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Utilizing Unmanned Aerial Vehicles (UAVs) for the Estimation of Beam Corrosion of Steel Bridge Girders

Gabrielle Pryor

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A Thesis Presented

by

GABRIELLE COURTNEY PRYOR

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

Master of Science in Civil Engineering

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ABSTRACT

UTILIZING UNMANNED AERIAL VEHICLES (UAVS) FOR THE ESTIMATION OF BEAM CORROSION OF STEEL BRIDGE GIRDERS

FEBRUARY 2021

GABRIELLE COURTNEY PRYOR, B.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

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The transportation infrastructure in the United States is a complex system that is vital to the everyday operations of the country. Bridges are a significant asset of this network, with many of them approaching the end of their service life. Corrosion is a common cause of deterioration which ultimately results to structural deficiency for the aging bridges. The deterioration rate is a multi-aspect factor that makes bridge inspections crucial. However, the current bridge inspections are very costly and potentially unsafe for the involved personnel. To lower costs and increase safety, many state DOT's and universities have decided to perform research on Unmanned Aerial Vehicles (UAVs), or drones. This thesis explores the implementation of drone technology in bridge inspections and investigates their limits for corrosion detection and estimation. The first part of this thesis summarizes the responses obtained from a questionnaire sent to the personnel from the Massachusetts Department of Transportation (MassDOT). The second and third parts of this thesis summarizes how states have utilized UAVs for bridge inspections, including the selected drones and the attached equipment. The last part

presents technologies that can be used to detect and measure corrosion, and how they can be used in conjunction with drones to quantify section loss of steel beams.

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LIST OF ABBREVIATIONS

UAV: Unmanned Aerial Vehicles (Also Referred to as Drones)

DOT: Department of Transportation

MassDOT: Massachusetts Department of Transportation

AASHTO: American Association of State Highway and Transportation Officials

NDT: Non-Destructive Testing

C-NDT: Contact Non-Destructive Testing

NC-NDT: Non-Contact Non-Destructive Testing

Chapter 1

RESEARCHING UAV USE FOR THE MASSDOT

1.1 Introduction

This study of the use of unmanned aerial vehicles (UAVs) for the estimation of steel beam corrosion was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.2 Background Information

The United States transportation network is one of the most vital systems in the country. Such a complex system, comprised of roads, bridges, tunnels, and even waterways, make it possible to get people, goods, and services from point A to point B. Millions of people rely on this transportation system every day; however, it has become evident over the past decade that the deteriorating infrastructure is hindering the safety and efficiency of the United States (U.S.) transportation system. Bridges particularly have been hit hard by the conditions they have been exposed to over time. According to [1], 9.1% of the bridges in the U.S. are structurally deficient. That means roughly 10% of the bridges in the U. S need to be periodically inspected or monitored and eventually repaired. The scenario only gets worse, considering the daily 188 million trips made over the 56,007 structurally deficient bridges are bringing them closer to becoming unsafe, decommissioned, and in need of repairs at a high cost of about $123 billion dollars [1].

Among the many aspects of aging and structural deficiency, corrosion is considered a common cause of steel deterioration. Steel beam end corrosion, in particular, is a crucial issue in the northern United States. The salt, water, and other chemicals used for de-icing the roadway seeps through leaking bridge joints and corrodes the steel. As the bridge edges rest on the bearing, the corrosion of this vicinity directly affects the load-carrying capacity. This pressing issue is why many state Departments of Transportation (DOTs), researchers, and universities have begun to think of how to best monitor this growing problem.

Corrosion identification and monitoring is an essential task, whose effectiveness depends on the performance of inspections. As the older bridges in the U.S. age and degrade, the need for frequent and detailed inspections becomes more crucial to determining when it is time to make repairs or completely replace the bridge. However, an increase in the number and quality of inspections is difficult given that the current bridge inspection practices disrupt traffic flow, are costly to the state, and are often unsafe for bridge inspectors. To circumvent these issues and enhance the inspections, many DOT's and Universities have begun to research using Unmanned Aerial Vehicles (UAV), or drones, to perform bridge inspections.

1.3 Research Goals and Methodology

The goal of this research project is to investigate the usage of drones for the inspection of transportation assets. More specifically, how drones can be used for bridge inspections, focusing, mainly, on the investigation of corroded beam elements.

The first phase of this research project was the creation and distribution of a questionnaire. This questionnaire had three sections and a total of 42 questions regarding general bridge inspections practice, bridge corrosion assessment, and bridge inspection equipment. The questionnaire was made using Google Forms and was distributed to those involved in with MassDOT bridge inspections. The responses obtained from 34 bridge inspection personnel is presented and analyzed in Chapter 2 of this thesis. From these responses it was concluded that inspectors need a corrosion technology that is accurate, reliable in most weather conditions, is easy to use, and can access hard to reach areas of the steel bridge girders without requiring too much rust and delamination to be removed.

The second phase of this research project was a literature review that focused on the use of UAVs for inspection and monitoring of general transportation infrastructure. During this phase reports from the California DOT (Caltrans), the Illinois DOT, the Iowa DOT, The Indiana DOT, the Ohio DOT, the Kansas DOT, the Kentucky DOT, the New Hampshire DOT, the Missouri DOT, the Vermont Agency of Transportation (VTrans), and the American Association of State Highway and Transportation Officials (AASHTO) were summarized. These reports focused on how they have each used UAVs to perform general transportation activities. The study and analysis of what each DOT used UAVs for, why they found it beneficial, and any other research they conducted using drones is presented in Chapter 3. From this information, it was concluded that the state DOTs found drones to be useful for many different transportation activities, such as surveys, traffic monitoring, and bridge inspections, because they are more effective, safer, and cheaper than traditional methods.

The third phase of this research project was a second literature review that focused on the use of UAVs for bridge inspection activities. For this phase, reports from the Idaho DOT, the Michigan DOT, the Minnesota DOT, the Nebraska DOT, the North Carolina DOT, the Oregon DOT, Carnegie Mellon University, Colorado State University, the Florida Institute of Technology, the Mid-America Transportation Center, Union Pacific Railroad, and Norfolk Southern Railway were studied. These reports contained information on bridge inspections that each research team had performed using UAVs. Chapter 4 of this report specifically records the research efforts of each entity, along with what drones were used, what other technology was used, and what conclusions were reached. It was found that those that carried out actual bridge inspections using drones felt they were able to detect the same amount of information, if not more, then traditional inspection methods. They also found that the additional technology that can be attached to the drones, such as thermal cameras, can help detect valuable information like delamination, cracks, and other distress features on a bridge.

The last phase of this research project was a third and final literature review that focused on different advanced technologies and how they can be combined with drones in order to estimate corrosion during a bridge inspection. The reports for this review were broken into two sections; contact non-destructive testing methods and non-contact non-destructive testing methods. Some methods had reports where researchers attached the technology to a drone, while others just detailed technology that could be used to measure steel thickness for corrosion estimation. The reports just dealing with corrosion measurement technology were included because the research had promising results and could potentially be used on drones as technology advances. Chapter 5 presents the methods proposed, research conducted, and outcomes of the research that were studied and recorded for this thesis. From this information it was found that C-NDT methods are readily available for use on drones and are viable option for implementation on drones for the purpose of estimating corrosion of a steel girder. However, NC-NDT could be a better option once the right technology is available because it can capture a larger area without needing a very skilled pilot to fly the drone up to the girder so it can make contact in order to estimate corrosion.

Ongoing research at UMass Amherst in the last several years has been studying the phenomenon of corrosion on beam ends [2]. A major part of this research is the experimental program of the state through which real corroded beams are shipped to the UMass Amherst Brack Structural Testing Laboratory after they have been removed from demolition projects. To the author's knowledge this is the first time real corroded beams have been tested for the assessment of their capacity [3 – 6]. Building on the findings from experiments, computational methods have been utilized to analyze the phenomenon combining real data from inspection reports gathered from the state. Using all this real data, experiments of real corroded beams and computational modeling a new set of procedures has been proposed for adoption in the new Bridge Manual. It should be mentioned here that previous work of the research group at UMass had focused in the past on other topics of damaged structures such as progressive collapse of structures [7-18] and knowledge from that field has been valuable for the analysis of aged bridges. Future work on deteriorated bridges would include analyzing the system behavior of deteriorated bridges and stability considerations as well as load distributions would be significant.

Chapter 2

QUESTIONNAIRE AND RESPONSES FROM MASSDOT INSPECTORS AND CONSULTANTS

2.1 Background Information and Questionnaire Goals

To begin this research it was decided that a questionnaire should be sent out to those involved in carrying out bridge inspections in Massachusetts. The purpose of this questionnaire was to determine what is and what is not working in terms of bridge inspection procedure, bridge corrosion assessment, and inspection equipment.

The questionnaire was made using Google Forms and the following goals were kept in mind while creating the questions:

1. Gather general information about the people who inspect bridges
2. Gather general information about the general bridge inspection procedures
3. Gather information on how corrosion and corrosion of beam ends is currently being estimated and assessed
4. Gather information on the equipment that inspectors have
5. Gather information on any drone use or possible drone for transportation related activities

Once the questionnaire was finished, it was sent through a link to MassDOT bridge inspection personnel. The MassDOT is divided into 6 Districts, each one having over 1000 bridges to inspect. Due to the large volume of bridges within Massachusetts, MassDOT decided it would be more feasible to have inspectors both internally and externally. Internally, there are MassDOT bridge inspection groups that are in charge of bridge inspections within their respective districts, and externally MassDOT hires consultants from different engineering companies to inspect the other bridges throughout the state. Because of this, the questionnaire presented in this work was sent to both the bridge inspection personnel within MassDOT and those outside consultants that are hired by MassDOT to do inspections.

The full questionnaire can be seen in Appendix A. The results of the questionnaire are recorded below, and they were used to determine the new method for corrosion estimation that would be researched and discussed for the remainder of this thesis.

2.2 Questionnaire Responses

After sending out the questionnaire, a total of 34 responses, 11 MassDOT employees and 23 consultants, were recorded and the data has been processed below.

2.2.1 General Bridge Inspection Practices Section Responses

For confidentiality, the responses for the first question that asked for their name and email address has be omitted from this report. To organize the four questions that followed, it was decided that the answers would be split into 2 categories: responses from MassDOT employees and responses from consultants.

Using the responses from the second question in the questionnaire that asks about the person's current position, Figures 2.1 and 2.2 were made. It is important to note that some respondents listed multiple positions in their response. Overall, there are more positions listed for the consultants, and the positions that are listed are more diverse then just "bridge inspector", which is to be expected from external engineering companies.

This was expected and it indicates that the consultants may have other responsibilities besides just bridge inspections, and therefore they may not have the same experience as the MassDOT employees when it comes to inspecting bridges.

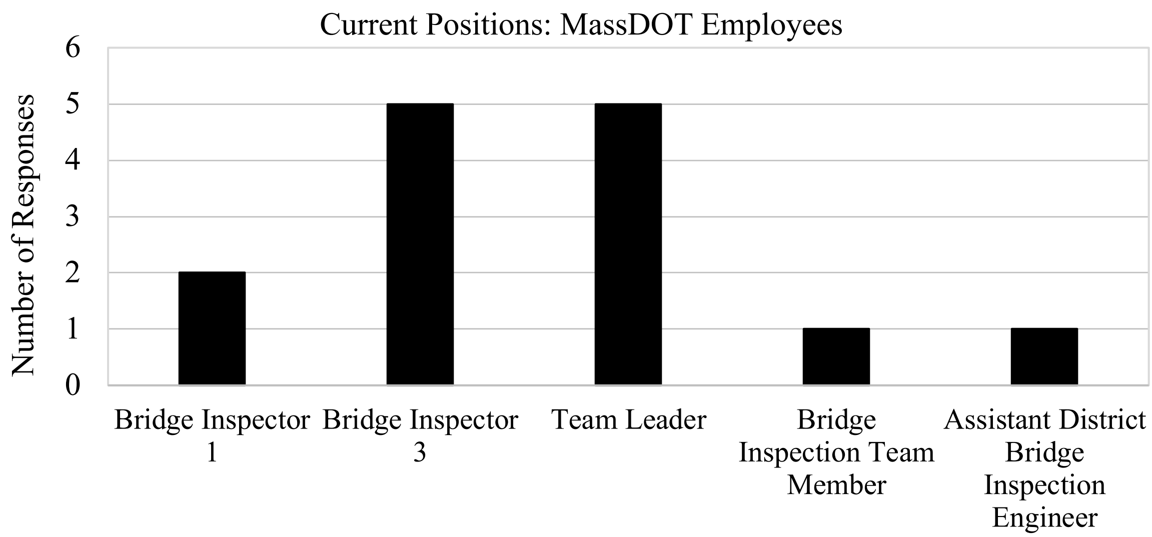
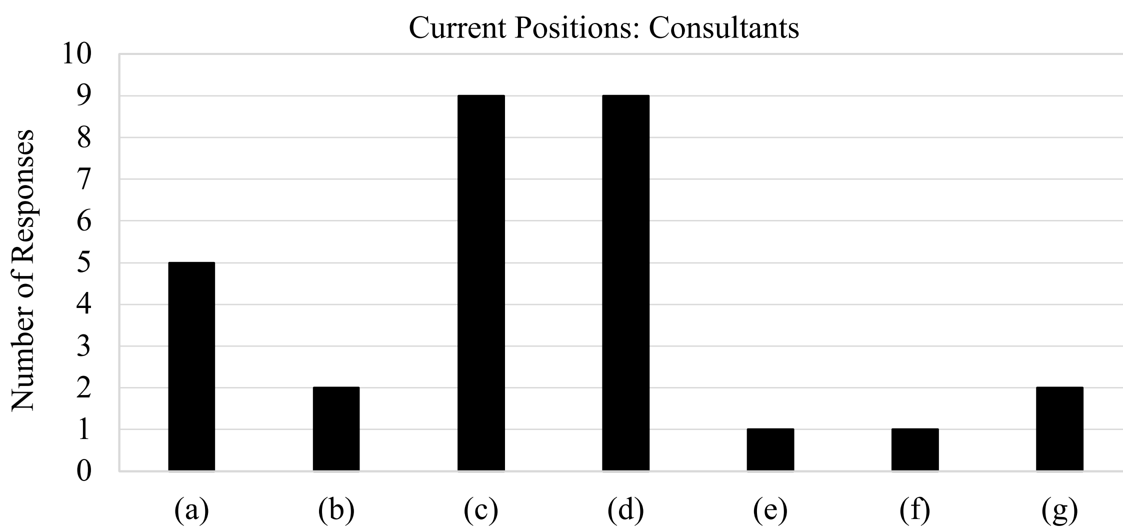


Figure 2.1: Current Positions of the MassDOT Respondents



(a)	Team Leader
(b)	Bridge Inspector
(c)	Project/Engineering Manager
(d)	Structural Engineer, Engineer, Assistant Engineer
(e)	Director of the Structures Group
(f)	Assistant VP
(g)	Manager of Bridge Inspector Contracts

Figure 2.2: Current Positions of the Consultant Respondents

The third question in the questionnaire asked what district the respondents work for. The more definitive answers for this question came from the MassDOT employees given that they are hired to work in one particular district. The answers from the MassDOT employees are recorded in Figure 2.3 below, and it is shown that at least one person responded from each district, except for Districts 3 and 6. In terms of scale, the MassDOT inspectors stated that Districts 2 and 5 have about 2000 bridges, District 1 has about 1200 bridges, and District 4 has about 1630 bridges. Since consultants aren't tied to one district, Figure 2.4 was produced for the consultant category of this question to show what engineering firms the consultants are from and how many consultants from each company answered the questionnaire.

It is important to note that the all the consultants stated that they work for all the districts. Although all the consultants said they deal with all the districts, two consultants added that they mostly deal with bridges from District 6, one consultant added that they deal mostly with Districts 3 and 4, one consultant added that they deal mostly with Districts 4 and 5, one consultant added that they deal mostly with Districts 4, 5, and 6, and one consultant added that they deal with all the districts except District 3. This is important because, although no MassDOT inspectors from Districts 3 and 6 responded, these districts are still being represented by the consultants that frequently carry out inspections within them.

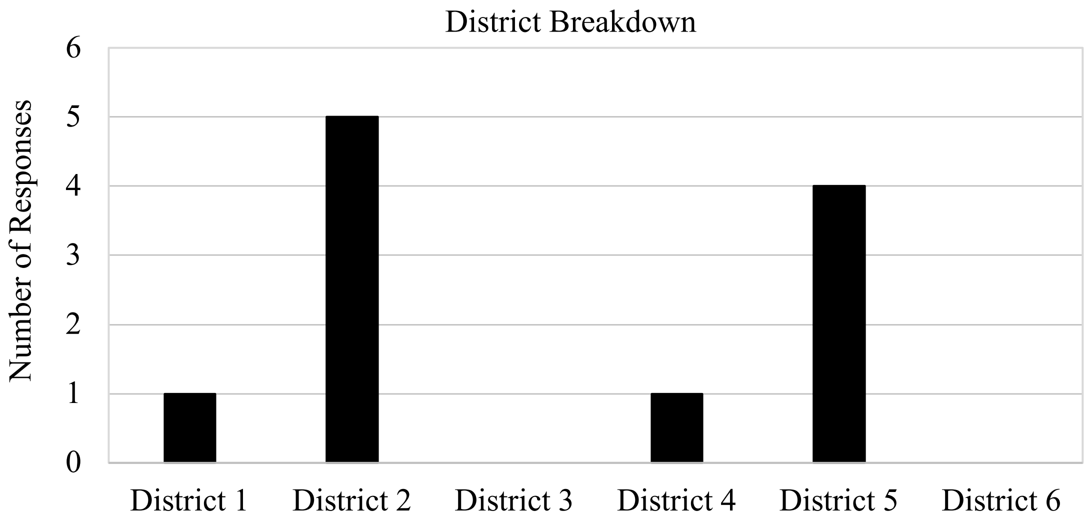
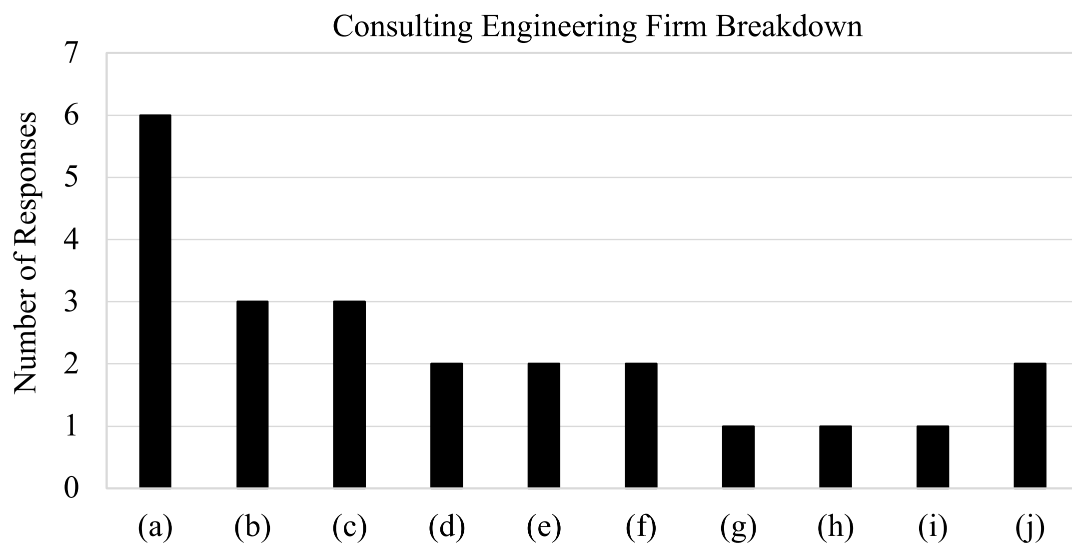


Figure 2.3: District Breakdown for the MassDOT Employees



(a)	TranSystems
(b)	Collins Engineering
(c)	Gill Engineering
(d)	AI Engineering
(e)	Benesch
(f)	HNTB
(g)	Engin Group
(h)	AE Com
(i)	Green International
(j)	Unknown

Figure 2.4: Breakdown of the Engineering Firms for the Responding Consultants

The next question focused on how many bridges the respondents were responsible for. The responses for the MassDOT employees are presented in Figure 2.5 and the responses for the consultants are presented in Figure 2.6. Overall, this shows that MassDOT employees are responsible for about 8 to 12 bridge per month, while the consultants are responsible for those they are assigned, which varies by inspection contract and/or task order. One of the more interesting responses for this question that is important to note was from a MassDOT Team Leader who said they are responsible for 8 to 14 bridges per month and then they “own” them for two years. The responses for this question show that MassDOT inspectors may typically be responsible for more bridges, which means they may not have as much time to carry out each inspection per month. Therefore, the new corrosion estimation method that will be proposed should not take too much time to carry out given the typical workload of the bridge inspectors.

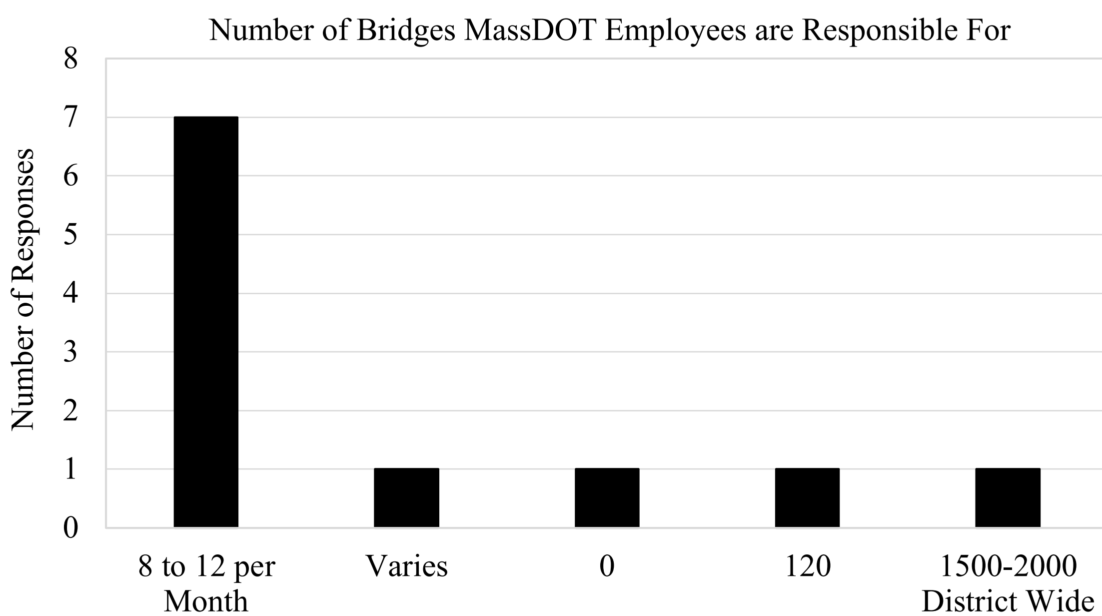


Figure 2.5: Bridges Responsible For: MassDOT Response Breakdown

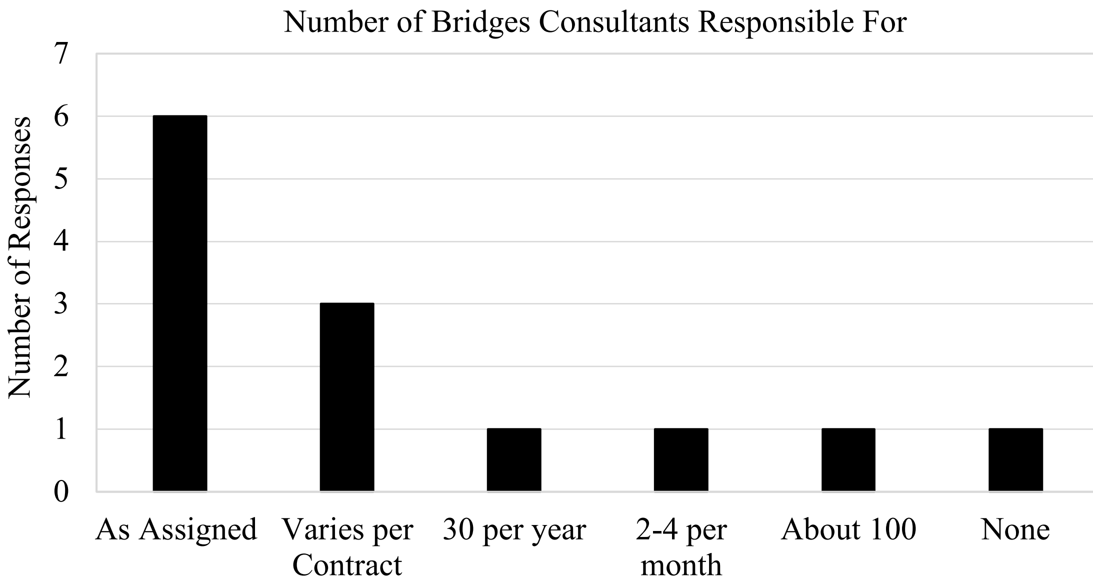


Figure 2.6: Bridges Responsible For: Consultant Response Breakdown

Moving on to question 5, the answers to how many bridges are inspected per week for both MassDOT employees and consultants are recorded in Figures 2.7 and 2.8. There is a lot of variation in answers for this question, but it seems that, overall, MassDOT employees inspect more bridges per week, which is to be expected since they are hired to mainly do inspections, unlike consultants. These responses again suggest that inspectors may not have as much time to carry out and document each inspection per week. Therefore, the new corrosion estimation method that will be proposed should not be time consuming so the number of inspections per week can remain the same or increase.

