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ENHANCED VISUAL BRIDGE INSPECTION PRACTICES FOR AN IMPROVED BRIDGE MANAGEMENT SYSTEM

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ENHANCED VISUAL BRIDGE INSPECTION PRACTICES FOR AN IMPROVED BRIDGE MANAGEMENT SYSTEM

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ABSTRACT

The bridge infrastructure in the United States, and particularly in Rhode Island, has deteriorated over the last decades. The state of Rhode Island is placed last in the United States' bridge condition ranking. To counteract the steady deterioration, it is necessary to have an overview of the current bridge conditions by implementing a Bridge Management System. Bridge inspections are the first entity in an effective Bridge Management System since they assess the bridge condition on site.

This thesis investigates two technologies that are promising to enhance and digitize the bridge inspection processes. Augmented Reality (AR) and Building Information Modeling (BIM) are techniques that have gained interest in the architecture and construction industries in the last decade.

Before analyzing the state-of-the-art bridge inspection processes, first a comprehensive literature review about the current bridge inspection methods and condition rating in the United States is conducted. Then, the two technologies, AR, and BIM, are exemplified and analyzed regarding their feasibility for bridge inspection purposes.

Next, a Bridge Information Data Model (BIDM) is developed. It is a 3D-database for storing and accessing inspection data on an element level, which follows BIM principles. Bridge elements can be addressed separately allowing the review of inspection history and the linkage of new defects.

Testing the applicability of the developed BIDM, a case study is conducted. It is found that the main capabilities of the BIDM are the enhanced comprehension of the bridge structure, since it displays the bridge as a 3D digital twin, the enhanced traceability of

location and inspection history of specific defects and elements, and the ability to enhance collaboration of bridge stakeholders.

Within the framework of the BIDM, the accuracy of AR-supported measurements is investigated. To prove the accuracy, AR-measurements are aligned with conventional measure tools used for bridge inspections. The performed case study is comprised of 141 measurement data pairs of which 88.65 % deviate less or equal to 0.5 inch, which is inside the deviation range for inspecting concrete structures. It can be stated that AR-supported measurements are as accurate as analog measurements. Therefore, they are applicable for inspecting concrete bridges.

The interaction of both techniques investigated in this thesis enhances the visual bridge inspection. It is proven that the human-centered approach is simply applicable to current inspection procedures.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
3D	Three-Dimensional
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AI	Artificial Intelligence
AM	Ante Meridiam
AR	Augmented Reality
BIDM	Bridge Information Data Model
BIM	Building Information Modeling
BIRM	Bridge Inspectors Reference Manual
BMS	Bridge Management System
$CaCO_3$	Calcium Carbonate
$CaOH_2$	Carbon Hydroxide
CO_2	Carbon Dioxide
Cm	Centimeter [Distance Unit]
CS	Condition State
DOT	Department of Transportation
Ea.	Each [Counting Unit]
E.g.	Example Given
FHWA	Federal Highway Administration
Ft	Feet [Distance Unit]
Ft^2	Square-Feet [Area Unit]
Ft^3	Cubic-Feet [Volume Unit]
GPS	Global Positioning System
H_2O	Water
IFC	Industry Foundation Class
IM	Information Modeling
In	Inch [Distance Unit]

ISO	International Standard Organization
LTBP	Long Term Bridge Performance Program
MAP-21	Moving Ahead for Progress in the 21. Century Act
MBE	Manual for Bridge Evaluation
MBEI	Manual for Bridge Element Inspection
MR	Mixed Reality
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NDT	Non-Destructive-Testing Methods
NHS	National Highway System
O_2	Oxygen
RIDOT	Rhode Island Department of Transportation
SHM	Structural Health Monitoring
TAMP	Transportation Asset Management Plan
UAV	Unmanned Aerial Vehicle
US	United States
USA	United States of America
VI	Visual Inspection
VT	Virtual Tour

CHAPTER 1 - INTRODUCTION

1.1 MOTIVATION

The United States' economy strongly relies on its public road and highway infrastructure. Passenger travel by car (FHWA, 2018) and freight transportation by truck (U.S. DOT, 2019) take the highest shares of transportation modes. The economic wealth and growth depend on functionality and reliability of this infrastructure. Along the United States' road and highway network, 617,084 bridges are listed currently in the National Bridge Inventory (NBI), but only 45 % are rated as being in good condition (FHWA, 2020).

Rhode Island's infrastructure condition is even more severe since only 18 % of the 779 bridges listed in the NBI are classified as being in good condition (FHWA, 2020). Structurally deficient bridges can result in deadly collapses. Hence, accurate condition monitoring over time must be ensured. The Rhode Island Department of Transportation (RIDOT) has the vision to reduce the percentage of poor condition rated bridges from currently 22 % (FHWA, 2020) to less than 10 % by 2025 (RIDOT, 2019b). Complying with this goal, on the one hand, requires investments in maintenance and rehabilitation while, on the other hand, preservative actions and tracking of conditions are important to create lasting effects. The process of condition monitoring is comprised of the inventory of each bridge condition and routine inspections to trace deterioration over time. Condition data must be quantifiable, reliable, and traceable to contribute requirements of stated RIDOT goals.

To ensure future efficient inspection procedures using state-of-the-art technologies, this thesis analyzes quantitatively the accuracy of Augmented Reality (AR) supported defect measurements and qualitatively the application of a

Bridge Information Data Model (BIDM) that adopts Building Information Modeling (BIM) approaches and serves as a central database with 3D-structure. The 3D-structure displays a digital twin of the real bridge environment, which promises enhancements of site orientation and defect traceability.

1.2 GOAL AND OBJECTIVES

Tracking infrastructure condition over time requires appropriate inspection procedures. Therefore, the goal of this thesis is the development and investigation of enhanced procedures for visual bridge inspections. To accomplish the stated thesis goal, the following objectives are required:

First, federal and state bridge inspection guidelines as well as accredited manuals are surveyed to derive current state-of-the-practice procedures for visual bridge inspections.

Second, deficiencies and strengths of visual bridge inspection procedures found in reviewed literature are emphasized.

Third, addressing deficiencies of current visual bridge inspections by developing enhanced procedures, the potential of AR-technology and 3D-databases are analyzed. The software solutions to conduct a case study are introduced and their capabilities emphasized.

Fourth, a case study comprising two bridges is developed to test the suitability and feasibility of selected technologies. For this purpose, 3D-data models are created and linked with previous inspection data. AR-supported and conventional measurements of defects are generated on site to provide data for accuracy analyses. Collected data is linked to the 3D-data model.

Lastly, the generated quantitative data is analyzed regarding accuracy and deviation between AR-supported and conventional measurements. Qualitative findings of implementing the two technologies will be compared to current inspection procedures.

1.3 METHODOLOGY AND STRUCTURE

This section gives insights about the methodology and the structure of this thesis. Necessary steps that fulfill the previously stated thesis objectives are explained and justified to develop a reasonable and comprehensible research approach.

The required background information for current bridge inspection processes is given in Chapter 2 by analyzing the authorized guidelines and manuals for bridges in the United States of America (USA). It is necessary to be aware of the current inspection processes to derive strengths and shortcomings for the development of future enhancements. In addition, the structure of the United States' Bridge Management System (BMS) and its function within the infrastructure asset management is displayed. Understanding the organization and function of BMSs justifies the importance of accurate and data-driven inspection procedures. Then, bridge rating methods and inspection procedures in federal and state guidelines are investigated to provide information about the current state-of-the-art bridge rating procedures. Since it is essential for the executability of and reliability on visual inspections, the perceptibility of defects on the surface of concrete and steel structures is investigated.

Next, based on the derived strengths and shortcomings of visual bridge inspections, an enhanced visual bridge inspection method is developed in Chapter 3. Basic BIM concepts and the data exchange format of the Industry Foundation Classes (IFC) are introduced. AR-technology is exemplified and requirements for its implementation in inspection processes are stated. These technologies define the framework for developed BIDM.

To test the applicability and feasibility of the developed BIDM, a case study comprising two highway bridges is established in Chapter 4. Two 3D-data models are created and inspection data from existing routine inspection reports is linked to the model. Then, two inspections are executed using the BIDM on site. Besides testing the applicability and feasibility of this method for visual bridge inspections, AR-supported measurements are taken and aligned with conventional measures.

Findings of this thesis are stated in Chapter 5 and comprise qualitative and quantitative statements. Analyses regarding the applicability of the BIDM for bridge inspection purposes is conducted qualitatively by comparing experiences and findings from conducted inspections to the processes stated in guidelines and manuals. Statements regarding the accuracy of AR-supported measurements in comparison to conventional measure tools are presented as quantified results.

CHAPTER 2 - LITERATURE REVIEW

This chapter exemplifies bridge inspection processes in context of the BMS and infrastructure management. Federal and state inspection guidelines and manuals are analyzed regarding their function as well as their part within the BMS. Further, state-of-the-practice and state-of-the-art inspection methods are analyzed as well as perceptibility of deterioration on surfaces.

2.1 TRANSPORTATION ASSET MANAGEMENT PLAN

Implementation of Transportation Asset Management Plans (TAMP) is one consequence of the Moving Ahead for Progress in the 21st century (MAP-21) act established in 2012 by the federal government of the United States. MAP 21 § 1106 defines the objective for each state to organize a state asset management plan as risk-based asset-management and performance-based management of their infrastructure. The term "asset management" is defined in MAP 21 § 1103 (a) (3) as "strategic and systematic process of operating, maintaining and improving physical assets, with a focus on both engineering and economic analysis" which minimizes cost over the life cycle and keeps structures in a state of good repair (MAP 21, 2012). Asset management relies on definitions and measurements of performance indicators that are incorporated within federal and state policies and targets (Hurt & Schrock, 2016a).

Since the road and bridge infrastructure in Rhode Island has deteriorated over recent decades and is below the United States (US) average, RIDOT released its latest TAMP in 2019 fulfilling the MAP-21 objectives and defining the goals to, first, manage its assets efficient, and second, to rely on state-of-the-art procedures to preserve Rhode Island's infrastructure (RIDOT, 2019b). Rhode Island's TAMP assists the RhodeWorks

Act, which was signed into law in 2016. This act focuses on creating data-driven decision support for maintenance, preservation, rehabilitation, and replacement of the bridge infrastructure.

Addressing stated goals of MAP-21, the RhodeWorks Act, and Rhode Island's TAMP, one efficient tool to inventory and monitor condition states over a bridge's life cycle is a BMS. Next, structure and functionality of BMSs are exemplified.

2.2 BRIDGE MANAGEMENT SYSTEM

Establishment of BMSs is compulsory for bridges on and off federal-aid highways. Highways are defined as roadways on the National Highway System (NHS). The NHS is designated as the United States' superordinate roadway network and is comprised of the Eisenhower Interstate System, principle arterials, the Strategic Highway Network, major strategic highway network connectors and intermodal connectors (FHWA, 2017a).

Bridges along the NHS are defined as structures spanning an obstruction or depression with more than 20 ft minimum clear widths and carrying a highway or an interchange on one or more levels on top (FHWA, 1995).

BMSs are required as stated by the 23rd Code of Federal Regulations (CFR) § 500.107, which defines minimum procedures for an effective BMS. According to the CFR, BMSs should incorporate the following tasks: (a) Collecting, processing, and updating data; (b) Predicting deterioration; (c) Identifying alternative actions; (d) Predicting costs; (e) Determining optimal policies; (f) Performing short-term and long-term budget forecasting; and (g) Recommending programs and schedules for implementation within policy and budget constraints (*CFR Title 23 - Highways*, 2012).

Incorporated in the 23rd CFR, the Manual for Bridge Evaluation (MBE) of the American Association of State Highway and Transportation Officials (AASHTO) provides guidelines for establishing BMSs. The latest AASHTO MBE defines three main BMS components: (1) Information Management, (2) Data Integration and (3) Decision Support. Their overall purpose is to provide bridge managers or DOTs with accurate information about physical conditions and propose investment plans to one specific asset within the superordinate asset management (AASHTO, 2018).

Appendix A displays the AAHSTO BMS organizational chart. The individual parts are discussed in the following three sections.

Since AASHTO is the leading organization for setting standards and guidelines related to highway and transportation issues in the USA, further paragraphs focus on their manuals particularly.

Ensuring the same serviceability for commercial, private, and public traffic is the purpose of managing bridges and other infrastructural assets. Since bridges are exposed to environmental impacts, daily traffic, and extreme events over their life span, keeping track of the structural condition and necessary maintenance and repair is inevitable. For that reason, the BMS serves as an interdisciplinary tool that is eligible to collect, combine, and analyze data as the considered bridge passes through various phases from development to removal, displayed in Figure 1.

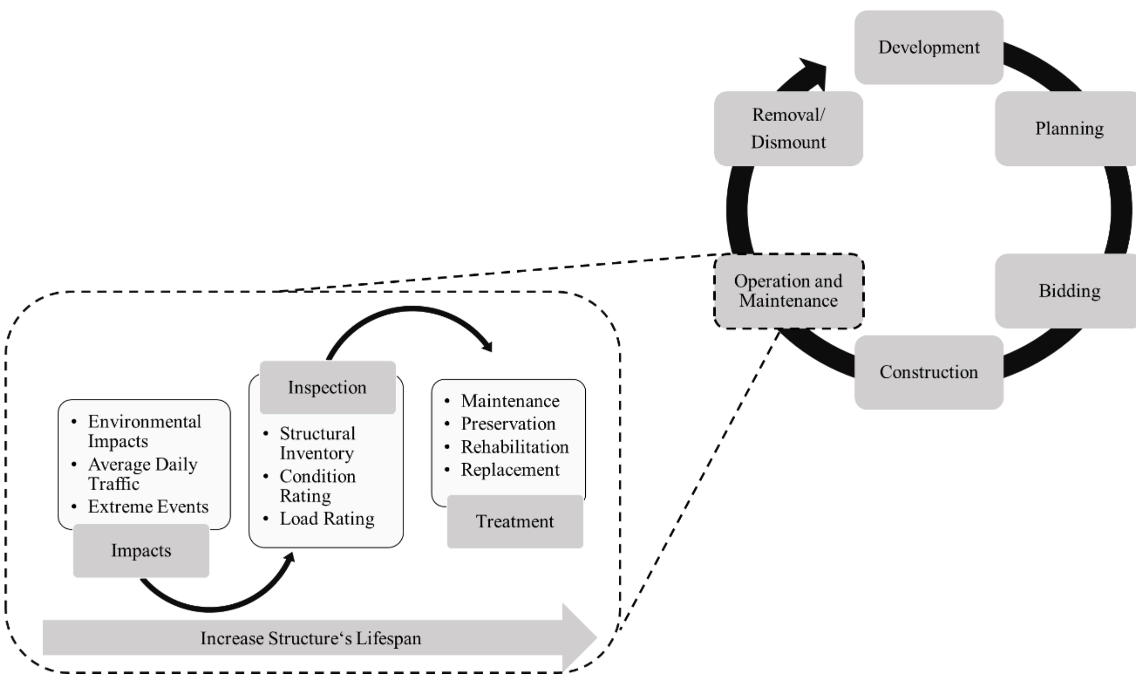


Figure 1: Bridge Life Cycle Phases with magnified O&M Phase. (extended and modified (Chipman, Costin, & Yang, 2016))

The figure above displays the common bridge life cycle. Development of a bridge is the result of a public demand for crossing a waterway or depression. If the planning and bidding process succeeds, next the bridge construction is conducted. The designated purpose of the bridge is serving public, private, and commercial traffic. Hence the Operation and Maintenance (O&M) phase is the most relevant phase. Once the bridge is in service, deterioration sets in. The impacting factors occurring during the O&M phase are separated into environmental impacts, average daily traffic, and extreme events. To detect the deterioration caused by these impacts, regular inspections are required. Depending on the severity of the deterioration, treatments of the bridge structure are required. Treatments span from maintenance of the current condition to replacement of the bridge.

Particularly during the O&M phase, a BMS provides valuable analyses for tracking deterioration and structural decrease. The more valuable data that is assessed over a bridge’s life cycle, the more accurate analyses that can be driven from it. Therefore Section 3.4 discusses the feasibility and usefulness of a BIM concept as a data-handling tool for BMS purposes, and inspection management particularly.

2.2.1 INFORMATION MANAGEMENT

Information management is the core of each BMS since it collects and organizes input data for later decision support (Hurt & Schrock, 2016a). During the O&M phase, the impacts of daily and exceptional scales cause deterioration on bridge structure, which is assessed by periodic scheduled and unscheduled inspections. Impacting factors along the whole life cycle of a bridge causing structural deterioration can be classified into five groups: (1) Basic Factors, (2) Load Factors, (3) Environmental Factors, (4) Maintenance Factors, and (5) Construction Factors (Pipinato, 2016). Physical data assessed during inspections determine bridge condition ratings. Furthermore, the designated treatment must be reasonable related, on the one hand, to the severity of the deterioration and, on the other hand, to the investment into labor or repairs.

Structural condition data assessed by inspections are entered into the BMS and define the technical limits for the decision support. Financial data and performance measurements provide economic and strategic limitations, defined by a state's DOT's policies (AASHTO, 2018). Technical, financial, and strategic restrictions set the scope for the following data integration and decision support.

The most important part for the significance of a BMS is its accuracy of displaying structural conditions assessed in the real environment. Hence, inspection procedures must be as detailed and accurate as possible. Inspection reports provide structural data on a component and more detailed on the element level with either Condition State (CS) ratings or General Condition Ratings. Both condition rating schemes are discussed in Section 2.3. The necessity of reporting element level data to federal agencies is stated in § 1111 of the MAP 21 Act (MAP 21, 2012).

Enforcing documentation of element level bridge inspections will serve the purpose of data-driven and risk-based standards required for asset management, and consequently better BMSs.

2.2.2 DATA INTEGRATION

In the Data Integration process sets the collected data from the Information Management process into relation. The goal of the data integration is to predict the future condition of the asset and to analyze related issues with optimization models. Therefore the following five components provide analyses within the data integration: (1) Data Analysis, (2) Risk Assessment (3) Agency Rules, (4) Cost-Benefit Analysis, and (5) Prioritization and Optimization (AASHTO, 2018). Optimization models are mathematical functions that minimize or maximize one or more arguments of a target function within limiting factors. The target function of a BMS minimizes risk and cost, while providing a continuous level of service (AASHTO, 2018).

Limitation of this target function is structural deterioration over time depending on environmental factors and the Average Daily Traffic (ADT). ADT is defined as the average 24 hour traffic volume at a given location for a defined time period (Roess et al., 2019).

Limiting or controlling environmental impacts is not possible and decreasing daily traffic does not comply with providing continuous and constant service for private and commercial traffic. Hence, deterioration must be slowed with the treatment or maintenance of structural components. Carrying out those actions causes costs, which affects financial limitation. Minimizing cost is part of the target function within a BMS and is limited by financial plans or funding restrictions of the responsible agency, respectively the DOT.

Bridge deterioration models are major prediction tools of a BMS, hence the accuracy of assessed bridge condition data affects the reliability of deterioration models most (AASHTO, 2018). The more accurate data that can be assessed and entered into the deterioration model, the more reliable predictions can be performed.

2.2.3 DECISION SUPPORT

The third part and actual purpose of a BMS is the decision support unit. The BMS is designed to support users with guidance and results from conducted analyses (AASHTO, 2018). Taken into account that the validity of a proposed decision is a model-view only, which probably lacks data accuracy or is based on assumptions, engineers or bridge managers must consider these shortcomings during decision-making (AASHTO, 2018). Although the BMS suggestions are data-driven and optimized within the program's restrictions, decision-making is practiced by engineers or bridge managers ultimately. Providing the best possible suggestions, the BMS should rely on valid and traceable input data that is comprehensive over time.

BMSs are complex systems with various tools, models, and analysis options. However, this thesis focuses on information management and data handling from existing real environment conditions into data storage, particularly.

2.3 BRIDGE CONDITION RATING

The bridge condition and appraisal ratings are the two rating schemes bridges' conditions are evaluated by in the USA. First, the structural condition rating assesses the bridge's condition over time compared to the as-built condition of the particular bridge. Second, the bridge appraisal rating is defined as the components condition of one bridge regarding its position and contribution to the infrastructure network in comparison to other bridges within the infrastructure network (Ryan et al., 2012).

Foremost, it is important that each bridge complies with the required structural sufficiency. Hence, bridge structural condition assessment is considered in the following ways. "Condition rating" is the procedure of converting real deterioration into a numerical scale to compare different objects – as in this case, bridges. The translation of real condition into a numerical scale of rated condition must be as accurate and detailed as possible to fulfil the data driven BMS requirements stated previously. Contributing this transformation of three-dimensional deterioration data into one-dimensional numerical ratings, manuals and guidelines provide objective categories and characteristics for specific condition ratings.

United States federal- and state-specific guidelines provide two general procedures to conduct bridge condition ratings. Component condition rating allows assessment of larger bridge parts, while element condition rating is a more detailed procedure. Both approaches compare a bridge's current condition state to its previous as-built condition, and evaluation of deterioration is, therefore, a static analysis of at least two points in time.

The basics of component condition rating and element condition rating are emphasized in detail below.

2.3.1 BRIDGE COMPONENT CONDITION RATING

The assessment of superordinate structural bridge components is conducted by bridge component condition rating. National Bridge Inspection Standards (NBIS) (*CFR Title 23 - Highways*, 2012) in accordance with the Bridge Inspector's Reference Manual (BIRM) (Ryan et al., 2012) and the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA, 1995) define components for rating the structural condition of bridges. Of note, it is differentiated between bridge-type structures and culvert-type structures. The comprehensive descriptions of bridges comprise multiple aspects, denominated as items, e.g. (Item 1) State Code, (Item 9) Location, or (Item 27) Year Built. Each single piece of information is designated as one item. For structural component rating, the following items are relevant.

The components for bridge-type structures are (Item 58) Deck, (Item 59) Superstructure, (Item 60) Substructure, and, if the bridge spans a waterway, (Item 61) Channel and Channel Protection. For culvert-type structures, (Item 62) Culverts is the relevant indicator for the component rating. Ratings of bridge components are reported by each state to the FHWA NBI to monitor every bridge structure on the NHS (Ryan et al., 2012).

Each component's current condition is scaled on a descriptive scale between 0 – failed condition, and 9 – excellent condition, in comparison to as-built condition (Ryan et al., 2012). Depending on the specific structure type, items might not occur, hence they do not apply to the rating and are classified as not applicable (N). Appendix B provides the scale for component condition rating by items.

