the four wireless ultrasonic sensing units. The gateway computer is configured to initiate ultrasonic data collection at scheduled intervals for each sensor. The collected ultrasonic data are then uploaded to the cloud.

Figure 17 displays the daily history of thickness measurement values obtained from April 4 to July 23, 2023. Three units U152, U156, and U164 installed at pile tops have provided consistent measurements over the last three months (up to the time of this report). However, reliable measurements from U166 have ceased near end of May. Soldering quality on the prototype circuit board is suspected to be the cause; replacement of the circuit board would resolve the issue.

Some data points are missing due to the challenge with the solar charging battery. Specifically, the battery was configured by the manufacturer to occasionally shut off, resulting in data gaps. To resolve this issue, we replaced the battery with one from a different manufacturer on July 10, 2023. The battery issue was successfully resolved after this replacement, and measurements are now being obtained consistently.

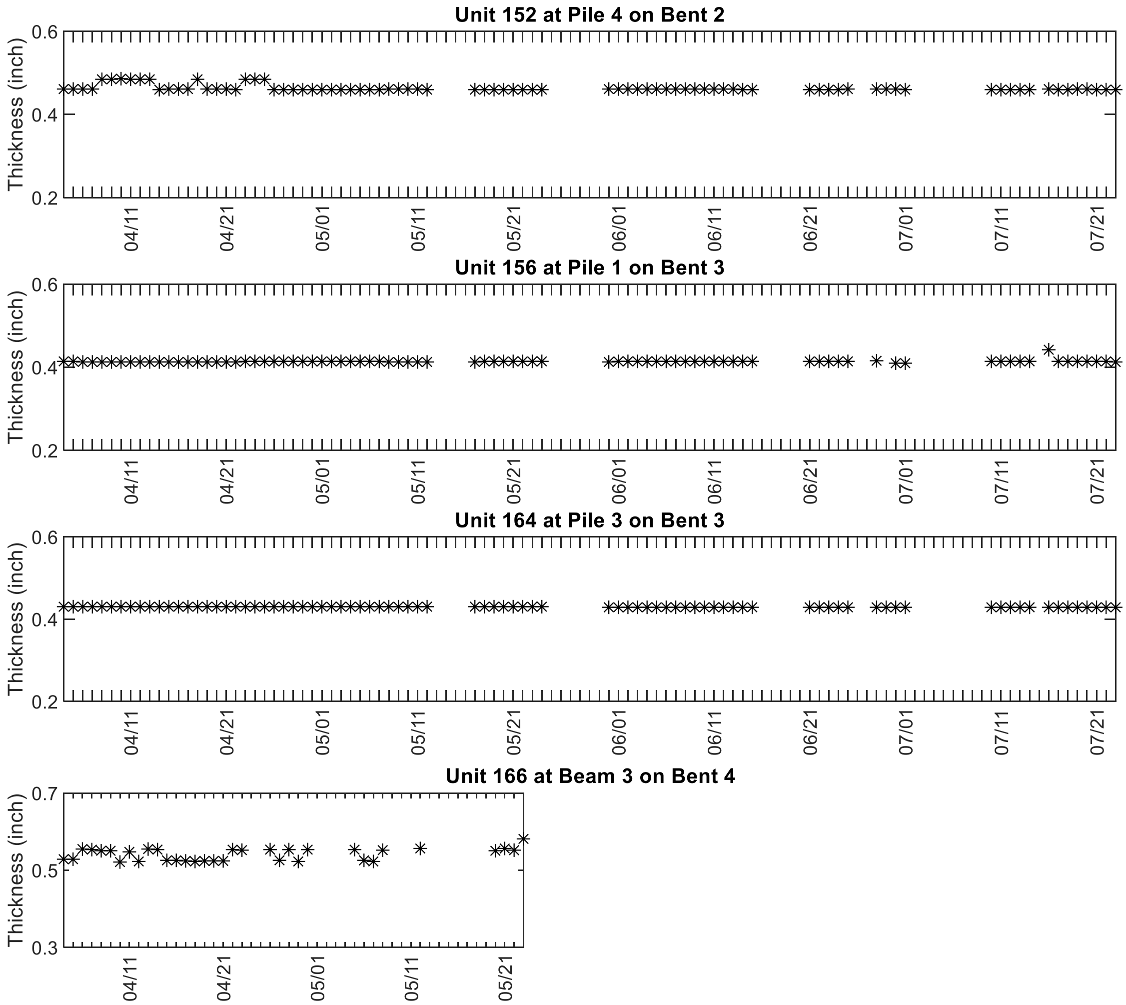


Figure 17. Plots. Daily history of thickness measurements on the Douglas County bridge.

CHAPTER 5. CONCLUSIONS

This project implemented long-term wireless ultrasonic thickness measurement systems on two testbed bridges in Georgia. The summary and conclusions are made as follows:

- The developed system consists of the *Martlet* wireless ultrasonic device, a gateway computer, and a solar charging battery. The system is configured to collect ultrasonic thickness data of steel bridge members and upload it to the cloud automatically. The developed system allows the remote monitoring of thickness values over time without physically accessing measurement locations.
- On the bridge in LaGrange, thickness values were recorded over about seven months. Although the measurements stabilized in the last three months, we observed slight variations for the first few months of installation. These variations could be attributed to cold weather conditions during the winter months or the couplant material requiring time to achieve a stable state.
- A second testbed bridge in Douglas County exhibits corrosion conditions on structural members. Three wireless sensing units have obtained reliable measurements since the installation and are still functioning properly till the time of this report’s preparation. Due to the short duration of the project, the measurement values have not yet shown any changes in thickness values.

ACKNOWLEDGEMENTS

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