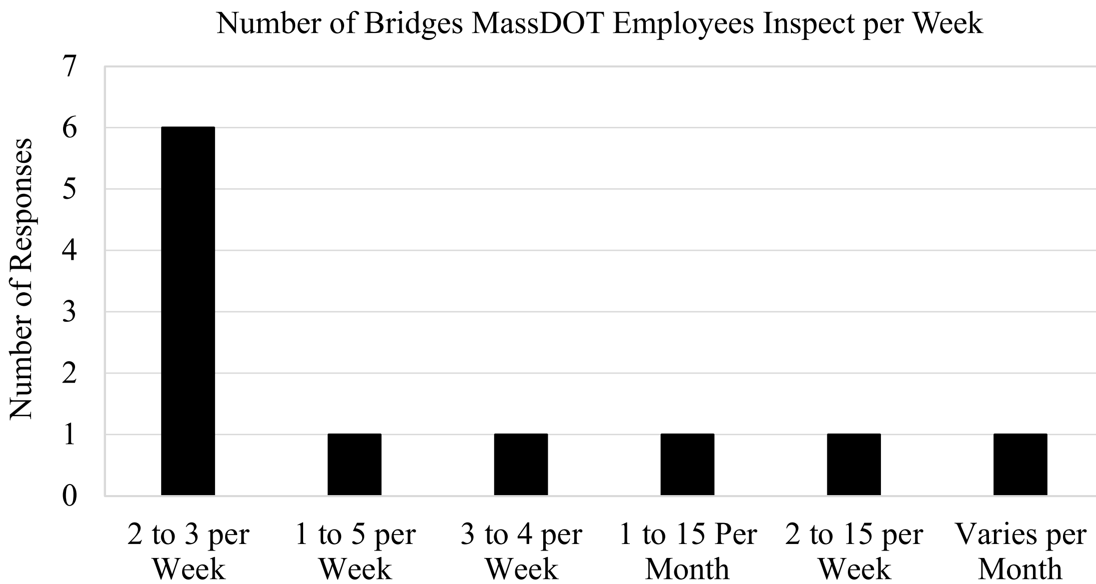
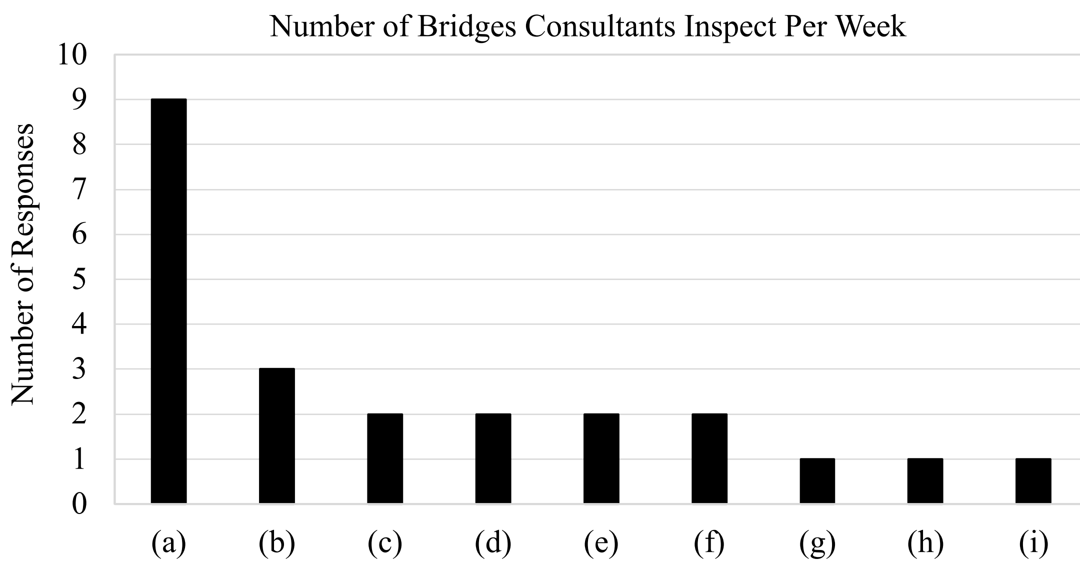


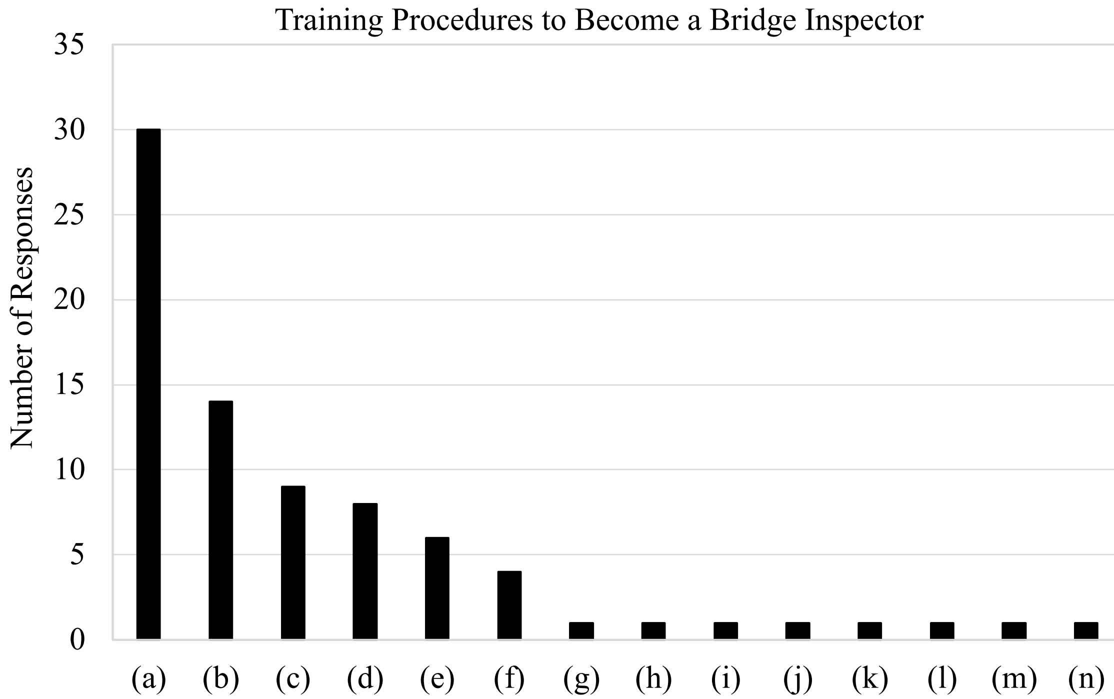
Figure 2.7: Number of Bridges Inspected per Week by MassDOT Respondents



(a)	0 to 1 per Week
(b)	Varies by Week and/or Month
(c)	Average of 2
(d)	Varies by Inspection Contract
(e)	1 to 2 per Week
(f)	1 to 2 per Month
(g)	1 to 3 per Week
(h)	3 to 4 per Month
(i)	4 per Year

Figure 2.8: Number of Bridges Inspected per Week by Consultant Respondents

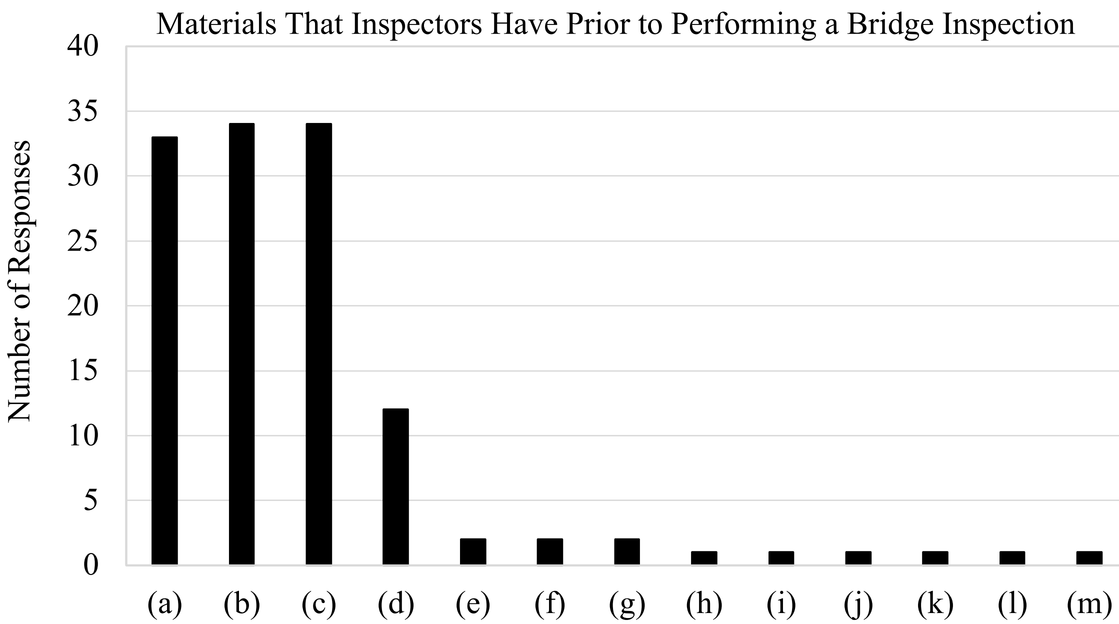
The remaining figures and tables contain the combined responses of both MassDOT employees and consultants. Figure 2.9 shown below is the figure that was made for question 6, and it shows that most inspectors took National Highway Institute (NHI) or Federal Highway Association Courses (FHWA) to become a bridge inspector. It is important to note that many of the respondents gave specific NHI/FHWA that they took. Those specific courses included a 2-week course on inspection of in-service bridges, an 80 hours bridge course, a course on fracture critical inspections, a course on tunnel inspection, a course on ancillary inspection, and the refresher courses that are offered for each course. This indicates that each inspector starts out with the same basic knowledge from the required NHI course, but their experience and on the job training will differ and ultimately influence how they perform bridge inspections. This should be kept in mind when considering how the bridge inspectors will be trained on the new corrosion estimation that will be made.



(a)	NHI/Federal Highway Course	(h)	NICET
(b)	College Degree (B.S. and/or M.S.)	(i)	Basic Civil Engineer 1
(c)	Year of Experience	(j)	OSHA 10 Hour Course
(d)	On the Job Training/Hands on Learning	(k)	Snooper Truck Training
(e)	EIT Exam	(l)	Bucket Truck Training
(f)	PE Exam	(m)	Aerial Lift Training
(g)	In-House Training	(n)	Destructive and Non-Destructive Procedures

Figure 2.9: Training Procedures for Bridge Inspectors

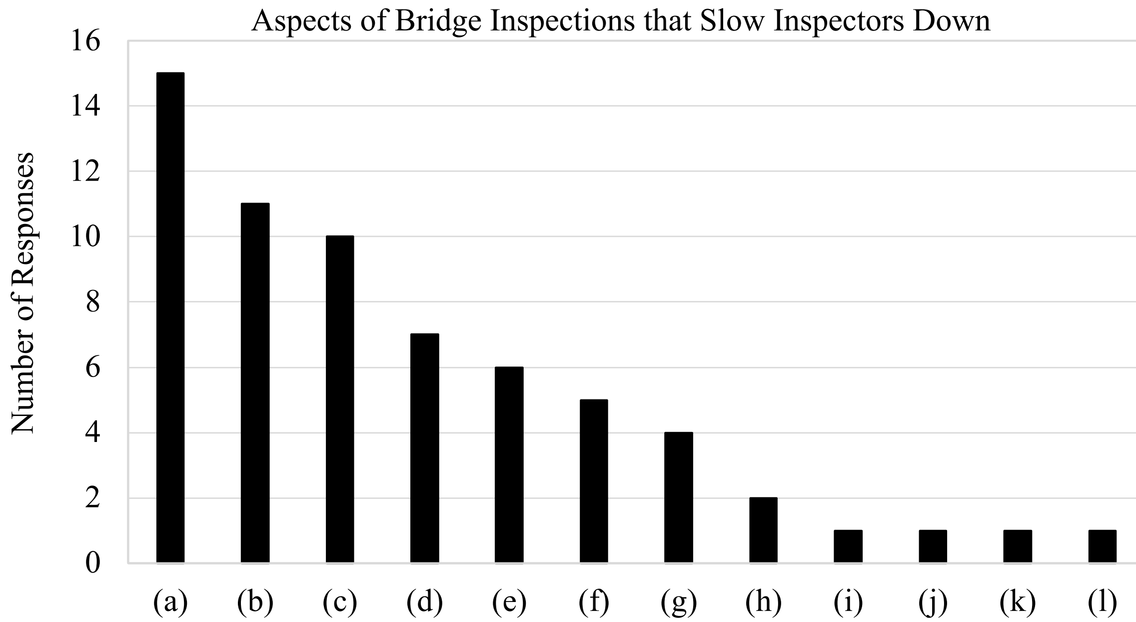
The responses for the next question indicate what materials both MassDOT inspectors and the consultants have prior to performing a bridge inspection. Figure 2.10 highlights that almost all the respondents chose the three given options: drawings, plans, and previous reports. Many people also provided an “other” answer, a majority of which wrote load rating reports as their other material that they typically have before a bridge inspection. It is good to know that inspectors have a lot of information prior to inspecting a bridge, and these materials can help in the development and execution of corrosion assessment procedures.



(a)	Drawings	(h)	MassDOT Bridge Inspection Handbook
(b)	Plans	(i)	Bridge Inspection Reference Manual
(c)	Previous Reports	(j)	Blank Diagram/Sketches
(d)	Load Rating Reports	(k)	Oral History
(e)	Talk to Previous Inspection Team	(l)	Forms Prepared Based on Received Information
(f)	Inventory Photos	(m)	Safety Equipment and Tools
(g)	Fracture Critical Procedures		

Figure 2.10: Materials Inspectors have Before Performing Bridge Inspections

For the next question, it seems that the ability to access, view, and be hands-on with the bridge, as well as measuring and documenting for inspection reports and traffic control for bridge inspections, are the aspects of bridge inspections that slow inspectors down the most. This is shown in Figure 2.11, along with several other aspects that slow inspectors down. It is important to note that for this question many inspectors made a list of several aspects and did not just give one aspect. The responses given for this question indicate that any new procedure and technology that is proposed should be able to easily access and measure corrosion without taking too much post-processing time so that the inspectors are not additionally slowed down using the new procedure and technology.



(a)	Access, Visibility, Hands-on Inspection	(g)	Tool Limitations (D-Meters, Trucks, Ladders)
(b)	Measuring, Documenting, Reporting, and/or Sketching	(h)	Timber, Mesh, Protective Shielding, Shearing
(c)	Traffic Control Issues	(i)	Scheduling in General
(d)	Railroad Issues	(j)	Previous Inspection Reports are Unclear
(e)	Large Amount of Deterioration	(k)	Deterioration Not Previously Noted
(f)	Removing Rust and Debris	(l)	Sand Accumulation

Figure 2.11: Aspects of Inspections that Slow Bridge Inspectors Down

For question 9, Figure 2.12 was created to recorded the parts of the 2015 MassDOT inspection handbook that inspectors find difficult to implement. There was an overall consensus that there is no part of the handbook that is hard to implement, but there were still 6 other responses recorded in Figure 2.12 below. It is important to note that some respondents gave additional comments besides just no. One such response that was found to be important to remember was that the state puts their requirements in the handbook and the inspectors find time to meet those requirements based on budget. Also, another respondent wrote that policy directives have been helpful in clarifying certain procedures or implementing new procedures, which highlights a promising way that a new corrosion estimation procedure could be introduced and explained to inspectors.

It is encouraging to know that the current handbook is written in a way so that it is not hard for inspectors to implement, therefore any new procedures should follow a similar format so that they too are not hard to implement. It is also encouraging to see that the concerns brought up by some of the inspectors are ones that can and should be fixed for corrosion estimation in particular.

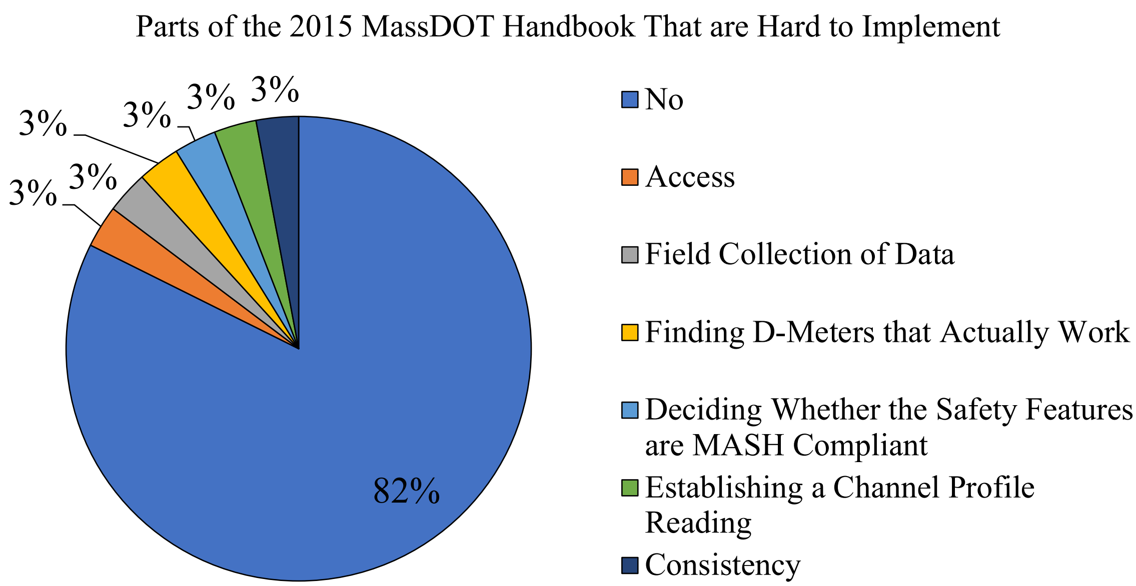
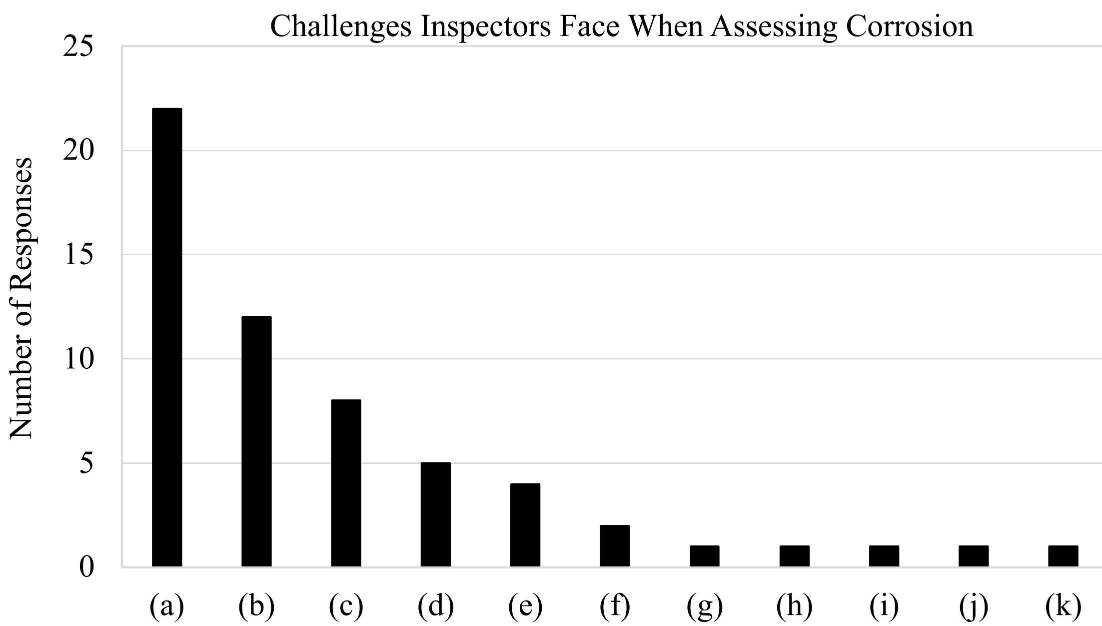


Figure 2.12: Parts of the 2015 MassDOT Inspection Handbook that are Hard to Implement

2.2.2 Corrosion Assessment Section Results

Moving into the corrosion assessment section of the questionnaire, Figure 2.13 summarizes the challenges inspectors face when assessing corrosion. Most respondents listed many challenges that they face, and it is apparent that cleaning off the rust from corroded areas, viewing the corroded area, and accessing the corroded areas are the biggest challenges with assessing corrosion. The removal of rust seemed to be frustrating for one inspector who claimed that they get discouraged when they find heavy rust and delamination because it should be removed every two years, so it doesn't build up. The challenges listed suggest that any new corrosion assessment technology and procedure should allow for the estimation of corrosion with little to no need for the cleaning and removing of rust and be able to access and view areas that are typically corroded.



(a)	Cleaning Steel/Removing Rust	(g)	Irregularities
(b)	Access/Visibility	(h)	Measuring Consistently Over Time
(c)	Measuring & Getting Accurate Measurements	(i)	Previously Documented Incorrectly
(d)	Tool Limitations (Especially on Uneven Surfaces)	(j)	Finding When Previous Inspectors Didn't Re-Check
(e)	D-Meter Problems	(k)	Cleaning When There is Lead Paint
(f)	Assessing Extent of Corrosion		

Figure 2.13: Challenges Faced when Assessing Corrosion

The next question in this section asked about technologies used for bridge inspections. All of the respondents chose more than one of the options, and many gave an additional technology. Of the 3 given choices, most of the respondents check off that they use visual technology, D-Meters, and other technology according to Figure 2.14. The other technologies noted by 27 out of 34 respondents were recorded in Table 2.1, and it shows that most respondents stated that the "other" technology they use includes calipers, a straight edge and a ruler. This indicates that many inspectors may not be as familiar with the more advanced technologies, so it may be harder to implement a corrosion technology if it is more advanced. Therefore, it is best to consider a corrosion estimation procedure that can be done just a well with technology they currently used as a more advanced technology.

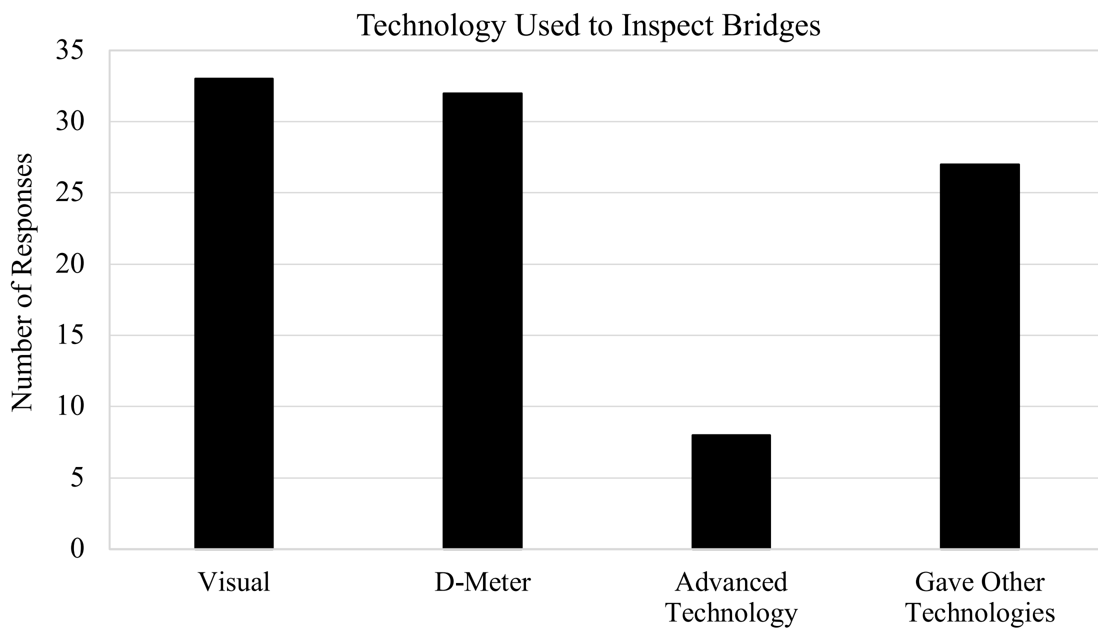


Figure 2.14: Bridge Inspection Technologies that are Used by Inspectors

Table 2.1: Other Technologies that are Used by Inspectors

Other Technologies	**Number of Responses for Each**
Calipers	9
Straight Edge/Ruler	5
Plumb Bob	2
Level	2
Pneumatic Drill/Needle Gun Scaler	1
Hammer/Hammer Sounding	1
NDT	1

Those that chose advanced technology were asked to list the technologies they were referring to. A list of those technologies is shown in Figure 2.15, which shows that most respondents count their dye penetrant testing kits as their "advanced technology". These answers were very informative and guided our research towards seeing if any of the technology listed in Figure 2.15 could be used for corrosion assessment and estimation.

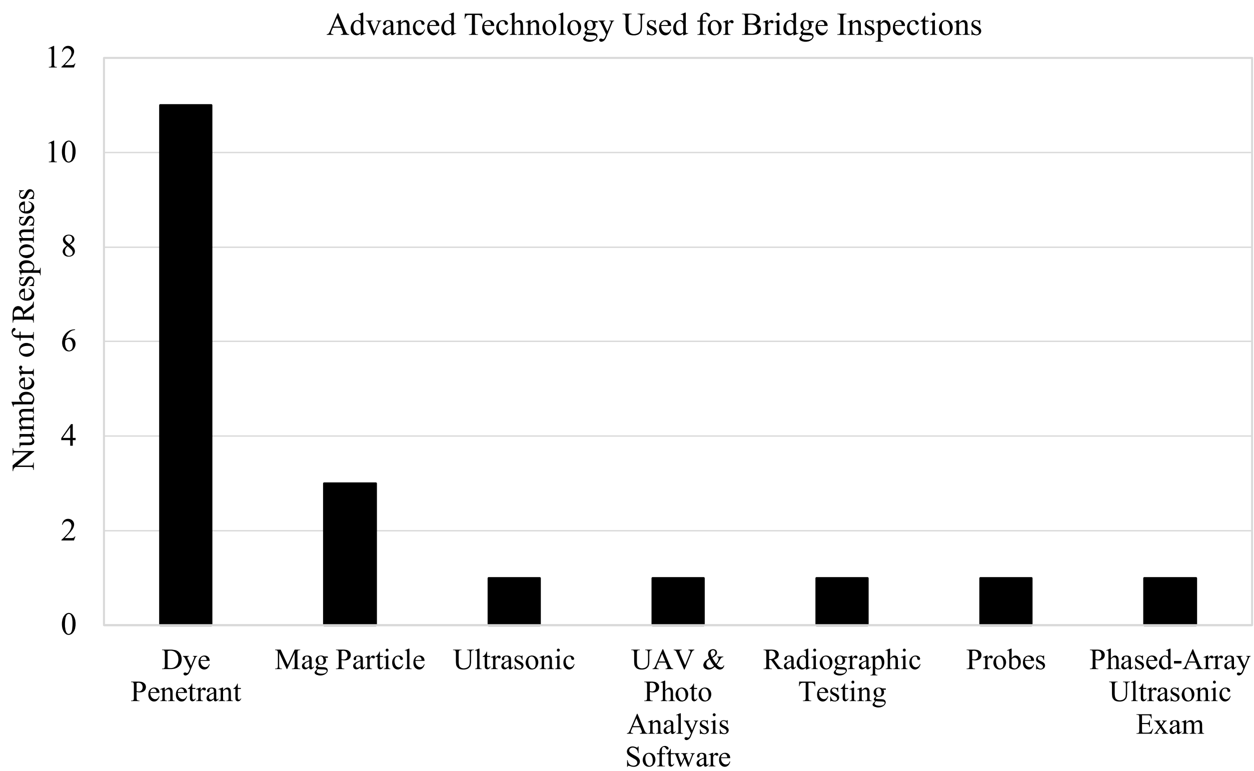


Figure 2.15: Summary of the Advanced Technologies Used by Bridge Inspectors

Given an example photo (Appendix A), the fourth question in the corrosion assessment section asked if inspectors have ever witnessed the upper edge of a web hole bearing on the flange for a stiffened and/or unstiffened bridge beam. Figure 2.16 shows that the most frequent answer saw 38.2% of those who took this questionnaire claim that they have seen this scenario for both a stiffened and unstiffened beam, while the second most frequent answer was that they had not seen this situation at all. Since there was an "other" option included in this question, 3 people did comment that they did not understand the question. It is concerning to see that more than 60% have seen this situation since it can greatly affect the structural integrity of the bridge beam. Since this situation is being seen by most inspectors it would be good to consider addressing it in any future handbook, particularly in the corrosion section since corrosion is typically the cause of holes in beam webs.