Subsequently, the overall bridge condition is derived from component rating, by using equations (1) to (3), provided below. The component with the lowest component condition defines the overall bridge condition as either "Poor", or "Fair", or "Good". (FHWA, 2017b). The following equations display the relation between component rating and the overall bridge condition rating:

$$Poor\ condition\ if: min(y_j) \leq 4 \quad (1)$$

$$Fair\ condition\ if: min(y_j)\ =\ 5 \vee 6 \quad (2)$$

$$Good\ condition\ if: min(y_j)\ \geq 7 \quad (3)$$

The equations use the following denominations:

$$y_j \in\ \{0,1,2,3,4,5,6,7,8,9\}, \qquad j\ \in\ \{Bridge\ Item\}$$

$$i\ = \in\ \{1,2,3,\ldots,n\};\ x = \{Good \vee Fair \vee Poor\}$$

$$Element\ Rating\ [x_{ij}], Component\ Rating\ [y_j]$$

For example, if the deck (Item 58) and the superstructure (Item 59) are both rated in condition 7, but the substructure (Item 60) is rated in condition 5, the overall condition of the structure is designated as "Fair". Besides this rating scheme, the bridge also gets an overall condition classification scaled between 0 and 9.

The BIRM, however, defines that each component consists of different elements. In addition to the rating scheme provided by equations (1) to (3), three descriptive element condition ratings are provided by the BIRM, namely "Good – element is limited to only minor problems"; "Fair – structural capacity of element is not affected by minor deterioration section loss, spalling, cracking, or other deficiency"; and "Poor – structural capacity of element is affected or jeopardized by advanced deterioration, section loss, spalling, cracking, or other deficiency" (Ryan et al., 2012).

This rating scheme does not allow any quantitative derivations but relies on descriptive assessment by the inspector. The procedure of the BIRM element rating scheme within the component rating and the overall bridge condition rating is displayed by the following mathematical relation (4):

$$\sum_{i=1}^{n} xij \equiv y_j \tag{4}$$

Each item j is separated into elements i and rated with condition *x*. The determination of the condition rating *y* of specific item *j* is displayed by equation (4). Since the scheme is not computable, the identity operator implies that the sum of element ratings within one item j is identical to item condition y_j. The overall bridge condition rating follows the scheme provided by equations (1) to (3). For example, the superstructure is comprised of five parallel aligned girders, and three girders are rated as “Fair” and two girders are rated as “Good”. The rating scheme does not allow a precise rating of the overall condition then.

Inspectors must record location, type, size, quantity, and severity of deterioration of each element (Ryan et al., 2012). However, this scheme misses accountability and data-driven process structure, due to descriptive rating guidelines and different rating schemes on the levels of element, component, and bridge.

2.3.2 BRIDGE ELEMENT CONDITION RATING

While bridge component rating defines bridge condition on a larger scale that is suitable for overall condition inventory of the NBI and comparison of bridge conditions within the jurisdiction of a DOT, bridge element condition rating is necessary for BMS purposes, since it provides more detailed bridge condition ratings.

Bridge elements are defined by the AASHTO Manual for Bridge Element Inspection (MBEI), which is comprised of National Bridge Elements (NBE), Bridge Management Elements (BME) and Agency-Defined Elements (ADE) (AASHTO, 2018). MBEI elements are listed by materials and frequently recurring damages are predefined within the manual. The latest defined NBEs and BMEs are provided in Appendix C.

Bridge element condition rating relies on four Condition States (CS), which provide information about the severity and extent of deterioration of each element. The extent is measured by the total amount of deteriorated surface in relation to the undeteriorated surface. Assessing the severity is supported by definitions of each condition state for various elements and materials (Ryan et al., 2012). However, as stated in the BIRM the scale provided by four condition states is not precise enough to quantify the defects' extent.

This rating scheme enables tracing the amount and severity of deterioration within one element and therefore provides more quantifiable data for the BMS databases than component ratings (Chase et al., 2016). Even though the severity and amount of bridge deterioration can be assessed with element condition rating, mapping of deterioration within the bridge structure is not addressed with this rating scheme. Furthermore, variability between inspectors determining bridge condition has been an issue, regarding a 2001 study and is still part of research activity (Phares et al., 2001).

Addressing this issue, Washer et al. (2019) published guidelines to improve quality of element-level bridge inspection data. The goal of their study was to implement a visual guide supporting inspection procedures and to enhance the objectivity of visual inspections. Using images of common deterioration and defect elements of the MBEI to illustrate different CS as a reference for inspectors is the chosen approach of this guideline. However, findings of the case study did not show the expected results, but still revealed inconsistency in damage assessment. Furthermore, they found that quantifying deteriorated areas and rating of applicable condition state varies between different inspectors.

The study revealed that research has been recently conducted to quantify and objectify the findings of visual inspections. Implementing a visual guide, which enhances the objectivity of visual inspections, is one big advantage if visual inspection stays the primary method for bridge inspections in the future.

2.4 BRIDGE INSPECTION FRAMEWORK

Bridge condition ratings are derived from findings and data assessed during bridge inspections and rely on the accuracy and intensity of the inspection itself. Since ratings are only as reliable as the accuracy of the inspection, this section analyzes national and state manuals to understand the framework of current inspection procedures. The goal of this section is to emphasize the strengths and address the shortcomings of current inspection procedures to derive requirements for later proposed enhanced inspection methods.

This section introduces the current framework of routine bridge inspections in the USA and, particularly, in Rhode Island. It provides an overview about the valid guidelines and manuals.

2.4.1 NATIONAL BRIDGE INSPECTION STANDARDS

The first consideration of nationwide standards for bridge inspection was stated in the Federal-Aid Highway Act (1968). With a call for inspection standards and responsible qualifications for inspectors, the NBIS were established (Federal Aid Highway Act, 1968). Current NBIS were released in 2004, but minor rules and regulations were updated in 2009 (FHWA, 2009). In 2019, the Federal Highway Administration (FHWA) issued a notice for proposed rulemaking for the NBIS addressing needs regarding the MAP 21 and incorporating new technologies.

The NBIS are part of the United States CFR Title 23, Section 650 *Bridges, Structures and Hydraulics* with the primary purpose of ensuring safety and reliability of highway bridges. Appendix D displays the classification of highway bridges in data terms by items defined for the NBI and NBIS.

The NBIS provides regulations for the following paragraphs:

- § 650.303 Applicability
- § 650.305 Definitions
- § 650.307 Bridge Inspection organization
- § 650.309 Qualifications of personnel
- § 650.311 Inspection frequency
- § 650.315 Inventory
- § 650.317 Reference manuals

These paragraphs provide the federal framework for conducting inspections on highway bridges on public roads (*CFR Title 23 - Highways*, 2012). Regarding the NBIS § 650.305, routine inspections should provide three major findings. First, the current physical and functional condition is assessed. Second, the physical, and functional condition are compared to previous inspections or the initial inspection to address changes over time. Third, routine inspections assess satisfaction of present service requirements (*CFR Title 23 - Highways*, 2012).

Condition changes over time are identified by observations and measurements in the field. According to the NBIS § 650.313, c) all bridge elements must be surveyed during routine inspections. Different bridge elements as well as rating criteria for element level inspections are discussed previously.

Furthermore, it is stated that routine inspections should be conducted at least every 24 months at each bridge. This interval might be extended to 48 months if written approval by the FHWA is published and conditions allow larger inspection periods (*CFR Title 23 - Highways*, 2012).

The newest proposed NBIS rules discuss dynamic consideration of inspection intervals with respect to the condition state (FHWA, 2019a).

The NBIS does not specify inspection procedures and policies, however, defined by § 650.313 in association with § 650.317, the AASHTO MBE is incorporated for conducting bridge inspections. Furthermore, each state DOT must provide agency wide inspection procedures, policies, and organization according to § 650.307 CFR Title 23.

2.4.2 BRIDGE INSPECTOR'S REFERENCE MANUAL

The BIRM published by FHWA and the National Highway Institute serves as the paramount inspection manual. It is the superordinate comprehensive inspection and evaluation manual for highway bridges and provides overall safety fundamentals, inspection reporting procedures, as well as specific inspection and evaluation techniques. The BIRM structures inspection and evaluation techniques by material and structural components. The hierarchy of inspection activities are similar for all materials and components and follow the order: first, visual examination; second, physical examination; and third, advanced inspection methods, which comprise non-destructive testing methods (Ryan et al., 2012).

Furthermore, the BIRM provides descriptions of anticipated modes of deficiencies for different bridge materials. Guidelines for examination of deficiencies as well as their causes are described in the manual (Ryan et al., 2012). Anticipated modes of deficiencies for concrete and steel as well as their visual perceptibility on surface are displayed in Appendix E.

2.4.3 AASHTO MANUAL FOR BRIDGE EVALUATION

As incorporated by the § 650.317 (b) (1) CFR Title 23, the AASHTO MBE is another reference manual that provides guidelines for bridge inspection procedures. It addresses the different inspection types, from initial inspection to complex bridge inspection, regarding their intensity and procedures (AASHTO, 2018). The MBE itself refers to the BIRM for conducting routine inspections.

Regarding preliminary work and inspection preparation, the MBE provides non-regulatory guidance. Preparation of equipment for assessing the bridge condition including sketches, photographs, and notebooks is recommended as well as to describe bridge elements with predefined nomenclature to ensure correct localization of deterioration within the structure (AASHTO, 2018).

The MBE provides limits of accuracy for field measurements and identifies different limits for each material. Measurements of length, width, and depth are necessary to track the development of deterioration over time. Limits given in Table 1 are applicable to each element of a bridge structure (AASHTO, 2018). It is suggested to track and record measurements in the bridge inspection file or an additional log to compare previous and future recordings and derive condition change over time.

Table 1: Limits of Accuracy for Field Measurements by Material (cp. (AASHTO, 2018))

Material	Imperial Unit	Metric Unit
Timber Members	Nearest ¼ in	Nearest 0.635 cm
Concrete Members	Nearest ½ in	Nearest 1.27 cm
Asphalt Surfacing	Nearest ½ in	Nearest 1.27 cm
Steel Shapes	Accuracy necessary to identify the section	
Span Lengths	Nearest 0.1 ft	Nearest 3.048 cm

Regarding the equipment necessary for bridge inspection, MBE states that each inspector should be equipped with cameras and hand tools besides their personal protective equipment. At the least, the equipment is comprised of cleaning tools, measurement tools, and tools for sound testing (AASHTO, 2018). These tools implicate visual inspection techniques and require a hands-on inspection. No additional guidelines for routine inspections are provided besides referencing the BIRM visual inspection method and possible advanced inspection methods if necessary.

2.4.4 RHODE ISLAND DOT BRIDGE INSPECTION MANUAL

The RIDOT Bridge Inspection Manual is developed in compliance with the previous explained federal guidelines and specifies procedures for Rhode Island's bridge inspections. Each bridge under the jurisdiction of RIDOT carrying a public roadway is required to be inspected within guidelines provided by the RIDOT Bridge Inspection Manual. It provides minimum requirements for executing bridge inspections within state and federal regulations but indicates that engineering judgement is still essential (RIDOT, 2013).

The result of each routine inspection is the evaluation of physical and functional conditions in comparison to initial or as-built conditions (RIDOT, 2013). Reporting of element condition data is required based on federal NBIS guidelines.

The manual requires routine inspections, usually conducted as in-depth inspections. In-depth inspection relies on hands-on inspection methods to investigate the bridge condition in detail (RIDOT, 2013). Each element gets a close-up investigation and requires detailed description of its condition state and deficiencies. The hands-on inspection itself is defined by NBIS as a visual inspection within an arm-length in distance from the structure (*CFR Title 23 - Highways*, 2012).

The routine inspection is comprised of field observations and measurements to evaluate the condition of the bridge structure. If an in-depth assessment is not feasible, the structure should be assessed within reach of 15 feet (RIDOT, 2013). The inspection is required to be as intense as possible to allow comparison of previously recorded information to the current condition. Information assessed should allow load rating analysis (RIDOT, 2013).

The following elements and sections are suggested to be inspected during routine inspections:

- Bridge Approaches and Traffic Safety Features
- Top Surface and Underside of the Deck
- Superstructure with Slabs, Beams, Girder and Trusses
- Bridge Bearings
- Abutments, Wingwalls and Intermediate Piers
- Waterway and Channel

The inspection manual provides guidelines to inspect bridges by component, but not on an element level. It states that engineering judgement is required during routine inspections to differentiate between critical and non-critical areas. However, no prescription to evaluate each bridge element with a hands-on inspection technique is intended (RIDOT, 2013).

In addition to the FHWA recording and coding guide (FHWA, 1995), RIDOT's Bridge Inspection Manual provides more detailed component rating guidelines that are descriptive and strongly rely on engineering judgement (RIDOT, 2013). The RIDOT Bridge Inspection Manual does not provide its own guidelines to rate bridge element level condition but refers to the AASHTO MBEI and MBE. Hence these guidelines for assessing element level condition determine the rating procedures in the State Rhode Island.

2.5 STATE-OF-THE-PRACTICE BRIDGE INSPECTION

As current valid inspection manuals and guidelines show, bridge inspection in the United States relies on various methods and procedures. However, visual inspection (VI) is the predominant method to assess bridge condition at the first level in the US (Dorafshan & Maguire, 2018; Hurt & Schrock, 2016b; Ryan et al., 2012).

Referring to a study performed by the FHWA in 2001, VI is the predominant bridge inspection technique within the field of nondestructive evaluation (NDE) methods (Moore et al., 2001). This survey investigated 42 State DOTs, 72 Iowa county DOTs, and six bridge inspection contractors regarding their inspection techniques and procedures for steel, concrete, and timber bridges. For all three construction materials, the majority of participants called VI the default and number one technique for bridge inspections as visualized in Figure 2.

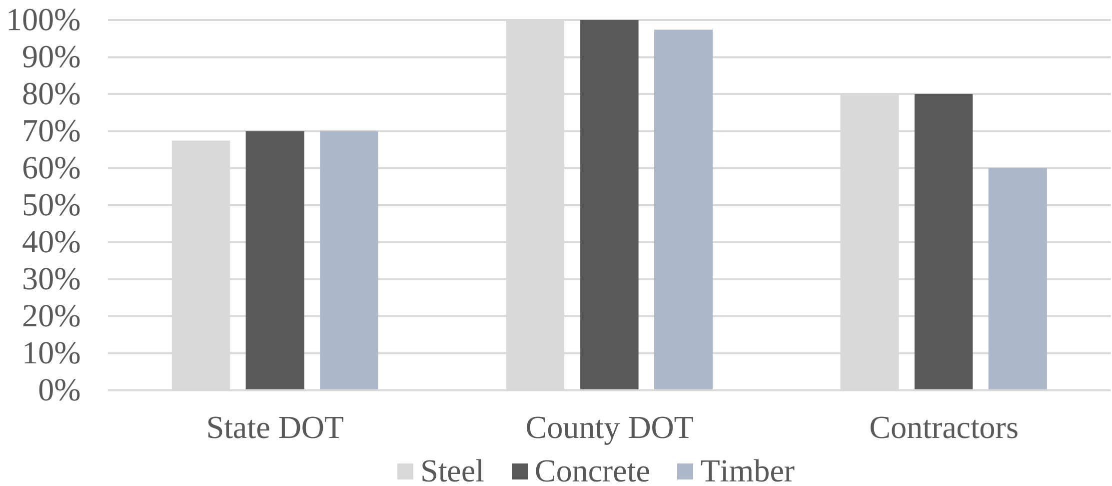


Figure 2: Share of Participants who rated Visual Inspection as primary NDE Technique. (own figure, data: (Moore et al., 2001))

Regarding Moore et al. (2001), only a few inspectors use tools in addition to their visual examination. One finding of their study was that the most common inspection tools used during routine inspections were sounding tools, comprised of masonry hammers and chains (40 % of participants), tape measures (24 %), extension ladders (22 %), magnifying glasses (14 %), and flashlights (13 %).

The survey also found that tool use for in-depth inspections, which were performed during routine inspections for critical areas, was slightly higher and more common. It was found that 50 % of participants used sounding tools and flashlights, 45 % used extension ladders, and 39 % used tape measures while performing visual examination as part of in-depth inspections.

The latest BIRM provides an inspection equipment guide and categorizes tools for cleaning, inspection, visual aid, measuring, documentation, access, and miscellaneous equipment (Ryan et al., 2012). Most tools mentioned in this guide implicate inspections within tactile reach of elements and comprise tools emphasized in the previously referenced study of Moore et al. The manual's suggestions reach from binoculars, flashlights, magnifying glasses, inspection mirrors, and dye penetrant as tools for visual aid to chipping hammers and chain drags for sounding tests, to pocket tapes, tiltmeters, optical crack gauges, and thermometers for measuring more precise conditions. Regarding bridge condition documentation, the manual suggests inspection forms, notebooks, drawing sketches, and cameras. It also is stated that routine inspections usually do not require any special equipment besides hand-tools (Ryan et al., 2012).

The tools mentioned in latest BIRM emphasize the importance of visual inspection techniques but also the requirement for reachability of structures within tactile distance;

since they are congruent with findings from the 2001 study of Moore et al., hence it can be assumed that they are transferrable to today's procedures.

Since the MAP 21 Act of 2012 states higher requirements for bridge inspections on the element level, Washer et al. (2019) conducted a survey to addresses current needs of bridge inspectors, enhancing the quality and reliability of element-level bridge inspection data by establishing a visual guide to identify deficiencies. In this study, 36 agencies, comprised of 34 state DOTs, the Washington D.C. Agency, and the Corps of Engineers participated. It was found that agencies are evolving in collecting element-level data and that visual inspection is still the predominant method for bridge condition assessment (Washer et al., 2019).

Furthermore, Washer et al. also found that reliability on element condition assessment increases since either MBEI-defined or agency-defined quantitative descriptors are used to define CS. In contrast, as Figure 3 displays, only 16 state DOTs of 36 participating agencies indicated that they estimate deteriorated areas on deck elements by objective measurements with measure tools, and 15 DOTs stated percentage estimation of deteriorated deck areas as the favored method to indicate element condition state (Washer et al., 2019).

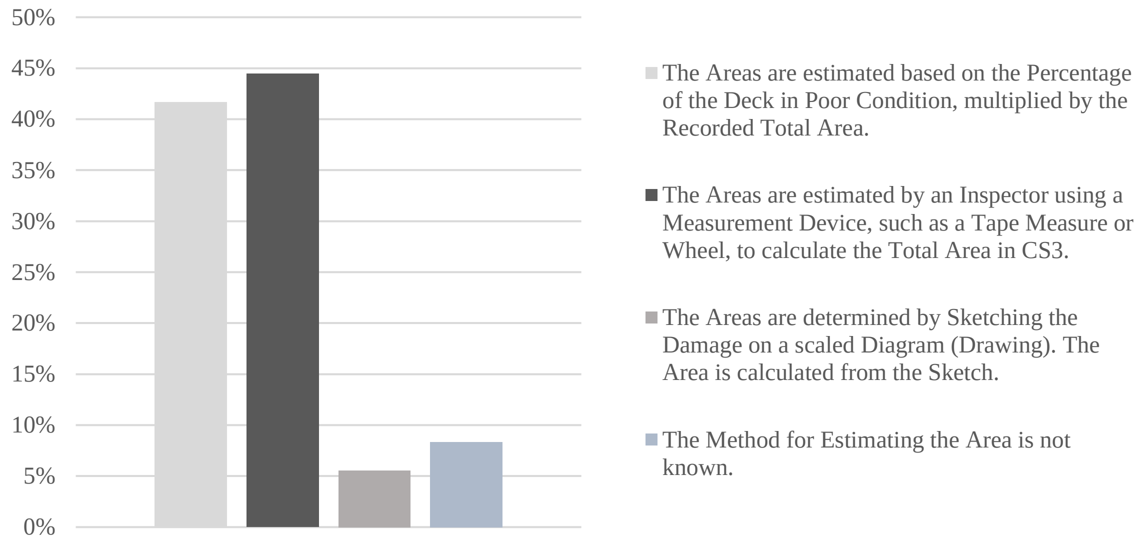


Figure 3: State DOTs Estimation Method for Deck Element's CS (own figure, data: (Washer et al., 2019))

The survey also found that few state inspection manuals prescribe methods of estimating deficient areas and specify measure procedures. Fewer than 10 % indicated that those methods are described in inspection manuals and guidelines, but more than 60 % of participants stated that the inspection team has the authority to decide on the measurement method. The remaining participants answered that specific methods are explained during trainings or periodic meetings (Washer et al., 2019).

As stated previously, routine inspections should assess deterioration over time by comparing current to previous recorded conditions. Washer et al. found that it is current practice for 32 of 36 participant DOTs to review previous inspection reports and to have them accessible during the execution of inspection in the field. Furthermore, most inspectors indicated that they have access to additional information that contributes to the inspection, as Figure 4 illustrates. The three most named additional information documents are photographs of damages and defects, bridge plans, and drawings of damages and defects. These documents underline importance of visual assessment of bridges since most defects and damages can be displayed either on photographs or drawings comparing current to previous conditions.

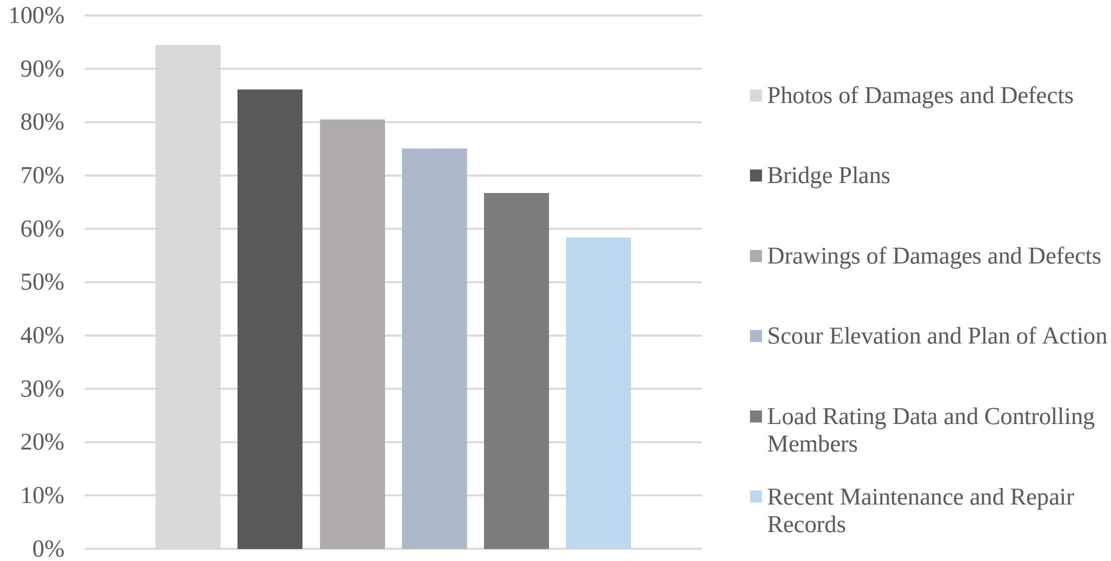


Figure 4: Additional Information accessible prior to the Inspection (own figure, data: (Washer et al., 2019))

Findings from Washer et al.'s study are used to create the visual guide for bridge element condition rating of the latest AASHTO MBEI. They underline the existence and importance of bridge condition assessment relying on VI and engineering judgement. The visual guide still does not quantify delimitation for each condition state, but does provide descriptive formulations that guide the inspector or engineer (AASHTO, 2019).