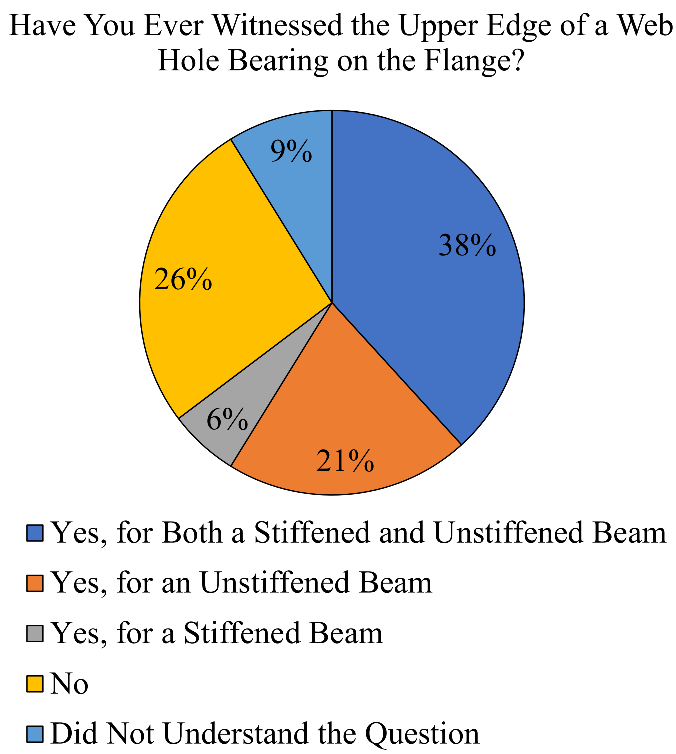


Figure 2.16: Responses for the Upper Edge of a Web Hole Bearing on the Flange

Moving on to question 5 in this section, 91.2% of the MassDOT personnel and consultants that took this questionnaire said that they use a D-Meter to measure web thickness (Figure 2.17). This shows that as of now the primary way inspectors measure corrosion is through the use of a D-Meter, and a new corrosion estimation procedure should yield accurate results when using D-Meter measurements

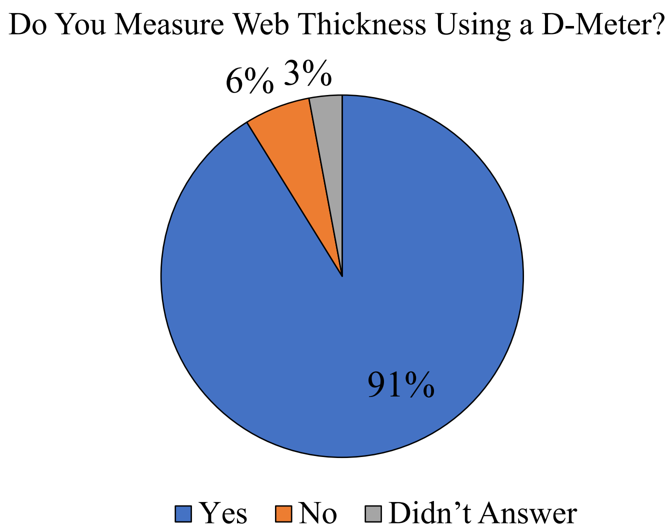


Figure 2.17: Use of D-Meters to Measure Web Thickness

To get a sense of the most popular D-Meter models, Figure 2.18 was created to show the responses from those who use D-Meters for inspecting bridges. The most popular model seems to be the Olympus brand D-Meter. It is good to know the models that are being used in order to assess their accuracy, reliability, and shortcomings.

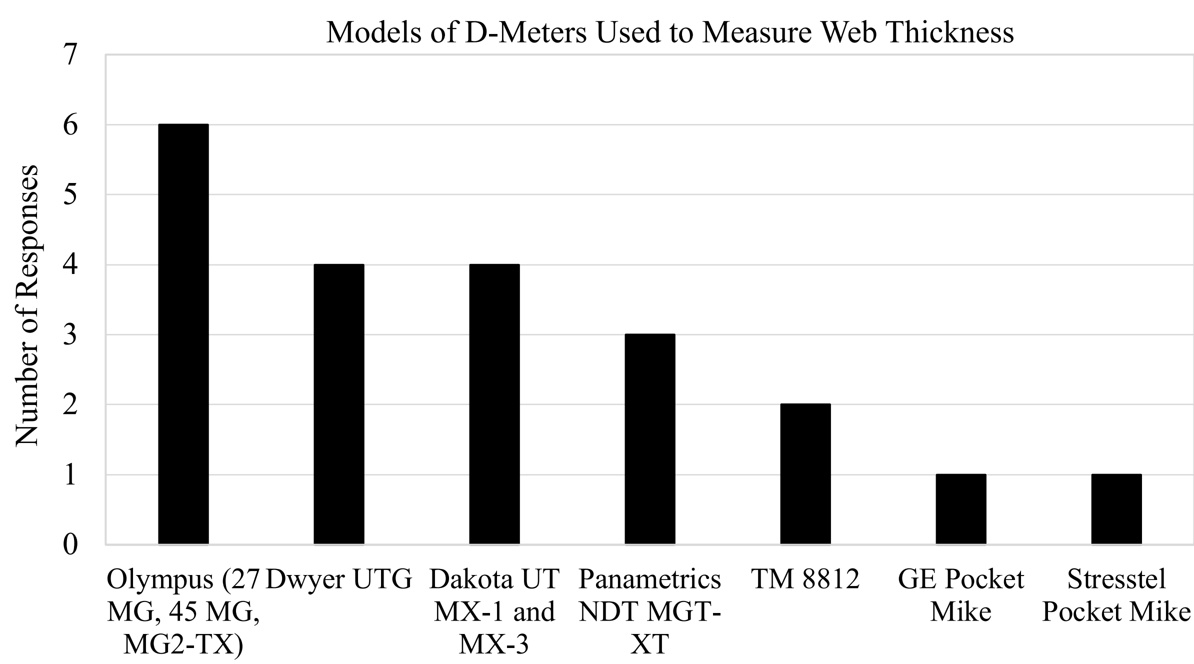


Figure 2.18: D-Meter Models used by Bridge Inspectors

To get a sense of what a new corrosion assessment method should encompass, it is critical to know the limitations of the equipment available to inspectors, especially the accuracy of that equipment. This is why question 7 was posed to bridge inspectors, and the results for this question are summarized in Figure 2.19. Most inspectors agreed that the D-Meter they used was only moderately accurate. It also shows that 11 respondents provided additional comments for this question. A summary of these comments is presented in Table 2.2 below. The comments provided revolve around how it is hard to judge the accuracy of the D-Meters and how some have found a way to try and verify the D-Meter measurements. It is promising that inspectors feel the D-Meter yields mostly accurate results, therefore if the D-Meter is the technology that will continued to be used, the new corrosion estimation procedure should account for any inaccuracies the D-Meter may provide. However, since most felt that the D-Meter readings are moderately accurate, that means there is room for improvement. This means research continue on ways to improve the accuracy of D-Meters so inspectors can more accurately assess the condition of a bridge.

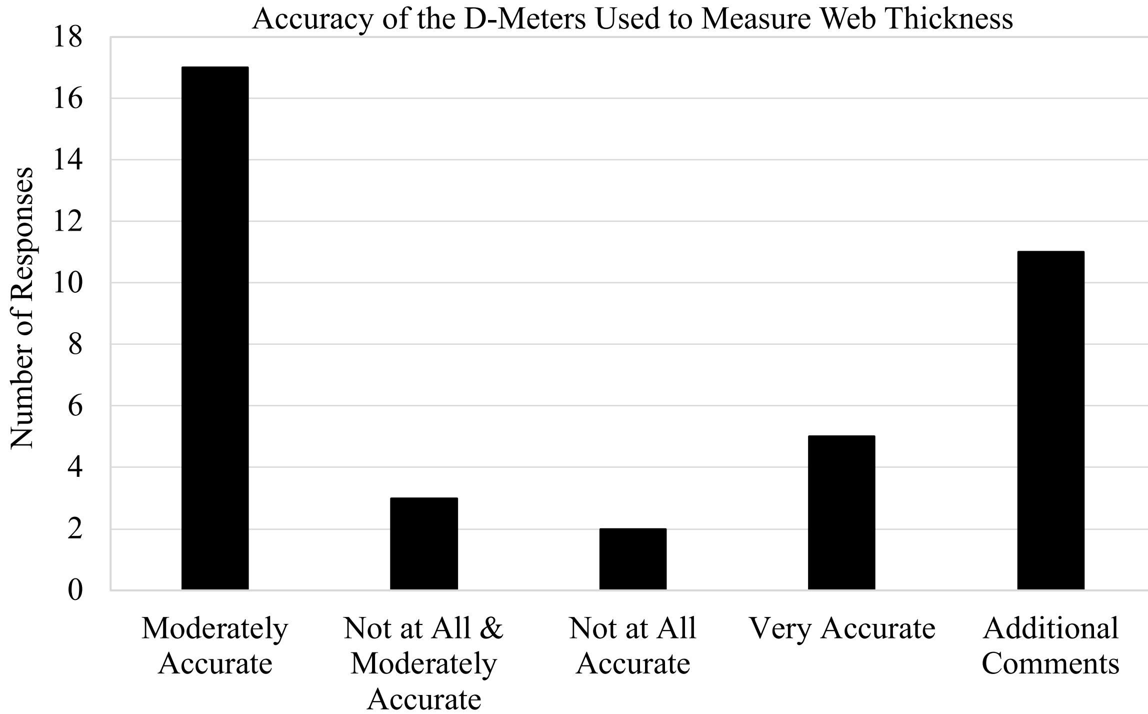


Figure 2.19: Accuracy of the D-Meters Used by Bridge Inspectors

Table 2.2: Comments Related to the Accuracy of D-Meters Used by Bridge Inspectors

Comments	**Number of Responses for Each**
Works Well in Fair Weather and On Clean Surfaces	4
Hard to Estimate the Accuracy	2
Check Against Straight Edge Measurement	2
Repeat Readings/Average the Reading you Get	2
Results Vary Widely and Are Often Unrepeatable	1
Hard to Measure on Uneven and Heavily Rusted Surfaces	1

For those who do not use D-Meters, question 8 was asked to get a sense of what technology they used instead to measure web thickness. Calipers and straight edge/rulers were the more popular tools to use in place of a D-Meter (Figure 2.20). The technology mentioned here is not very advanced and the measurements from these tools would be harder to verify.

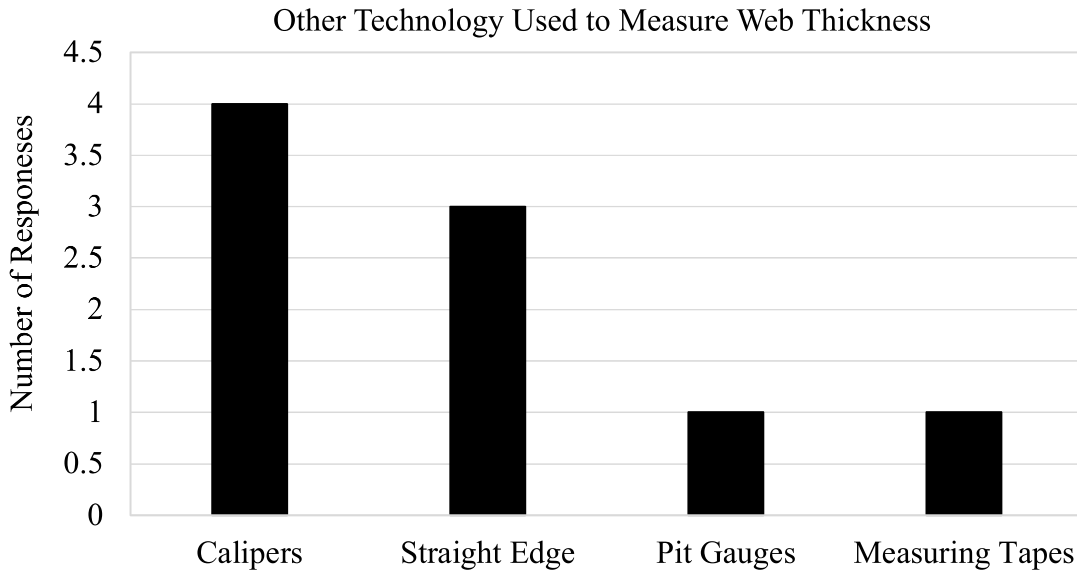


Figure 2.20: Summary of the Other Technology Used to Measure Web Thickness

To account for any other possible tool used to measure web thickness, Figure 2.21 was constructed to summarizes the responses for the question asking about what technology could potentially be used to measure web thickness. Similarly to the responses above, calipers and straight edges/rulers were the most common possible technologies. Although all responses are important to consider, the responses that were most interesting for this study were the ultrasonic technology, infrared imaging via drone or camera, and laser scanning. These technologies were investigated further to see if they could be used for corrosion estimation.

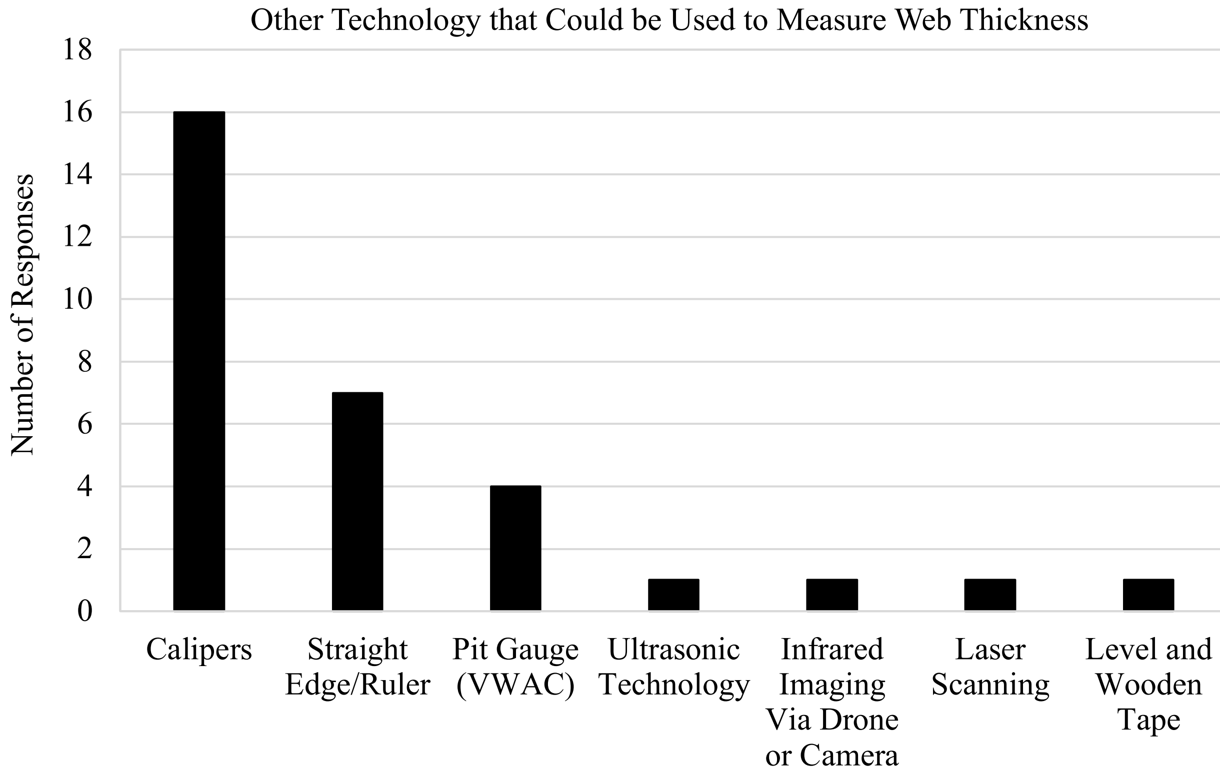


Figure 2.21: Summary of the Technology that Could be Used to Measure Web Thickness

Question 10 in this section had respondents pick numbers from the provided figure that represent the points at which they would take thickness measurements on an unstiffened beam (Appendix A). Figure 2.22 below shows the same images as Figure, but this time with certain points boxed in red. The numbers that are boxed represent the points that were chosen by 10 or more respondents. Along with naming the points they would choose to measure, several inspectors added additional comments to their responses, which are recorded in Tables 2.3. Many of the points that were frequently measured fall within, or slightly above, 4 inches from the bottom of the web. It is good to know these points so that the accessibility issue can be addressed by any future corrosion procedures and technology.

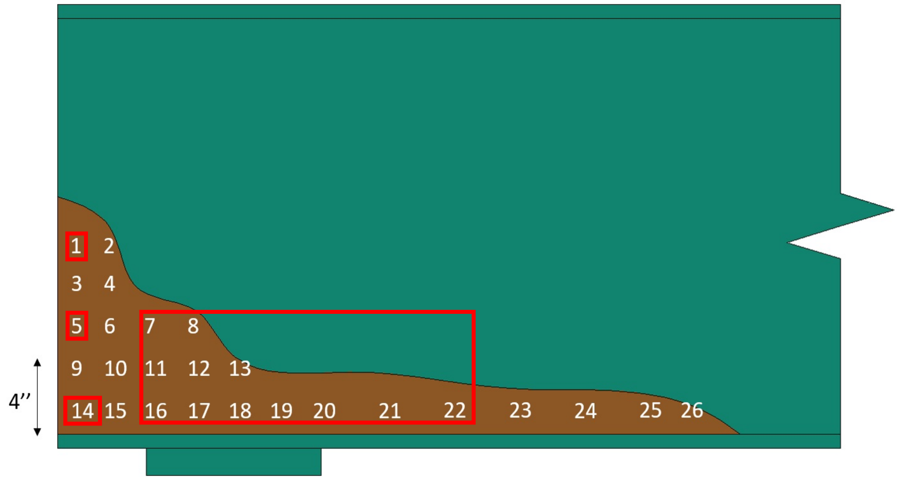
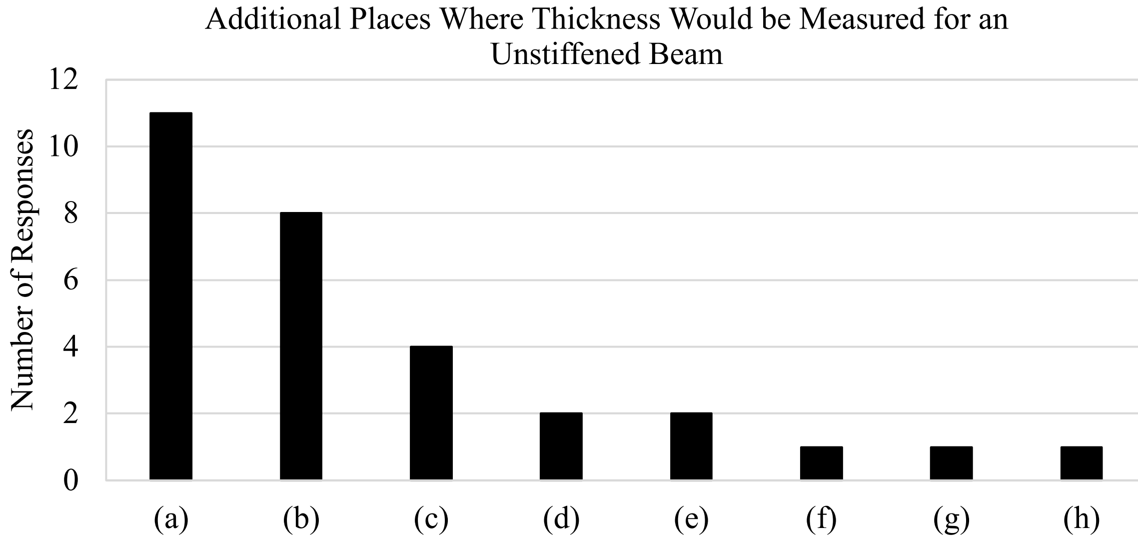


Figure 2.22: Possible Thickness Measurement Points for an Unstiffened Beam with the Most Frequently Picked Points Boxed in Red.

Table 2.3: Additional Comments for Measurement Points on an Unstiffened Beam

Additional Comments
Points Should be Taken on Either Side of the Bearing
Whether to Continue Measuring or Stop Measuring Depends on Readings Acquired and the Inspectors Judgement
Emphasis Should be Places on the Numbers in Over and In Front of the Bearing
Sudden Dips and Holes Would Change the Chosen Points
What is Actually Recorded may be Different than what is Measured

Knowing that there are many other places that could be measured on Figure 2.22 above, Figure 2.23 details the additional points respondents recorded for question 11. Many stated they would measure points without any corrosion to compare with the corroded measurements, verify the accuracy of the D-Meter readings, and confirm the dimensions on the bridge plans. It is important to note that those who said they would measure the top flange losses are doing so because that is typically the location of negative bending. Additionally, those who said they would measure the bottom flange losses are doing so because that is usually necked down. It is good to know that some inspectors are both checking the accuracy of their measurements against uncorroded areas and checking structurally critical areas. Since not all the inspectors mentioned checking these areas, it may be helpful to provide recommendations for measurement points that fall within the areas mentioned in Figure 2.23.



(a)	Uncorroded Area for Comparison	(e)	Point(s) on the Bottom Flange
(b)	No Additional Places	(f)	Check for Buckling
(c)	Points Where There are Obvious Thickness Changes	(g)	Losses Noted Wherever They are Found
(d)	Point(s) on the Top Flange	(h)	Points Along the Height of the Web Above the Bearing

Figure 2.23: Additional Thickness Measurement Points for an Unstiffened Beam

The same questions were asked for stiffened beams, and as above the points that are boxed in Figure 2.24 are points that were picked by 10 or more inspectors. Table 2.4 lists the additional comments included with the points selected for the stiffened beam, while Figure 2.25 presents the additional points that inspectors would take measurements of. The additional points are similar to those stated for the unstiffened beam, but it is important to point out that the person who wrote heavily laminated areas chose that as an additional point because steel section loss will begin to accelerate in that area. Also, the person that said they would additionally measure previously identified loss points would do so because they will get worse with time once rust has begun. For stiffened beams, it appears that more than half of the points most frequently mentioned are above 4 inches from the bottom of the web on the beam itself. This is different for the stiffener measurements, where it appears that most of the highlighted points fall within 4 inched from the bottom of the web. Much like the unstiffened beam, knowing the points that are highlighted here will help address accessibilities issues and make proper measurement recommendations within future procedures and technology.

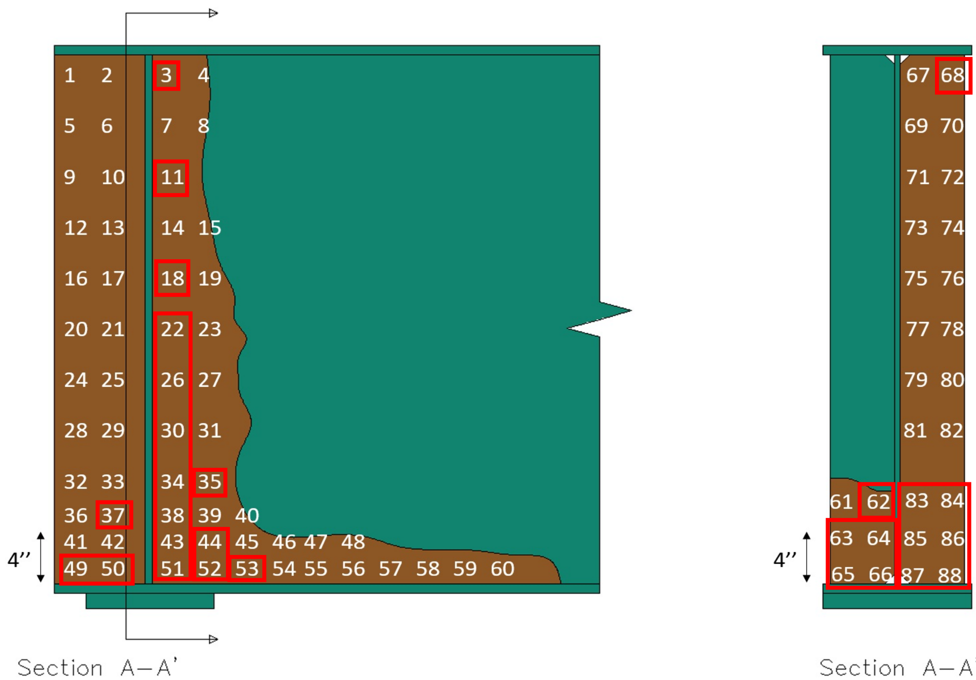
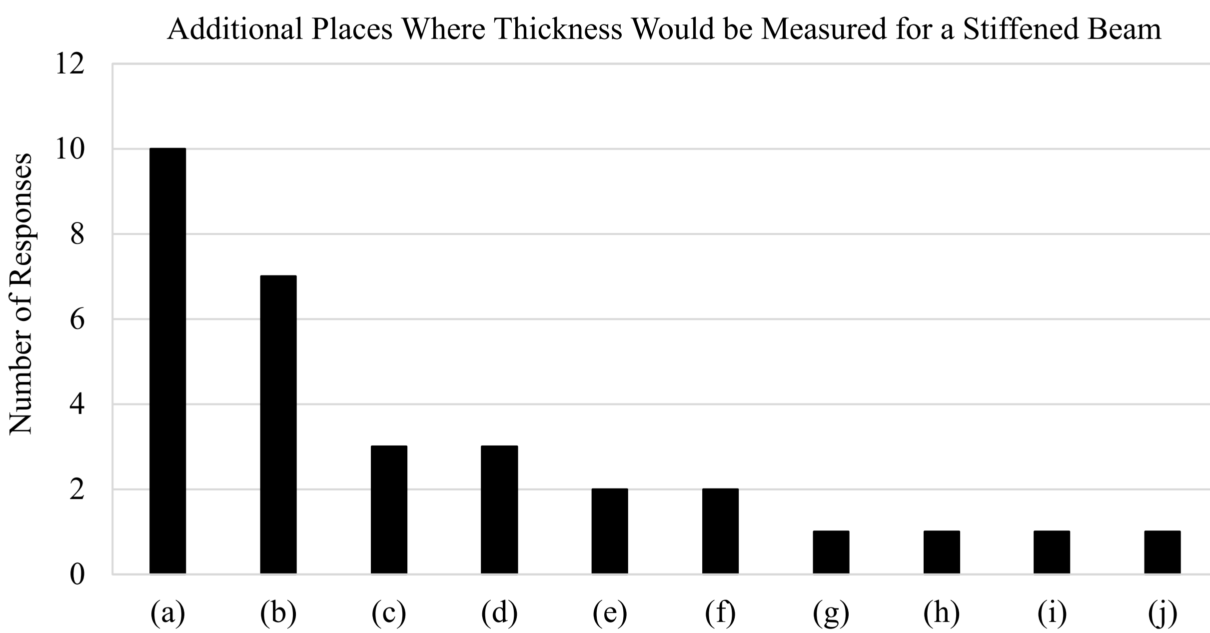


Figure 2.24: Possible Thickness Measurement Points for a Stiffened Beam with the Most Frequently Picked Points Boxed in Red.

Table 2.4: Additional Comments for Measurement Points on a Stiffened Beam

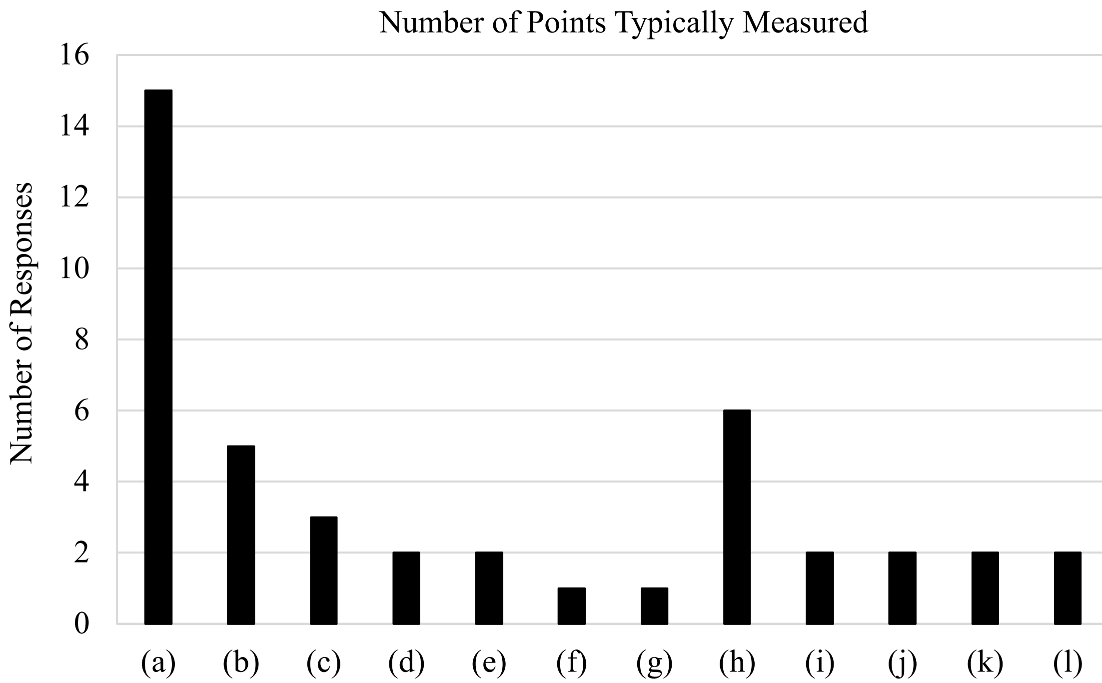
Additional Comments
Important to Measure Points until you Find Full Thickness above the 4”, then Find the Minimum Below the 4”
Use the Minimum Stiffener Dimensions
Whether to Continue Measuring or Stop Measuring Depends on Readings Acquired and the Inspectors Judgement
Sudden Dips and Holes Would Change the Chosen Points
Emphasis Should be Places on the Numbers in Over and In Front of the Bearing
Very Critical to Measure the Bearing Stiffener and Web on the Side of the Bearing Stiffener Extending Towards Midspan
Web Holes are Common in End Potion of the Web Behind the Bearing Stiffener Due to Leaking Deck Joints
What is Actually Recorded may be Different than what is Measured



(a)	Uncorroded Area for Comparison	(f)	Check for Buckling
(b)	No Additional Places	(g)	Tell by Eye Where Section Loss is on the Stiffener
(c)	Points Where There are Obvious Thickness Changes	(h)	Average 1/16” Pitting Along Lengths of the Top Flange from 10’ to 30’ from CL Bearing
(d)	Point(s) on the Top Flange	(i)	Previously Identified Loss Points
(e)	Point(s) on the Bottom Flange	(j)	Heavily Laminated Area

Figure 2.25: Additional Thickness Measurement Points for a Stiffened Beam

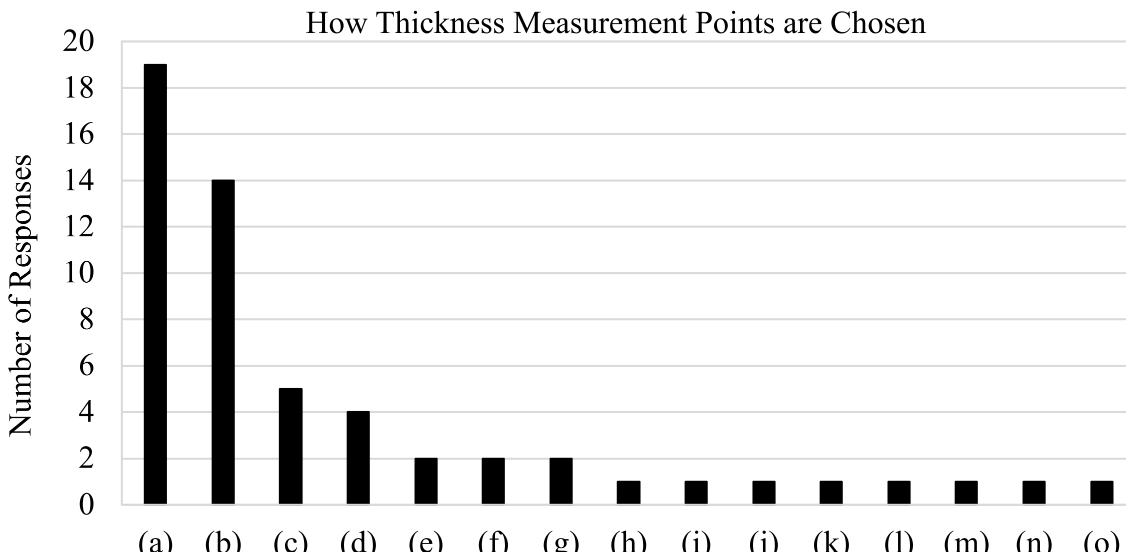
As to how many points would actually be measured for a bridge inspection, those who responded to the questionnaire offered many different responses. Amongst those recorded in Figure 2.26, the most frequent response was that the number of points measured depends on the amount, distribution, and variability of the corrosion. The more corrosion and corrosion variability, the more points that are taken to capture the in-situ condition of the beam. Along with that, the more consistent a corroded area is the less points need to be measured. While some inspectors gave a more qualitative response, some did offer a quantitative response, the most frequent response being that they would take between 2 and 5 web thickness measurements. Based on these results, it may be beneficial to make recommendations on how many measurement points to take in order to ensure that there is more consistency with measurements. It may also be helpful to provide a recommendation on technology that can measure more points or scan the entire area in order to estimate the amount of section loss.



(a)	Depends on Amount, distribution, and Variability of Corrosion	(g)	DBIE Wants Several Points for Load Ratings
(b)	Depends on Beam Size and Depth	(h)	2 to 5 Points
(c)	Depends on How Many Measurements to Accurately Show the Section	(i)	5 to 10 Points
(d)	Depends on How the Critical Location is	(j)	At Least 5 Points
(e)	Work in a Grid Pattern	(k)	4 to 6 Points
(f)	Record Mapped Loss and Not Singular Points	(l)	10 Points

Figure 2.26: How Many Thickness Point Measurements are Taken During Inspections

Similar to how many points are taken, the responses for how the thickness measurement points are chosen also varied substantially. However, although there is a variety of choices, it is very apparent that most of the inspectors measurement points typically fall within areas that are the most corroded (worst area) and/or they choose points they feel will accurately represent the corroded area. Many of them also stated that they would choose points in areas that would affect the structural strength of the system. The "*" symbol in that graph is there to highlight that the points that affect the structural strength of the system are usually in areas that experience high amounts of stresses, shear, compression/buckling, and/or moment/bending, which is noted below Figure 2.27. An interesting thing to note for this question is that 4 inspectors said they would use a caliper to measure the thickness of the stiffener, and they would use a D-Meter or straight edge with a ruler to measure the rest. It is encouraging to see that most points that are measured represent the worst of the corroded area and some also account for structurally important areas because a good assessment of the safety of the bridge can be done with that information. This information could direct recommendations for how to choose measurement points, which could be included within the corrosion estimation procedure to promote more consistency amongst inspection reports.



(a)	Worst and/or Most Representative Areas of Corrosion	(i)	How Variable the Corrosion is
(b)	How Loss Will Affect Overall Structural Strength of the System*	(j)	How Thin the Original Section Was
(c)	Web at Beam Ends and in Front of the Bearing	(k)	Whether or Not an Element is Fracture Critical
(d)	Flange at Midspan	(l)	Maximum Depth of the DBIE
(e)	Where the Steel Can Access and Cleaned	(m)	Requirements of the DBIE
(f)	Structure Type and Configuration	(n)	Loading Type
(g)	Grid Pattern the Inspector Creates	(o)	Visual Inspection and Experience
(h)	Verify Previous Measurements		

Figure 2.27: How Thickness Measurement Point are Chosen
*Those points are usually within areas that will experience high amounts of stresses, shear, compression/buckling, and/or moment/bending.

The last of the thickness measurement questions asks inspectors whether or not they take thickness measurements of the stiffeners. A majority, 79.4%, of the picked yes to indicate that they do in fact measure the thickness of the stiffeners (Figure 2.28). While a majority of inspectors do measure corroded stiffeners, it would be important to include a statement within the new estimation methods that specifically says that inspectors must measure the thickness of corroded stiffeners in order to thoroughly assess the corroded bridge girder and promote consistency.

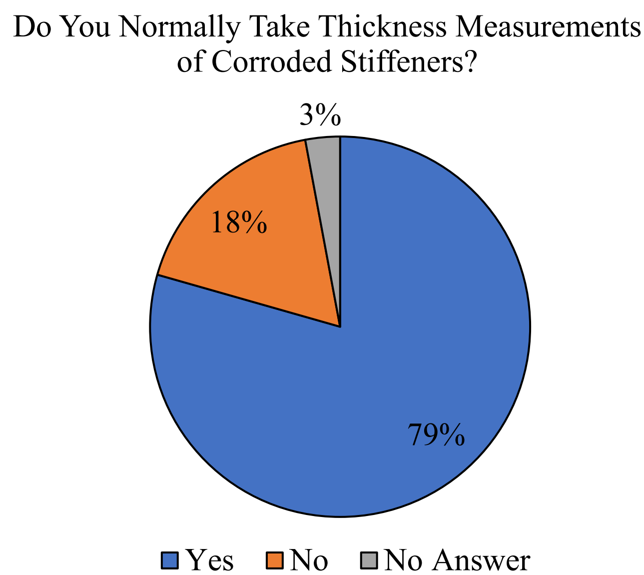


Figure 2.28: Responses to Whether Thickness Measurement of the Stiffener are Taken

Question 18 is the first question in a series of question about web deviation from straightness, or out of plane displacement. This first question asks inspectors if they have witnessed beam webs that deviate from straightness for stiffened and/or unstiffened beams. There was an image included in the questionnaire (Appendix A) that showed an example of this situation. A majority chose “Yes for an Unstiffened Beam”, 53%, or “Yes for Both a Stiffened and Unstiffened Beam”, 38.2% (Figure 2.29). Nobody answered that they have seen this for only a stiffened beam. Two inspectors did add additional comments, one stated that they have only seen this occur due collision, usually at midspan, and the other stated that they have seen if for a stiffened beam, an unstiffened beam, and a compression member of a truss. It is concerning that most of the inspectors that responded to the questionnaire have seen webs that deviate from straightness because this can cause significant loss in beam capacity and can be very unsafe. Any new procedure should address how to estimate the condition and safety of the bridge based on how much web deviation there is.

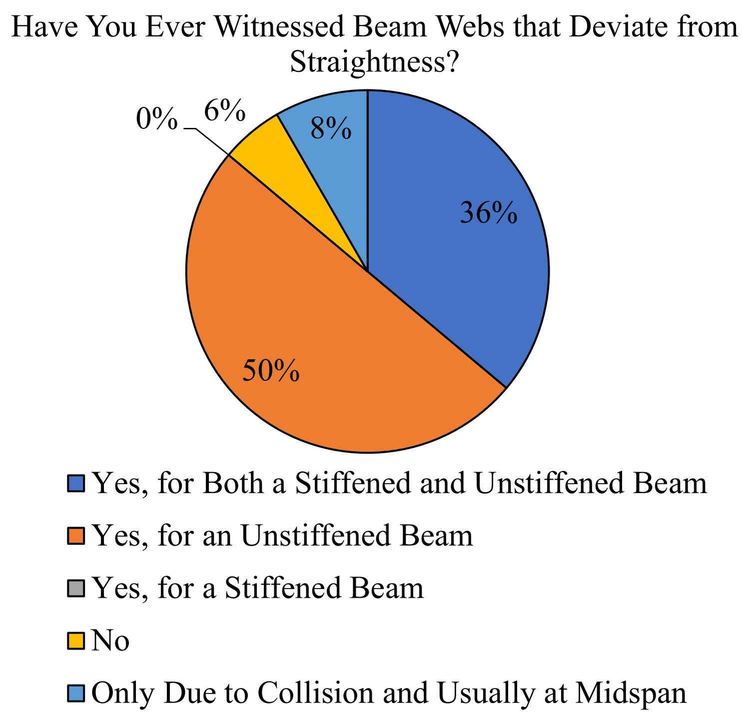


Figure 2.29: Response to Witnessing Web Deviation from Straightness

When asked if they measure web deviation from straightness, all but one inspector said responded that they do in fact measure out of place displacement. This means that 97% of inspectors that answered this questionnaire measure web deviation from straightness (Figure 2.30). It is very encouraging to know that inspectors are consistently measuring how much the bridge beam web deviates from straightness, therefore there may not be a need to reinforce this in any future standard.

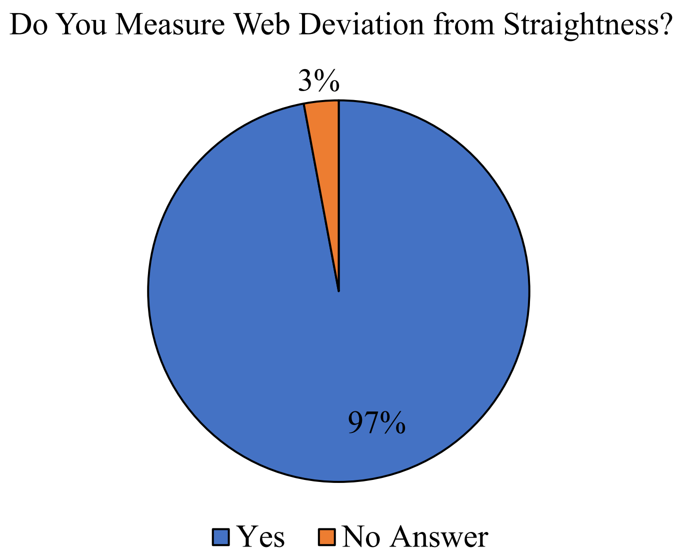


Figure 2.30: Responses to Whether Web Deviation from Straightness is Measured

To measure the out of plane displacement of a beam web, many inspectors said that they would use a straight edge and a ruler, a level, a plumb bob or plumbline, a tape measure, and/or magnetic angle gravity tools. The first three tools proved to be the most common amongst inspectors (Figure 2.31). Much like the web thickness measurement, when asked about accuracy, many respondents felt that their measurements were moderately accurate using the tools they have (Figure 2.32). It is promising to see that even without advanced technology inspectors can still get a moderately accurate measurement of the web deviation in order to assess the bridges condition, but it is still important to consider improving the equipment so that inspectors can improve the accuracy of their measurements.

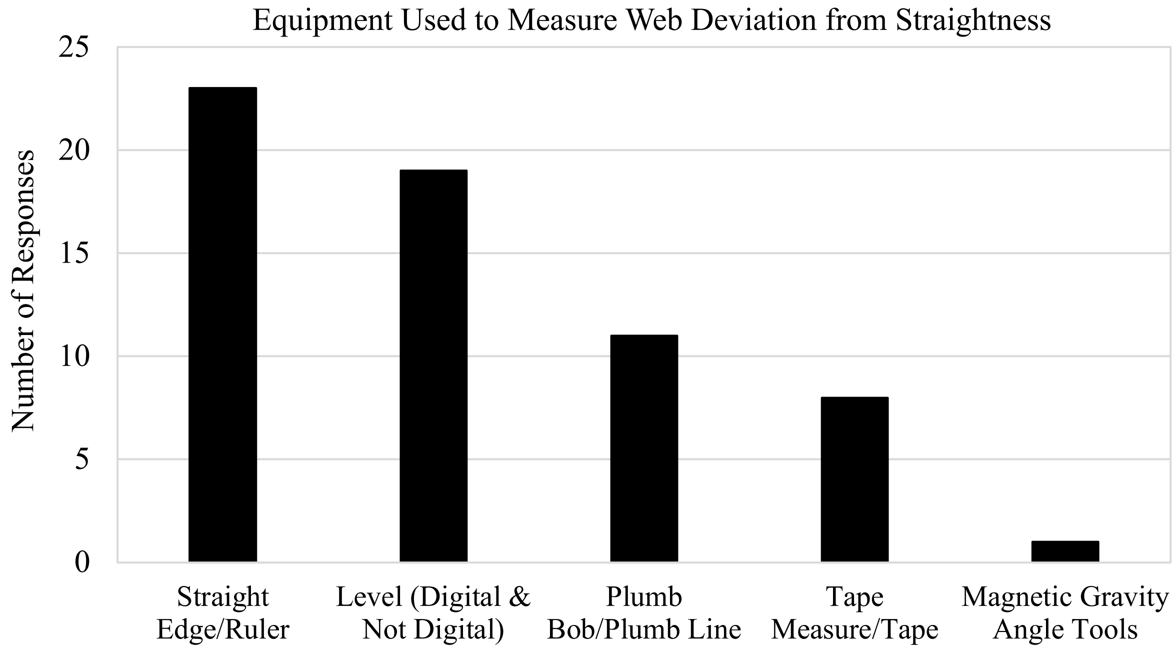


Figure 2.31: Equipment Used to Measure Web Deviation from Straightness

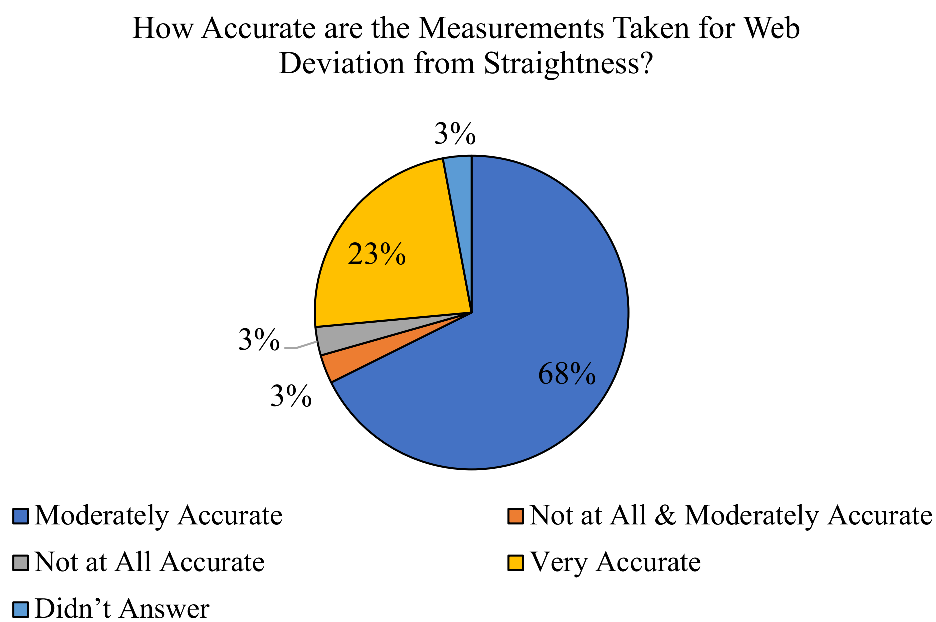
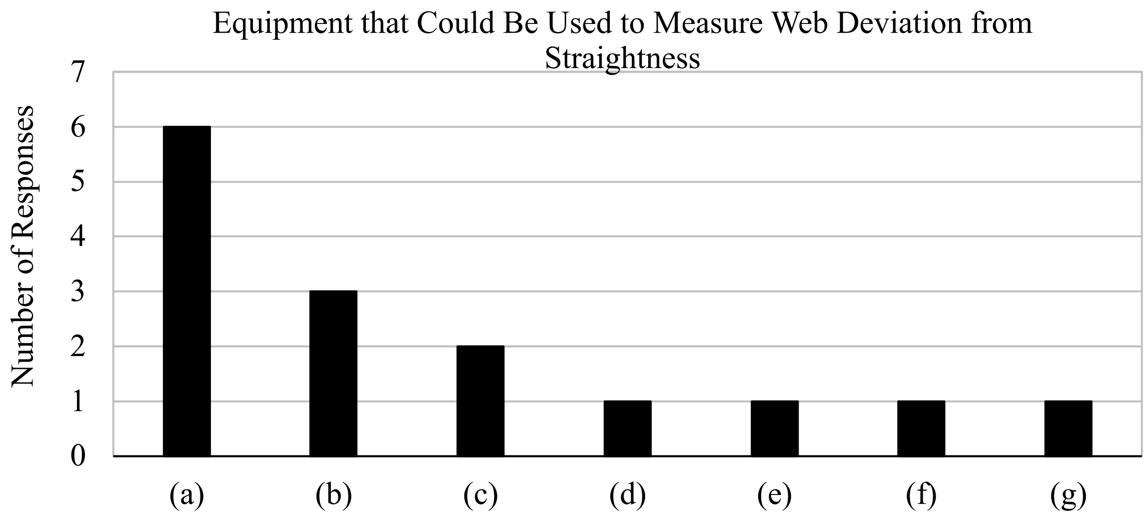


Figure 2.32: Accuracy of Equipment Used to Measure Web Deviation from Straightness

The next question asked about any other equipment that could possibly be used to measure web deviation from straightness. Most of the answers presented in Figure 2.33, were also mentioned in Figure 2.31, except for the laser scanning, which is a more advanced technology that should be kept in mind when coming up with a new corrosion assessment methodology.

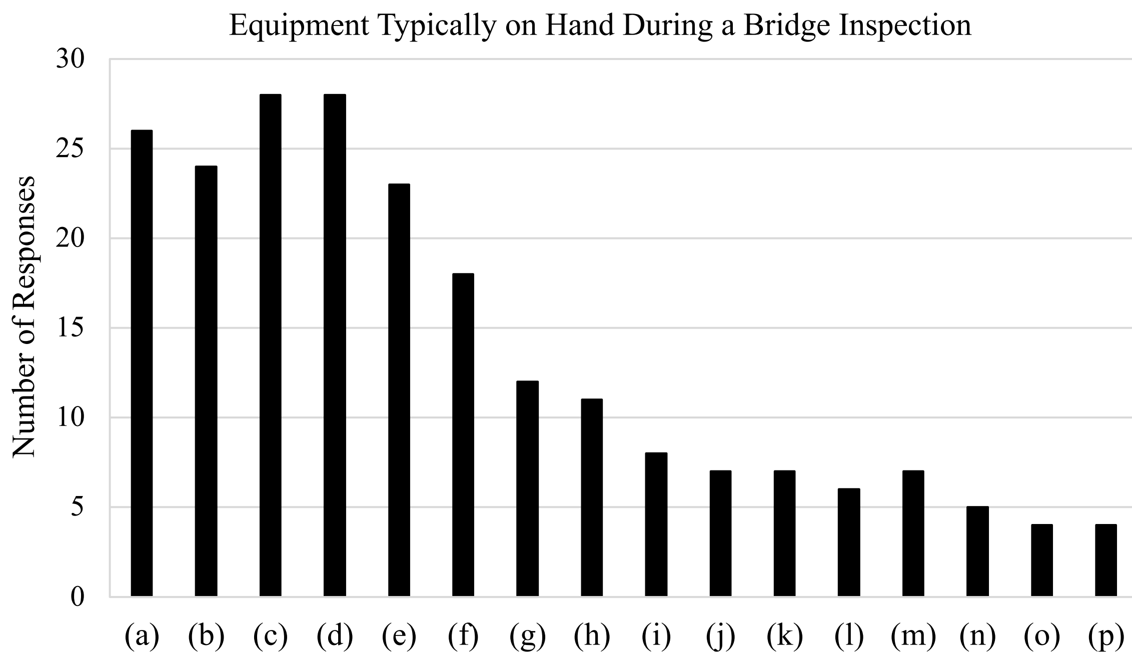


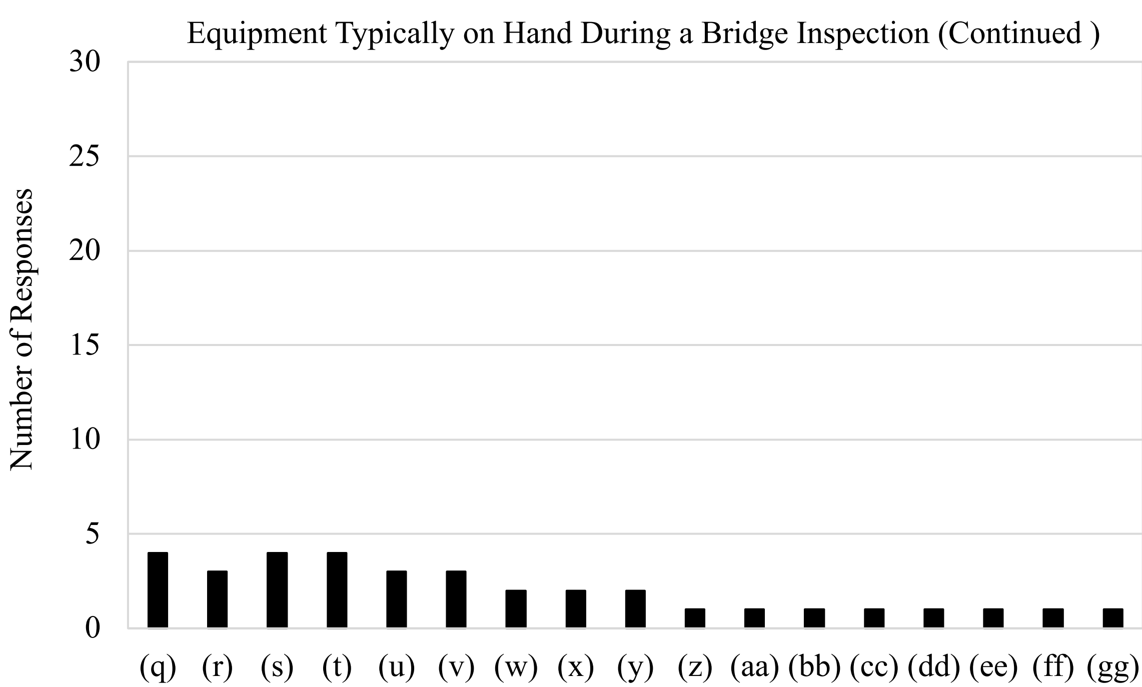
(a)	Laser Level/Digital Levels
(b)	Plumb Bob
(c)	Laser 3D Survey/Laser Scanning
(d)	Tape Measure
(e)	Magnetic Angle Tool
(f)	Straight Edge & Ruler
(g)	Speed Square/Other Right-Angle Tools

Figure 2.33: Equipment that Could be Used to Measure Web Deviation from Straightness

2.2.3 Equipment Section Results

Moving on to the equipment section of the questionnaire, Figure 2.34 provides a summary of the responses for the first question that asked inspectors to list the equipment that they have on hand to perform a bridge inspection. The most popular answers included D-Meters, calipers, straight edge/ruler, hammer(s), and tape measures, amongst many others. Along with listing the equipment, respondents were also asked to state the advantages and disadvantages of the equipment they listed. Unfortunately, only 14 out of 34 people actually gave advantages and disadvantages for their equipment, so advantages and disadvantages were not supplied for all the tools, but the information gathered was still very informative. Most of the advantages and disadvantages provided focuses on ease of use, accuracy, and reliability, amongst many others (Table 2.5). Knowing this information will help guide research towards a technology that has ease of use, accuracy, and reliability as advantages instead of disadvantages.