Relying on human judgement and VI allows broad evaluation of the entire structure within a short time. It is possible to detect a variety of defects since cracks, spalls, discoloration, and misalignment are surface visible indicators for deterioration. Shortcomings of state-of-the-practice inspection methods are the quantifiability of visual inspection and subjective rating scale, even with the named guidelines (Agdas et al., 2016; Hurt & Schrock, 2016a).

2.6 STATE-OF-THE-ART BRIDGE INSPECTION

The following sections provide overview of current state-of-the-art inspection methods and research activity in the field of bridge inspection and associated processes as condition assessment, data acquisition and storing.

2.6.1 3D-BRIDGE INFORMATION-SYSTEMS

In recent past the Nebraska Department of Roads (NDOR) and the Michigan Department of Transportation (MDOT) put effort into developing enhanced BMS processes including 3D-models and connected applications for inspection purposes. Funded by the NDOR, Shen and Jensen (2015) developed and investigated a data management system for bridge inspection purposes. Two years later, Brooks et al. (2017) created a software tool that allows entering of inspection data into the bridge database in a field that is linked to a 3D-model.

Shen and Jensen (Shen & Jensen, 2015) developed a 3D bridge inspection data management system that is capable of combining 3D visualizations with a database that stores bridge inspection information, bridge plans, and maintenance records. The purpose of their research was to develop a visualization technique to display bridge condition within a 3D-model (Shen & Jensen, 2015). Their research investigated the software solution SketchUp by Trimble Inc. and its functionality to serve as a user interface for an updatable 3D-database. The 3D-model is combined with an external database by using an application programming interface. SketchUp allows different levels of detail for objects, hence elements can be created and later comprised to components. Linking each element with specific information and unique identifiers or element names are required to match database entries and combine information appropriately. Once the database is filled with inspection reports, construction records, and additional information, the data is linked to associated elements and the information is accessible in the 3D-model for each element. Next, each condition rating is linked with a specific color and the 3D-model displays the corresponding color at the specific element. Shen and Jensen created a method that allows quick visual assessment of overall bridge component condition in a convenient display mode. However, the data input is still a manual process, which requires accurate observations and notes made by the inspector in the field. Data must be entered into the database after inspections are conducted and the model is not able to be displayed in mobile applications, which could be carried during field inspections.

The report of Brooks et al. (2017) summarizes a project intended to enhance inspection procedures by supporting inspectors with a digital 3D-bridge-model in the field, which allows entering inspection findings immediately into the database linked to the 3D-model. The project scope included the development of mobile inspection software, allowing the inspector to link damages on bridge structures on the surface of the digital 3D-model (Brooks et al., 2017).

Two requirements controlled the development process. First, element-level inspection data must be assessable to meet federal guidelines, and second, the attachment of photographs and comments associated with recorded damages should be enabled. The software solution also should be able to compile records of assessed information and link current data to previous inspection records. Linkage to the MDOT BMS should also be implemented to reduce labor of inspectors to enter information manually into data bases. The developed application, named 3D Bridge App, is capable to address the requirements but misses accuracy for modeling irregular or more complex bridges than average bridge structures. The application allows attaching defect tags with different properties within the digital model. Each bridge element is accessible by a dropdown selection menu, and defect categories are based on the AASHTO MBEI definitions. Furthermore, the application allows the attachment of photos and notes. Hence, it is possible to collect necessary information for element condition rating and to attach it within the digital bridge structure.

Furthermore, McGuire et al. (2016) developed a method to enhance the bridge evaluation process by connecting BIM software with customized damage information collection and evaluation tools. The study developed a damage-location-tool to provide information about the location of deterioration within the structure and a damage-evaluation-tool to automize the damage evaluation. Both tools access information via the BIM software, which incorporates databases and visualization (McGuire et al., 2016).

Although the study showed the feasibility and usefulness of BIM for bridge inspection and management purposes, it revealed that further research of the BIM application for use during inspection on site is needed.

2.6.2 AUGMENTED REALITY SUPPORTED INSPECTION

Augmented Reality (AR) is one technology that allows the superposition of digital layer and tools within the field of vision. This section analyzes the research activity of AR-technology in the architecture and construction industries. Detailed background of this technology is given in Section 3.5.

One early consideration of AR-technology for inspection purposes evolved when Webster et al. (1996) developed a head-mounted display to overlay virtual layers on the real environment. This paper gives an insight into the early stages of AR-implementation in the architecture and construction industries and it provides the first consideration of the potential for inspection purposes in the construction industry. It states that AR might help to guide inspectors through inspections and substitute printed construction drawings (Webster et al., 1996).

Earlier, Park et al. (2013) developed a framework implementing AR and BIM for construction defect management to enhance the productivity of construction sites. BIM is the central collaboration tool between stakeholders of the project. Detected defects on site are entered into the BIM model with specific requirements to fix the defect. Next, defect information is transformed to a digital marker, then a physical marker is attached to the location in the built environment. The physical marker is scannable by the AR-application and accesses the necessary information needed for executive personnel to fix the defect. Once the defect is repaired, inspectors superimpose as-planned and as-built condition with the AR-application and delete the defect from the defect information database. This project displays the potential of AR and BIM in terms of enhancing collaboration on site. Needs of construction sites are transferrable to inspections during the O&M phase of a bridge, such as having multiple stakeholders, the work environment on site, and the heterogeneity of data and information (Park et al., 2013).

The Transportation Research Board (TRB) announced in 2018 that research on implementing Virtual Tours (VT), Information Modeling (IM) and AR would contribute to inspection procedures of large infrastructure objects. It is stated that these human-centered inspection methods are mainly applicable to transportation infrastructure like bridges and tunnels (Glisic et al., 2018).

Karaaslan et al. (2019) developed a human-centered inspection approach in combining AR-technology and Artificial Intelligence (AI) to detect defects partly autonomous. Since it is a human-centered approach, it combines engineers' expertise and AI-enhanced objective measurements. Defects can be detected autonomously by AI installed in the AR-headset of the inspector, but the AI still allows inspectors to manually add defects or information that are not detected yet. This is one major advantage in comparison to fully automated inspection techniques and marks the importance of engineering expertise on site. The developed method can detect the defect extent on a surface, quantify it, and rate classify its condition by the AASHTO CS (Karaaslan et al., 2019).

Moreu et al. (2019) conducted a study regarding the implementation of AR technology using head-mounted AR-glasses to enhance the inspection of transportation infrastructure. Part of this study investigated the accuracy of AR-supported measurements and the side effects of using digital tools instead of conventional tools to measure distances and areas. One finding is that AR-supported measurements were conducted 2.75 times faster than those using a conventional tape measure (12 seconds vs. 33 seconds) (Moreu et al., 2019). Furthermore, the study is comprised of three area measurements on concrete surfaces, with the average results displayed in Table 2. In addition, the study investigated a network connection between AR-glasses and a remote server that allows access to bridge properties and previous inspection reports during the inspection on site. One application is the so-called Change Detector, which allows the superposition of previously assessed renderings on top of today's condition to display changes and modifications over time.

Table 2: Accuracy of AR-supported Measurements (cp. (Moreu et al., 2019))

	Reference Measurement (ft^2)	HoloLens Average Measurement (ft^2)	Difference (ft^2)	Difference (%)
Area 1	187.98	191.50	3.52	1.9
Area 2	147.67	149.00	1.33	0.9
Area 3	129.00	127.40	1.60	1.2

A framework for implementing AR technology and the capabilities of a BIM model has been developed by Dang & Shim (2020). The proposed framework relies on a marker-based alignment of the digital 3D-model in the real environment. The superposition of both digital and real environment can be adjusted, and image capturing or defect capturing is conducted by the inspector supported by a head-mounted AR-device. Captured visualizations are then processed by image-processing technology to determine the extent and condition of the assessed object (Dang & Shim, 2020). The framework promises to be feasible but does not provide further information about the status of implementation on site.

Recent research activity on implementing AR-technology in the architecture and construction industries, and particularly for bridge inspection purposes, shows that it has potential to enhance inspection procedures in the future. The implementation of state-of-the-art technology while relying on engineering expertise is promising to balance the contributions of each and eliminate the shortcomings of one or the other side. The conducted literature review also shows that there is still little knowledge about the accuracy of AR-supported measurement on site.

2.6.3 OTHER BRIDGE INSPECTION TECHNIQUES

Besides the development of enhancements for bridge inspection purposes by creating 3D-databases and the use of AR-technology, the following three sections provide an overview of current research activity of bridge inspection methods in related-fields.

New inspection techniques and procedures for bridge infrastructure have been subject to research recently. In 2019, the FHWA published proposed rules in its NBIS with special research interest in sonar technology for underwater inspection and the performance of unmanned aerial vehicles (UAV) (FHWA, 2019a). Since this section has no intent to be all-embracing of all research conducted in the field of bridge inspections, only the predominant research topics are surveyed.

2.6.3.1 NON-DESTRUCTIVE TESTING METHODS

Non-destructive testing methods (NDT) are inspection procedures that comprise imaging methods, sounding methods, chromophore methods, and sensor-based methods as structural health monitoring (SHM). The BIRM designates 20 different NDT for concrete evaluation and 13 NDT for steel structure evaluation. NDT usually are only applied to areas that require further evaluation as found by visual inspection, since the equipment required exceeds visual inspection by far. Strengths of NDT are the quantifiability by calibrated testing equipment, which allows objective assessment of the found deterioration. The NDT mentioned in the BIRM are partially part of current bridge inspections, but development of these methods is ongoing (Aquino Rocha & Vieira Póvoas Tavares, 2017; Kashif Ur Rehman et al., 2016; Le et al., 2017).

Most NDT are, similar to visual inspections, discontinuous assessments at specific points in time. SHM, however, is a wireless-sensor-based assessment acquiring data continuously, transferring them digitally to an algorithm-lead condition assessment tool (Agdas et al., 2016). SHM systems can recognize specific damages only, depending on their programmed sensors and the density of their sensor-network. The more complex the SHM system is, the more sensitive it measures damages. But also, maintenance and service requirements increase with complexity of the system. Furthermore, relying on SHM systems raises the question of liability in case the bridge collapses (Agdas et al., 2016; Cawley, 2018).

2.6.3.2 UNMANNED AERIAL VEHICLES

The FHWA (2019a) has a particular interest in UAVs for inspection procedures as stated in the NBIS proposed rules of 2019. UAVs – also known as drones – equipped with image generating technology comprised of three-dimensional laser scanners and high-resolution cameras are claimed to be one promising technology for future bridge inspections. They are able to provide images from high elevations and hard-to-reach areas without exposing the inspector to harmful situations (Hallermann & Morgenthal, 2014; Lovelace & Zink, 2015). Since Moore et al. (2001) found in their study that one third of inspectors fear working in high elevated areas, UAVs are able to address this issue and contribute to the safety of inspectors.

Besides increasing inspectors' safety with inspecting high-risk areas from a safe distance, UAVs promise to have time and economic benefits, since larger areas can be assessed in less time, which leads to savings in reduced cost and labor on site. However, for usual bridge structures, the UAV inspection might require more time for post-inspection processing in case images and records need post-processing care. Furthermore, road closures and traffic disturbance can be reduced to a minimum if the UAV does not disturb the traffic flow. However, the current Federal Aviation Administration regulations require visual contact between drone and pilot at all time. The next adjustment factor is that the drone must not be visible by traffic. These regulations limit the application of UAVs for bridge inspections since bridge components above deck level are almost unfeasible with current regulations. UAVs require Global-Positioning-System (GPS) signals to be controlled accurately. Since GPS signals are limited or not accessible below bridge structures, skilled pilots are necessary to conduct an appropriate inspection flight. Another challenge related to flight control is weather condition during the inspection. Bad weather might cause low quality recordings or require the inspection to be rescheduled, which might disturb the inspection program with further challenges (Dorafshan & Maguire, 2018; Morgenthal & Hallermann, 2014).

However, the major challenge of implementing UAVs for bridge inspection purposes is the lack of tactile or physical inspection, as long as robotics are not developed to be feasible for this use-case (Dorafshan & Maguire, 2018).

2.6.3.3 IMAGE PROCESSING TECHNOLOGY

Artificial Intelligence (AI) for image processing technology has evolved over the last several years. It promises to be highly contributive for visual inspection purposes, since it automizes defect assessment (Silva & Lucena, 2018).

High resolution images taken on site by the inspector or UAV provide the input data for image-processing algorithms to determine deterioration on surfaces. AI develops patterns to detect and assess defect properties and surface deterioration in an objective and quantifiable manner.

However, most research activity focuses on crack assessment only and is therefore not feasible for a comprehensive assessment of bridge structures (Yeum & Dyke, 2015). Mohan et al. (2018) found that many difficulties exist using image processing technology since lighting conditions, image resolution, and irregularities on surfaces affect accurate measurements by the algorithms.

Fast and data-driven measurements and the resulting data-driven condition ratings are advantages of image processing technology. However, algorithms are trained to detect only one kind of deterioration and further accuracy is needed to determine properties of damages and their localization within the structure particularly. Furthermore, high resolution and quality images are required to allow good judgement by the algorithm, which cannot always be ensured and depend on the conditions on site (Mohan & Poobal, 2018).

2.7 SURFACE PERCEPTIBILITY OF DETERIORATION

Previous sections outline the dependency of inspection procedures on visual inspection techniques. Bridge rating at the component and element level primarily relies on data acquired by visual inspection, hence this section provides an overview of perceptibility of deficiencies at the surface of bridge structures. As later analyzed in section 3.1, the US' and Rhode Island's bridges primarily rely on steel and concrete as main their design material. Therefore, the scope in this section is narrowed to steel and concrete structures.

Bridge element defects are defined by the latest AASHTO MBEI 2019, which is the superordinate manual for bridge element condition rating and reporting of structural condition, as it is incorporated in the NBIS. In its entirety, the manual is a representative guideline, since it is comprised of all defects needed to conduct element condition assessment. The MBEI has its origins in the report of Washer et al. (2019). In this report the authors provided visual guides and descriptive categories for rating elements as CS2 (Fair) and CS3 (Poor), and partly provided visual guides and descriptions for CS1 (Good). For elements rated in CS4 (Severe), no visual guide is provided and the description indicates a structural review to determine strengths or serviceability of the element (AASHTO, 2019).

2.7.1 REINFORCED CONCRETE STRUCTURES

Reinforced and prestressed concrete structures rely on the compression strengths of concrete and tensile strengths of steel reinforcements. This concept of distributing loads is well known and has been proven for decades. Besides bearing axial compression loads, concrete also provides an alkaline environment for steel reinforcement and prevents steel from corrosion. Figure **5** displays the carbonation process of concrete.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

Figure 5**: Carbonation of Concrete caused by CO_2 Exposure** (cp. (Portland Cement Association, 2019))

If carbon-dioxide (CO_2) penetrates the concrete surface and reacts with the alkaline environment of concrete that has the chemical composition of calcium hydroxide ($CaOH_2$), the process of carbonation creates calcium carbonate ($CaCO_3$) and water (H_2O) (Portland Cement Association, 2019).

The decrease of the alkaline level and the existence of H_2O leads to the corrosion of the steel reinforcement. This in-concrete deterioration leads to delamination of the steel and concrete compound and can cause spall at the surface. Inversely, deterioration might be caused by surface damages that lead to more sensitive exposure of concrete to environmental impacts due to a lack of protected surface. The next sections outline the comprehensive concrete defects stated in the MBEI and their perceptibility on surface.

2.7.1.1 DEFECT 1080 DELAMINATION, SPALL AND PATCHED AREAS

Delamination is the lack of compound between concrete layers caused by air and water enclosure below the outer concrete layer (Portland Cement Association, 2002). This defect lies below the surface and therefore is not assessable with visual methods only. Since vibrancy can cause chipping of delaminated areas, advanced deterioration of delaminated areas will be visible. It is the state-of-the-practice method to check for delaminated areas by sounding with chain drags or hammers (AASHTO, 2018).

Spall and patched areas are concrete damages that can be identified with the MBEI visual guide. For spall and patched areas in CS 2 and CS 3, visual guides and descriptions are provided as Figure 6 shows. Quantified boundaries are also provided to separate CS 2 and CS 3 for spalled areas. Surface perceptibility of defect 1080 can mostly be assessed by visual methods. However, assessing delaminated areas at an early stage requires tactile methods, since it evolves below the surface.

Condition State 2	Condition State 3
Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.	Spall greater than 1 in. deep or greater than 6 in. Diameter. Patched area that is unsound or showing distress. Does not warrant structural review.

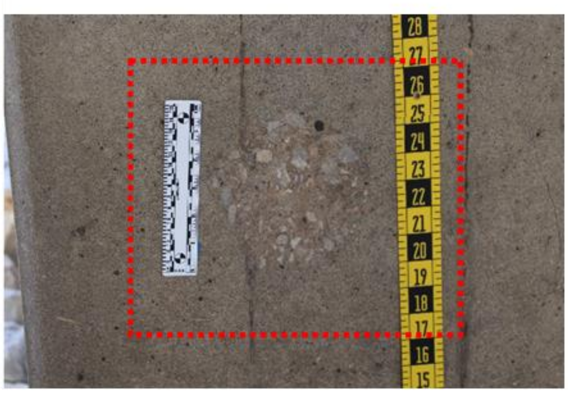


Figure 6: Visual Guide for Defect 1080 CS 2 and CS 3 (AASHTO, 2019)

2.7.1.2 DEFECT 1090 EXPOSED REBAR

As stated previously, reinforcement steel bears tension forces and bending stress applied to reinforced concrete structures. A concrete cover is designed to protect rebars from environmental impacts and secure the alkaline environment that contributes to the structural health of reinforcement steel. If the concrete cover is reduced and rebars are exposed to changing weather conditions, chlorides, or other environmental impacts, they can corrode, and section loss will occur. The MBEI provides visual guides for CS 2 and CS 3 to assess the element condition if rebars are exposed. It is differentiated between exposed rebars with and without section loss. Exposed rebars are clearly visible on the surface since the concrete cover is eliminated in this area. Therefore, exposure of rebars is visible at the surface and can be addressed by visual inspection techniques.

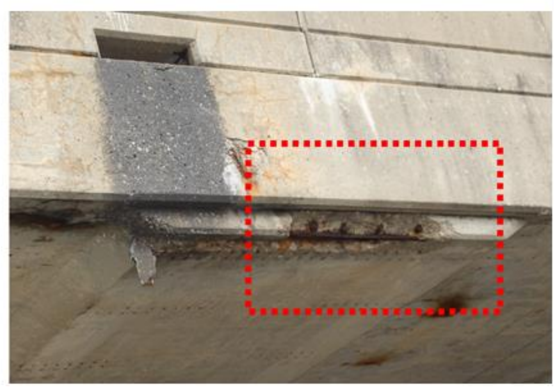
Condition State 2	Condition State 3
Present without measurable section loss.	Present with measurable section loss but does not warrant structural review.
	

Figure 7: Visual Guide for Defect 10390 CS 2 and CS 3 (AASHTO, 2019)

2.7.1.3 DEFECT 1120 EFFLORESCENCE AND RUST STAINING

The existence of white flow marks on the concrete surface indicates the generation of $CaCO_3$, which can be classified as efflorescence (Dow & Glasser, 2003). Efflorescence, if not expansive, does not harm the structural reliability of concrete. However, since processing of $CaCO_3$ generates H_2O, which can damage steel reinforcements within the concrete, the generation of white flow marks is rated as CS 2 by the MBEI. If staining is expansive and rust marks are visible at the surface, the MBEI suggests rating the specific element as CS 3. Rust staining at the surface indicates that corrosion of steel reinforcement has developed. As Figure 8 displays, efflorescence and rust staining are perceivable at the surface and are therefore assessable with visual methods to assess CS 2 and CS 3. Regarding CS 1, the MBEI specifies that no efflorescence, white flow marks, or rust stains are visible.

Condition State 2	Condition State 3
Surface white without built-up or leaching without rust staining.	Heavy built-up with rust staining.

Figure 8: Visual Guide for Defect 1120 CS 2 and CS 3 (AASHTO, 2019)

2.7.1.4 DEFECT 1130 CRACKING

The cracking of reinforced concrete structures is necessary to transfer loads to reinforcement steel and activate their tension resistance. These cracks are minor and predictable at specific locations within a concrete element. Other cracks, however, as the result of shrinkage, settling, freeze-thaw cycles, temperature variation, or overloading, are harming the structure and can lead to severe damage of the concrete structure. Hence, the MBEI provides visual guidance for defect 1130 – cracking in CS 1, CS 2, and CS 3 as displayed in Figure 9. Furthermore, the MBEI defines spectra for widths and spacing of cracks to classify between different CSs. Crack widths are measured within tenths of an inch while spacing is measured in feet.

Condition State 1	Condition State 2	Condition State 3
Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.
Width less than 0.012 in.	Width 0.012 – 0.05 in.	Width greater than 0.05 in.
Spacing greater than 3.0 ft.	Spacing of 1.0 – 3.0 ft.	Spacing of less than 1 ft.