	First Graph		Second Graph
(a)	D-Meter	(q)	Keel/Kiel
(b)	Calipers	(r)	Other Hand Tools
(c)	Straight Edge/Ruler	(s)	Plumbob/Plumbline
(d)	Hammer(s)	(t)	Grinder
(e)	Tape Measures	(u)	Lumber Crayons/ Marking Utensils
(f)	Wire/Steel Brush	(v)	Paint Pen, Paint Crayons, Tape Paint
(g)	Ladders, Accessing Equipment, PPE	(w)	Crack Gauge
(h)	Level	(x)	Thickness Gauges/Filler Gauges
(i)	Camera	(y)	Apple Laptop or Tablet with AC/DC Converter
(j)	Laser Distance Measurer	(z)	Gravity Angle Measurement Tool
(k)	Pitting Gauge (VWAC)	(aa)	Wood Tape
(l)	Flashlight/Headlamp	(bb)	Pneumatic Drill
(m)	Dye Penetrant	(cc)	Wheel
(n)	Chalk	(dd)	Awl
(o)	Pen, Pencil, Paper	(ee)	Mirror
(p)	Chisel/Scraper	(ff)	NDT Tools Used for Previous Inspections
		(gg)	Steel Square

Figure 2.34: Summary of the Equipment Inspectors Have to Inspect Bridges

Table 2.5: Advantages and Disadvantages of Bridge Inspection Equipment

Equipment	**Advantages**	**Disadvantages**
Field Papers	- Quickest Way to Verify and Note Deterioration	- Cleanliness - Legibility
Tablet	- Cleaner Notes - Less Time in office Cleaning up field notes	- Takes more time to use - Limited battery life - Data could be lost
D-Meter	- Small and Easy to transport - Easy to read - Potentially Accurate and Precise - Best to use for web losses - Best to use when one side is not accessible (example given) - Good to use when losses are too widespread, and a straight edge cannot be projects to an area of no loss - Provides section remaining instead of section loss	- Questionable Reliability of the D-Meter - Readings may be inaccurate on uneven surfaces - Hard to Clean and Flatten the Surface enough to get an accurate reading - Hard to get consistent readings - Easy to get inaccurate readings - Requires more time to use because of the surface preparation that is required - Can be large in size and cords can be in the wat - Requires batteries - Requires training

		- With the right set-up, it can survey large areas - Only gives a point measurement
Hand Tools	- Gives an overall assessment of losses, not just a point measurement - Relatively Simple Tools that Everyone has for Easy Reproduction	N/A
Calipers	- Easy to use - Easy to read - Easy to transport - Accurate and Precise - Durable - No Batteries - Can get Flange and Beam End Web Measurements - Effective and economical to use for flange and bearing stiffener measurements	- Limited Access if measuring too far into web - Can only measure where it can reach - Not Feasible in All Situations - May require more space than what's available - Training required for proper use - Steel must be clean to use for measuring - Can't measure large areas of section loss
Hammer	- Can Clean/Remove Delamination and Rust from Beam Ends - Can be effective - Good for sounding	- Can be a lot of work to use - Tiring - Weight/Can be Heavy - May not have room to swing it - Destructive and sets a path for more losses
Wire Brush	- Good for Cleaning Surfaces	- Destructive and sets a path for more losses - Sharp bristles
Ladders	- Can be Effective	- Can be a lot of work to use
Tape Measure	- Good for Measuring Large Objects - Accurate - Cheap - No Batteries	- Bad for Measuring Depth and Distance - Can be Inaccurate - Fails in dirty environments
Ruler	- Cheap - No Batteries - Good for Measuring Small Objects - Simple to Use - Easy to Transport - Easy to Read - Accurate Enough for Most Purposes	- Limited Precision - Bad for Large Objects - Can be Inaccurate

Straight Edge and Ruler/Tape Measure Combo	- Can get Accurate Web Loss Measurements - Good for one sided web loss measurements - Faster than using a D-Meter	- Decrease in Measurement Accuracy as the Surface becomes more uneven
Level	- Small and Easy to Carry	- Works only on small areas
Pitting Gauges	N/A	- Limited to a Small Area
Dye Penetrant	N/A	- Messy - Only allows you to spot things, doesn't actually measure anything
Laser Measure	N/A	- Only to Get Longer Lengths - Not to Measure Losses
Camera	N/A	- Sometimes it breaks
NDT Used in Previous Inspections	N/A	- Can get bulky - Unable to use in some areas

Going to the next question in this section, the MassDOT employees and consultants were asked how often gauges were calibrated. The responses were split into the two categories of MassDOT Inspectors and Consultants in order to compare the difference between the two sets of inspectors. Those directly from MassDOT claimed that they calibrated gauges before every use to ensure accurate measurements. Most of the consultants also stated their gauges are calibrated before each use, but others said that they are calibrated based on the manufacturers guidelines or that there is a built-in calibration, amongst other answers (Figure 2.35 and Figure 2.36). It is encouraging to know that the gauges are typically calibrated often or as recommended, which leads to the conclusion that the readings they get should be moderate to very accurate. Although it was not a frequent answer, it may be good to check why some inspectors responded with "yearly", "every few years", or "no" to see if that has a substantial effect on their measurements.

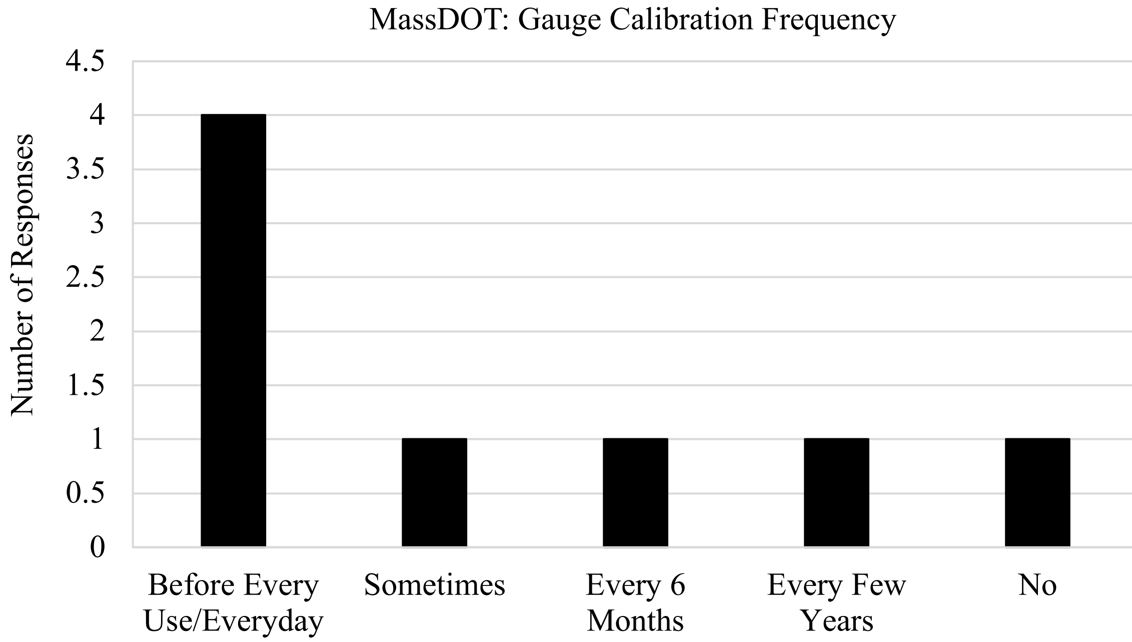
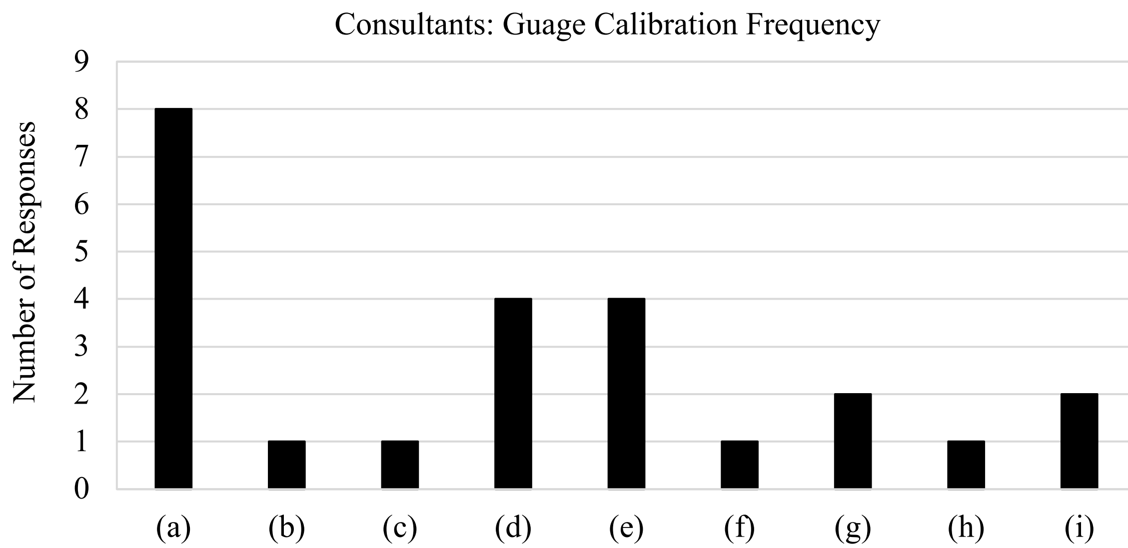


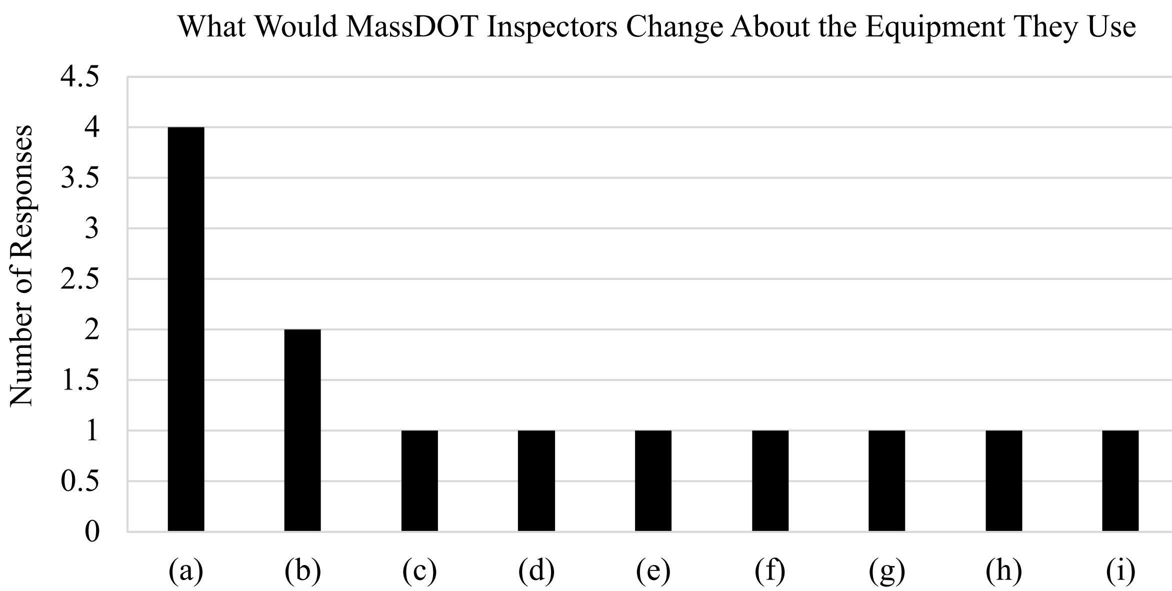
Figure 2.35: How Often are Gauges Calibrated by MassDOT Inspectors



(a)	Before Every Use/ Everyday
(b)	Weekly
(c)	Monthly
(d)	Once a Year/Yearly
(e)	According to Manufacturer Recommendations
(f)	When Measurements Seem Off
(g)	Built in Calibration
(h)	Calibration Cube with Known Depth
(i)	No

Figure 2.36: How Often are Gauges Calibrated by Consultants

To get an understanding of what inspectors want and need their equipment to do, they were asked to provide what changes they would make to the equipment they currently used. As before, the responses were split into the two categories to clearly view how these groups differ. Looking at Figure 2.37 and Figure 2.38, it is apparent that the MassDOT inspectors felt that their equipment is in need of more changes compared to the consultants. Overall, the key changes that were mentioned were more accurate and more reliable equipment that is durable in the field. This question provided really good criteria that should be considered before selecting any new corrosion technology, or bridge inspection technology in general.



(a)	More Accurate/More Reliable D-Meter	(f)	Functioning Speech Text Software
(b)	Battery Powered Angle Grinder/Wire Wheel	(g)	PocketMike in Place of Another D-Meter
(c)	Better Methods for Cleaning Steel	(h)	Newer Equipment
(d)	Bucket Truck with More Lateral Reach	(i)	Truck That They Can Stand Up In
(e)	Tripod for Laser Level		

Figure 2.37: Equipment Changes- MassDOT Inspectors

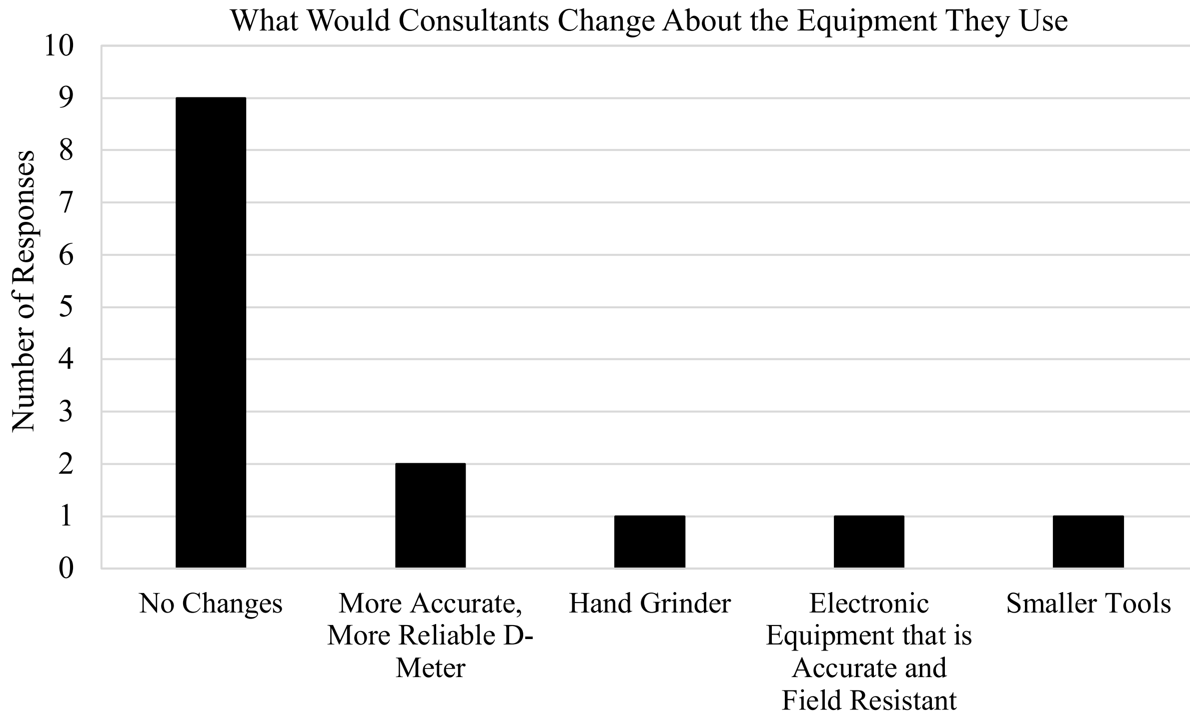


Figure 2.38: Equipment Changes- Consultants

The fourth question was focus on the inspectors ability to carry a portable laser scanner and possibly a tablet or cell phone as well. It was thought that inspectors may not have two hands available to be able to carry certain equipment, which is why it was important to ask this question. Despite this hypothesis, a majority of inspectors, 71%, felt that they could potentially both, while the rest of the inspectors, 29%, felt is may be possible to carry both (Figure 2.39). It was known before this questionnaire went out that laser scanning and LiDAR could be used for corrosion estimation, so it is promising to see that no one felt they could definitely not carry the portable laser scanner on a cell phone or tablet, making this a viable option for future corrosion assessment. It is also good to know that some inspectors are at least aware of laser scanning technology, since they stated that in questions regarding technology that could be used, so it may not be a completely new technology to them.

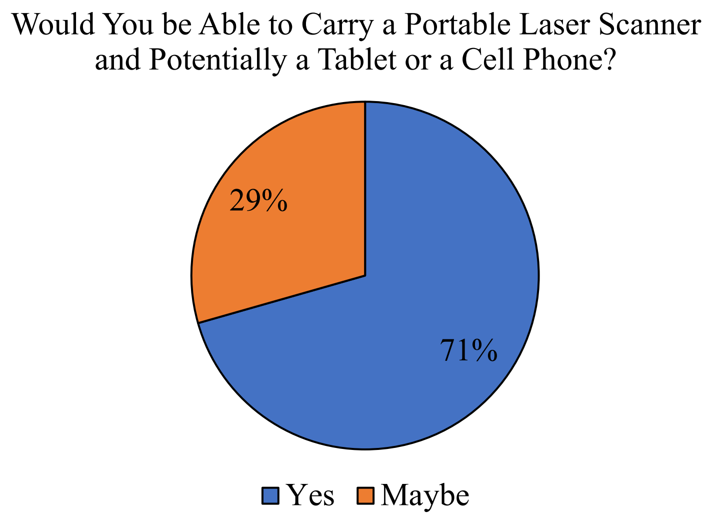


Figure 2.39: Carrying a Portable Laser Scanner and a Tablet or Cell Phone

Many times corrosion causes the build-up of delamination, and the fifth question of this section asked if it is possible to remove the delamination that has built-up over the support. Measuring corrosion of beam ends may require the removal of that delamination above the support, so it was important to know whether or not this could be done. 47% of those who responded to this questionnaire felt that they may be able to remove the delamination above the support, while the rest of those who answered said a definitive yes (Figure 2.40). Much like the previous question, it is encouraging that none of the inspectors chose "No", but in this case a lot more respondents said maybe. This makes sense given that many expressed the difficulty they have removing rust and delamination in the previous questions, and the possibility of not being able to remove the rust above the support should be taken into consideration when formulating new corrosion methods.

Is it Possible to Remove Delamination Along the Domain Above the Support?

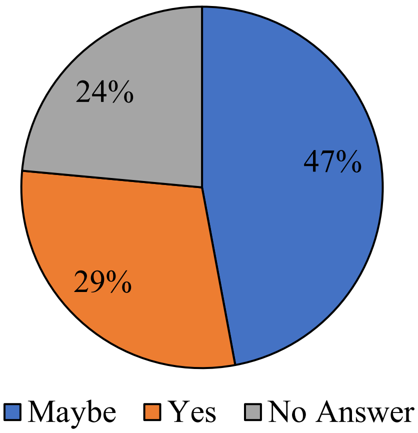


Figure 2.40: Is Removing Delamination Above the Bridge Support Possible

To account for those who responded no or maybe to question 5, the next question for this section asked why it is sometimes or all the time not possible to remove delamination above the supports. Figure 2.41 shows the responses for this question, and it is apparent that delamination is hard to remove when it can't be reached and when the design of the bridge doesn't allow for it. Creating a procedure and/or selecting a technology that required little to no removal of delamination to measure corrosion would be the ideal solution to this issue. A new method for removing delamination that addresses the issues mention in Figure 2.41 below is also a possible solution that was and should be considered.

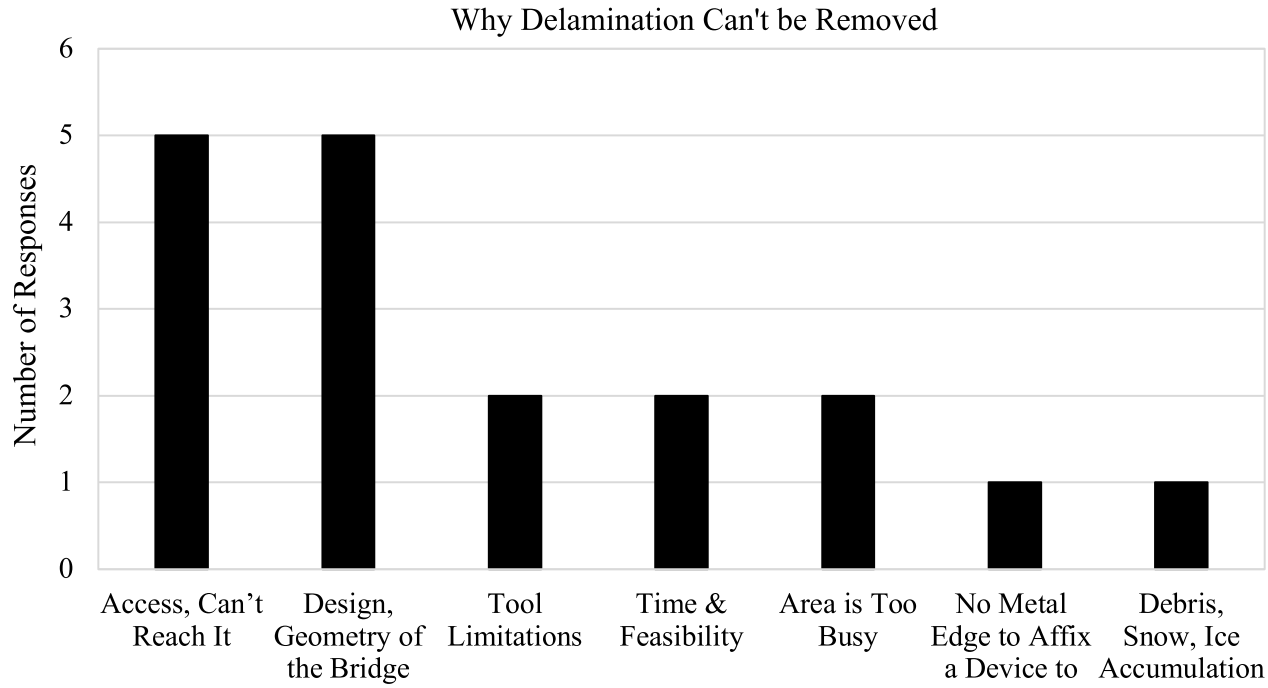
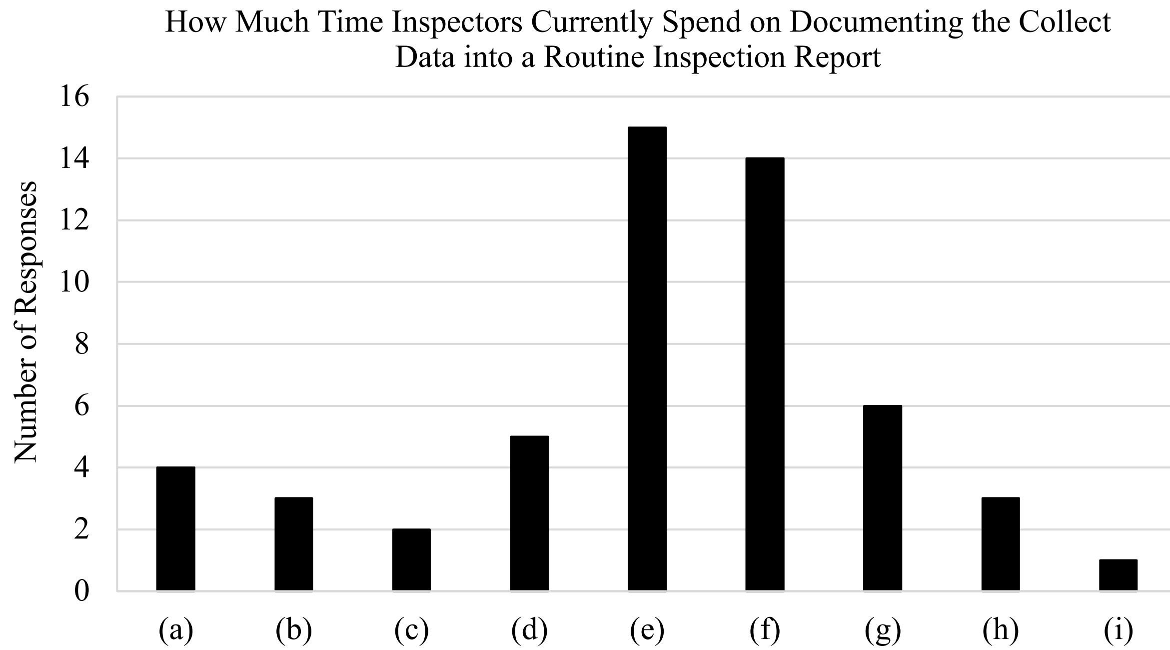


Figure 2.41: Why Delamination Cannot be Removed by Bridge Inspectors

When implementing new procedure, it is important to keep the amount of post-processing to a reasonable amount. To get an idea of what a reasonable amount of time would be for bridge inspectors, question 7 in this section asked how much time is currently spent on documenting the data that inspectors collect. 9 out of the 34 respondents chose one of the choices provided, while the rest provided other response besides those that were given. Looking at Figure 2.42 it would appear that that the actual time spent on documentation varies too much on bridge size and bridge condition, amongst other factors, to give a definitive amount of time. However, more often than not, it appears that more than 6 hours are typically spent on documentation, especially for a bridge that is heavily corroded. This is the time that should be considered when formulating a new corrosion method.



(a)	1-2 Hours
(b)	3-4 Hours
(c)	5-6 Hours
(d)	More Then 6 Hours
(e)	Varies on Bridge Size
(f)	Varies on Bridge Condition
(g)	Depends on Scope of Work and How Detailed the Documentation Needs to be
(h)	Depends on Length of Bridge Inspection
(i)	Varies Too Much to Say

Figure 2.42: Time Spent on Documenting the Collected Data into a Report

Along with how long it takes to document collected data, it is important to know if bridge inspectors they spend additional time for measurements and documentation that makes them feel that a new load rating is required. Figure 2.43 below shows the amount of people who responded yes, no, or sometimes. In addition to these answers, some inspectors left comments as to why they answered the way they did. These comments are recorded in Table 2.6. A common consensus amongst those that answered “no” or “sometimes” was that they don’t need a new load rating, or they only sometimes feel they need a new load rating, because they are typically able to gather enough data during the inspection. For those that answered “yes”, most of the comments centered around a new load rating for section loss measurements. These comments are important to consider when providing a new way to estimate corrosion given that the measurement of section loss is the measurement of corrosion.

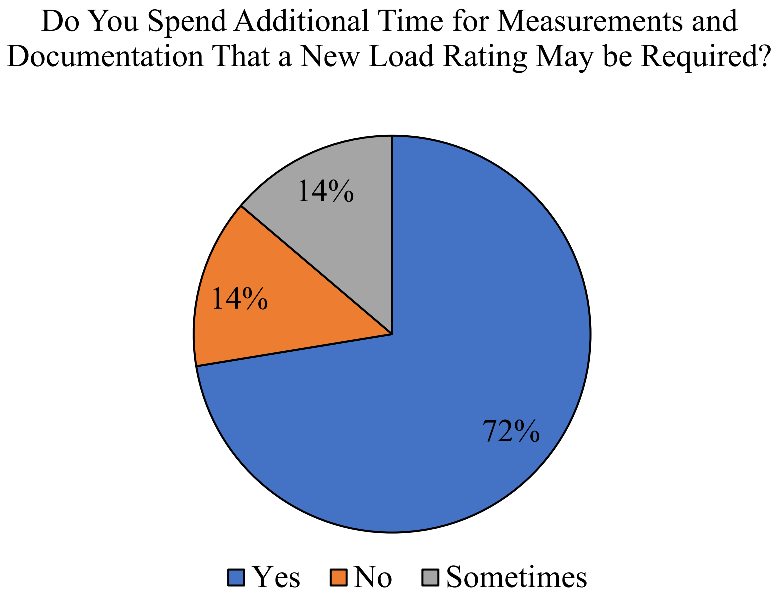


Figure 2.43: Do Inspectors Feel a New Load Rating is Needed

Table 2.6: Additional Comments on Whether a New Load Rating is Needed

Additional Comments	Number of Responses for Each
Typically Gather Enough Information/Data During Inspection	5
No, Sizes are Verified regardless of losses	1
Yes, for Section Loss Measurements	2
Yes, If required by MassDOT	1
Yes, if Load Rating is because of New and/or Widespread Section Loss has been discovered	1
Yes, Locations that could affect load rating	1
Yes, and a higher level of measurement will be taken for subsequent load rating	1
Depends on Section Loss	1
Depends on Bridge Complexity	1

The three of the last four questions of this questionnaire were focused on the use of Unmanned Aerial Vehicles (UAVs), or drones. Prior to the creation of this questionnaire it was known that UAVs have been used for bridge inspections by many different states DOTs, so it was decided to include these questions to see if inspectors were familiar with this technology.

The first of the UAV questions simply asked if they have ever used a drone or witnessed a drone being used for any MassDOT related activities. 25 out of the 34 people who responded, 73.5%, said that they had not used a UAV or witnessed a UAV being used, while 26.5% said they had. Of those who said they had used a UAV or witness one being used, only 1 person was a MassDOT employee and the other 8 were consultants (Figure 2.44).

For those who answered yes were asked what they activities they had witness a drone being used for. The MassDOT employee did not say what activity the drone was used for, but the consultants did provide the activities in their responses. One consultant said for both a bridge inspection and an ancillary structure inspection, another said for both a bridge inspection and a MassDOT communication tower load rating analysis, two said for high mast light tower inspections, another had for automated and manual flights to gather inspection photos, another for cell tower measurements, and the last said for a tunnel air supply plenum fly through. These responses are recorded in Figure 2.45.

The last question focused on drones asked if the inspectors have ever considered using drones for bridge inspections. Most people, 58.8%, responded that they had considered using drones for bridge inspections, while 32.4% said they had not considered it but think it could be useful in the future (Figure 2.46). Although a majority of respondents believe that drones can be used in some way for bridge inspections, there were 3 people out of 34 who expressed that they haven't considered using drones for bridge inspections and they do not think it would be useful to implement in bridge inspections in the future.

Overall, although many inspectors have not witnessed a drone being used, many of those that have saw them being used for inspections. This highlights that UAVs may be a viable option for the inspection of bridges if they can address the challenges mentioned in the responses recorded above. It is also promising that many have considered or would consider using drones in the future for bridge inspections, which means that many inspectors are aware of possible UAV usage and they are open to using this technology in the future. This awareness and willingness to use drones will help ease into a transition to drone use it that is deemed by the MassDOT to be the new way for bridge inspection.

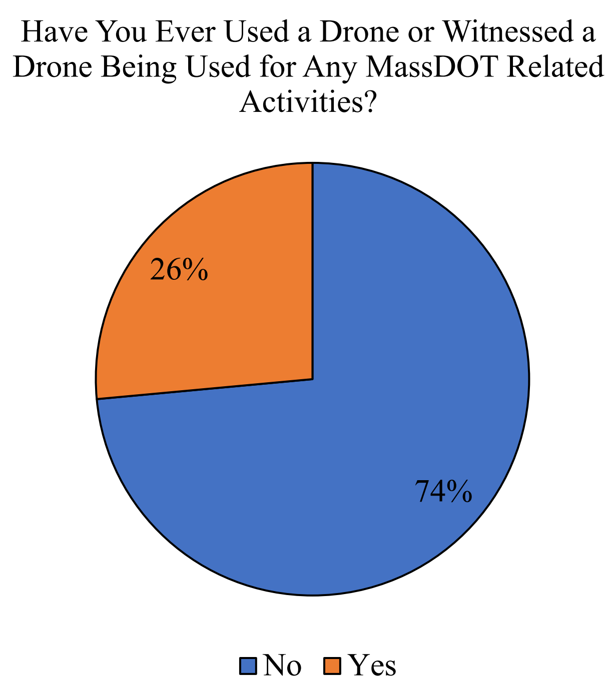
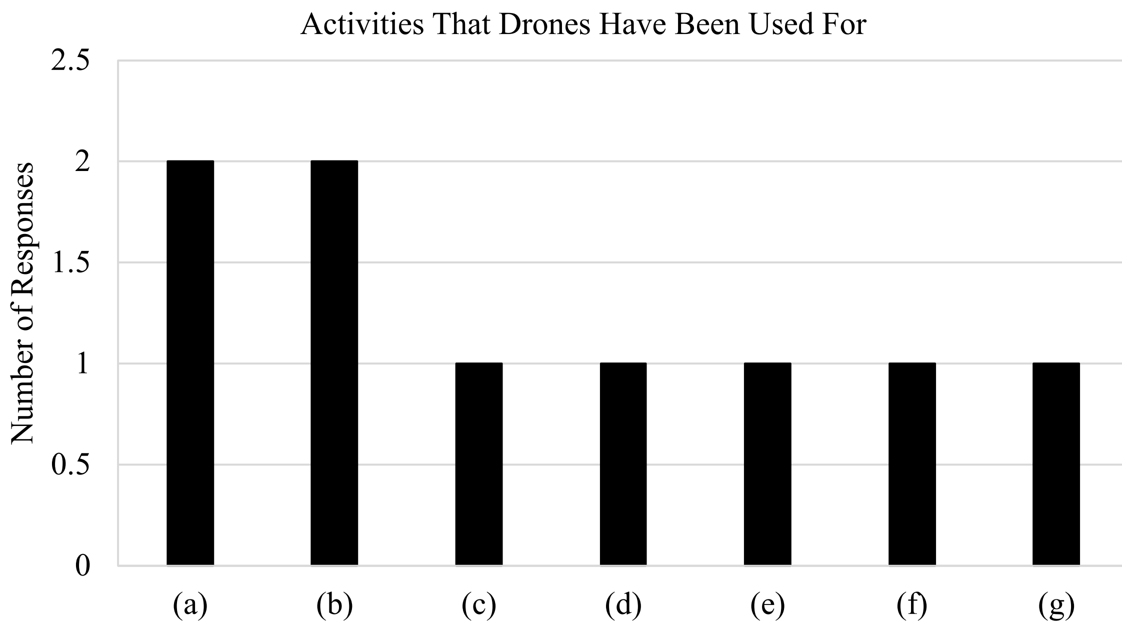


Figure 2.44: Using or Witnessing the Use of Drones for MassDOT Activities



(a)	Bridge Inspections
(b)	High Mast Light Tower Inspections
(c)	Ancillary Structure Inspection
(d)	Automated and Manual Flights to Gather Inspection Photos
(e)	Cell Tower Measurements
(f)	Tunnel Air Supply Plenum Fly Through
(g)	MassDOT Communication Tower Load Rating Analysis

Figure 2.45: Activities that the Drones were Used For

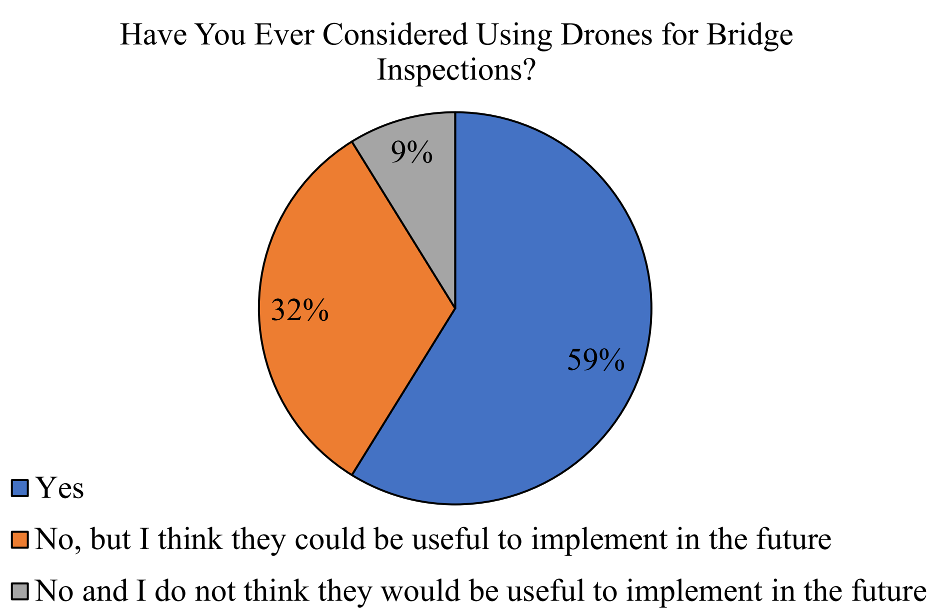


Figure 2.46: Have Bridge Inspectors Considered Using Drones

The final question of this survey asked for any additional comments and/or suggestions that they felt needed to be known for this research project. The additional comments are as follows:

- “ I am very interested in the portable scanning device shown and how it could be used for bridge inspections as well as cost for such a device. I suspect it could be helpful to more accurately document member distortions such as web crippling or gusset plate distortions and field measurement of plate sizes and rivet layout used in the analysis. I am glad to hear of your study and think it will be of value as such a high degree of deterioration occurs to the beam ends under the joints (as well as substructure components in same region). One other area that I am interested in (though not related to the current steel beam end loss study) is in the use of thermal imaging to detect delamination of concrete members such as bridge decks, beams, piers and abutments. Currently we typically hammer tap to locate these areas which can be very time consuming. This technology seems to be developing rapidly and there are devices that can now work with smartphones so maybe there could be an application there?”
- “Every bridge is unique, so several of these questions are restrictive. A beam end inspection should follow the general procedure of: Clean an appropriate amount of delamination -> measure the loss. I can't tell you the number of times a previous report noted just "heavy rust" to a beam end, and upon cleaning it I find significant measurable loss over the bearing, or even a rust hole or crack.”

- “Please reach out to me if you want us to team up for a field visit, especially to try out the laser modelling hardware. I would love to show you some real-world examples of what we run into. I inspect all the way to Conway or Williamsburg, so I can make a special trip if it means helping you guys. I want to keep helping you guys out when I can!”
- “We try to minimize time on the road/bridge due to safety of inspectors and public. We tend to collect data fast in the field and then spend time in the office to translate/communicate into a report.”
- “D-meters are a practical tool when the rating engineer requires member section properties greater than 1/32" accuracy for specific rating controlling members.”
- “D-meters need to be waterproof, function below 30F and read on dimpled, pitted, rusted junk steel. I'd like feedback from load raters on what they want.”
- “Any recommendations you have to implement are welcome but simplest is best - let's not try to make bridge inspection into rocket science.”
- “For some of the questions I am not sure I gave answers fitting what you were looking for. Feel free to contact me for clarifications.”
- “I typically inspect bridges for emergency repairs, so my answers are coming from a different perspective.”
- “Drones Would Be Useful At Points Of Limited Or No Practical Access(Damage/Heights), And For Visual Data Collection Only(Drones Lack Hands-On Applications).”

- "Drones are worthless for most instances. Losses like in beam ends are often behind an end diaphragm and would not be visible to a drone. Drones can't remove rust to assess remaining sections. Drones are good for taking general photos of exterior elements only."
- "Drones can be an extremely effective tool to help document and convey inspection findings to owners. Certain types of structures lend themselves better for drone use during inspections, so their use and desired deliverable can be tailored based on the structure type and desired purpose. At the current state of technology, while moving very quickly, I'm not of the opinion drones can replace the human element to inspection, but they can certainly help."
- " We should have drones for access to bridges hard to inspect."

These additional comments, along with the other responses of the questionnaire, were kept in mind for the duration of this project to help guide the research and aid in the decision process.

2.3 Questionnaire Conclusions

After collecting all the data and analyzing it, it was apparent that there are many improvements that can be made regarding the procedure bridge inspectors follow, the corrosion assessment methods they follow, and the equipment they use. All of the information gathered helped guide the research in this thesis on a new technology that can be used to estimate corrosion, and it will be helpful in the creation of a new corrosion estimation procedure in the future.

For the procedure itself, it was clear that there is a struggle with consistency amongst inspectors. There are often times inspectors were not clear about what they did during their bridge inspection, which makes it harder when that bridge is inspected by another inspector later on. This must be addressed in any new procedure, corrosion or otherwise, in order to ensure that the condition of all bridges is thoroughly assessed and monitored over time. This will help prevent any catastrophic structural failures in the future.

For corrosion estimation and technology in particular it is clear that there is a lot of room for improvement. Many inspectors struggle with accessibility and visibility of the corroded area due to the bridge configuration and equipment limitations. This often means that inspectors are not able to remove the rust and delamination as well as they need to, especially above the support. It also means that they are often not able to measure all the points necessary to get an accurate representation of the corroded area.

Inspectors also struggled a lot with measuring and documentation. Aside from not being able to measure due to accessibility and visibility issues, inspectors often cannot get accurate measurements due to tool limitations, particularly when measuring in harsh weather and/or measuring on uneven surfaces. Documenting also becomes time consuming as the bridge ages since the older the bridge, the more corrosion there is, and therefore the more measurements that need to be taken, documented, and analyzed. When considering the number of bridges inspectors are responsible for, along with the number of bridges in each district and the amount that they inspect per week, it is clear that any increase in documentation time can lead to added stress for the inspectors.

Given the challenges inspectors are facing and the suggested changes they would make, it is crucial that a new method of corrosion assessment must be able to easily access most areas of a bridge girder, must accurately measure the thickness of steel, must be easy and safe to use, must be reliable in most field conditions, must not take too much time to use in the field, and must not take a lot of post-processing. After doing preliminary research on technology before the questionnaire was sent out, it was known that laser scanning, or LiDAR, and UAVs are possible options for bridge inspection and corrosion estimation. The questionnaire results made clear that some inspectors are at least aware of these two technologies, so it was decided that more investigation be done on these methods or measurement before deciding on which would be best to focus on for this thesis.

After investigating these two methods, it was determined that further research would be done on using Unmanned Aerial Vehicles for the inspection and corrosion assessment of steel bridge girders. This decision was made based on the fact that UAVs can help address and correct the challenges that inspectors are experiencing, and additional technology add-ons can be added to UAVs, including LiDAR, in order to measure and assess steel beam end corrosion. Therefore the remainder of this thesis will focus on UAV usage in order to make recommendations on their ability to be used for bridge inspections and corrosion estimation.

Chapter 3

UAV USAGE FOR GENERAL TRANSPORTATION PURPOSES

3.1 Literature Review on the Use of UAVs for General Transportation Purposes

Many states, universities, and other organizations have begun to research and use unmanned aerial vehicles for various different purposes. For the first part of this research project, a review of reports and PowerPoint presentations that are geared towards using UAVs for transportation purposes was conducted. The studies summarized in this chapter come from DOTs in California, Illinois, Iowa, Indiana, Ohio, Kansas, Kentucky, New Hampshire, Missouri, and Vermont. Information from AASTHO is also presented.

3.1.1 California DOT

In California, the Department of Transportation (Caltrans) has created a Division of Aeronautics, which oversees its UAV operations [19, 20]. As of 2016, Caltrans had received a number of questions from various offices asking if drones could be used in order to cut costs, improve safety, and increase efficiency. Such query led to an increase in research on UAVs in general.

After concluding that drones can be beneficial to their operations, Caltrans began to dig deeper into how to operate UAVs effectively. Part of the research conducted by Caltrans looked into either having in house drones or outsourcing to inspection companies. As part of their research, the University of California at Davis built their own drone for Caltrans [19]. They felt that making their own drone would insure it could collect the data they need and fit in the spaces they need. Besides drone outsourcing, Caltrans also considered what they could use drones for. They focused on the possibility of using drones for terrain investigations, vegetation and soil investigations, disaster response surveys, confined space inspections, roadway inspections, and bridge inspections [20].

3.1.2 Illinois DOT

In Illinois, the IDOT took on a “phased implementation” to determine if and how drones should be implemented into their transportation operations [21]. After initial research was done, the IDOT found that using drones is very promising as long as you have good communication, adapt to changing environments and needs, and use the proper equipment. They also found that there are 3 main categories of UAV use: surveying, inspections, and visuals. There was such high interest throughout the different transportation departments within IDOT, that they are planning to do further testing into how they can use it for other general transportation services such as construction documentation, asset management, corridor planning, material estimation, traffic flow observation, resource identification, and land acquisition. These tests fall into “phase 2”, which also includes looking into more technology, methods of making data deliverables for post processing, and collaborating with other agencies [21].

3.1.3 Iowa DOT

For the Iowa DOT, the Office of Aviation is in charge of their unmanned aircraft systems (UAS). Iowa is the first state in the US to fly a UAV and get a waiver to fly in all airspaces [22]. So far, they have been testing and using the DJI Phantom 4 drone [5] for many different purposes such as airport/heliport directories, flood monitoring, railroad inspections, wetland mitigation, and highway surveys. Their tests for these have gone so well that they are thinking about performing more tests on crash investigations and bridge inspections, but those are just concepts for now [22].

3.1.4 Indiana DOT and Ohio DOT

In Ohio, their DOT has joined forces with the Indiana DOT to create the UAS center [23]. After getting the proper approval and waivers, the Ohio/Indiana UAS Center has been able to successfully perform various general transportation activities. Those activities included environmental mapping and assessment, modeling and simulations, and precision agriculture. This center has helped a number of different agencies across Ohio and Indiana, which use drones to perform data procession and valuable analysis for future decision making [23].

3.1.5 Kansas DOT

The Kansas DOT, along with Kansas State University, conducted a broad survey centered around drone usage [24]. Their goal was to see what activities are suitable for drones. After sending a survey to all state DOTs, the Kansas DOT conducted a Strength, Weakness, Opportunities, and Threats/Challenges, or SWOT, analysis. From this analysis, they concluded that there are significant benefits that come from drone usage. The benefits are mainly related to cost, efficiency, and safety. They also summarized how UAVs have been successfully used for surveying, mapping, stockpile measurement, inventories, traffic data collection, and inspections of different structures. From this study, the KDOT felt they could also utilize this technology [24].

3.1.6 Kentucky DOT

In Kentucky, the Department of Transportation created a UAS program [25]. So far that program has done extensive research on using drones for surveying to prove that drones can be a useful tool to their transportation activities. Since their “proof of concept” was so successful that they are now looking into using drones for digital terrain modeling, construction monitoring, as-built plans, stockpile measuring, crash management, GIS, and inspections [25].

3.1.7 New Hampshire DOT

The New Hampshire DOT, in collaboration with the University of Vermont, has undertaken a research project to determine what UAVs can be used for, as well as their limitations and cost-benefits [26]. The project is going to be testing six possible activities: accident reconstruction, traffic monitoring, aeronautics, construction monitoring, rock slope inspection, traffic, and bridge and rail inspections. The researchers involved in this project plan to compare the UAV results to the results produced by their current methodologies to come up with advantages and disadvantages. Based on this study, researchers will be able to inform the NHDOTs decisions for UAV usage [26].

3.1.8 Missouri DOT

The Missouri DOT (MoDOT) is very keen on implementing drones as soon as possible [27]. They started the process by first sending out a survey to several state DOTs, as well as several different agencies, such as police and fire departments. Using the survey information collected, the MoDOT has recommended using UAVs as soon as possible, developing a UAV policy, developing a UAV education program, and developing a UAV partnership with different stakeholders. They also recommend using UAVs for various construction, agriculture, and manufacturing purposes associated with the DOTs activities [27].

3.1.9 Vermont Agency of Transportation (VTrans)

Instead of a report, the Vermont Agency of Transportation (VTrans), along with the University of Vermont, put out a PowerPoint of pictures taken by their UAVs and images constructed using the data taken from their UAVs. From the images you can see that they have been able to use drones to analyze roadway conditions, capture pictures of traffic collisions, surveying and mapping different sites, flood monitoring, damage assessment, and inspections [28].

3.1.10 American Association of State Highway and Transportation Officials (AASHTO)

Along with different state DOTs, the American Association of State Highway and Transportation Officials (AASHTO) has put out several reports detailing what states are doing with their UAVs. The reports that were reviewed summarized the results of the survey that AASHTO sent out in regard to using drone in order to be more efficient, safe and cost effective. Their survey was performed in March of 2016, and it found that 17 state DOTs had used UAVs for accident clearance, surveying, monitoring and mitigating risks, and inspections [29-31].

3.2 Motivation for State DOT Usage of UAVs in General

There is a common consensus amongst the reports read for the first literature review. That consensus is that state DOTs want to start using UAVs for a number of different transportation activities. That conclusion was reached because states have seen that UAVs are a technologically advanced tool that can cut costs for their DOTs by helping DOT employees quickly and safely carry out many of the daily transportation activities that occur across the nation. The specific activities that were discussed by the various state DOTs mentioned above are listed in Table 3.1.

Table 3.1: Summary of the Transportation Activities that UAVs Could be Used for.

Transportation Activities That UAVs Could Be Used For
Traffic Monitoring
Crash Response and Reconstruction
Stockpile Measurement
Land Mapping and Surveying
Construction site monitoring
Disaster Response
Flood monitoring
Soil and Vegetation Investigation
Bridge, Rail, and Road Inspections

Chapter 4

UAV USAGE FOR BRIDGE INSPECTIONS

4.1 Literature Review on the Use of UAVs for Bridge Inspections

In their efforts to ensure safety and maintain the infrastructure of the state, DOT engineers perform periodic bridge inspections that conform to the requirements of the Code of Federal Regulations [32]. DOTs have introduced and are currently using a variety of standard inspection report forms [33] that fulfill the requirements of the National Bridge Inspection Standards. These reports provide extensive information for the overall condition of the structure (e.g., deck, superstructure, substructure, culvert) or can focus on specific bridge components. Depending on the amount of information included, the inspection reports can serve as a relatively detailed description of the condition of the different components of the bridge.

Over the past decade, there has been an increase in the amount of research done to determine whether UAV technology is suitable for roadway and railroad bridge inspections. Many of the reports published by various state DOT's and universities start by exploring previous use of drones for bridge inspections in order to determine if it is feasible to launch a UAV bridge inspection program. Most of the references that explored previous drone usage reached the same conclusion; using UAVs for bridge inspections has the potential to be very beneficial. Such a resolution has been a common consensus amongst those who have considered utilizing UAVs for bridge inspection, for it is both cost effective and safer.

Cost efficiency of utilizing UAVs comes into play when you consider, amongst many other factors, that they will not have to halt all traffic to perform inspections, they will not have to spend as much time at each bridge in order to conduct inspections, and they will not need as many people on-site during the inspections. In terms of safety, using UAVs means there is no need to put inspectors into situations where they could sustain injuries, specifically when they need to be dangled over the side of a bridge using a special truck

After verifying how promising UAV use is, many states have gone on to perform lab tests and test inspections on actual bridges in order to determine which drones to use, which equipment to use, what can be detected, and if in fact drones can detect what inspectors are expected to. Some states have decided to focus on specific detection areas and equipment, while others have conducted a general study on all detection areas and available equipment. For this research, reports from six states, three universities, a transportation agency, and two railroad companies who have launched extensive research projects geared towards bridge inspections were analyzed. Those 6 states are Idaho, Michigan, Minnesota, Nebraska, North Carolina, and Oregon. The three universities are Carnegie Mellon University, Colorado State University, and the Florida Institute of Technology. Finally, the transportation agency is called the Mid-America Transportation Center and the two railroad companies are Union Pacific and Norfolk Southern.

4.1.1 State DOTs That Have Done Research on UAV Bridge Inspection

4.1.1.1 Idaho DOT

A 2017 Report put out by the Idaho DOT and Utah State University details their efforts on utilizing UASs to detect fatigue cracks during under bridge inspections [34]. Their research project was broken into four parts. The first was a literature review where they looked at how other state DOTs have used UASs. The second part was a small bridge experiment where they flew a 3DR Iris with a GoPro Hero 4 and FLIR E8 Thermal Camera around a mock bridge constructed at a Utah State University Lab. During this small bridge experiment, it was evident that it is possible to map a bridge in 3D and detect concrete cracks and delamination visually using the UAV and the different cameras [34].

The third part of the Idaho DOTs research involved determining the requirements for fatigue crack detection. During this part of the research they tried out three different drones, the 3DR Iris, the DJI Mavic, and their hand made drone called "The Goose", along with a GoPro Hero 4, the DJI Camera onboard the Mavic, a Nikon COOLPIX L830, a FLIR E8, and a FLIR SC640. After picking the proper equipment, they tried to detect the fatigue cracks in a test specimen both inside and outside the lab; creating different lighting conditions, in order to determine the proper technology, lighting, and conditions that will capture an image clear enough to get an accurate fatigue crack mapping from the automatic fatigue crack software Utah State created. From these experiments, they concluded that the DJI Mavic and its onboard camera could detect fatigue cracks in any lighting condition, particularly those with an illumination of 200 lx or more, and the FLIR cameras could detect the cracks only through active thermography [34]. Active thermography is a process where they heat up the specimen using lights and take photos using the thermal camera.

The last part of the project was performing an actual bridge inspection on the Fall River Bridge in Ashton, Idaho using a UAV. This bridge is on a 12-month inspection cycle because of the fatigue cracks present in the steel members underneath the bridge, which is the main reason it was chosen [34]. The research team chose to use the DJI Mavic to capture images of the bridge, specifically where there are known fatigue cracks. Overall, the conclusions from this part of the experiment were that the UAV was able to capture concrete cracks and delamination, but it was unsuccessful in capturing fatigue cracks due to visibility and the drones ability to get close to the crack location. After analyzing all the findings from the four parts of this research project, the research team concluded that a UAS could not detect fatigue cracks using only images, therefore, their future research will focus on thermal imaging for fatigue cracks along with research into other uses for UAVs for bridge inspections [34].

4.1.1.2 Michigan DOT

The Michigan DOT, in collaboration with the Michigan Technical Research Institute (MTRI), has been very involved with using drone for transportation related activities, especially bridge inspections [35-39]. For this research, three PowerPoint presentations and two research reports were read in order to evaluate what the state has been doing with drones. The MDOT launched a multi-phase project to test the viability of using drones for bridge inspections.

The first phase of this project focused on the feasibility of using UAVs for transportation projects, which ultimately led the state and MTRI to conclude that it was worth continuing their UAV research, given the promising cost, safety, and efficiency benefits that was shown in this phase [35]. The report from the second phase, published in 2018, delved deeper into the actual testing and use of UAVs [36]. This project started with analyzing five different UAV platforms; the Bergen Hexacopter and Bergen Quad 8

Octocopter, both made in Michigan, the DJI Phantom 3 Advanced quadcopter, the DJI Mavic Pro quadcopter, and the Mariner 2 Splash quadcopter, which is waterproof. They also tested out the Nikon D810, the FLIR Vue Pro and Vue Pro R, the FLIR Duo, and a Velodyne LiDAR Puck-16 [36].