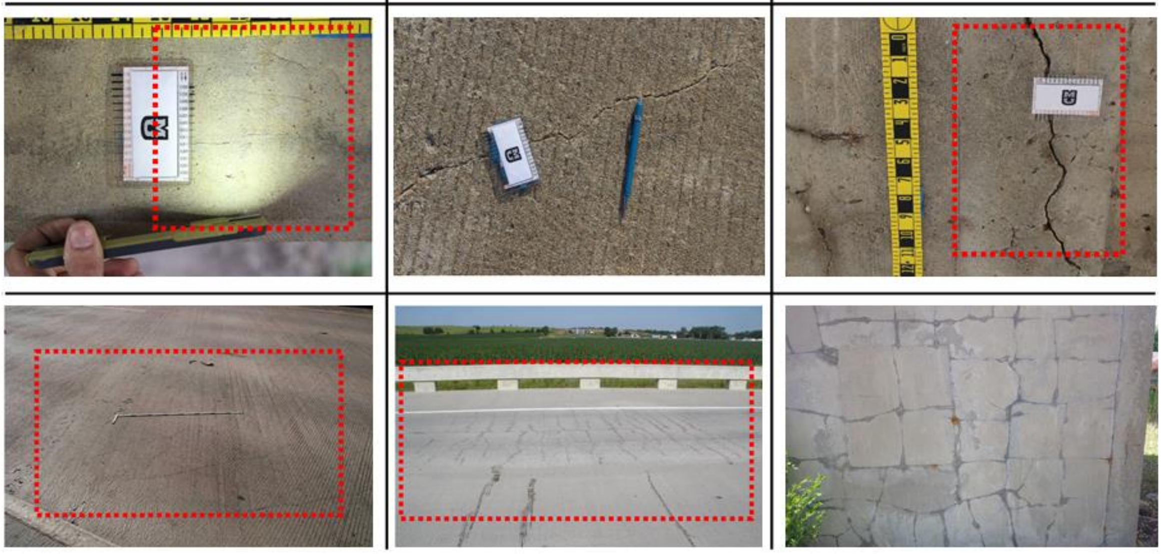


Figure 9: Visual Guide for Defect 1130 CS 1, CS 2, and CS 3 (AASHTO, 2019)

Cracks are perceptible on surfaces, as the visual guide of the MBEI shows. Addressing the correct crack width is important to classify the bridge element in the exact CS. As displayed in Figure 9, a crack comparator card can be used to determine the correct crack width (AASHTO, 2019). Crack lengths as well as spacing can be determined by inch rule or tape measure. The visual perceptibility of cracks on the surface is feasible.

2.7.1.5 DEFECT 1190 ABRASION AND WEAR

Abrasion and wear can be considered as synonyms, as they describe surface damage caused by external forces (Ryan et al., 2012). Usual causes of abrasion and wear are water, which rinses around abutments and piles of substructures, as well as traffic, which cause abrasion on top of the deck. Their extent is classified by the visual guide provided in the MBEI and displayed in Figure 10. However, quantifiable references to differentiate between CSs are not provided.

Condition State 1	Condition State 2	Condition State 3
No abrasion or wearing.	Abrasion or wearing has exposed coarse aggregate, but the aggregate remains secure in the concrete.	Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear

Figure 10: Visual Guide for Defect 1190 CS 1, CS 2, and CS 3 (AASHTO, 2019)

The existence and extent can be assessed by visual methods. For elements located above water level, the visual assessment is uncritical, and elements that are under water require additional effort or tools to lower the water level, allowing assessment of abrasion.

2.7.2 PRESTRESSED CONCRETE STRUCTURES – DEFECT 1110 CRACKING

Previously exemplified defects for reinforced concrete also apply for prestressed concrete. However, since crack behavior of reinforced concrete differs to prestressed concrete, defect number 1110 – Cracking (PSC) specifies cracks for prestressed concrete elements. Prestressing forces are applied to the steel reinforcement of prestressed concrete elements, hence the formation of cracks to activate steel members is not necessary. Cracks in prestressed concrete elements are thinner than in comparable reinforced concrete elements, as the MBEI displays in its visual guide. The deficiencies stated for reinforced concrete structures are similar on prestressed concrete structures. But since prestressed concrete shows different cracking behavior than reinforced concrete cracking defects are distinguished between reinforced and prestressed concrete.

Condition State 1	Condition State 2	Condition State 3
Insignificant cracks or moderate-width cracks that have been sealed.	Unsealed moderate width cracks or unsealed moderate pattern (map) cracking.	Wide cracks or heavy pattern (map) cracking.
Width less than 0.004 in.	Width 0.004 – 0.009 in.	Width greater than 0.009 in.
Spacing greater than 3.0 ft.	Spacing of 1.0 – 3.0 ft.	Spacing of less than 1 ft.

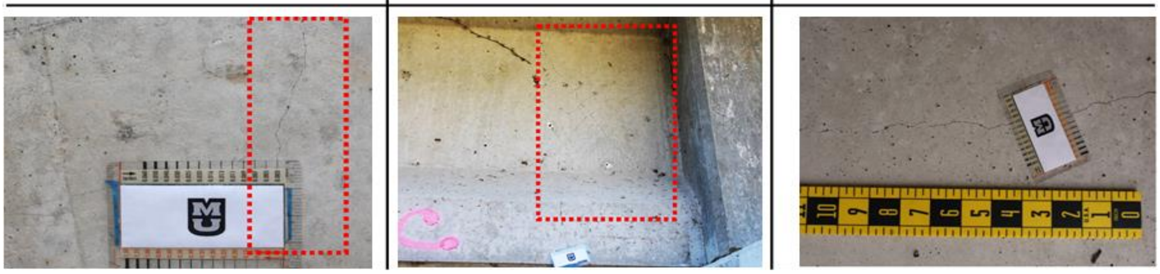


Figure 11: Visual Guide for Defect 1110 CS 1, CS 2, and CS 3 (AASHTO, 2019)

2.7.3 STEEL STRUCTURES

The second most common main design material type of US bridges and the most common main design material type for Rhode Island bridges is steel (FHWA, 2020).

Steel has properties withstanding tension as well as compression, however, it mainly will be considered due to its tensional resistance (Wright, 2015). Figure 12 displays the common strain-stress diagram of mild steel and its limits of uniform strain and necking strain.

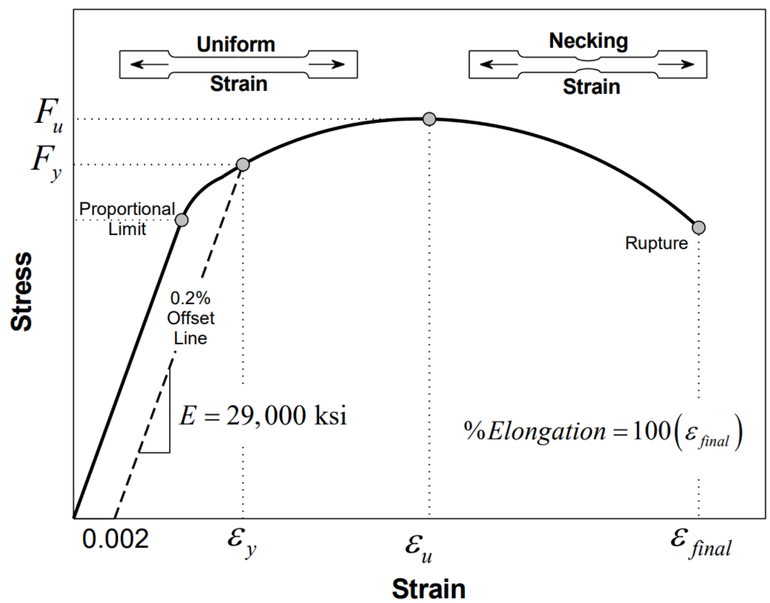


Figure 12: Stress-Strain Curve of regular Construction Steel (Wright, 2015)

The elastic behavior of steel allows proportional extension and elastic reduction until the yielding. If applied loads increase and tension exceeds the yielding point, the plastic zone is reached, and steel elements deform. Plastic deformation cannot be reversed. If applied loads exceed the ultimate extension ε_u steel members start necking and section loss occurs, which can result in decreased load capacity.

The next sections analyze the three common steel bridge defects and their surface perceptibility, regarding the latest AASHTO MBEI.

2.7.3.1 DEFECT 1000 CORROSION

Corrosion is the electrochemical process of steel and metal when exposed to oxygen (O_2) and H_2O, which causes loss of iron atoms within the structure and leads to ferrous ions dissolved in water (Bentur et al., 1997). If undetected corrosion evolves, it can cause serious section loss and may lead to structural deficiency of elements. Once corrosion is started, rust stains and red to brown discoloration witness the existence of steel corrosion. Early detection of corrosion and tracing of evolving extent is important. A steel coating can prevent steel from high exposure and lead to an extended life span of steel elements. Existence of and exposure to chlorides accelerates the process of corrosion, hence steel elements should be protected in high exposure areas (Kulicki et al., 1990).

Usually corrosion starts at the surface of steel members, hence the assessment of its extent can at first be classified visually. Initial corrosion can be identified by areas covered in red to brown freckles, which is defined as CS 2 by the AASHTO MBEI as Figure 13 displays.

Condition State 2	Condition State 3
Freckled rust. Corrosion of steel has initiated.	Section loss is evident or pack rust is present but does not warrant structural review.
	

Figure 13: Visual Guide for Defect 1000 CS 2 and CS 3 (AASHTO, 2019)

More severe corrosion with evident section loss or pack rust is classified as CS 3. The visual guide shows a delamination of steel layers which are scaling. Corrosion can be detected quickly by visual methods because of is local red to brown discoloration. Measurement of extent, however, is not quantified in current manuals.

2.7.3.2 DEFECT 1010 CRACKING

Cracking of steel members might be caused by local corrosion and/or existence of overloading and exceeding of strain limits. The MBEI defines CS 2 and CS 3 by differentiating between arrested and non-arrested cracks as Figure 14 displays.

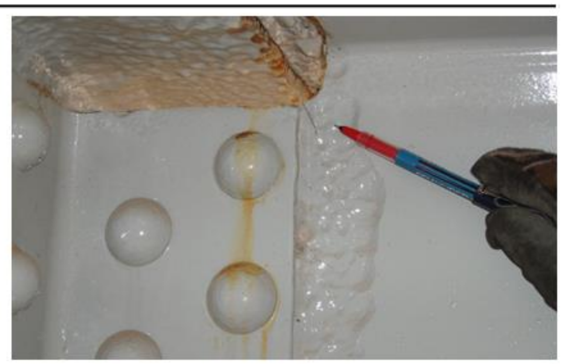
Condition State 2	Condition State 3
Crack that has self-arrested or has been arrested with effective arrest holes, doubling plates, or similar	Identified crack that is not arrested but does not warrant structural review.
	
	

Figure 14: Visual Guide for Defect 1010 CS 2 and CS 3 (AASHTO, 2019)

Cracks are perceivable on the surface of uncoated steel members and are partly visible if a coating is applied and it is not yet cracked to the same extent as the steel itself. Arrested cracks are limited in their extent by either structural limits or subsequent added actions. One opportunity to arrest cracks is the creation of so-called arrest holes to stop the crack from extending further into the structure.

2.7.3.3 DEFECT 1020 CONNECTION

Steel structures consist of prefabricated steel members that are assembled on site and connected by bolts, rivets, or welds. Connections depict discontinuity within a steel structure and diminish the cross section of a steel member in cases of connections with bolts and rivets. They display weak spots in the structure and need special attention, since their reliability is fundamental for the structural behavior.

The MBEI differentiates between CS 2 and CS 3 for steel connections in its visual guide (AASHTO, 2019). As shown in in Figure 15, connections with loose fasteners or pack rust are classified as CS 2, while missing connection elements and distorted connections are defined as CS 3. Since steel structures usually are not covered but by paint or resin, their visual assessment is feasible without replacement of coverings.

Condition State 2	Condition State 3
Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, or fasteners; broken welds; or pack rust with distortion but does not warrant structural review.

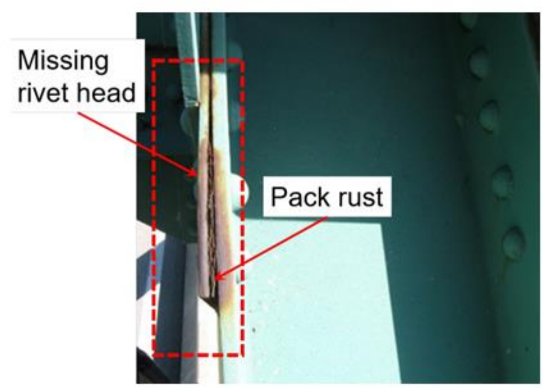


Figure 15: Visual Guide for Defect 1020 CS 2 and CS 3 (AASHTO, 2019)

CHAPTER 3 - ENHANCED VISUAL INSPECTION METHOD

This chapter provides the framework and principles for the conducted case study, testing enhanced procedures for visual bridge inspection. First, a short justification of the selected approach and the importance of human-centered bridge inspection is provided. Second, the study scope is defined and justified by analyses of the NBI. Third, subprocesses of current inspection procedures and their potential for enhancement are derived. Then, the two investigated technologies and their application to the case study are described.

3.1 FRAMEWORK

The developed enhanced bridge inspection procedure is comprised of two parts. First, a Bridge Information Data Model (BIDM) is created to store bridge properties and inspection data in a 3D-database environment. Second, an AR-technology is applied to the visual inspection process to enhance the objectivity and traceability of deterioration measurements. Figure 16 displays the concept and dataflow of the developed method.

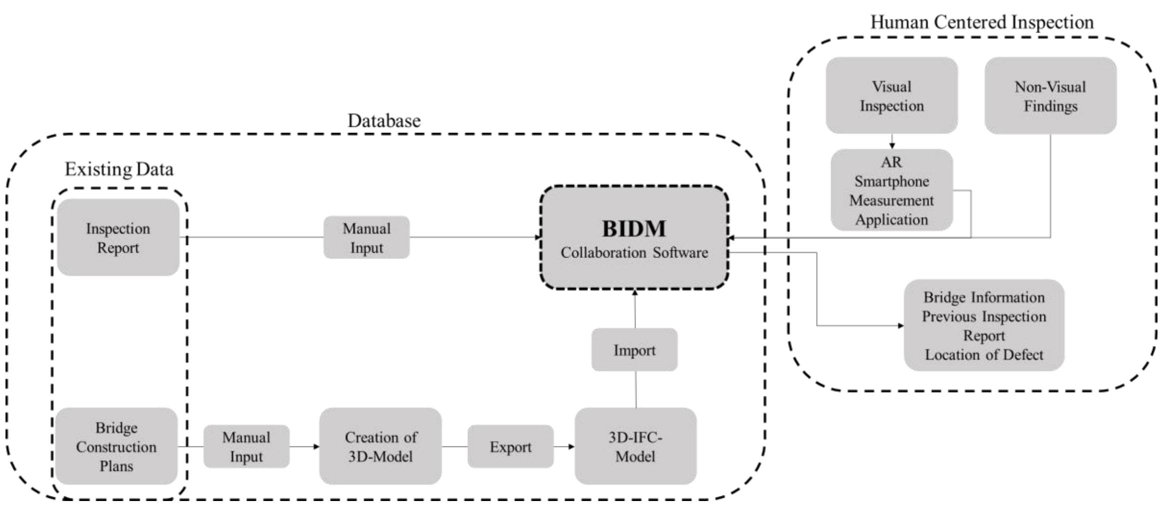


Figure 16: Concept and Dataflow of developed Method (own figure)

The created digital 3D-model is based on construction plans or as-built information and represents the database's structural component. Once created, the model is exported as an Industry Foundation Class (IFC) file and imported to a collaboration software. This is the BIDM's central interface since it connects the 3D-model and inspection data. Defects assessed in previous inspections are entered and linked manually in the BIDM database. Conducting an inspection with the BIDM, data can be accessed during the inspection on site. Assessed information, photographs, and additional data can be reviewed at the exact element it is attached to. If the element condition has changed since last inspection, the tool enables the inspector to update information about the deterioration severity.

The inspection method is a human-centered approach and still requires an inspector on site, which is different to other research approaches for bridge inspections (compare to Section 2.6.3). However, a human centered inspection allows the assessment of a broad variety of damages and even unexpected damages are assessable, which is not possible with algorithm-based methods only. Tactile assessment of elements is still important for routine inspections as previous literature review revealed. The human-centered inspection approach is capable to fill this need. Furthermore, the BIDM promises a short-term applicability to current procedures since AR-applications are easy adaptable and data is accessible at one central location. Relying on human judgement might cause subjective assessments but can also ease processes if appropriate subprocesses are enhanced. AR-supported measurements are promising to be accurate enough and traceable for review and future use. Hence, the accuracy of AR-supported measurements is tested in this thesis to justify its eligibility for visual bridge inspection. AR-supported measurements are also called digital measurements in the further process of this thesis.

As Section 2.7 revealed, most defects on steel and concrete structures are assessable by visual methods, but still require engineering expertise to differentiate between condition states. The developed BIDM concept is a hands-on approach, combining human-centered inspection methods with enhanced data-handling and visual assessment of bridge element conditions, and incorporates the MBEI condition assessment. The application of digital measurements is implemented in the inspection process to enhance objectivity and traceability of defect measurements. It allows quick applicability to current inspection procedures and is adaptable for future changes of inspection manuals since its enhancements are incrementally adaptable. Further elaboration of enhancements to current inspection processes as well as the background of applied technologies are provided in next sections.

3.2 DEFINITION OF SCOPE

The US bridge infrastructure is diverse in terms of main design material, main design type and ADT volume they serve. Not every bridge is eligible for the inspection approach developed in this thesis. Justifying that the developed approach can be feasible and contributive for the majority of bridges, analyses of bridges stored in the NBI database are conducted.

The scope is narrowed to steel and concrete bridges only, since they are the most common main bridge materials in the US and Rhode Island, particularly. This statement is justified with analyses of the NBI below. Furthermore, as emphasized in Section 2.7, most deterioration and defects are visible on the surface of steel and concrete structures, which makes them eligible for enhanced visual inspection methods.

Since each DOT is required to develop its own inspection procedures in compliance with the federal requirements of the NBIS, the NBI analyses provided in the next section comprises particular analysis of Rhode Island bridges only (FHWA, 2009).

3.2.1 NBI DATABASE ANALYSIS

The NBI stores structural information and component level condition of bridges being covered by the jurisdiction and inspection requirements of NBIS. Access to the federal database operated by the FHWA is provided by the Long-Term Bridge Performance (LTBP) program, InfoBridge (FHWA, 2020). Currently, 617,084 bridges are registered in this federal database of which 779 bridges are in the state of Rhode Island. Analyses of the NBI with respect to main design material, main design type, ADT, and their correlation to condition rating is executed below.

3.2.1.1 BRIDGE DESIGN MATERIAL

The first analysis focuses on the shares of bridge design material types in the US and Rhode Island. Out of ten design material types differentiated in the NBI, four superior groups can be composed, namely: (1) Concrete, (2) Steel, (3) Timber, and (4) Other Main Design Material. The grouping of “other main design material” is comprised of Aluminum, Wrought Iron, Cast Iron, Masonry, and not further specified materials. Figure 17 displays the distribution of main design materials on a national level.

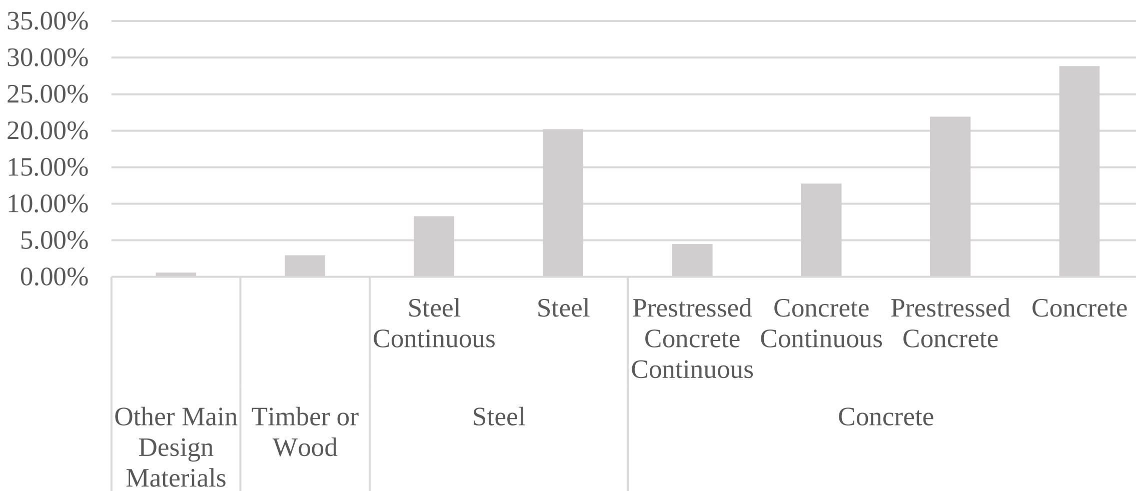


Figure 17: Share of Main Design Material of US Bridges (own figure, data: (FHWA, 2020))

Steel and concrete are the leading two materials used in bridge structures on a national level, taking a combined share of more than 96 %. Concrete bridges take the leading share of roughly 68 %, followed by steel bridges with a share of almost 29 %, comprised of continuous and single steel bridges. Timber or Wooden bridges have a share less than 3 % and other main design materials have a share of less than 1 %.

Compared to the main design materials in the US, Figure 18 shows the distribution in Rhode Island.