From this first experiment, the research team concluded that the Bergen hexacopter equipped with a FLIR thermal camera and the Bergen Quad-8 with a digital camera or LiDAR sensor are the best platforms for infrastructure inspections. Along with that, the team also felt the Phantom 3 was best for quick overview shots for roads and bridges, the Mavic Pro was best for quick traffic monitoring video, and the Mariner 2 worked best for capturing images underneath a bridge. After determining which drone/technology combo worked best for each task, the state decided to perform field tests on five bridges, three road corridors, one construction site, and one test near MTRI's office building. Using the images and data collected by the drones and their attachments, the team was able to construct Digital Elevation Models (DEMs), Hillshade Models, Orthophotos, Thermal Images, and Point clouds for each field test, while also being able to test their Automatic Spall and Delamination algorithms for them as well [36].

The DEMs are created using Agisoft Photoscan Pro, which utilizes optical images to create a 3D model that has accurate elevation data. These models worked best for spall detection because the algorithm could compare the elevation change between pixels to determine if there is spall. The Hillshade models, which is a grayscale 3D representation of a surface, were derived from the DEMs using ESRI's ArcGIS Software to better display distress features without the inclusion of elevation data. The orthophotos were also created by Agisoft Photoscan, but instead of a 3D model, the software produced an orthorectified image using the optical images, which were then used for comparing potential delamination to visible deck features. The thermal images captured by the FLIR camera also aided in delamination detection, while the Point Clouds allowed for accurate production of 3D models. Python, MATLAB, and ArcPy were used to create the spall and delamination algorithms that proved to work reasonably well during testing [36].

After successfully performing field testing and post-processing of the photos and data, the research team determined that UAV technology could meet the needs of the MDOT concerning both data and decision support. The conclusion was based on the improved bridge inspection, road assessment, and traffic monitoring they were able to conduct. Also, to further prove that UAVs should be implemented into MDOT operations, a cost-benefit analysis was done at the end of the report, which demonstrated the savings that would come with using UAVs. Lastly, the phase two report includes the next steps for implementing UAV in day-to-day DOT operations [36].

The PowerPoint presentations prepared by the Michigan DOT highlight the important findings that the research team presented in their papers [37-39]. These presentations aim to inform the public about the promising results UAV research has been producing in the hopes of gaining support for their efforts. They also detailed their "3D Bridge App" that allows MDOT Inspectors to interact with a 3D bridge model on an element-level to increase the department's efficiency and decrease paper usage [35]. Overall, the Michigan DOT has decided that UAVs can and should be used in day-to-day operations, especially for bridge inspections.

4.1.1.3 Minnesota DOT

Similarly to Michigan, the Minnesota DOT (MnDOT) has also launched a multi-phase project focused on using drones for bridge inspections [40-42]. The first phase of this research was a demonstration project where four bridges were inspected using drones in order to determine their effectiveness compared to traditional inspection methods. The four bridges selected for this phase varied in both type and size. The drone used for these inspections was the Aeyron Skyranger.

From the first phase results, the MnDOT pointed out that UAVs are more useful for large bridges. Also, they concluded that developing technology is very cost effective and presents the potential to improve their overall effectiveness. However, more research is needed to create a program manual for using drones for inspections [40].

Phase two of the MnDOT research project involved inspecting four more bridges, performing a cost-benefit analysis, and creating a summary of best practice and safety guidelines. Also, for this phase, the Sensefly Albris was used instead because it is able to fly under bridge decks and look straight up, unlike the Aeyron Skyranger.

The research conducted in this phase proved further that UAVs will be a useful and cost-effective tool for inspectors to use for bridge inspections [41]. The last report herein included a summary of phase one and phase two along with a description of the UAVs used, the post-processing and deliverables, a cost analysis, and the safety improvements. This report not only highlighted the Sensefly Albris, but also introduced the Flyability Elios UAS, which is collision tolerant and shows promise for bridge inspections.

In terms of deliverables, this report detailed 3D models, photo logs, and orthophotos that can be made using the drone data, all of which can be stored in an interactive map that can be updated over time to show the evolution of a bridge and its specific elements. The cost and safety analysis showed that drones can significantly reduce spending, protect inspectors, and increase efficiency [42]. Overall, the research project conducted by MnDOT has brought them closer to implementing UAVs in daily bridge inspections.

4.1.1.4 Nebraska DOT

In "The Roadrunner", published in 2018, the Nebraska DOT detailed how they conducted UAV field tests on 11 bridges [43]. In order to test a variety of conditions, the NDOT chose to do UAV inspections on three bridges in downtown Omaha, an urban area, two bridges over the Platte River, to test under bridge inspections, one culvert, one long bridge over the Mississippi River, two arch bridges, and two fracture critical bridges.

After performing all the inspections, the NDOT concluded there were far more advantages than disadvantages to implementing drones for bridge inspections. NDOT reported that drones were faster and safer than using the typical snooper truck and boats, usually used for bridge inspections. As drones can get closer to the structure than inspectors, UAVs would be able to replace "within arm's reach" inspections. The document also reported disadvantages, which are mainly related to the training and education needed in drones operation and FAA regulations, which interfere with the operation of drones [43].

4.1.1.5 North Carolina DOT

The North Carolina DOT (NCDOT) partnered with North Carolina State University (NCSU) to analyze the potential of using UAVs for various transportation activities, including bridge inspections [44]. Their research report, from 2016, details the 6 field tests performed with drones, which are: (i) a small survey on Lake Wheeler; (ii) a high-resolution survey of Kinston Jetport; (iii) a construction site survey in Waynesville; (iv) geotechnical monitoring of I-40 in Haywood County; (v) traffic monitoring at Diverging Diamond Interchange; (vi) a bridge inspection of Gallants Channel Bridge.

The bridge inspection was performed using the DJI Inspire drone. According to researches of this report, the inspection confirmed that UAVs would be helpful to reach new locations on every bridge, especially the underside of bridge decks. Using the FLIR E4 and FLIR Tau 640X480, the research team was able to detect delamination on the bridge deck. Using the other images captured by the drone, a 3D model and a DEM was constructed for this bridge using Agisoft Photoscan. Overall, after the research finished, the NCDOT felt that the use of UAV was promising, and, as technology improves, it will be an even better tool to use for their transportation activities, especially bridge inspections [44].

4.1.1.6 Oregon DOT

A 2018 research report published by the Oregon DOT (ODOT) shows that this state is also interested in implementing drones for bridge inspections, as well as radio tower inspections [45]. This report details the six bridge test inspections and four radio tower test inspections conducted by the DOT. A Sensefly Albris, which has a regular and thermal camera, a custom DJI S900 hexacopter with a Sony a5000 camera, and a DJI Phantom Pro 3 were used to perform the bridge inspections.

After inspecting all six bridges of varying sizes, the ODOT was able to draw several conclusions. Firstly, the report states that all inspection types can use drones in some way. They also concluded that UAVs could capture several details, although a high resolution is required. The ODOT study has also analyzed flight modes, concluding that the two optimal flight modes are the manual mode with sensor assistance and the waypoint-assistance mode. Concerning the flight, the wind is the most impactful condition. Lastly, the report points out that it is critical to plan post-processing before the flight. Overall, the ODOT has concluded that UAS is an important tool that they would like to use for inspections in the near future [45].

4.1.2 University Research on UAV Bridge Inspection

4.1.2.1 Carnegie Melon University

Carnegie Mellon University launched the Aerial Robot Infrastructure Analyst (ARIA) project [46]. This project aims to utilize small, low flying drones equipped with 3D imaging technology for infrastructure inspection, particularly bridges. Their Micro Air Vehicles (MAVs) are octo-rotor and equipped with a single-line laser scanner, three video cameras, an inertial measurement unit, GPS, and wireless communication technology. Such features make them superior when flying over water and other hazards compared to drones with ground-based sensors.

The ARIA program involves a quick process that starts by completing a flight route over the bridge, all the while using the onboard technology to capture valuable data and images [46]. Using what the MAV has captured, researchers and inspectors then create a 3D point cloud that is developing into a semantic component-based model used for visual detection of defects. That component model is then converted into a finite element model for simulation and further structural assessment. This process allows inspectors to have an immersive experience to better analyze the infrastructure over time. Overall, the inspections performed by these drones are safer and more efficient than typical inspection practices, and the university is working closely with the Pennsylvania DOT Inspectors to make this project useful for everyone [46].

4.1.2.2 Colorado State University

In a 2019 project, Colorado State University detailed their plans for phase two of their research project [47]. In the search for better inspection methods, the university's research team launched a project focused on feasibility of drone use and post-processing techniques. The first phase was a feasibility study, which has already been completed. For this phase, the team conducted live bridge tests where optical and thermal images were collected. These images were used to make 3D models that allowed researchers to identify damage and assess the bridges conditions, which proved the feasibility of using drones for inspecting bridges. Phase two being proposed is about research that is centered around developing a way to automatically detect damage and quantify that damage using the data and images captured by the drone. There are four tasks outlined for this project, which are estimated to take about 12 to 24 months each from the project start date [47].

4.1.2.3 Florida Institute of Technology

The Florida Institute of Technology prepared a research report for the Rail Safety IDEA Program that centered around the inspection of railroad bridges [48]. This 2016 report, in particular, dealt with imaging sensors and mobile LiDAR's for remote sensing of concrete cracks and bridge element displacement. Along with the sensors, the research team developed an algorithm to detect and classify concrete cracks. To test both the sensing technologies and algorithms they chose, researchers conducted 3 experiments.

The first experiment consisted of an in-lab experiment. The researches built a "bridge" out of PVC pipe and scanned it using a stationary Velodyne HDL-32E LiDAR. Afterward, they put several wood blocks under one end one-by-one. Each time they added a block of wood they took another scan to see if they could detect movement using the LiDAR. They also moved the LiDAR closer to the bridge, aiming to see if distance affected the scans. From this experiment, with only a few scans, they were able to accurately measure the displacement of the bridge, as well as observe that the closer the LiDAR was, the denser the point cloud became [48].

The second experiment again involved keeping the LiDAR a set horizontal distance from the bridge, but this time they scanned a concrete bridge in Melbourne, Florida. This bridge had battered piles that deviated from 90 degrees. They raised and lowered the LiDAR vertically to get a complete scan, and they were able to get enough scans to get a point cloud that accurately displayed the angled piles [48]. The last experiment utilized a UAV that Florida Tech built, known as the MAV-F8. They then strapped the LiDAR to this drone and flew it around the PVC bridge to collect scans. They found that they got the same quality of scans as a stationary LiDAR, therefore a drone could be used. They also did a successful railroad bridge inspection on a bridge in Palatka, Florida using the UAV/LiDAR combo. The successful experiment conducted for this IDEA program has led to support from the Florida DOT, and a push toward further research into the use and implementation of drones for railroad bridge inspections [48].

4.1.3 Mid-America Transportation Center

The Mid-America Transportation Center is comprised of the University of Nebraska Lincoln, Kansas State University, the University of Kansas, Missouri University of Science and Technology, Lincoln University, the University of Missouri, Iowa State University, and the University of Iowa [49]. These universities completed a cooperative research project centered around developing a UAS to automatically conduct bridge inspections. As part of this project, the research team built their own UAVs and algorithms. They conducted several experiments to test the external sensors they put on their drones to see if they could be used with or without GPS. As the results were promising, they developed a prototype UAV system to inspect bridges autonomously, which one hopes to improve the sustainability of transportation infrastructure [49].

4.1.4 Railroad Companies Involved in Research on UAV Bridge Inspection

4.1.4.1 Union Pacific

Two major railroad companies in the United State, Union Pacific Railroad and Norfolk Southern Railway, have already begun to implement drones for bridge inspections [50, 51]. Union Pacific has been using drone since 2014, and in 2016 the use of UAVs made it possible for them to have the best safety record in their history.

According to [50], Union Pacific has a program to train their inspectors and continuously trying to advance the technology for railroad bridge inspection. One such technology Union Pacific developed is the Perceptive Navigation Technology (PNT) that allows drone flight without a GPS signal.

4.1.4.2 Norfolk Southern

Norfolk Southern has also been progressive with their drone use, and they have partnered with HAZON Solutions in Virginia Beach, Virginia to further their UAV program. They have seen great result so far, particularly with the speed of inspections as they have been able to perform 64 inspections in 18 months. Besides speed, Norfolk Southern is particularly in favor of using drones in order to obtain angles they couldn't obtain before [51].

Overall, implementing drones for railroad bridge inspections is progressing at a fast rate and the technological advancements being made are helping to make the implementation of drone for both railroad and regular bridges easier and more efficient [50, 51].

The tables below present several pieces of key information from the reports above. Table 4.1 presents the outputs that can be made using the data collected by UAVs, along with how they can be used by inspectors. Table 4.2 presents what drones are able to detect, along with how they can be detected. Table 4.3 lists the different drones that are mentioned above along with their corresponding state and some of the specifications that are important to know before picking that drone to use for bridge inspections. Lastly,

Table 4.4 the other technology that researchers used with the drones, along with their corresponding states and key specifications.

Table 4.1: Summary of the Possible UAV Outputs and their Uses.

Output	Uses
Images and Video	Detecting Visible Defects
Thermal Images	Detecting Delamination, Fatigue and Other Distresses
Point Clouds	Helps construct the different models
Digital Elevation Models	Input for Automatic Spall Detection Algorithm
Hillshade Models	Helps Detect Possible Distresses
Orthophotos	Input for Automatic Delamination Detection Algorithm
3D Models	Determining bridges structural health and response Monitor changes over time

Table 4.2: Summary of the detection possibilities of UAV and how they are detected

Detection Possibilities	Detection Method
Concrete Delamination	Regular and Thermal Images
Concrete Cracks and Spall	Regular Images and Video
Weld, Bolt, & Connection Health	Regular Images and Video
Visible Stress	Regular Images and Video
Fatigue	Thermal Images
Rust/Corrosion	Regular Images and Video
Structural Response	3D Model Constructed from the data collected by the drone
Overall Bridge Health	Everything collected during the bridge inspection

Table 4.3: Summary of the UAV Features, Flight time, Payload, Cost, Size, and State(s) that Used them that are Mentioned in this Report.

Technology	**Features**	**Flight Time**	**Payload**	**Cost**	**Size**	**States**
DJI Mavic Pro	4 Blades Onboard Camera 3-Axis Gimbal	21-27 minutes	2 lbs.	$1000-1500	3.3x3.3x7.8 in	Idaho & Michigan
DJI Phantom 3 Advanced	4 Blades Onboard Camera 3-Axis Gimbal	23 minutes	3 lbs.	$800	18x13x8 in	Michigan
DJI Inspire	4 Blades Onboard Camera 3-Axis Gimbal	18 minutes	6.27 lbs.	$2500	17.2x11.9x17.8 in	North Carolina
DJI S900 Hexacopter	6 Blades	18 minutes	3 lbs.	$3300	18.1x17.7x14.2 in	Oregon
Bergen Hexacopter	6 Blades 2 Axis Gimbal	16 minutes	5 lbs.	$4900	N/A	Michigan
Bergen Quad-8 Octocopter	8 Blades 2 Axis Gimbal	20 minutes	10 lbs.	$5500	N/A	Michigan
Sensefly Albris	4 Blades Onboard Camera Thermal Camera Inspection Drone	22 minutes	N/A	$35,000	22x32x7 in	Minnesota & Oregon
Flyability Elios 2	Onboard camera Protective Cage	8-10 minutes	N/A	$2500	15.8 in Round Cage	Minnesota
3DR Iris	4 Blades Can be Autonomous	12-19 minutes	0.8 lbs.	$650	19.5x24.5x12 in	Idaho
Mariner 2 Splash	4 Blades Waterproof	12-19 minutes		$1200		Michigan
Aeryon Skyranger	4 Blades Military Use	30-50 minutes	1.5 lbs.	N/A	40 in diameter 9.3 in height	Minnesota

Table 4.4: Summary of the Other Technology Used with the UAVs, Along with their Weight, Cost, Size, and State(s) that Utilized Them.

	Technology	**Weight**	**Cost**	**Size**	**States**
Video & Photos	GoPro Hero 4	0.19 lbs.	\$400	1.6x2.3x1.2 in	Idaho
	Nikon COOLPIX L830	1.125 lbs.	\$400	4.4x3.0x3.6 in	Idaho
	Nikon D810	1.95 lbs.	\$1200	5.8x4.9x3.3 in	Michigan
	Sony a5000	0.59 lbs.	\$600	4.3x2.5x1.4 in	Oregon
Thermal Cameras	FLIR E8	1.3 lbs.	\$3000	6.3x15x12 in	Idaho
	FLIR SC640	4.2 lbs.	\$3250	11.1x5.7x5.8 in	Idaho
	FLIR E4	1.3 lbs.	\$1000	6.3x15x12 in	North Carolina
	FLIR Tau 640X480	0.15 lbs.	\$10,000	1.8x1.8x1.2 in	North Carolina
	FLIR Vue Pro	0.25 lbs.	\$3850	2.26x1.75 in	Michigan
	FLIR Vue Pro R	0.25 lbs.	\$4850	2.26x1.75 in	Michigan
	FLIR Duo	0.9 lbs.	\$7000	1.6x2.3x1.2 in	Michigan
LiDAR	Velodyne LiDAR Puck-16 (VLP-16)	1.9 lbs.	\$4000	4 in Diameter 2.8 in Height	Michigan
	Velodyne HDL-32E	2.9 lbs.	>\$4000	3.4 in Diameter 5.7 in Height	Florida Tech
Software	Agisoft Photoscan Pro	N/A	\$3500	N/A	Michigan & North Carolina
	ESRI ArcGIS	N/A	\$3500/yr.	N/A	Michigan

4.2 State DOT Motivation for Usage of UAVs for Bridge Inspections

Much like the first literature review, there is a common conclusion that can be made taken from the reports above. That conclusion is that states want to use of UAVs for a bridge inspection and begin to implement them as soon as possible. That conclusion was reached because UAVs and their respective attachments are able to capture what a bridge inspector can, but much quicker, much safer, and at a much lower cost.

Chapter 5

UAV USAGE FOR CORROSION ESTIMATION

5.1 Background Information

Among the many aspects of structural deficiency, corrosion is considered a common cause for the deterioration of aging bridges. The environmental effects, the exposure of the material, the steel type, the surface protection, and the bridge design are some of the parameters that significantly affect the rate of corrosion. This means that any steel surface along a bridge, from areas between the concrete deck and the steel stringers on stringer span, to the cable system of cable suspension bridges, to even the girder splices in deck girder bridges, can be subjected to corrosion action (Figure 5.2). Figures 5.1, 5.2, and 5.3 show a range of bridge conditions, deterioration levels, and corrosion amounts that have been seen by inspectors.

Figure 5.1: Example of an Aging Bridges in Good Condition with Slight Corrosion

Figure 5.2: Example of an Aging Bridges in a Deteriorated Condition with More Corrosion

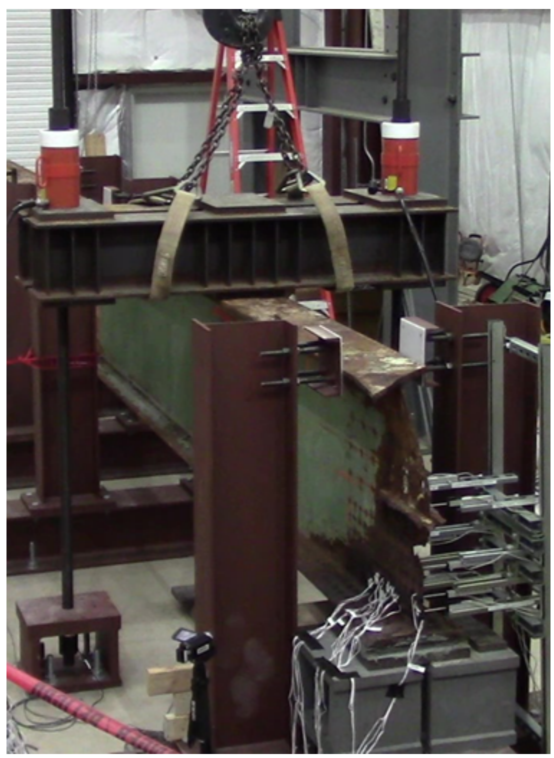


Figure 5.3: Example of an Aging Bridges in a Very Deteriorated Condition with a lot of Corrosion

This research focuses on techniques for corrosion detection and estimation for steel girder bridges which is very common in the state of Massachusetts. Section loss due to corrosion is observed at the boundaries between the web and the concrete diaphragms or along the bottom flange where the steel is repeatedly splashed with water from the roadway below. However, the locations that are most vulnerable to corrosion are the beam ends.

This research focuses on techniques for corrosion detection and estimation for steel girder bridges, which are very common in the state of Massachusetts. Section loss due to corrosion is a well-known phenomenon, commonly found at the boundaries between the web and the concrete diaphragms or along the bottom flange, where the steel is repeatedly splashed with water from the roadway below. However, special attention must be given to beam ends since their location makes them the most vulnerable to corrosion.

Aging bridges are prone to malfunctioning expansion deck joints, mainly because these components are periodically subjected to impact loads by passing vehicles, as well as to environmental factors. These conditions induce damage allowing leaking water to penetrate into the bridge superstructure, triggering corrosion along the girders. Typical bridge designs contain expansion joints located above the girder supports. Consequently, deterioration at those locations can dramatically reduce the bearing capacity of the beams, highlighting the need for effective and periodic inspection of these elements.

Nowadays, thickness gauges are commonly employed by bridge inspectors to measure the remaining material throughout the deteriorated areas. Inspectors must address accessibility difficulties and troubled instrument readings to provide single point measurements. In addition, in order to operate the gauges, inspectors have to previously remove rust and paint locally, making use of a hammer.

The deterioration phenomenon is topologically non-uniform and highly uncertain. Unavoidably, because this type of documentation is rarely combined with a plethora of measurements, the actual member's condition is usually not reflected. Research conducted at the University of Massachusetts Amherst [35] explored the remaining capacity of steel beams with corroded beam ends. In the framework of this work, field corroded girders, obtained from bridge deconstruction projects, were experimentally tested and evaluated. Before testing, detailed thickness measurements were obtained employing a thickness gauge. In contrast to the plethora of measurements illustrated in Figure 5.2, usually no more than two or three measurements are documented in the inspection reports.

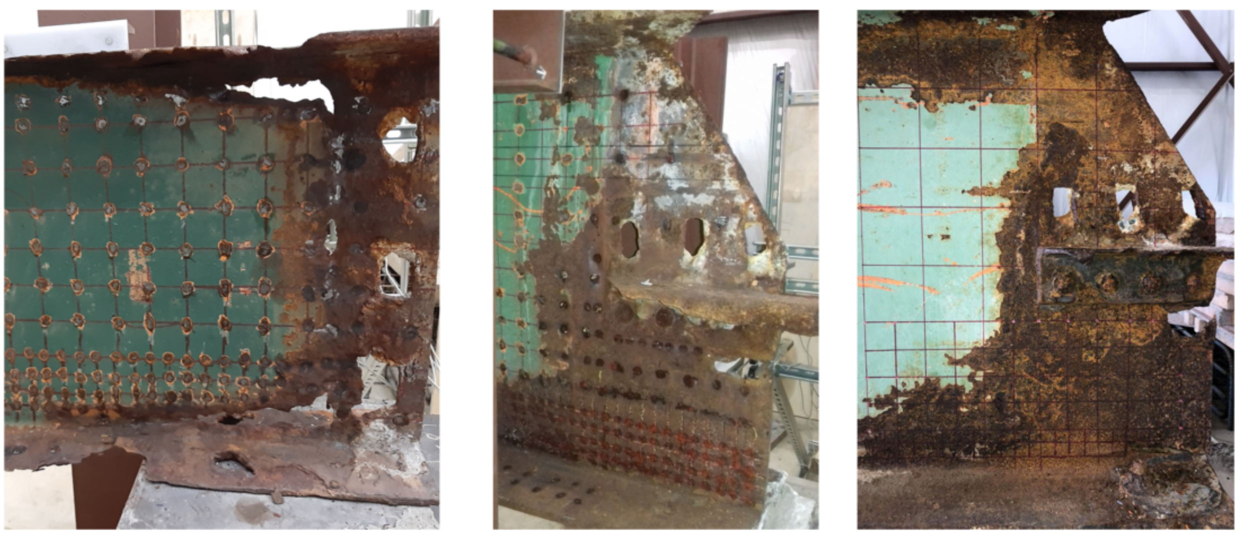


Figure 5.4: Corroded Girder Ends Extracted from Decommissioned Bridges. Points Along the Grids Indicate Locations where Paint has been Removed in Order to Obtain Thickness Measurements [52].

After reviewing the work that different researchers have put out detailing how they have used drones, it is clear that MassDOT could utilize drones for various transportation activities, specifically bridge inspections. The purpose of this research is not only to prove drones can improve MassDOTs general activities and inspections, but also determine if and how they can better estimate corrosion of beams and beam ends using available technology and UAVs. To conduct this part of the research, papers about corrosion and corrosion technology embedded on drones were selected to analyze the potential of their use. Although these technologies may not be ready for use immediately, they should be considered for use in the future as technology improves, and inspection needs change.

In general the reports that were collected for the corrosion estimation portion of this research project can be separated into two categories of Non-Destructive Testing (NDT) Methods. Non-Destructive Testing (NDT) Methods are testing techniques that analyze a material, element, or structure without damaging the component under test. The two categories that the reports have been split into are Contact (C-NDT) and Non-Contact (NC-NDT) NDT Methods. Contact NDT methods consist of pressing a probe or instrument directly to the bridge element itself. In this case, the drone will carry the instrument/probe and hold it against the corroded area. This experiment outputs the thickness of the corroded area directly under the contact point. On the other hand, Non-Contact NDT methods do not require any instrument to be pressed against the bridge element. Instead, these methods require the drone to hover at a certain distance from the corroded area aiming to read the thickness of the area.

5.2 Contact Non-Destructive Testing Methods

There are three main Contact Non-Destructive Testing methods that have been proposed to measure the thickness of a corroded area. The first is through the use of eddy currents which use electromagnetic induction to capture flaws by measuring changes in flow or magnitude of the current. There is a research study detailing how researchers built their own eddy current probe to detect and measure corrosion of steel rebar embedded in concrete [53]. It is worth noting that this equipment has not been employed yet to measure section loss along steel girders, whether as part of a drone or not. However, recent progress in the field has resulted in the creation of an ultra-light and compact tester that could potentially be combined with UAV technology. According to the published specifications, the probes included with the tester can be used for crack detection, weld inspection, metal sorting, material properties, coating thickness assessment, and corrosion detection [54]. Therefore, using eddy currents is very promising for the purpose of detecting and measuring corrosion of steel girders.

The second contact method that has been researched is the Impedance-Based Non-Destructive Testing Method, which uses vibrations to identify and measure damage. The researchers tested the accuracy of a piezometer and the ability to use it on a drone [55]. The piezometer measures electrical admittance and converts that to an impedance value. In the same research work, the authors tested the piezometers ability to measure progressive damage and thickness loss of a material. Both tests proved the usefulness of piezometers and impedance testing to detect and quantify corrosion [55]. It is also proposed to attach the piezometer to a magnet and then having a drone fly up and stick it to the corroded area [56]. The readings would then be transmitted to a laptop to be recorded for post-processing. The piezometers or nodes similar to it can also be placed there permanently to record readings over time, as proposed by [56]. Both papers support the fact that impedance testing can measure thickness losses due to corrosion and be strapped to a drone to measure that loss during a bridge inspection [55, 56].