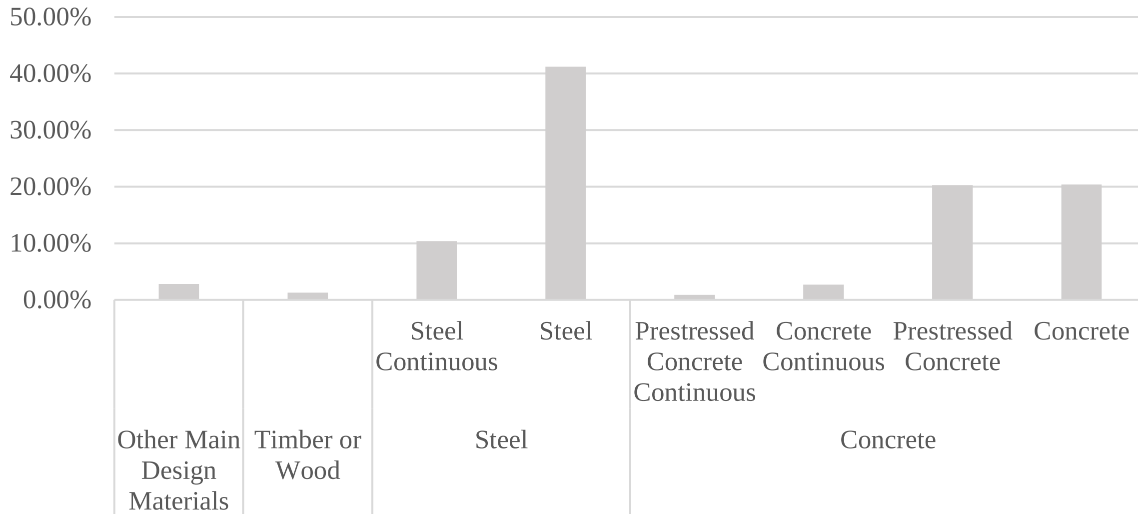


Figure 18: Share of Main Design Material of Rhode Island Bridges listed in the NBI (own figure, data: (FHWA, 2020))

Steel and concrete structures are the leading two materials used in bridge structures in the state of Rhode Island. They take a combined share of more than 95 %. However, the distribution is inverse to that found at the national level: steel bridges take the leading share of roughly 52 %, followed by concrete bridges with a share of almost 41 %, comprised of prestressed and regular reinforced concrete bridges. Other main design materials take a share of less than 3 % and Timber or Wooden Bridges are ranked last with roughly 1 % of the share.

Both graphs show the predominant existence of steel and concrete as main design materials. Even though rate and ranking of steel and concrete as main materials for bridges differ between national and state levels, accordance of their leading shares is obvious. For the process of this thesis, the scope is narrowed to these materials. Neglecting other materials but steel and concrete narrows the scope to a total of 747 bridges in Rhode Island.

Justifying the limitation to steel and concrete bridges, a two-parameter analysis with respect to main design material type and the share of daily traffic served by each bridge material is conducted. As Figure 19 displays, steel and concrete bridges also take the first and second highest shares of the ADT volume.

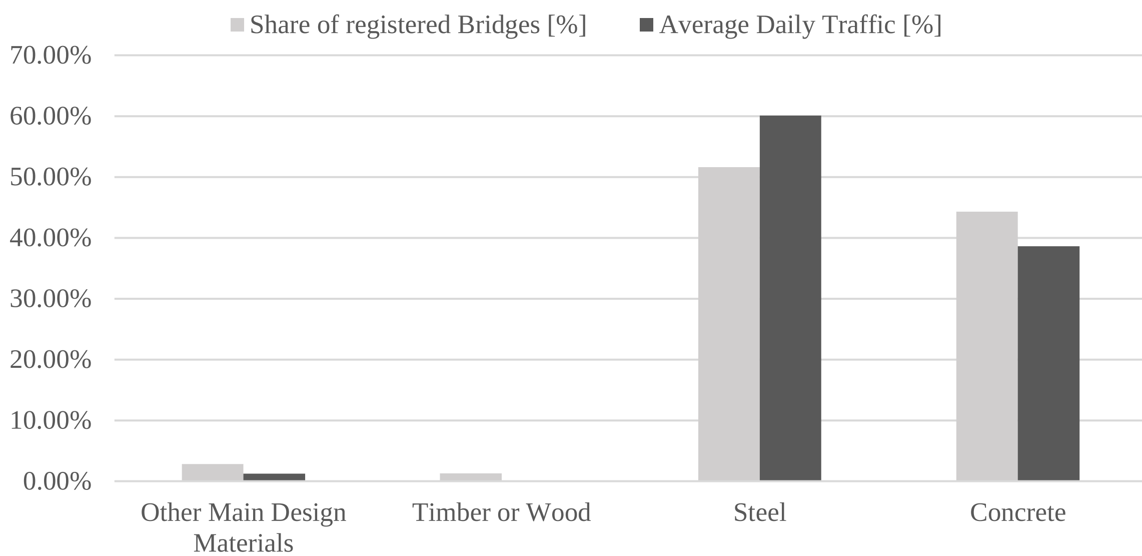


Figure 19: Share of Main Design Material and Average Daily Traffic, RI (own figure, data: (FHWA, 2020))

Steel and concrete bridges serve more than 98 % of vehicles passing on bridges in Rhode Island. Comparing the ADT allows a classification of importance within a road network. Assuming that more frequented bridges are more relevant for a road network than less frequented bridges, it can be stated that steel and concrete bridges are essential for Rhode Island's private and commercial traffic. Enhancing inspection methods for these structures particularly contributes to the goal of ensuring the reliability of Rhode Island's road network.

3.2.1.2 CORRELATION OF CONDITION RATING, MATERIAL TYPE AND ADT

Next, analyses of steel and concrete bridges with respect to the condition rating and their share of ADT volume is conducted. The distribution is displayed in Figure 20. Only the 747 steel and concrete bridges are considered.

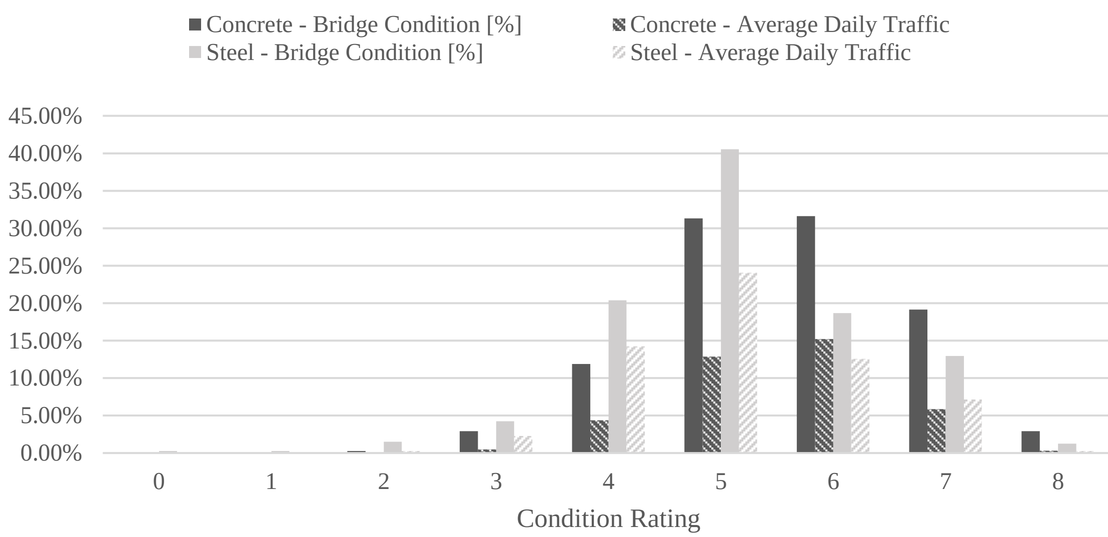


Figure 20: Correlation of Condition Rating, Material Type and Average Daily Traffic, RI (own figure, data: (FHWA, 2020))

The summed share traffic volume served by steel and concrete bridges comprises more than 98 % of the total ADT volume on Rhode Island's bridges as analyzed before. The bridge condition rating is explained in Section 2.3.1. The distribution shows that most steel and concrete bridges are classified between condition rating 4 and 7. Of the 747 bridges, 59 % of steel bridges are designated as in fair condition since their condition is rated as 5 or 6. They serve roughly 36 % of the total ADT volume on Rhode Island's bridges. The majority of concrete bridges (almost 63 %) are rated as in fair condition, while they serve roughly 28 % of the ADT volume on Rhode Island's bridges. More than a quarter of steel bridges (roughly 26 %) are rated as poor since their condition is rated less than 4. Still, they serve roughly 16 % of the traffic on Rhode Island's bridges. In comparison, concrete bridges, however, are in slightly better shape since only 15 % are rated in poor condition, while serving less than 5 % of the ADT volume.

3.2.1.3 CORRELATION OF ADT AND MAIN CONSTRUCTION DESIGN TYPE

Next, the correlation of ADT and the main construction designs of steel and concrete bridges are analyzed. Figure 21 displays the share of ADT on Rhode Island bridges in relation to the main construction design.

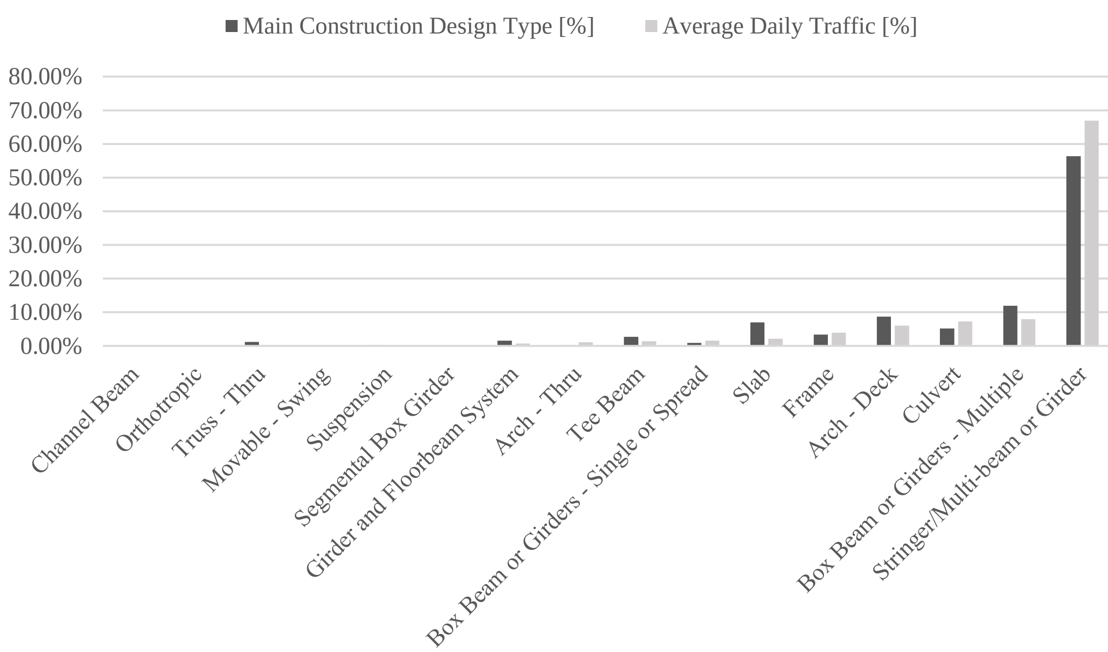


Figure 21: Correlation of Construction Design Type and Average Daily Traffic, RI (own figure, data: (FHWA, 2020))

The dark columns display the share of each construction design type, while the light columns display the share of ADT volume served by each construction design type. The leading main construction design is stringer systems with a share of 56 % while serving more than 66 % of the total ADT volume on Rhode Island's bridges. Next, the five most frequented structures are multi- and single-span box beam bridges, culverts, arch-deck constructions, frame structures, and slab systems with a summed ADT volume of 29 %.

The NBI analyses demonstrate that it is eligible to narrow the scope of this thesis to steel and concrete structures only. Developing a new bridge inspection method is only reasonable if its applicability to most bridges is feasible. Analyzing the main construction design type shows that most bridges in Rhode Island rely on conventional construction design types and are no complex bridges that would require additional inspection methods as stated in the BIRM (Ryan et al., 2012).

Exact data of these graphs is attached in Appendix F or can also be accessed online at the LTBP database (FHWA, 2020).

3.3 ENHANCEMENT OF INSPECTION PROCEDURES

The literature review conducted in Chapter 2 about current inspection procedures, data handling, and bridge management reveals the potential for easements and enhancements of bridge inspection procedures. Current BMSs rely on optimization models, risk assessment, and cost-benefit analyses to provide data-driven, comprehensible suggestions. The BMS procedures are based on statistical prediction models and can be adjusted by software programming. Still, BMS depend on raw-data collected by inspection and inventory procedures that lack accuracy and objectivity (Washer et al., 2019).

The TRB issued a research needs statement in 2018 calling for new methodologies comprised of documentation, organization, and visualization of data for infrastructure objects (Glisic et al., 2018). Infrastructure management faces three main challenges, namely the heterogenous nature of deterioration data, the size and geometry of infrastructure objects, and the collaboration of multiple stakeholders with different interests and knowledge. More available information might turn into underutilization of data if not professionally managed and might cause less-than-optimal decisions. Therefore, a new method for managing data is necessary. The TRB denominates three digital tools, VT, IM, and AR, as possible solutions to face emphasized challenges.

The BIDM and AR-supported measurements that are investigated in this thesis partly address each of the named tools. Denominating actual enhancements along the inspection processes, steps from inspection planning to identify items for repairs and maintenance are displayed in Figure 22. Particularly the procedures for inspection preparation, inspection performance, and report preparation exhibit potential for enhancements with the developed tools of this thesis. Since the processes themselves comprise multiple steps and documents, Appendix G displays the inspection organizational chart with detailed activities derived from the BIRM.

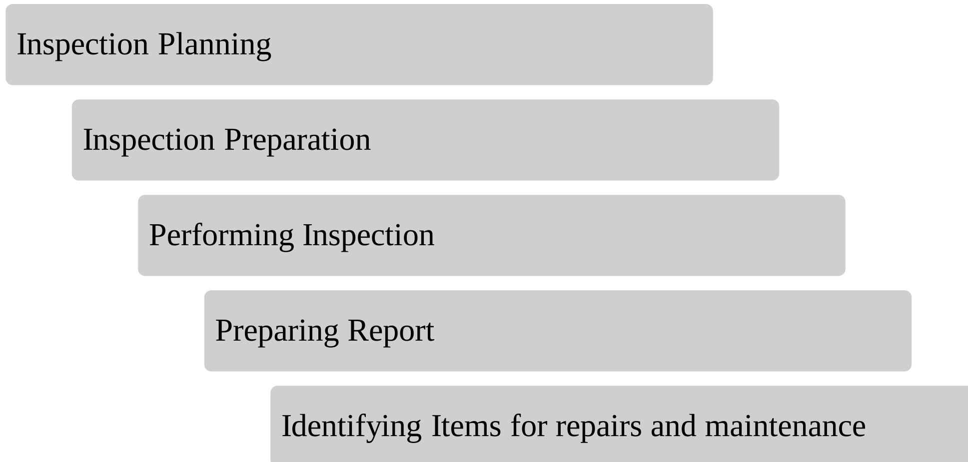


Figure 22: Bridge Inspection Process (cp. (Ryan et al., 2012))

The inspection process starts with inspection planning to determine the actual necessity of inspection type and the scheduling of the inspection. Next, the inspection preparation is comprised of the collection of data and information for the specific planned inspection at one location. Performing the inspection is the actual assessment of the real bridge structure on site. New information about the current condition is collected. To document the assessed condition, next the inspection report is prepared. If further action is required, it is required to document the specific elements and address the issues to the according personnel.

In order to ensure the reliability of inspections and ratings, raw-data must be inventoried as objectively as possible (Ryan et al., 2012). However, current inspection outcomes strongly rely on human factors, and therefore are subjective (Washer et al., 2019). Enhancing the objectivity and traceability of data acquisition and preserving the advantages of engineering judgement, a human-centered method is developed in this thesis.

In the following two sections, major enhancements for the inspection process are emphasized.

3.3.1 DATA HANDLING AND ACCESSIBILITY

Current inspections have reoccurring steps along inter-inspection and intra-inspection processes. Data from previous inspections are reviewed and arranged, deteriorated elements must be identified, and an inspection sequence must be developed. Paper-based inspection reports with attached photos, sketches, and construction drawings must be aligned with findings from the inspection report. These steps are part of the inspection preparation as Appendix G displays.

The process of identifying components and elements before each inspection from previous inspection reports is eliminated when using the BIDM. Each bridge element is identified by one unique identification code once the 3D-model is created. Repeated identification before each biennial inspection can be eliminated.

Using unique identification codes eases the process of storing and accessing deteriorated elements and associated photos, construction drawings, or other information. Each bridge element can be addressed separately, and associated information can be attached or read. This feature eases the process of collocating information of one element from different sources. Furthermore, the 3D-database structure contributes to the orientation and identification within the bridge structure. The inspector can navigate within the 3D-model on a smartphone, laptop, or other mobile device. Defect information of each element is stored in the digital model as it is recorded at the real structure on site.

Prior to the inspection, execution sketches, notes, and forms must be prepared to record data on site at the upcoming inspection. Since the BIDM already provides a visualization of the bridge structure, it is not necessary to prepare construction drawings or sketches. Notes are added via one incorporated tool to one or more elements, depending on how many elements are addressed by one issue.

While performing the inspection, the BIDM contributes to the orientation on site once it is positioned. It helps localize previously recorded conditions by showing tags on defect elements in the 3D-model. The inspector can follow these tags and either update information if changes since previous inspection have occurred or add new tags to the structure if new defects exist. Information attached and stored at one element is not limited to visual assessment only; tactile, sounding, or other findings can be recorded with the tags as well.

Furthermore, using the BIDM eases the collaboration of different stakeholders over the bridge’s life cycle and contributes to efficient workflows since the platform updates in real-time and is accessible by multiple users at the same time. Regarding quality assurance and quality control required by the latest RIDOT Bridge Inspection Manual (RIDOT, 2013), the BIDM enables enhanced quality assessment. Since traceability of changes of the element condition and their localization within the structure are enhanced, peer reviewing is eased, and quality control enhanced. Furthermore, transferring information regarding follow-up inspections, reporting of critical areas, or directing repairs is eased with the BIDM.

3.3.2 AR-SUPPORTED MEASUREMENTS

Enhancing the defect measurements on site, AR-supported measurements by mobile applications are under survey. Currently, defects and deterioration are either estimated or measured with conventional tape measure or inch rule (Washer et al., 2019). Current state-of-the-art technology allows digital measurement by using AR-enabled mobile-devices, like smartphones and smart-glasses, which promise to contribute to the collection and assessment of deterioration on site.

First, the handling of measuring tools is eased, since the inspector does not need a tape measure, notebook, and camera anymore, but only the mobile device that incorporates these three tools into one. The inspector uses one application to digitally measure the extent of deterioration on an element's surfaces and captures the assessed measurements by taking a photo of the digital measure superimposed on the real defect. AR-applications are designed to take measurements from short distances; hence the inspector is not obligated to be within an arm-length from each object. For conventional measurements, it is required to attach the measure tool directly to the surface of the object. Still, if areas require more detailed assessment, the inspector can apply tactile methods to assess the element's condition.

Second, the quantifiability of defects is enhanced by AR-supported measurements. Providing simplified methods to assess the extent of defects and deterioration contributes to the demands stated by the Rhode Island TAMP to install a data-driven bridge management approach (RIDOT, 2019b). If more quantified data is entered at the first stage into the BMS, data driven BMS decisions are more comprehensible. The acquisition of more detailed data on the element level also supports the data-driven approach of state-of-the-art BMSs and further calculation of structural sufficiency.

Third, AR-supported measurements address objectivity of visual inspections as the traceability and replicability are enhanced. The measurement is executed digitally by superimposing the real environment with the digital measure tool of the AR-application. Proving measured defects, the application allows the inspector to capture photos of superimposed digital measurements and the defect's real environment. Each distance is explicitly defined by nodes and therefore is replicable for future assessment of the same defects. It can measure multiple distances and areas at once without capturing multiple photos as is currently necessary when using conventional tools.

One side effect of conducting measurements with an AR-enabled mobile device is the increased safety of inspectors. Since the method is executable with one hand, inspectors can hold themselves with the other hand while standing on ladders or scaffoldings, which increases their personal safety.

As the enhancements for inspection processes are illustrated, next, requirements for implementing the proposed technologies into current inspection procedures are stated. The following sections also provide necessary software solutions to conduct the case study in Chapter 4.

3.4 BRIDGE INFORMATION DATA MODEL

The BIDM follows basic principles of BIM concepts. BIM implies the existence of a digital 3D reconstruction of a facility, which is measurable and quantifiable, comprehensible for planned use cases, accessible for different users and interoperable, and durable over all phases of a facility's life cycle (Eastman et al., 2008).

Derived from this BIM definition, the BIDM at its current stage is a measurable and quantifiable 3D-model that combines the needs for inspection purposes and exchange of information between bridge stakeholders. As defined, a BIM model is required to serve all phases of a facility's life. However, applying a BIM method to build infrastructure is comprised of requirements for the O&M phase and removal and dismounting phase (R&D phase) (compare Figure 1) and their stakeholders. Figure 23 displays stakeholders of highway bridges, with the superordinate agency FHWA.

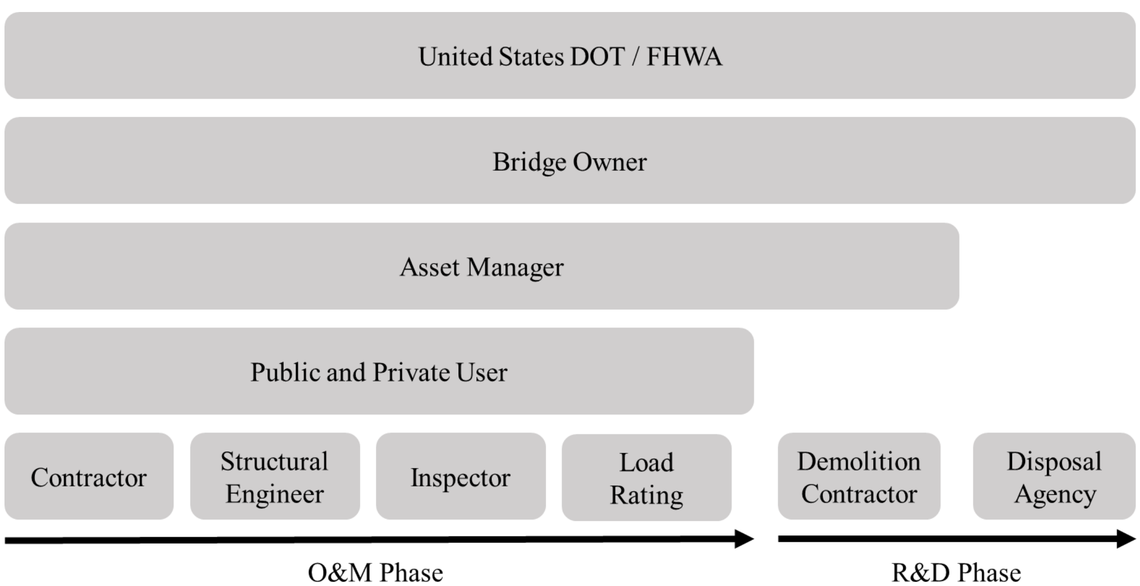


Figure 23: Bridge Stakeholders during O&M and R&D Phase (own figure)

The FHWA defines federal guidelines and demands inspection reports and condition statements over a bridge’s life cycle from bridge owners. Bridge owners might change over a bridge’s life cycle if the state DOTs sources specific bridges out to subsidiaries, like state owned toll agencies or for other purposes. However, both stakeholders are involved over the whole life cycle. Other stakeholders are only involved in the bridge life cycle part-time or are just contracted for specific purposes, e.g. contractors and special engineers. Exchanging data between these stakeholders requires structures that are easy to adapt and understandable for the different users. Important information might get lost if not handled properly. Hence, the BIDM provides a central database that allows stakeholders to access required data quickly and enhances interoperability of involved partners. The stakeholders mentioned in the figure above can be expanded by various amounts since sub-contractors or other specialized or consultant engineers are hired. Easement of the data handling is then even more important since more parties collaborate.

Interoperability between stakeholders is enabled by establishing the IFC data format, which is emphasized below. Furthermore, model requirements of BIDM for enhancing bridge inspection procedures are stated. Then, the selected software solution is presented and explained.

3.4.1 INDUSTRY FOUNDATION CLASSES

Representing different stakeholders' needs, the BIDM is required to be interoperable and transferrable between different software solutions without losing specific capabilities, specifications, or information. Collaboration is one of the major advantages of the developed BIDM, hence a data format that allows high interoperability is required.

IFC are designed to combine various information within the lifecycle of a building or structure (buildingSmart International, 2020a). The format is a vendor-neutral and open international standard that stores physical and structural objects as well as other associated information and allows users to add information of various sources to predefined elements. It allows defining properties and attribution of elements. The data format is designed to serve as an information exchange platform between different stakeholders, providing necessary information for designated use-cases of different recipients. It is approved by the International Standards Organization (ISO) as a data exchange format for the construction and facility management industries (International Standards Organization, 2018).

IFC can be accesses and encrypted by various software applications, which allows different changes or operations within the data file. BuildingSmart defines categories for the different software applications. For the O&M and R&D phases of bridges, the categories Model Authoring, Data Server and Facility Management are contributive. Currently, 288 different software applications are listed that serve IFC files (buildingSmart International, 2020b). The interoperability between different software solutions of various software suppliers is ensured.

The FHWA investigated possible data exchange formats and found IFC as the best fitting solution for the use case of bridges (Chipman, Costin, Eastman, et al., 2016). Pivotal arguments for relying on this file format are that most vendors in the construction industry already implement the data format, the certification as an ISO standard ensures continuous support and maintenance, and its operability is already proven by practice since it passed vendor validation and certification.

The IFC format is chosen as the central exchange format for the BIDM due to the former stated strengths and the advanced implementation in current practice. The case study tests if the selected exchange format is feasible for the developed method.

3.4.2 BRIDGE INSPECTION – BIDM REQUIREMENTS

To enhance the visual bridge inspection processes, the following requirements must be fulfilled. The BIDM is required to contain element level accuracy and as-built status, allowing it to address the specific element that might exhibit defects. It is required to divide elements in reasonable parts to ensure identification and traceability of defects within the structure. Therefore, elements should be definable on site by joints or other marks. These aspects are addressed by a Model Authoring software that can create a 3D-model of a bridge.

Addressing correct elements, it is required to establish consecutive and comprehensible nomenclature of bridge elements. The nomenclature should follow reasonable alphabetic or numeric schemes supporting the orientation on site with cardinal points or level token.

Next, the BIDM is required to allow the assessment and attachment of information to elements or specific locations within the structure. This is comprised of information from previous inspections as well as new inspection data assessed on site, such as notes, photographs, and measurements. The connection between element properties and element information must be permanent to be traceable and allow assessment of deterioration over time. Therefore, storing information to one element should not be limited in terms of data type and size.

As stated previously, the BIDM should contribute to the whole process chain of bridge inspections. Hence, one requirement is the accessibility on different devices to contribute to the workflow and data handling between assessment on site and further post-operations. The BIDM is required to be accessible by mobile devices as well as personal computers or laptops.

3.4.3 SOFTWARE SOLUTION

The BIDM is based on two software solutions that are trademarks of Trimble Inc. Tekla Structures 2019i, with the authorization of an educational license, serves as the Model Authoring software. Trimble Connect is used as a data server and collaboration software on mobile device and personal computer.

Tekla Structures 2019i is a BIM software to design and analyzes structures (Trimble Solutions Corporation, 2019). It offers multiple functions for customizing and adapting shapes and objects and allows parametric modeling. Nomenclature for construction elements can be defined before the model is created to guarantee the singularity of each element description and unique identification. Furthermore, construction objects can be manipulated in the model if required. Hence, findings from inspections can be added to the digital structure to display the damage. With the analysis tool, it is possible to compute load restrictions and structural behavior if elements show defects.

The collaboration software, Trimble Connect, was originally developed for construction management purposes and the design stage of structures. Its collaborative properties, however, allow using it for inspection purposes and for the previously stated requirements. Trimble Connect embeds an IFC model that provides a variety of model views and a walk-through option. Information, data, and additional files can be added by so-called Markups and ToDos. ToDos allow the storing of associated information and linkage of multiple files, but Markups can be added for more precision to specific locations in the structure.

The Trimble Inc. solutions are chosen since they provide uniformity for the whole BIDM use-case. Data exchange between Tekla Structures 2019i and Trimble Connect is simplified by an interface. This interface allows interchanging of the IFC model between the model authoring software and data base. IFC structural properties can be changed in Tekla Structures 2019i and uploaded to Trimble Connect without losing connected data.

3.5 AUGMENTED REALITY TECHNOLOGY

This section is comprised of a short introduction into AR-technology and then focuses on its contribution for visual bridge inspection processes. After stating the general applicability of AR technology for visual bridge inspections, the specific use-case of AR-supported measurements and their requirements and implementation are emphasized.

3.5.1 AR TECHNOLOGY – BACKGROUND

The idea of Augmented Reality (AR) technology reaches back to the early 1990s when the first interaction between computer graphical images and the real environment were developed and researched. Acceleration in computer science, image-processing, and camera technology during recent decades determined the path of AR, leading to today's precise accuracy and versatile use cases.

AR can be categorized as one technology in the broader field of mixed reality (MR) or as a variation of virtual environments, as Figure 24 displays.

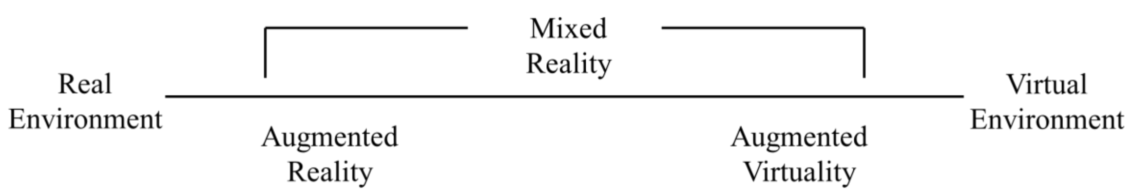


Figure 24: Position of Augmented Reality in the Field of Mixed Reality (modified, cp. (Milgram & Kishino, 1994))

MR itself spans the gap between singular real environment and total virtual environment. AR can be characterized as a combination of the real and virtual environments that interact in real time and it has the potential to address 3D objects. Since AR interacts in the real environment and supports digital or virtual layers and tools for the user, it tends more to real environment than virtual environment (Azuma, 1997).

Using AR, real and virtual objects coexist besides or within each other (Azuma, 1997). Real objects can be defined as actually existing in a real environment with haptic surfaces, however, virtual objects cannot be touched and exist in essence or effect only (Milgram & Kishino, 1994).

Placing or locating virtual objects or tools in the real environment requires accurate superposition of real and virtual layers. Synchronizing and aligning of the virtual and real environment is called tracking (de Souza Cardoso et al., 2020). One common method to attach virtual elements or layers to an accurate position is through the use of fiducial markers (Khan et al., 2015). This method requires one image or specific point in the real environment that can be scanned. Virtual layers and objects are attached with respect to this marker. In the recent past, other marker-less tracking methods were developed and are part of research activity (Paulo Lima et al., 2017). "Simultaneous Localization and Mapping" and "Natural Feature Tracking" are two methods that have gained the most interest (de Souza Cardoso et al., 2020).

Depending on the digital tools displayed in the virtual environment, information from the real environment can be assessed and transferred into digital information. Information as images, distances and area measurements, and positioning data are only a few examples that can be inventoried from the real environment into the virtual environment. Ensuring exact overlaying of both environments, AR needs continuous orientation within the 3D environment.

Regarding AR enabled devices, these devices are classified between head-mounted and hand-held devices. Hand-held devices are common, like smartphones or tablets, while head-mounted devices are also known as AR-glasses or specific AR-helmets.

3.5.2 BRIDGE INSPECTION – AR REQUIREMENTS

The requirements of implementing AR technology for bridge inspection purposes can be separated into two categories: First, specific requirements for implementing AR-supported measurements – as it is researched in this thesis; and second, for the implementation of AR technology as comprehensive assessment method for future application.

To implement AR-supported measurements, accuracy on the same level or higher as conventional measurements is necessary. It must be ensured that the digital layer is able to detect the real environment surface correctly. As stated in Section 2.4.3, the AASHTO MBE defines the level of accuracy required for measurements of different materials. For concrete elements, the accuracy of a measurement up to 0.5 in is defined as acceptable, for steel members the accuracy must be as high as to identify the section as Table 1 emphasizes. Ensuring traceability and replicability of conducted measurements, the AR device must be able to take pictures of measured defects. The application is required to detect length, width, height, and depth of surface defects. Accuracy, traceability, and replicability are tested by the case study conducted in Chapter 4.

In addition to the previous stated requirements for AR-measurements it also is required to superimpose the digital model to the real environment to apply AR technology as a comprehensive method for bridge inspections. Therefore, the model must be as accurate as the built bridge. Furthermore, it is required that the software recognizes movements of the inspector within the structure to ensure the continuous alignment of digital and real surfaces. This enables automatic localization of defects within the structure and simplifies the process of attaching defects to the correct element.

3.5.3 SOFTWARE SOLUTIONS

To focus on the applicability of AR-supported measurements for bridge inspection purposes, free available software solutions are investigated. The smartphone application Measure developed by Apple Inc. enables measurements up to 0.5 in or 1.0 cm (0.3937 in), and matches the requirements regarding accuracy of visual inspections and measurements as displayed in Table 1. The application allows multiple measurements at a time and provides area measurement. It has photo functions to record digital measurements superimposed on the real environment. Measured distances are displayed with limitation-nodes that are as accurate as to allow the reproduction and traceability of measurements by other parties. Applicability and accuracy of measurements will be tested in the case study emphasized in Chapter 4.

The process of assessing element's condition and conducting the bridge inspection on site is displayed in Figure 25.

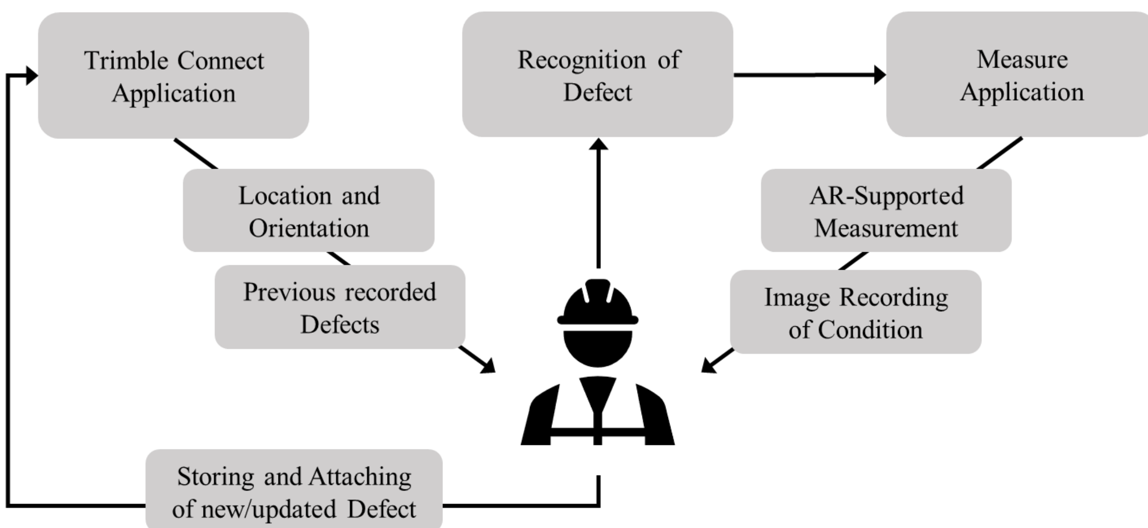


Figure 25: Human Centered Inspection using Trimble Connect and Measure (own figure)

The Measure application provides digital measurements and photos but misses an interface to collaborate with the BIDM. To connect assessed information with elements in the BIDM, the mobile solution of Trimble Connect is used. An assessed element is selected and collected information is attached. The inspector can identify the location and access previously recorded conditions by Trimble Connect. The Measure application supports the inspector with enhanced and simplified measurements and image recording, but the defect must be recorded manually. Recorded data is then stored and attached by the inspector via the Trimble Connect to the BIDM.

The latest version of the mobile Trimble Connect application provides an interface for Microsoft HoloLens AR-glasses, which is promising to incorporate the data collection and measurement process into one application. Furthermore, this interface would contribute to the comprehensive implementation of AR that is comprised of superposition of the digital and the real environment.

CHAPTER 4 – CASE STUDY BRIDGE INSPECTION

Testing hypothesized enhancements from previous chapters on site, a case study involving two concrete bridges is developed below. The case study investigates quantifiably the accuracy of AR-supported measurement and qualitatively enhancements for inspection processes using BIDM. Bridges with RIDOT agency-IDs 091101 and 091201 are determined as objects for this case study.

4.1 BRIDGE LOCATION AND SERVICE

The selected bridges are located in southern Rhode Island in the town of Jamestown, as Figure 26 displays. A larger overview of Figure 26 as well as photos and model views of the case study objects are provided in Appendix H.

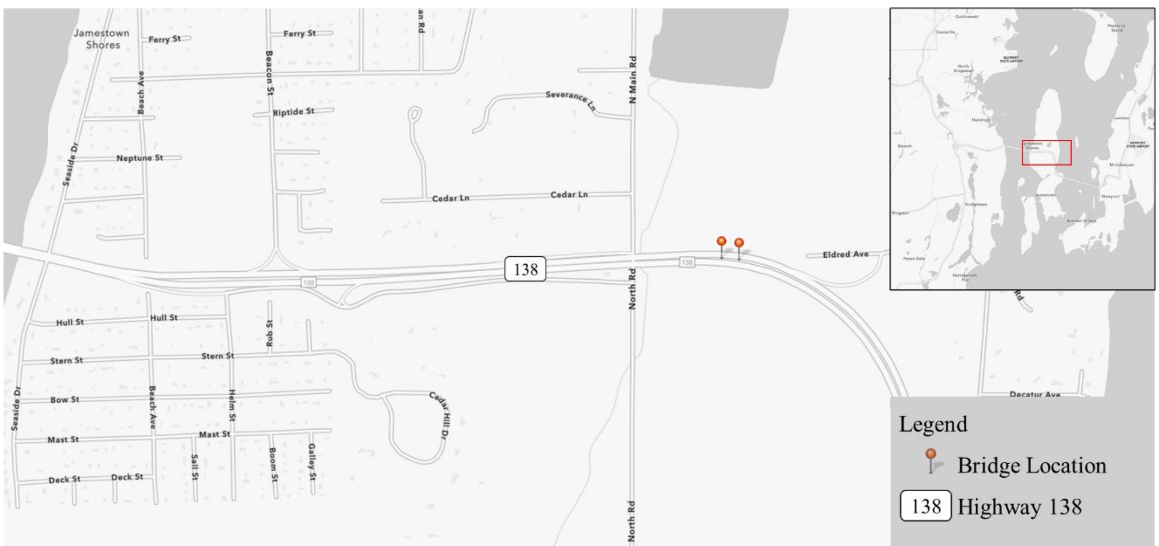


Figure 26: Location of Surveyed Bridges in Jamestown, Rhode Island (modified, map: (ESRI, 2020))

Route 138 is the inventory route that is served by the bridges. The four lane highway is designated as a freeway (RIDOT, 2019a) connecting Washington County and Newport County and is serving an ADT of 26,700 vehicles (FHWA, 2020). On the lower level, both bridges serve as wildlife passages and allow wildlife to cross below the highway from north to south and vice versa (RIDOT, 2019a).

The western located bridge with the RIDOT agency-ID 091101 (NBI-ID 000000000009110) is denominated Arch III. The eastern bridge with the RIDOT agency-ID 091201 (NBI-ID 000000000009120) is denominated Arch IV. These denominations will be used for the remaining parts of this thesis.

The bridges are currently owned and under the jurisdiction of the Rhode Island Bridge and Turnpike Authority (RITBA). A routine inspection in May 2018 rated both bridges as in good condition, with a condition rating of 7 for the superstructure and substructure, which is above the average of Rhode Island's bridges. Findings and ratings from the latest routine inspection, conducted on May 21st, 2020, are not published yet. The bridges were built in 1994, hence their age is below the average of 57 years for NBI listed bridges in Rhode Island (FHWA, 2020).

4.2 BRIDGE SELECTION PROCESS

This section emphasizes briefly the selection process to find eligible bridges for conducting this case study and justifies the selection of Arch III and Arch IV. Considerations in the selection process have been: first, safety aspects and accessibility; second, matching previous set limitations to steel and concrete briges only; and third, the relevance of the bridge structure as part of the highway road network.

Minimizing exposure to traffic and other harming circumstances before, during, and after the inspection had first priority. In consultation with RIDOT, the RITBA ,and engineering consultancies Michael Baker International and Steere Engineering Inc., Arch III and Arch IV are determined as safe and accessible bridges. With the risk of being exposed to highway traffic to a minimum, it was decided to only permit access to the lower level of both arches. The lower level is accessible safely from Eldred Avenue in the east or North Main Road in the west, and serves as wildlife passage only, hence harming circumstances were mimized.

Second, as determined in Section 3.2, only concrete and steel structures can be considered. The selected bridges are made of reinforced concrete arches as superstructure and reinforced concrete abutments as part of the substructure. Spandrel walls and wingwalls at the northern and southern ends are reinforced concrete elements. These elements are assessible from the ground level. The asphalt deck and steel railings at the top of the bridge are not part of this examination, since they can only be assessed from the top level. Arch III and Arch IV are eligible for this case study, since they match the set limitations.

Third, the relevance of the bridge structure is evaluated. Arches III and IV serve the highway Route 138, which is designated as part of the NHS, and is the only direct connection between Washington County and Newport County (FHWA, 2019b). The ADT of 26,700 vehicles is 1.3 times higher than the average of 20,456 vehicles per day on Rhode Island's bridges (FHWA, 2020). The ADT volume of both bridges in comparison to the other bridges in Rhode Island is displayed in Figure 27. Arch III and Arch IV are red marked.

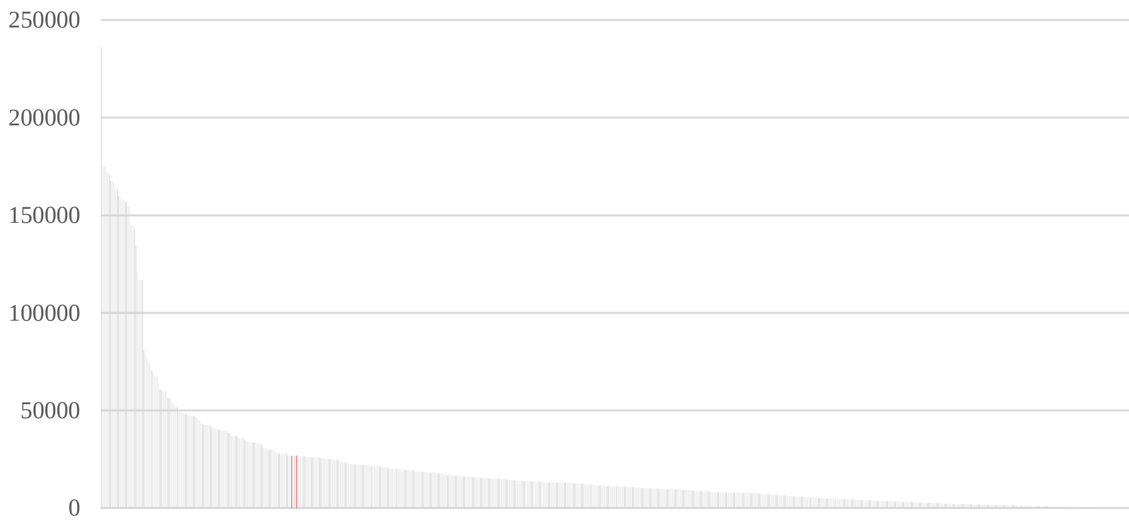


Figure 27: ADT Distribution of Rhode Island Bridges, Case Study Bridges highlighted red (own figure, data: (FHWA, 2020))

Route 138 is highly frequented and relevant for southern Rhode Island's residents and economy. Hence, the reliability of the bridge structures Arch III and Arch IV are important for the functionality of Route 138. Arches III and IV serve more traffic than the average bridge in Rhode Island, but are not the highest frequented.

Complying with all three considerations, Arches III and IV in Jamestown are eligible for application of the case study. Next, the creation of bridge models, implementation of the BIDM, and data acquisition is emphasized for each bridge.

4.3 CASE STUDY PROCEDURE

For conducting the case study on the two bridges, Arches III and IV in Jamestown, construction plans, inspection reports from the latest inspection in 2018, and associated images and data were requested from RIDOT. Then, 3D-models of both bridges were created based on construction plans' level of detail, using Tekla Structures 2019i. For the specific purpose of contributing to visual inspections, the model is comprised of elements that are visual assessable and does not provide comprehensively each structural element. Once the model is created, it is transferred as an IFC file to the Trimble Connect collaboration software. The structural 3D-model is turned into a 3D-database called BIDM when information from the 2018 routine inspection reports is entered and their respective location linked to the elements. Localizations of defects are derived from images attached to the inspection reports. Linking defects to correspondent elements, the ToDo-function of the Trimble Connect interface is used. The inspection report is turned into a 3D-database, which stores associated data in one location.