Ultrasonic testing is the last contact NDT testing method that can be used for corrosion estimation. Ultrasonic testing is when a probe sends an ultrasound pulse through a material and uses the returning echo to determine the material's thickness [57]. Researchers in the R&D Department at Amerapex Corporation in Houston, Texas, created a testing rig by attaching two electromagnets to an ultrasonic probe, similar to the tritex Multigauge 6000 Drone Thickness Gauge. Subsequently, this rig was attached to an arm that extended from the drone that was employed [57]. The drone was then driven up to a metal storage tank and held the probe up to the side so that the electromagnets could stick to the metal and the probe could get a reading. They took many readings around the tank, with each reading taking about 3-5 seconds, and found that the drone/probe combo was successful in reading the thickness of the metal walls of the tank [57]. Overall this shows the great promise in using ultrasonic testing technology on drones to measure corrosion. All three contact NDT methods have proved to be promising for use in detection and measurement of corrosion, and with more research they could be used on drones for bridge inspections in the near future.

5.3 Non-Contact Non-Destructive Testing Methods

In addition to the Contact NDT Methods, there are three main Non-Contact NDT methods that have been proposed to be used for corrosion detection and measurement. All three methods are spectroscopic, which means that they observe how electromagnetic radiation interacts with the corroded area in order to determine and measure the corrosion of metal. The first spectroscopic method involves using Microwave Signals in order to detect corrosion in steel rebars that are embedded in cement and steel corrosion under paint [58, 59]. Using microwave technology for both purposes would be helpful for both steel beam end corrosion estimation, as well as doing general inspections on other steel elements of a bridge. After making several samples, researchers used microwave 3D imaging to capture images that could be used to make observations about the embedded steel rebar and the steel specimens. The resulting images led researchers in both studies to conclude that using Microwave 3D imaging is a promising non-contact NDT method for corrosion detection, but there is a lot of research that needs to be done to fully utilize this technology for this purpose [58, 59].

The second spectroscopic method is Terahertz (THz) Radiation, utilized to detect corrosion under paint [60]. Produced by Picometrix, Inc., the THz system used for this experiment sends the THz frequency from the transmitter through a focusing lens and then the receiver picks up the THz response amplitude from each scan point. Those points are plotted on a graph and on an image in order to determine paint layer thickness, surface roughness, and ultimately corrosion. After conducting experiments on several corroded pieces of metal, thicker paint and a rougher surface indicated corrosion of the metal. From the results of the experiments, researchers also concluded that using Terahertz Radiation and Imagery is a promising method to detect corrosion, but more research needs to be conducted in order to use this method in the field [60].

The last non-contact spectroscopic method that has been researched for use in corrosion detection is Infrared (IR) Thermography. Passive Infrared Thermography uses infrared cameras to capture the IR admitted from a material and compares them with the IR radiation from its surroundings. Active Infrared Thermography, which is more commonly used for NDT, uses an external stimulus, such as lasers or lights to heat up a material in order to achieve a temperature gradient. Pulse thermography is the most common of the active thermography methods and it utilizes flash lamps and infrared cameras to observe where the heat accumulates, which indicates a defect.

Two research efforts that utilize this technology to detect and measure corrosion [61, 62]. The first is a study where they utilize pulse thermography to determine if they can detect blisters and filiform corrosion. These researchers captured IR images of carbon steel and magnesium specimens with these defects and used them to measure the height and area of both types of corrosion [61]. The second study was done at the University of Firenze in Firenze, Italy. These researchers utilized pulse thermography to map corrosion of two aluminum plates; one plate was machined on one side to simulate corrosion. Heat was applied to one side of both plates and IR images were captured on the other side at a set interval. After performing extensive data analysis, researchers were able to map the corrosion pretty accurately, but they would like to try mapping it in 3D in the future [62]. Both studies concluded that Infrared Thermography is a promising method of corrosion detection, measurement, and mapping, but more research needs to be done to perfect this method for use in the field.

All three non-contact NDT methods proved to be promising for detecting and measuring corrosion, but all of them are far from being ready to use in the field in the near future. Also, the equipment being used is too large and heavy to be attached to a drone. Perhaps as technology improves and these spectroscopic methods are perfected, they can be used on drones for bridge inspections in the future.

Overall, the researchers of each of the six NDT methods found that they were able to detect and measure corrosion of metal surfaces to some extent. The technology for the contact methods are more available, ready to use, and small enough to be attached to a drone, which means that the contact methods have the potential to be utilized for drone bridge inspections in the near future (Table 5.1). The non-contact methods, however, need a lot more research in order to be ready to use in the field, as they need to be small and light enough to fit on a drone. Therefore the non-contact methods could not be used for drone bridge inspections in the near future, but the promising results from these methods should not be ignored for there is great potential for their use in corrosion monitoring (Table 5.1). For both C-NDT and NC-NDT it is important to note that weather could greatly affect the thickness readings obtained, especially wind. Wind tends to make drones unstable and susceptible to movement that the pilot did not intend, and this unintended movement can cause inaccuracies in the thickness readings for all of the methods mentioned. This is a big disadvantage that must be considered when deploying this advanced technology on a drone for the purpose of corrosion estimation.

Table 5.1: Methods for Corrosion Assessment

	Method	Use	Equipment	Advantages	Disadvantages
	Current	Steel bridges	Thickness Gauge Hammer	Low-cost equipment	Single point measurement Accessibility Required labor
C - NDT	Eddy Current	Steel Bridges	Thickness Gauge Hammer	Low Cost Light Weight	Single point measurement Accessibility Required labor
C - NDT	Impedance-Based	Steel Bridges	Piezometer Magnet	Small Low Cost	Single point measurement Accessibility Hard to Attach & Detach
C - NDT	Ultrasonic	Steel Bridges	Ultrasonic Probe Electromagnets	Small Low Cost Easy to Use Excludes Paint Layer	Single point measurement Accessibility Required labor
NC - NDT	Microwave	Steel Rebar	Vector Network Analyzer Open-Ended Waveguide Probe	Large Scan Penetrates through Concrete No Contact Needed	High Cost Large Set-Up Heavy Equipment Required Labor
NC - NDT	Terahertz	Metal	Transmitter Receiver Beam Splitter Focusing Lens	Large Scan No Contact Needed Detect Corrosion Under Paint	High Cost Large Set-Up Heavy Equipment Required Labor
NC - NDT	Infrared Thermography	Metal	Infrared Camera Flash Lamp(s)	Large Scan No Contact Needed Blistering and Filiform Corrosion Can be Measured	High Cost Large Set-Up Heavy Equipment Required Labor

Chapter 6

SUMMARY AND CONCLUSIONS

This thesis presents the responses from a questionnaire, a review of the use of Unmanned Aerial Vehicles (UAV) for general transportation activities, a review of the use of UAV for bridge inspections, and a review of methods for the detection and estimation of corrosion along steel girders.

The questionnaire was sent out to the individuals that participate in MassDOT bridge inspections in order to gather and summarize information on the general inspection practices, corrosion assessment practices, and the equipment used for bridge inspections. Based on the responses from the questionnaire, the following conclusions were made:

- There are many improvements that can be made regarding the bridge inspection procedure, corrosion assessment methods, and equipment.
- There is a consistency issue amongst inspectors that should be addressed in any new procedure, corrosion or otherwise, in order to ensure that the condition of all bridges is thoroughly assessed and monitored over time to prevent any catastrophic structural failures in the future.
- Inspector struggle with accessibility and visibility of corroded areas due to the bridge configuration and equipment limitations. This means that inspectors are not always able to remove the rust and delamination, and they may not be able to measure all the points necessary to get an accurate representation of the corroded area.

- Inspectors often cannot get accurate measurements due to tool limitations, particularly when measuring in harsh weather and/or measuring on uneven surfaces.
- Documentation becomes time consuming as the bridge ages since older bridges are typically more corroded, which means more measurements need to be taken, documented, and analyzed for them.
- Any increase in documentation time can lead to added stress for the inspector given the amount bridges there are to inspect in the state of Massachusetts.
- A new method of corrosion assessment must:
  - Be able to Easily access most areas of a bridge girder
  - Accurately measure the thickness of steel
  - Be safe and easy to use
  - Be reliable in most field conditions
  - Not take too much time to use in the field
  - Not take a lot of post-processing
- Laser scanning, or LiDAR, and UAVs are known by some inspectors and are advanced technologies that can be used to estimate corrosion
- Further research should be done on using Unmanned Aerial Vehicles for the inspection and corrosion assessment of steel bridge girders because….
  - UAVs can help address and correct the challenges that inspectors are experiencing.
  - The additional technology add-ons can be added to UAVs, including LiDAR, in order to measure and assess steel beam end corrosion.

To properly research the viability of using UAVs for MassDOT bridge inspections, a two-part literature review was done. The literature presented in Chapters 3 and 4 of this thesis identified the transportation activities, detection possibilities, drone types, drone attachments, and common conclusions that have been researched and presented by the many state DOT and University papers that were analyzed. This review led to the following conclusions:

- UAVs are a technologically advanced tool that can cut costs for DOTs by helping DOT employees quickly and safely carry out daily transportation activities.
- State DOTs want to start using UAVs for a number of different transportation activities, which are presented in Table 3.1.
- UAVs and their respective attachments are able to capture what a bridge inspector can, but much quicker, much safer, and at a much lower cost.
- A proper procedure and training program is needed to successfully implement drones.
- Manual mode with sensor assistance and the waypoint-assistance mode are the best flight modes.
- The weather condition that has the biggest effect on drone performance is wind.
- States want to start using UAVs for bridge inspections as soon as possible.
- There are many different outputs, uses, detection possibilities, drones, and drone equipment that are mentioned in the literature, all of which are presented in Tables 4.1, 4.2, 4.3, and 4.4.

The third and final round of literature review was focused on several Non-Destructive Testing techniques that can be used to detect and measure corrosion. The conclusions from that review are as follows:

- Each of the six NDT methods were able to detect and measure corrosion of metal surfaces to some extent.
- The technology for the contact NDT methods is more available, ready to use, and small enough to be attached to a drone.
- C-NDT methods have the potential to be utilized for drone bridge inspections in the near future.
- Skilled pilots would be needed in order to make proper contact with the steel bridge girders.
- Non-contact NDT methods need a lot more research in order to be ready to use in the field.
- NC-NDT technology needs to be made small and light enough to fit on a drone.
- NC-NDT methods could not be used for drone bridge inspections in the near future, but the promising results from these methods should not be ignored for there is great potential for their use in corrosion monitoring
- Non-contact technology won’t need as skilled of a pilot since they don’t need to touch the girders and will be able to capture a larger area.
- For both C-NDT and NC-NDT, weather could greatly affect the thickness readings obtained, especially wind. Wind tends to make drones unstable and susceptible to movements that can cause inaccuracies in the thickness readings.

- The methods, uses, equipment, advantages and disadvantages for C-NDT and NC-NDT are summarized in Table 5.1

Overall, drones and their respective attachments are promising technologies to use for bridge inspections and the estimation of corrosion of a steel bridge girder. There is more research and testing that needs to be done before drones can be implemented regularly for this purpose, but the cost savings and safety improvements that come with the use of drones should be enough to encourage more research on this viable topic.

CHAPTER 7

RECOMMENDATIONS AND FUTURE WORK

7.1 Recommendations

Based on the research conducted there are several recommendations that can be made. The main recommendation is that the Massachusetts Department of Transportation should use the Unmanned Aerial Vehicles for bridge inspections because they are safer, cost effective, and able to collect valuable data that can be used to monitor the condition of bridges over time. UAVs should also be used for bridge inspections because when properly equipped they can effectively measure corrosion of steel bridge girders. In the near future, to measure bridge girder corrosion, it is recommended that Ultrasonic Technology (UT) be utilized because it has been most effective at measuring steel thickness, there is a special UT probe made for drones that is currently available, and that drone-probe combo has been successfully tested in the field.

To safely implement this corrosion estimation technology it is recommended that MassDOT creates a standardized procedure to ensure the safe and effective use of drones by bridge inspectors. Because wind it the biggest factor the affects drone performance, it is advised that the drones not be operated in high winds. The proper wind speed thresholds should be determined by referring to the manufacturers guidelines. It is recommended that the DOT set up a training program to train inspectors on how to use the UAVs properly. In terms of equipment for proper implementations of drones, it is recommended that the DOT purchase several DJI drones that can handle the payload of the UT probe since DJI drones are less costly, are easy to control, and can handle wind. A manual flight mode with sensor assistance and a waypoint-assistance flight mode should be utilized. The proper software, such as Agisoft Photoscan, should also be installed on inspectors computers in order to properly post-process the data and document it in an inspection report in a reasonable time and effective manner. Along with the software, a data storage network needs to be set up in order to store the large files that are outputted by the drone.

Although UT drone technology is effective, it is also recommended that work continue on the three non-contact methods of measuring corrosion because with the right technology they will be able to capture a larger corroded area in less time, and a less skilled pilot will be able to take these measurements.

7.2 Future Work

Future work on deteriorated bridges alone would include analyzing the system behavior of deteriorated bridges and stability considerations as well as load distributions would be significant. In terms of drone, future work would be done to decide on which drone would best suit the needs of the MassDOT. This work would include conducting an actual bridge inspection with a drone and comparing those results to the results of a bridge inspection conducted using the current inspection methods.

For drone technology, future work would include the field testing of the different technology in order to determine the proper equipment and settings to detect certain bridge defects, such as delamination, cracking, and fatigue. Future work should also be done for the corrosion technology presented in this paper. For contact NDT methods the work would include attaching the eddy current, impedance, and ultrasonic technologies to a drone and estimating the corrosion of an actual steel bridge girder. The results would allow for a better determination of which contact NDT method can properly estimate corrosion for the purposes of assessing a condition of a bridge. For non-contact NDT methods work would include extensive work on perfecting microwave, terahertz, and infrared thermography technology to work in laboratory settings. Once those are developed, work would begin on making that technology small enough to work on a drone so the technology can be tested for use on a drone for the estimation of corrosion on a steel bridge girder during a bridge inspector.

Finally, future work on this topic could include constructing a drone that includes everything that the MassDOT needs, such as thermal cameras, a zoom lens, and corrosion estimation technology, and testing that drone in an actual bridge inspection. This work would be expensive and time consuming, but it would create an all-in-one drone that meet all, if not most, of the MassDOT's needs.

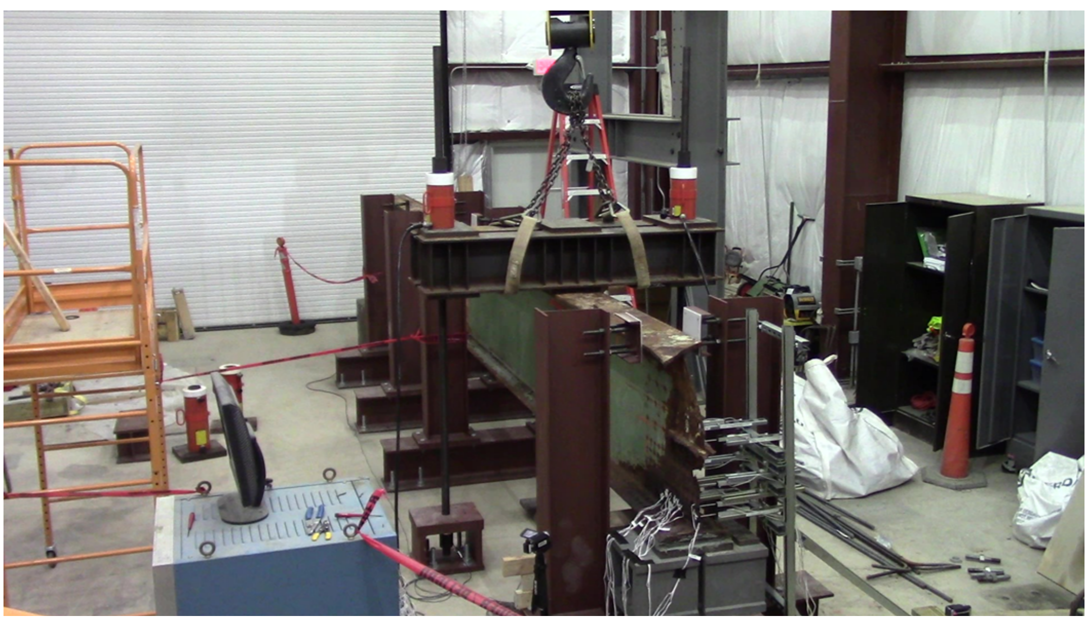
APPENDIX A

Questionnaire for the Development of MassDOT Inspection Procedures for Corroded Steel Beam Ends

Ongoing research at UMass Amherst is studying the corrosion and deterioration of steel beam ends. We are currently looking into developing and improving the MassDOT inspection procedures for corroded steel beam ends.

This questionnaire will help us collect important information about the current state of MassDOT inspection procedures. This is an opportunity for inspectors and engineers to tell us what is and what is not working in regard to how bridges are inspected for steel beam end corrosion.

Your answers will be kept confidential and only be used for the purposes of the research. We are not going to send you an abundance of emails after you fill this form out. We may contact you at a later date if we need more elaboration on certain questions. This questionnaire should take about 15-20 minutes.



The Brack Lab at UMass Amherst: Setup for Tests Conducted on Corroded Steel Bridge Beams Taken from Decommissioned Bridges in Massachusetts.

General Bridge Inspection Practices
The purpose of this section is to get an overall understanding of the current bridge inspections practices. This will help us understand what aspects of the current MassDOT procedures are and are not working, so that we may develop an improved inspection procedure.

When answering these questions, consider you overall MassDOT bridge inspection experience. If you do not have an answer, you may skip the question.

1. What is your name and email address?
2. What is your current position?
3. What district do you work for?
4. How many bridges are you responsible for?
5. How many bridges do you inspect per week?
6. What training procedure did you follow to become a bridge inspector?
7. Prior to preforming a bridge inspection, do you have any of the following materials? (you may choose more than 1)
    a. Drawing
    b. Plans
    c. Previous Reports
    d. Other:_________________
8. What aspect(s) of inspections slow you down the most?
9. Is there any part of the 2015 MassDOT inspection handbook that is hard to implement?

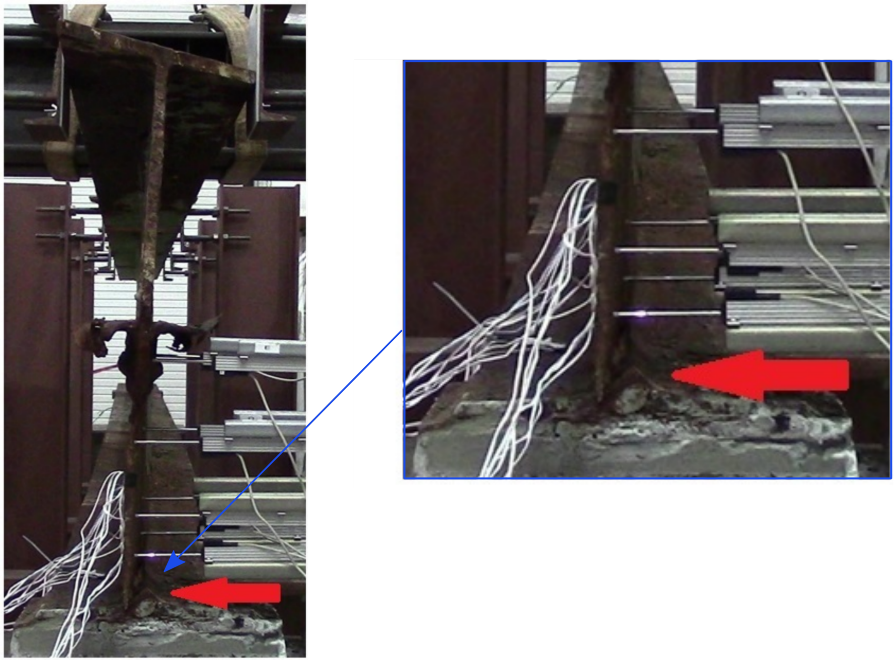
Corrosion Assessment
The purpose of this section is to get an understanding of how corrosion of steel bridge beam ends is being assessed during bridge inspections. This will help us understand what aspects of the current MassDOT procedures are and are not working, and how to best develop the procedures for the assessment of corroded steel beam ends.

When completing this section of the survey, please only refer to your knowledge and experience with steel bridge corrosion. If you do not have an answer, you may skip the question.

**Some multiple-choice questions have an "other" option where you can add comments if needed.

1. What challenges do you face with assessing corrosion?
2. What technologies have you used for bridge inspections? (you may choose more than 1)
    a. Visual
    b. D-Meter
    c. Advanced Technologies
    d. Other:____________
3. If you selected Advanced Technologies, List those technologies.

4. Have you ever witnessed the upper edge of a web hole bearing on the flange?

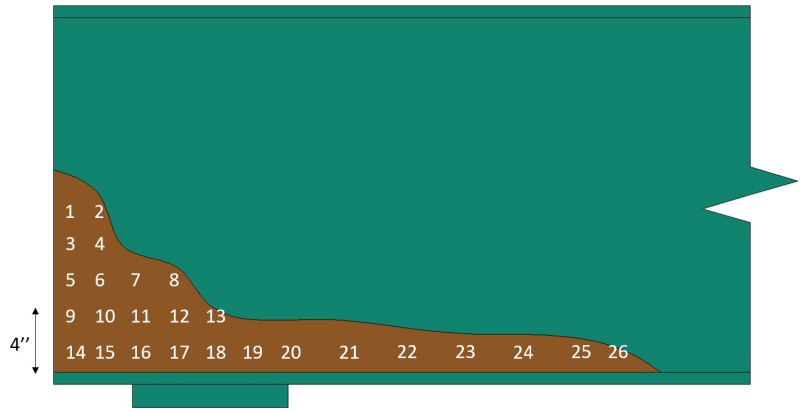


The arrow in the picture above is pointing to an example of the upper edge of a web hole bearing on the flange.

    a. Yes for a stiffened beam
    b. Yes for an unstiffened beam
    c. Yes for both a stiffened and unstiffened beam
    d. No
    e. Other:____________________________

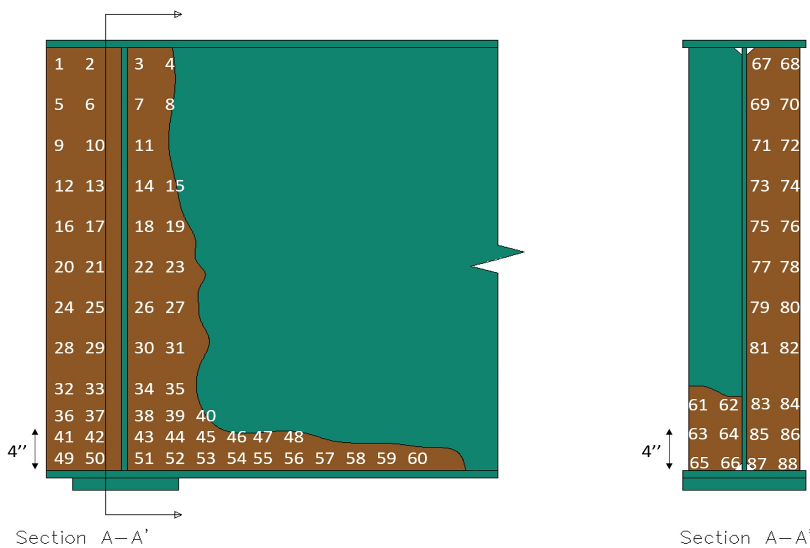
5. Do you measure web thickness using a D-Meter?
    a. Yes
    b. No
6. If you answered yes, what D-Meter model(s) do you use?
7. If you answered yes, how accurate are the measurements of the D-Meter you use?
    a. Very Accurate
    b. Moderately Accurate
    c. Not at all Accurate
    d. Other:___________
8. If you answered no, what technology do you use to measure web thickness?
9. What other technology could be used to measure web thickness?

10. At which points would you take thickness measurements for an Unstiffened Bridge Beam?



Please list the number(s) shown in the image above that correspond to the points at which you would take measurements for both web and stiffeners

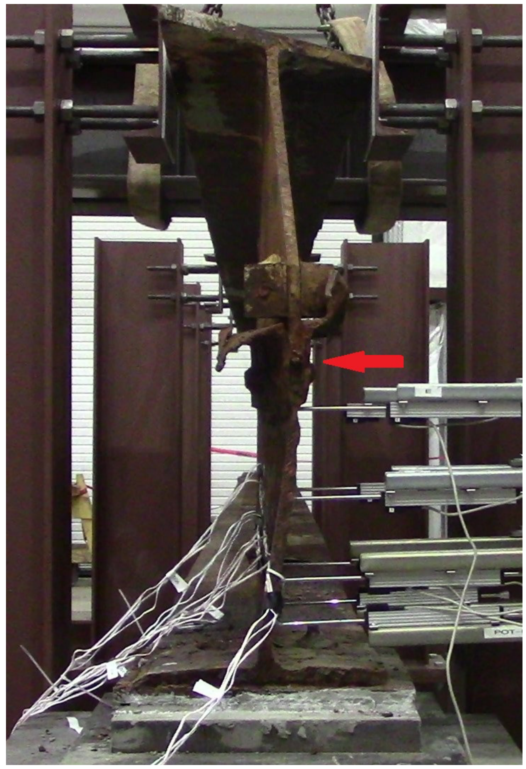
11. Are there any additional places where you would take measurements from that are not shown in the sketch?
12. At which points would you take thickness measurements for a Stiffened Bridge Beam?



Please list the number(s) shown in the image above that correspond to the points at which you would take measurements for both web and stiffeners

13. Are there any additional places where you would take measurements from that are not shown in the sketch?
14. How many points do you typically measure?
15. How do you choose where to take thickness measurements?
16. Do you normally take thickness measurements of corroded stiffeners?
    a. Yes
    b. No

17. Have you every witness beam webs that deviate from straightness?



The image above shows an example of a web deviating from straightness

a. Yes for a stiffened beam
b. Yes for an unstiffened beam
c. Yes for both a stiffened and unstiffened beam
d. No
e. Other:____________________________

18. Do you measure web deviation from straightness?
a. Yes
b. No

19. If you answered yes, What do you use to measure web deviation from straightness?

20. If you answered yes, How accurate are the measurements you take for web deviation from straightness?
a. Very Accurate
b. Moderately Accurate
c. Not at all Accurate
d. Other:________________

21. What other technology can be used to measure web deviation from straightness?

Equipment

The purpose of this section is to get an understanding of the equipment being used for bridge inspections. This will help us understand what is available for inspections to better inform our decisions regarding inspection protocol.

When completing this section of the survey, please only refer to your knowledge and experience of the technology utilized for bridge inspections. If you do not have an answer, you may skip the question.

1. What equipment do you typically have on hand during an inspection? (Please provide the advantages and disadvantages for each)
2. Are gauges calibrated periodically? If so, how often?
3. What would you change about the equipment you use?
4. Would you be able to carry a portable laser scanner like the one below, and potentially a tablet or a cell phone?

    a. Yes
    b. No
    c. Maybe
5. Is it Possible to remove delamination along the domain above the support?
    a. Yes
    b. No
    c. Maybe
6. If not, why?
7. How much time do you currently spend on documenting the collect data into a routine inspection report?
    a. None
    b. 1-2 hours
    c. 3-4 hours

    d. 5-6 hours
    e. Other:________
8. Do you spend additional time for measurements and documentation for a bridge that a new load rating may be required?
9. Have you ever used a drone or witnessed a drone being used for any MassDOT related activities?
    a. Yes
    b. No
10. If so, What was that activity?
11. Have you ever considered using drones for bridge inspections?
    a. Yes
    b. No, but I think they could be useful to implement in the future
    c. No and I do not think they would be useful to implement in the future
12. Any additional comments and/or suggestions that we should know

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