Next, the BIDM is transferred to the mobile application of Trimble Connect to investigate its feasibility for bridge inspections on site. Arch III and Arch IV are inspected and the data collection is conducted as described in Section 3.5.3. Each bridge is inspected two times for testing applicability of the software solutions Trimble Connect and Measure for mobile devices. Both inspections are executed using an Apple iPhone 8 smartphone as a single inspection tool. Each defect is entered manually into the BIDM on site with a specific code, photo documentary, and location. The defect extent is measured with the Measure AR-application, and a photo comprising the real environment defect and the digital measurement are transferred manually to the Trimble Connect mobile application and linked to the corresponding element. Data collected during the inspection on site is reviewed and processed afterwards for the accuracy analyses.

For quick identification of deficient elements in the BIDM, a defect coding scheme following the MBEI structure is created. Bridge elements and defects have specific MBEI codes (AASHTO, 2019). The existing MBEI coding is extended by the inspection-ID to identify the registration date of detected defect. Figure 28 shows the composition of this created code. The first four digits identify the inspection ID, the next 3 or 4 digits identify the specific bridge element according to MBEI element code, and the last four digits identify the defect. The example code displayed in Figure 28 implies that the inspection conducted in 2018 identified defect 1080, which is comprised of delamination, spall and patched areas, at one reinforced concrete arch element (NBE-144).

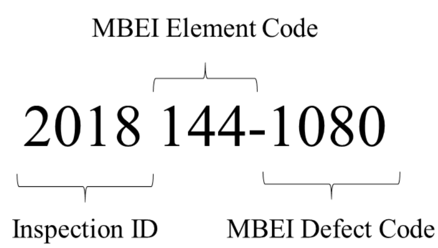


Figure 28: BIDM Coding Example for Element Defects (own figure)

This information is displayed on the tags in the structure and allows an overview identification of the defect at the connected element. It provides information about when the element was inspected last and what defect was assessed at last inspection. The inspection-IDs used in this case study are displayed in Table 3 below.

Table 3: Inspection IDs for conducted Case Study

Inspection ID	Origin and Date of Assessment
2018	Routine Inspection Report from 2018
2020	Data Sample I assessed on May 21st, 2020
2021	Data Sample II assessed on June 5th, 2020

The case study is comprised of three inspection events and their corresponding data. The first inspection event is the 2018 routine inspection report of Arches III and IV, and their inspection information is entered into the BIDM. Furthermore, two data samples compiled at two different dates in 2020 display the second and third inspection events. Two data samples to test the accuracy of AR-supported measurements are collected at these events. The second inspection event took place on May 21st, 2020 in conjunction with the biennial routine inspection at Arch III and Arch IV. The first data sample is collected at this event. The inspection started at 8:30 AM and both arches were lit up by bright sunlight. To examine the accuracy of AR-supported measurements, measurements are verified by using an inch rule. The first sample is comprised of 67 data pairs of AR-supported measurements aligned with conventional measurements.

The third inspection event took place on June 5th, 2020 at the same location at 7:30 AM. The second data sample is collected at this event. Due to cloudy skies and rain, visual conditions below the bridges were worse than during the first visit. To examine the accuracy of AR-supported measurements, each measurement is verified using a tape measure. The second sample is comprised of 74 data pairs of AR-supported measurements aligned with conventional measurements.

For accuracy, analyses with AR-supported and conventional measurements are entered manually into a Microsoft Excel workbook. In total, 303 images are recorded on site, from which 141 eligible data pairs are derived. Eligible data pairs are digital measurements that are verifiable with conventional measurements. Irreproducible data or inaccurate alignments of conventional and AR-supported measurements are not considered for further analyses.

4.4 BRIDGE 091101 – JAMESTOWN ARCH III

Jamestown Arch III (RIDOT agency-ID 091101) is the western located bridge of the two case study bridges. It has a deck width of 109.60 ft serving two highway lanes and one breakdown lane in each direction with a median strip in between. The bridge is designed as a reinforced concrete arch-deck type. Clear width of the arch equals to 30.00 ft and clear height is equal to 13.67 ft (FHWA, 2020). An overview of the created bridge model is given in Figure 29. The construction plans used to create the 3D-model of Arch III are attached in Appendix H.

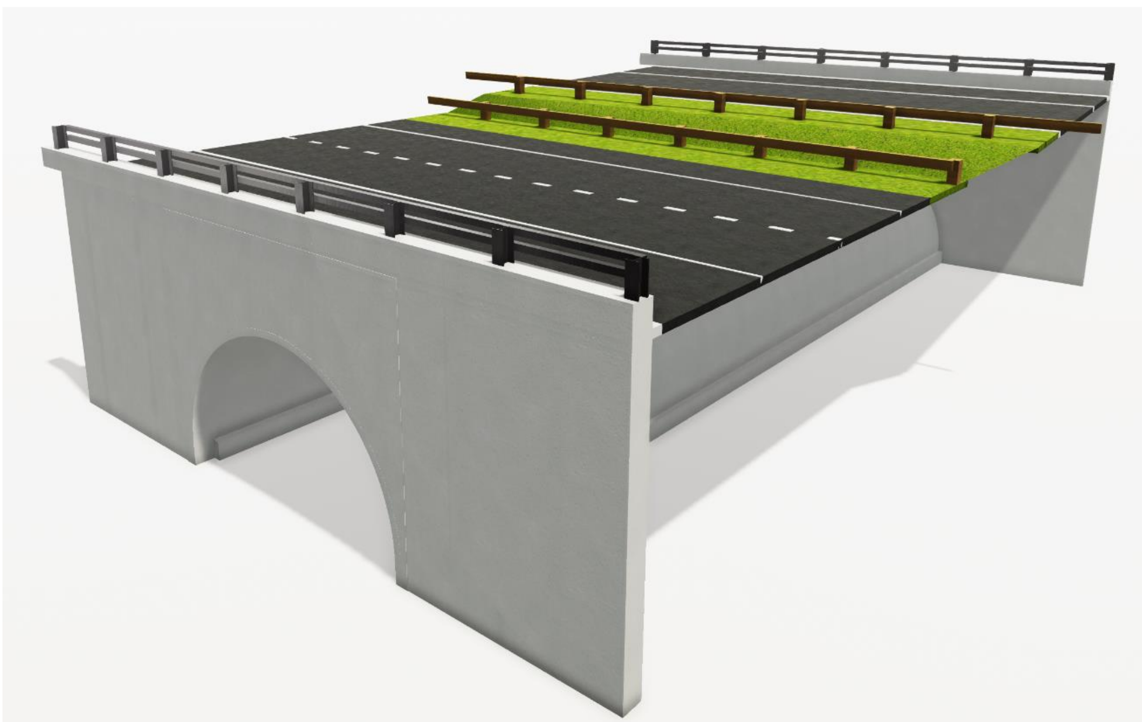


Figure 29: Jamestown Arch III, 3D-Model Overview, View to North-West (own figure)

4.4.1 BIDM MODELING

The bridge model is created with the Tekla Structures 2019i Model Authoring software and contains 193 single elements to make up the substructure, superstructure, deck, and road installations with railings and curbs.

As defined by the MBEI, reinforced concrete arches are designated as elements NBE-144 (AASHTO, 2019). The superstructure is comprised of 19 NBE-144 segments, which are denominated from north to south with nomenclature A to S. Segments B to Q are regular arch segments, each spanning 6.0 ft in length. Modified segments A, R, and S are specially shaped to fit the alignment of the structure as Figure 30 displays.

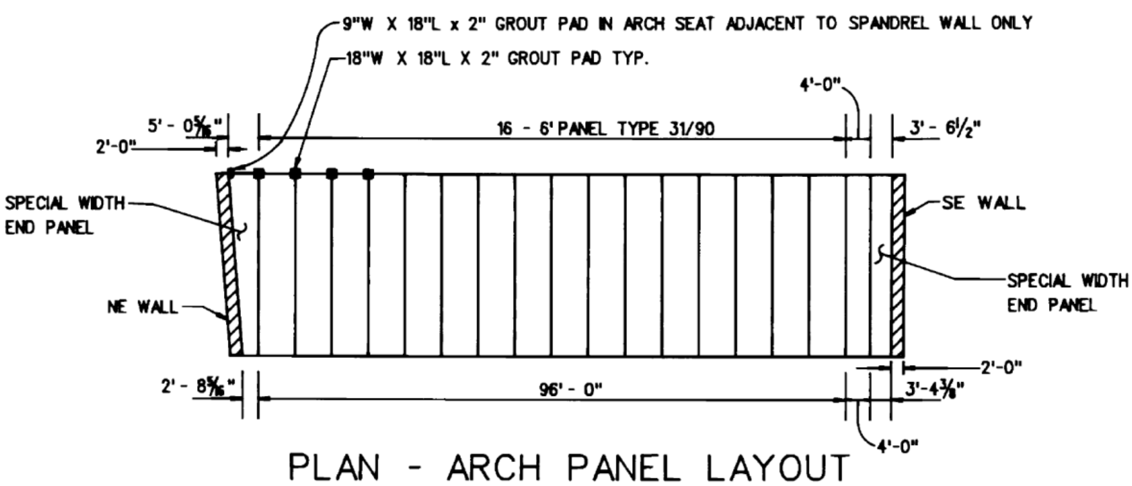


Figure 30: Cut-Out Plan View of Arch III Construction Plan (cp. Appendix I)

Each NBE-144 segment is beard by one pedestal on either side. Pedestals are part of the substructure and are defined as NBE-215 (AASHTO, 2019). Pedestal 1 is aligned at the west end of the arch, while pedestal 2 is aligned at the east end. The pedestals' nomenclature follows the denomination of the attached arches and includes numbering of either west or east side.

Spandrel walls, defined as ADE-8208 as the latest routine inspection report from 2018 states, are attached at the northern and southern ends of the bridge. The spandrel wall is comprised of the vertical rising wall of the bridge ending, including the spandrel-arch-underside. In the digital model, the spandrel wall is separated into two objects, the bearing arch, and the vertical rising wall. The spandrel arches are denominated as North Spandrel, and South Spandrel, respectively. The vertical spandrel walls are denominated as North Portal, and South Portal, respectively. Wingwalls aligned east and west of the spandrel walls are included in the model as well, since the bridge's extent is not explicitly defined.

On deck level, each lane is modelled as one element, and the curbs on either side are separated into 5.00 ft long elements. The railings on the northern end, the southern end, and between the directions of travel are separated into 10.00 ft long parts and can be addressed individually, as are railing posts.

The nomenclature for the bridge elements NBE-144, NBE-215, and NBE-8208 is derived from the 2018 inspection report and attached photos. Due to limited access as stated previous, only 71 of 193 created bridge elements are considered for the investigation. The elements investigated are listed with associated nomenclature in Table 14, Table 15, and Table 16 of Appendix I.

4.4.2 DATA ACQUISITION

The data stored in the BIDM of Arch III is composed of three events, the 2018 routine inspection, the first data sample collected on May 21st, 2020, and the second data sample collected on June 5th, 2020. In total, the BIDM contains 58 recorded defects displayed as ToDos and 63 data pairs for the accuracy analyses of AR-supported measurements.

Analyzing the 2018 routine inspection report of Arch III, 17 defects for bridge elements NBE-144, NBE-215, and ADE-8208 are found eligible to be entered into the BIDM with correspondent linkage to specific element locations. The 17 defect tags are distributed along 14 different elements. Since the inspection report itself only partly supports information regarding defect location, associated photos in the inspection report additional file must be reviewed to retrace the location. The inspection report additional file comprises 44 photos, 22 of which display defects at the superstructure assessable from below and at the substructure. The photos are used to determine defect location when entered into the BIDM.

Collection of the first data sample on May 21st, 2020 led to 24 assessed defects distributed along 17 different elements. A total of 57 photos were taken during the inspection to record element condition and justify AR-supported measurements. Of these 57 photos, 22 data pairs that are reproducible and traceable, and therefore eligible for quantitative analyses, are derived.

Collection of the second data sample on June 5th, 2020 led to 16 assessed defects distributed along 15 different elements. A total of 66 photos were taken during the inspection to record element condition and justify AR-supported measurements. Of these

66 photos, 41 data pairs that are reproducible and traceable, and therefore eligible for quantitative analyses, are derived.

Defect tags and their locations within the bridge structure are displayed in Figure 31 as a 3D-database representation or in tabular form in Table 17, Table 18, and Table 19 of Appendix J.

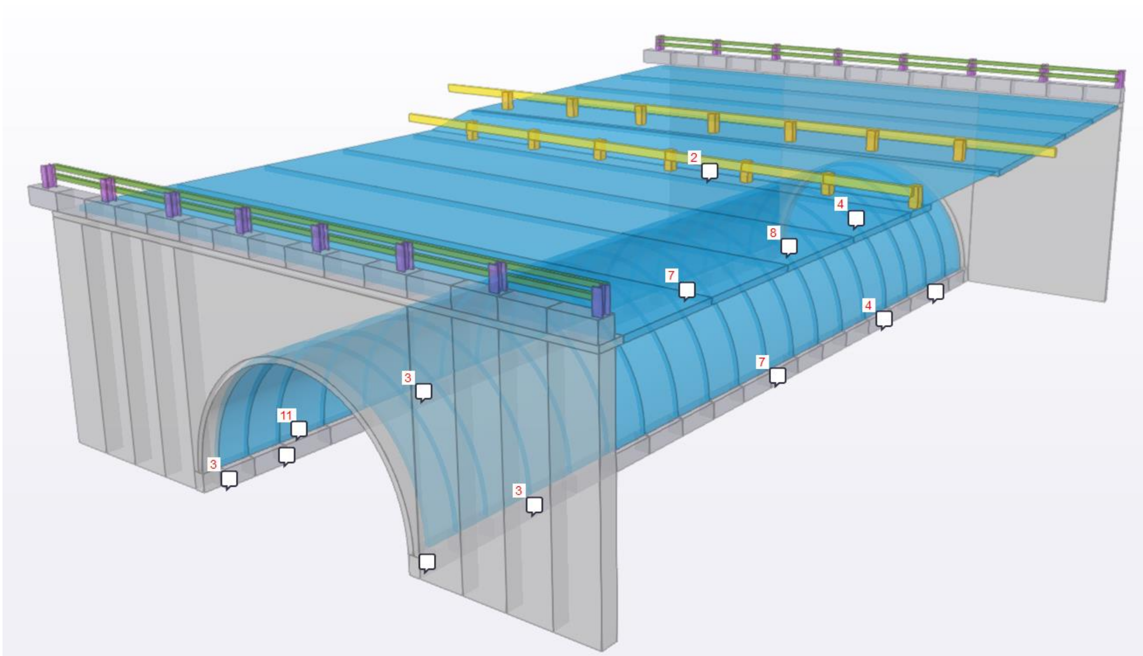


Figure 31: Jamestown Arch III, Model Overview with Defect Tags' Location, View to North-West (own figure)

4.5 BRIDGE 091201 – JAMESTOWN ARCH IV

Jamestown Arch IV (RIDOT agency-ID 091201) is the eastern located bridge of the two case study bridges. It has a deck width of 114.50 ft serving two highway lanes and one breakdown lane in each direction, and a median strip in between. The bridge is designed as a reinforced concrete arch-deck type. Clear width of the arch equals to 30.00 ft and clear height is equal to 11.33 ft (FHWA, 2020). An overview of the created bridge model is given in Figure 32. The construction plans used to create the 3D-model of Arch IV are attached in Appendix K.

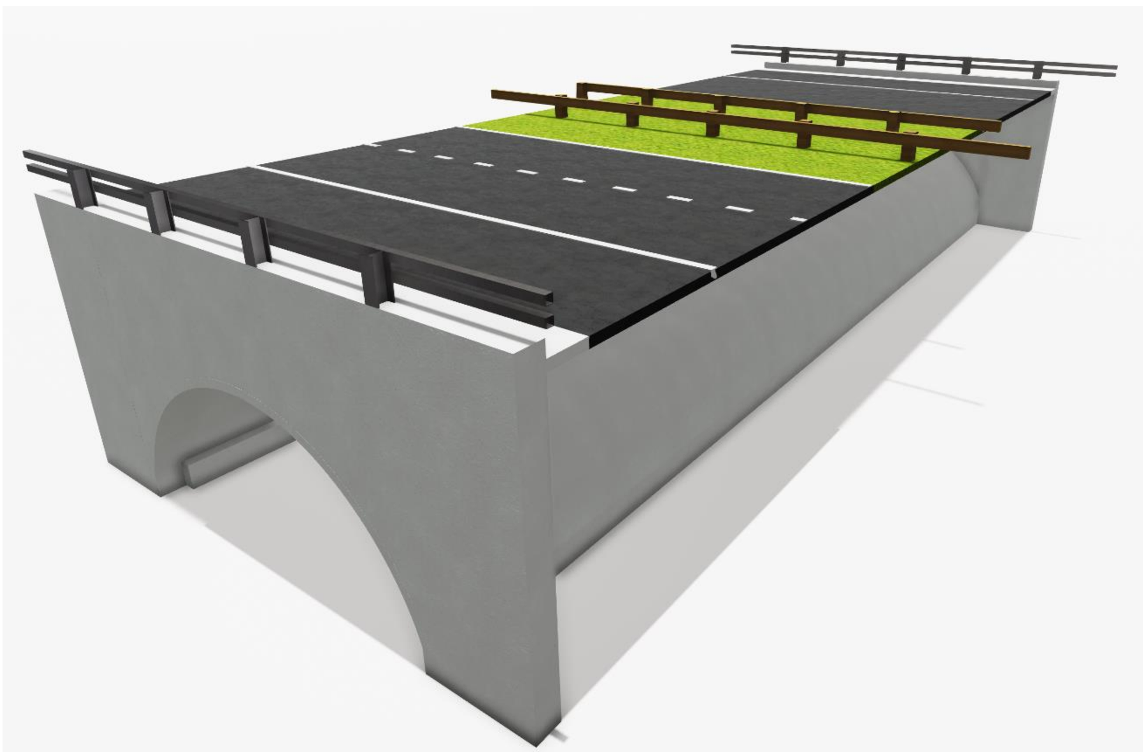


Figure 32: Jamestown Arch IV, 3D-Model Overview, View to North-West (own figure)

4.5.1 BIDM MODELING

The bridge model is created with the Tekla Structures 2019i Model Authoring software and contains 223 single elements to make up the substructure, superstructure, deck, and road installations with railings and curbs.

As defined by the MBEI, reinforced concrete arches are designated as element NBE-144 (AASHTO, 2019). The superstructure is comprised of 19 NBE-144 segments that are denominated from north to south with nomenclature A to S. Segment B to R are regular arch segments, each spanning 6.00 ft in length. Modified segments A and S are each 3.80 ft long to fit the alignment of the structure as Figure 33 displays.

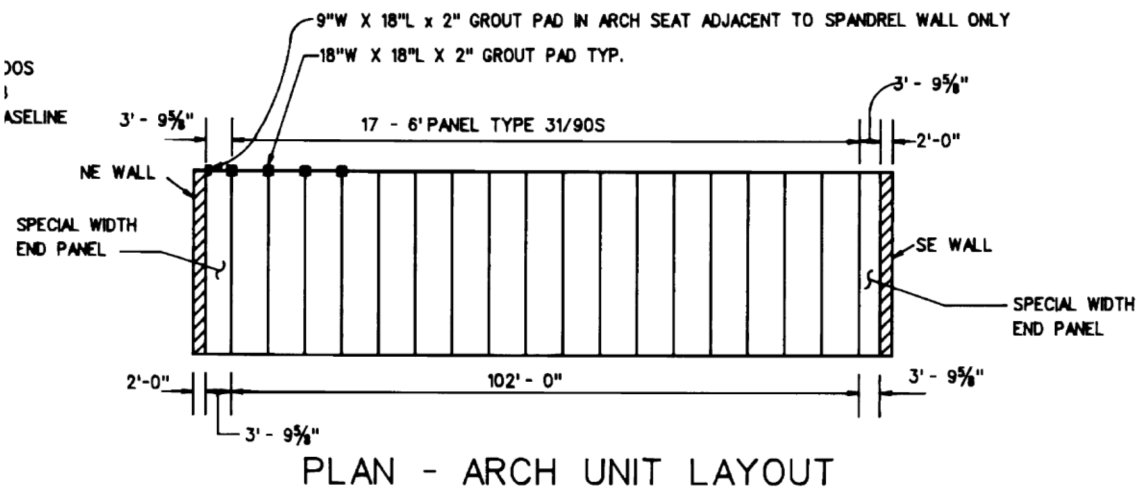


Figure 33: Cut-Out Plan View of Arch IV Construction Plan (cp. Appendix K)

Each NBE-144 segment is beard by one pedestal on either side. Pedestals are part of the substructure and are defined as NBE-215 (AASHTO, 2019). Pedestal 1 is aligned at the west end of the arch, while pedestal 2 is aligned at the east end. The pedestals' nomenclature follows the denomination of attached arches and includes numbering of either west or east side.

Spandrel walls, defined as ADE-8208 as latest routine inspection report from 2018 states, are attached at the northern and southern ends of the bridge. The spandrel wall is comprised of the vertical rising wall of the bridge ending, including the spandrel-arch-underside. In the digital model, the spandrel wall is separated into two objects, the bearing arch, and the vertical rising wall. The spandrel arches are denominated as North Spandrel, and South Spandrel, respectively. The vertical spandrel walls are denominated as North Portal, and South Portal, respectively. Wingwalls aligned east and west of the spandrel walls are included in the model as well, since the bridge's extent is not explicitly defined.

On the deck level, each lane is modelled as one element, and the curbs on either side are separated into 5.00 ft long elements. The railings on the northern end, the southern end, and between the directions of travel are separated into 10.00 ft long parts and can be addressed individually, as are the railing posts.

The nomenclature for the bridge elements NBE-144, NBE-215, and NBE-8208 is derived from the 2018 inspection report and attached photos. Due to limited access as stated previous, only 73 of 223 created bridge elements are considered for the investigation. The elements investigated are listed with associated nomenclature in Table 20, Table 21, and Table 22 of Appendix K.

4.5.2 DATA ACQUISITION

The data stored in the BIDM of Arch IV is composed of three events, the 2018 routine inspection, the first data sample collected on May 21st, 2020, and the second data sample collected on June 5th, 2020. In total, the BIDM contains 80 recorded defects displayed as ToDos and 78 data pairs for the accuracy analyses of AR-supported measurements.

Analyzing the 2018 routine inspection report of Arch IV, 37 defects for bridge elements NBE-144, NBE-215, and ADE-8208 are found eligible to be entered into the BIDM with correspondent linkage to specific element locations. The 37 defect tags are distributed along 28 different elements. Since the inspection report itself only partly supports information regarding defect locations, associated photos in the inspection report additional file must be reviewed to retrace the locations. The inspection report additional file comprises 40 photos, 27 of which display defects at the superstructure assessable from below and at the substructure. The photos are used to determine defect location when entered into the BIDM.

Collection of the first data sample on May 21st, 2020 led to 28 assessed defects distributed along 20 different elements. A total of 108 photos were taken during the inspection to record element condition and justify AR-supported measurements. Of these 108 photos 45 data pairs which are reproducible and traceable, and, therefore eligible for quantitative analyses are derived.

Collection of the second data sample on June 5th, 2020 led to 15 assessed defects distributed along 13 different elements. A total of 63 photos were taken during the inspection to record element condition and justify AR-supported measurements. Of these 63 photos, 33 data pairs that are reproducible and traceable, and therefore eligible for quantitative analyses are derived.

Defect codes and their specific location are displayed in Figure 34 as a 3D-database representation or in Table 23 to Table 26 of Appendix L in tabular form.

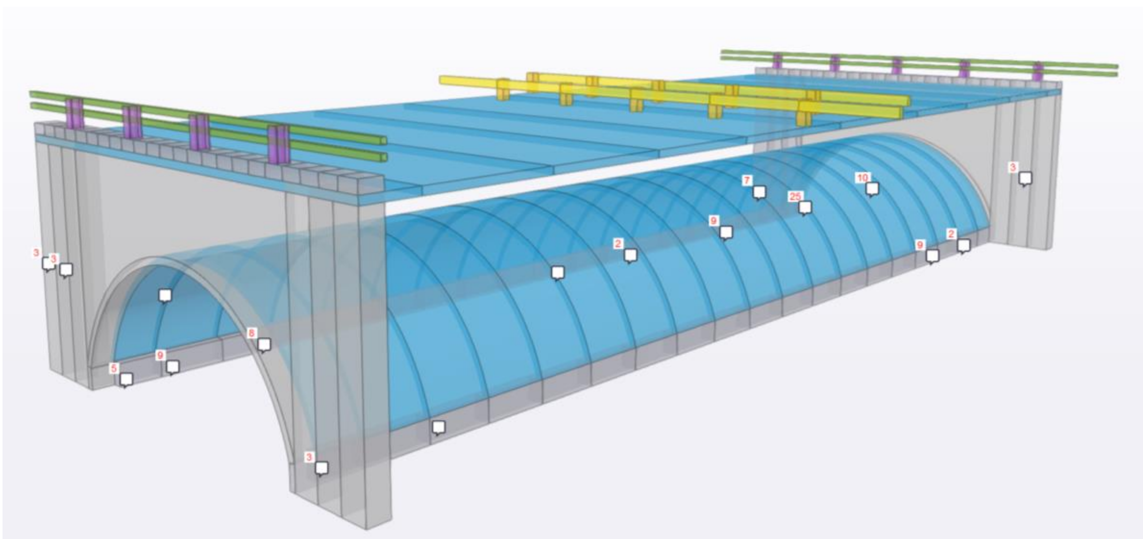


Figure 34: Jamestown Arch IV, Model Overview with Defect Tags' Location (own figure)

CHAPTER 5 - FINDINGS

Hypothesized enhancements for bridge inspection processes stated in Chapter 3 are investigated by the case study emphasized in Chapter 4. This chapter summarizes the findings of the conducted case study and proves or disproves the hypothesized statements. Findings for process enhancements are given as qualitative statements and justified by case study examples. The accuracy of AR-supported measurements, however, is quantifiable and therefore quantified findings are stated.

5.1 DATA HANDLING AND WORKFLOW

The BIDM is an eligible tool for routine bridge inspection purposes. It supports the processes of inspection preparation, inspection execution, and inspection post-processing. Furthermore, it enhances accessibility and representation of the inspection data. The 3D-database eases understanding and recognition of defects within the bridge structure. Data sharing between bridge's stakeholders is enhanced since distribution of data and traceability is eased. The data handling and workflow enhancements are emphasized by the examples I to III of Appendix M.

5.1.1 INSPECTION PREPARATION

The BIDM enhances the inspection preparation process since it eases review of previous recorded conditions within the digital 3D structure, eliminates recurring processes, and provides a central database for information along a bridge's lifecycle. Reviewing the bridge as a digital 3D-model improves familiarity of the inspector with the bridge itself and element locations before entering the site.

Conventional inspection preparation requires identification and denomination of bridge components and elements before each inspection. This reoccurring step is eliminated by using the BIDM since the identification of bridge elements is only done once when the model is created. The inspector is no longer required to identify and denominate elements before each inspection. Next, developing an inspection sequence and preparing notes and sketches to record the bridge condition on site is eased. Notes and sketches are created to either highlight defects that are recorded in previous inspections, or to provide a surface for recording information of an upcoming inspection.

Regarding the inspection sequence planning, the labeling distribution along the bridge supports the inspector in identifying critical areas that might need more cautious inspection than other areas. As Figure 35 displays, the defects attached at Arch IV tend to be more at northern and southern end and less in the middle part.

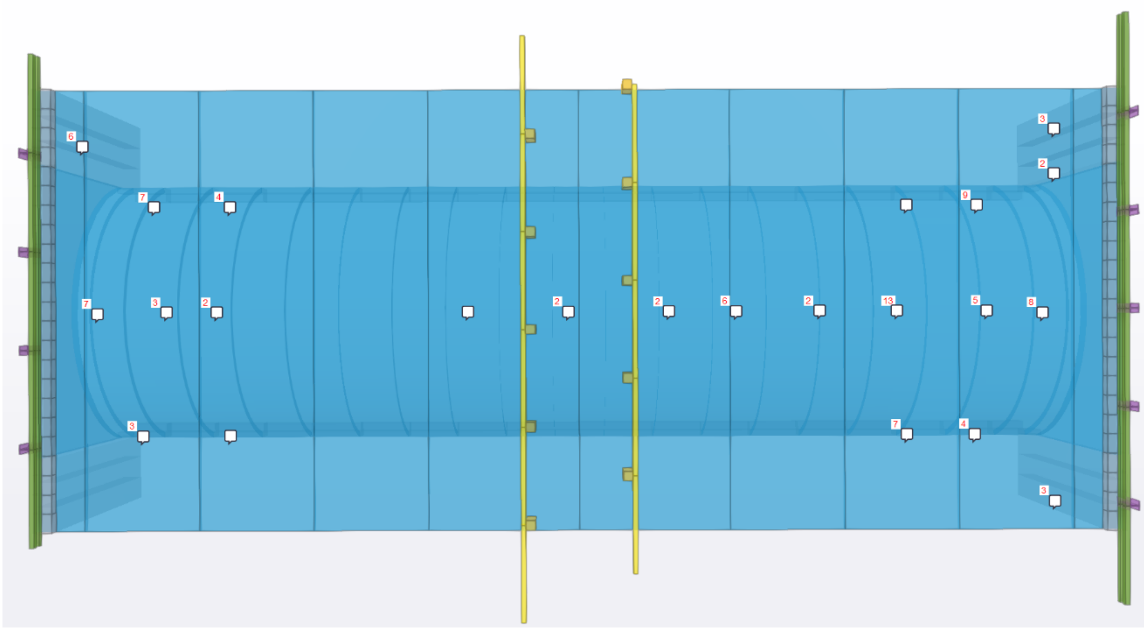


Figure 35: Arch IV Top View with Defect Tags, Trimble Connect Desktop View (own figure)

This might be caused by the higher exposition to environmental impacts at the bridge ends. The inspector might plan to spend more time inspecting these areas.

The BIDM provides functions for noticing defects on site and linkage to specific elements, which makes preparation of sketches redundant, since the defect location can be addressed and traced within the structure. Regarding the preparation of notes of previous recorded conditions and their associated locations, the BIDM provides the inspection history of each element in its database, so the conventional process of preparing these notes can be eliminated. Retracing inspection history and specific locations of deteriorated elements is enhanced by the BIDM and requires less document sighting than conventional inspection preparations. This statement is exemplified with the help of Example III in Appendix M. The 2018 inspection report states spalls at arch segments C, D, I and P as Appendix L, Figure 64 shows. The element ID for reinforced concrete arches is NBE-144 and the defect ID for spall is 1080 (compare sections 2.4.3 and 2.7.1.1). Searching the BIDM database for ID 144-1080 to find all arch segments with defect 1080 leads to Appendix M, Example III. The 3D-model highlights affected elements and displays the inspection history as Appendix M, Figure 89 and Figure 90 show. Defect description and photo documentation is accessible by clicking on the specific inspection-ID. The conventional method to trace the location and inspection history requires three different inspection reports, associated photo documentation, and different construction plans to localize the elements. The digital connection between location and information, and the ability to access these data at one central database, is one achievement of the BIDM, as Appendix M, Example I and II display. The inspection history of each element can be traced by the inspection ID. By clicking on the specific BIDM code, information of the selected defect and attached documents are provided to the inspector.

5.1.2 INSPECTION EXECUTION

The BIDM supports the inspector on site by enhancing the orientation within the structure, providing information about defect type and location, and by easing the process of data collection and measuring defect extent.

The inspector's orientation on site is enhanced, since the BIDM provides a digital 3D-model of the bridge structure on a mobile device, as Appendix M, Example I, Figure 79 displays. The model can be rotated and zoomed by the inspector, depending on whether an overview or a detailed view of the structure or elements is needed. Moving within a digital 3D-model is more intuitive than localizing a position by two-dimensional ground plans or sections. However, the mobile application at its current stage is not able to track location within the structure automatically. The digital model must be manually moved when moving in the real environment. Superposition of the digital model and the real environment is not feasible at the current stage and with the equipment available at the time of this case study.

The BIDM database is accessible by the mobile device, and the advantages emphasized in previous sections are valid here as well. Providing information on site allows guidance of the inspector's attention to characteristic defects or deteriorated locations of the bridge. Accessing the information digitally in a 3D-database on a mobile device is more convenient and handier than bringing individual documents and aligning them. The argument of more intuitive orientation by providing the 3D-structure is also valid for data handling.

The collection of new defect information is eased by using the Trimble Connect and the Measure application. The inspector selects an element in the digital model and enters the assessment or comments manually. Since defect and location are connected, the traceability within the structure for future inspections is given. The Measure application substitutes camera and measurement tools and eases the process of documenting the inspector's assessment. Images provided by this application are eligible for justifying the defect appearance, and the superposition of digital measurements on images contributes to the verification of the defect extent.

Legitimizing these statements, Examples I and II of Appendix M show the differences between the conventional inspection reports and the BIDM approach. Traceability of defect location within the bridge structure is enhanced.

Besides the improvements for data handling, the BIDM also eases the inspector's tasks on site. Measuring defect extent and providing verification images with current methods requires a tape measure and a camera. The inspector either handles two tools at the same time when providing pictures of measured defect extent or a second person is required to assist. Holding a tape measure and taking eligible photos is a taxing task. Only a few photos in the existing inspection reports provide photos of defect extent aligned with a tape measure, hence the traceability of these measurements is low. The Measure application, however, can be operated one-handed, which enhances the convenience of measuring defect extent. In addition, it enables the traceability of measured defect extent and allows the inspector to measure defects from farer distances. AR-supported measurements are required to be as accurate as conventional measurements when implementing them for future bridge inspections. Verification of their accuracy is analyzed in Section 5.2.

The BIDM consolidates the strengths of engineering judgement and the objectivity of quantifiable and traceable measurements by providing this human-centered approach. The engineer or inspector decides which elements and defects require more intense inspection, but the actual assessment of the defect and its extent is quantified. This increases the quantifiability of the BMS input data and therefore contributes to the overall quantifiability based on BMS decisions.

5.1.3 INSPECTION POST-PROCESSING

Applying BIDM to bridge inspection eases and shortens inspection post-processing. Most post-processing steps can be operated in the BIDM itself as it provides collaboration and data organizing options. Since the BIDM links and displays assessed inspection data in an eligible and comprehensible manner, the inspector is no longer required to produce sketches and paper-based reports after the inspection. The BIDM database can be shared with appropriate stakeholders to report the current bridge condition for further processing. Informing others about further follow-up inspections or instructing immediate maintenance of specific elements is eased by the BIDM.

Review of the inspection findings is enhanced, since the BIDM coding allows eased tracing of defects over time. Providing the digital 3D-structure with linked defects enhances comprehension of the reviewing inspectors or agencies on the bridge overview level, even if they have never visited the real bridge environment. The traceability of defect extent provided by the Measure application enhances the review on the element-level. Therefore, the quality of element condition rating can be enhanced since defect extent and location are better documented. Engineering judgment is still required to determine the condition state of an element, but quality-control of condition rating is improved by the enhanced documentation of the BIDM as different experts can trace and justify the collected data.

5.2 ACCURACY OF AR-SUPPORTED MEASUREMENT

The accuracy of AR-supported measurements is tested in this thesis by two data samples comprising 141 data pairs. It can be stated that AR-supported measurements are as accurate as conventional measurements within the allowed limits for concrete structures of 0.50 in of deviation as stated in Section 2.4.3, since 88.65 % of measured distances deviate less than or equal to 0.50 in. The second sample shows a higher accuracy and fewer deviations of AR-supported measures in comparison to analog measurements. This increase in accuracy might be caused either by increased familiarity with the method or change of the measure tool for justifying the AR-supported measurements. Weather and therefore lighting conditions below the bridges were worse on June 5th, 2020, than on May 21st, 2020. Therefore, it seems that the accuracy of AR-supported measurements does not seem to be related to lighting conditions of the surroundings.

The following two sections analyze the data samples separately.

5.2.1 SAMPLE I

The first data sample is comprised of 67 data pairs of digital and analog measurements, collected on Arch III and Arch IV on May 21st, 2020. Most defects measured are between 1 in and 20 in long, one crack with 40 in length was assessed, the average length measured is 9.10 in. The mean deviation between the digital and analog measurements is negative 0.35 in and the standard deviation of this data sample is 0.74 in. The average percentage deviation of AR-supported measurements is 7.0 %. Out of 67 data pairs, 57 are within the allowed limits of positive or negative 0.5 in, hence the reliability of AR-supported measurements is 85.07 %.

Figure 36 displays the 67 data pairs collected on site. Each point displays the relation between the AR-supported and the conventional measures.

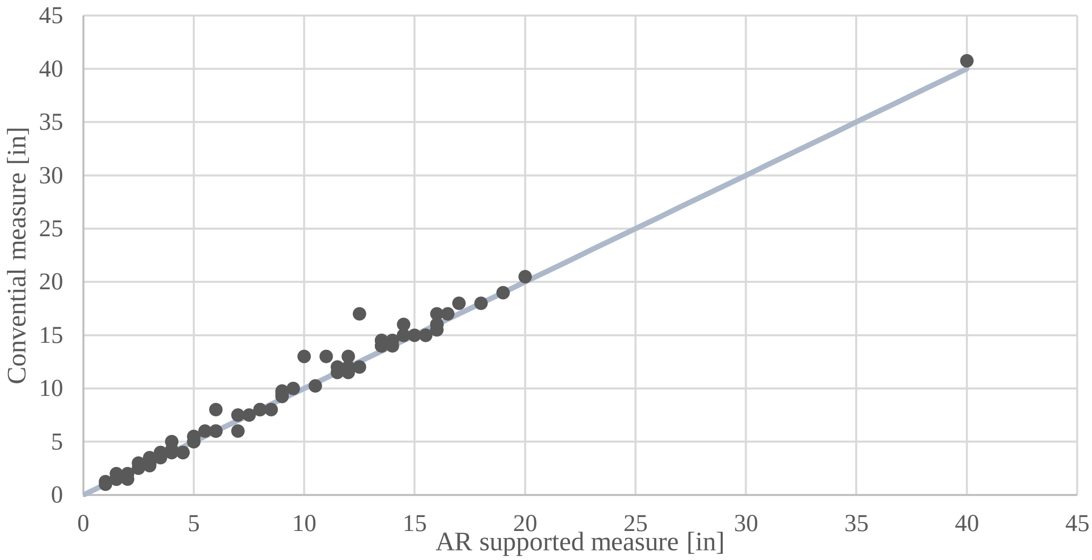


Figure 36: Sample 1 AR-supported Measures Compared to Conventional Measures (own figure, own data)

The light grey linear graph has a gradient of 1.0, hence the closer the datapoints are to the gradient, the smaller the deviation of digital and analog measures. Most data points are aligned next to the light grey graph which implies that the difference between digital and analog measurements is small. Four outliers show larger deviation.

Justifying the accuracy of AR-supported measured values, next, absolute deviation of each data point is displayed and analyzed. The sample shows most values in the range between positive and negative 1.0 in deviation as Figure 37 displays.

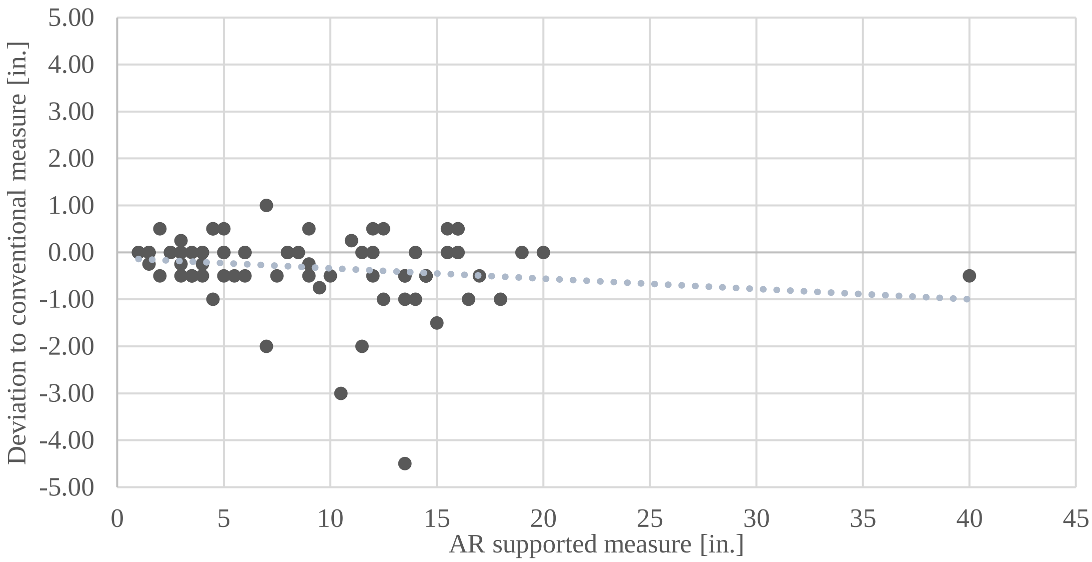


Figure 37: Sample 1 Absolute Deviation of AR-supported Measures to conventional Measures (own figure, own data)

The four outliers spotted in the previous graph show deviation of -4.5 in, -3.0 in, and two times -2.0 in. The light grey trendline tends slightly to the negative side, which implies that AR-supported measurements tend to be smaller than the justification per inch rule.

The histogram in Figure 38 shows the deviation distribution of AR-supported measurements. It is proven that most digitally assessed values deviate within 0.5 in compared to the analog measurements. Furthermore, the tendency of digital measurements to be smaller than the analog justification by inch rule is confirmed.

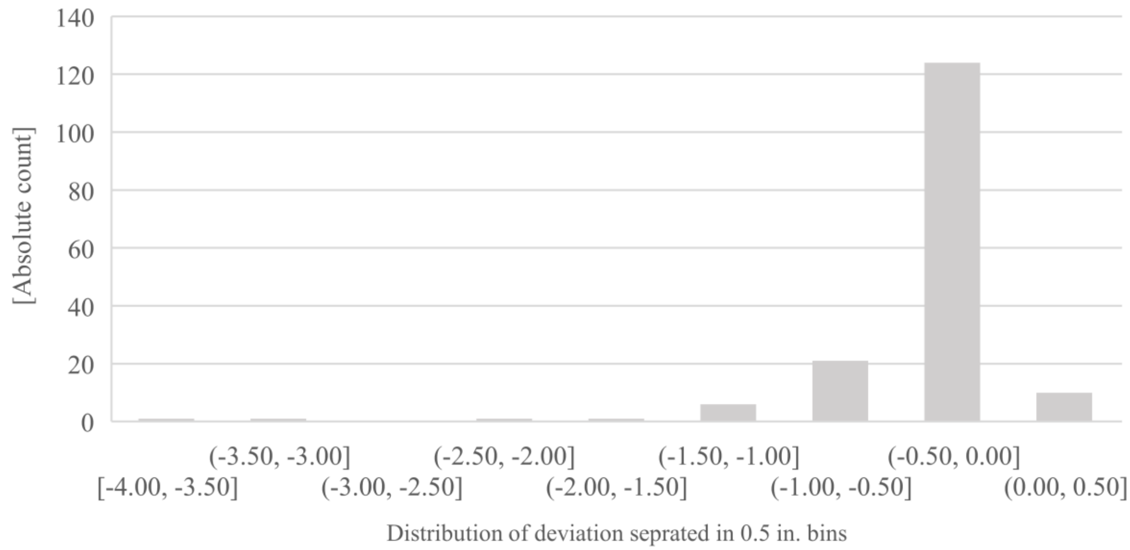


Figure 38: Sample 1 Histogram of Deviation Distribution (own figure, own data)

5.2.2 SAMPLE II

The second data sample is comprised of 74 data pairs of digital and analog measurements, collected on Arch III and Arch IV on June 5th, 2020. Most defects measured are between 1 in and 20 in long, one crack with 40 in length was assessed, the average length measured is 8.33 in. The mean deviation between the digital and analog measurements is -0.07 in and the standard deviation of this data sample is 0.41 in. The average percentage deviation of AR-supported measurements is 4.4 %. Out of 74 data pairs, 68 are within the allowed limits of positive or negative 0.5 in, hence the reliability of AR-supported measurements is 91.89 %.

Figure 39 displays the 74 data pairs collected on site. Each point displays the relation between the AR-supported and the conventional measures.

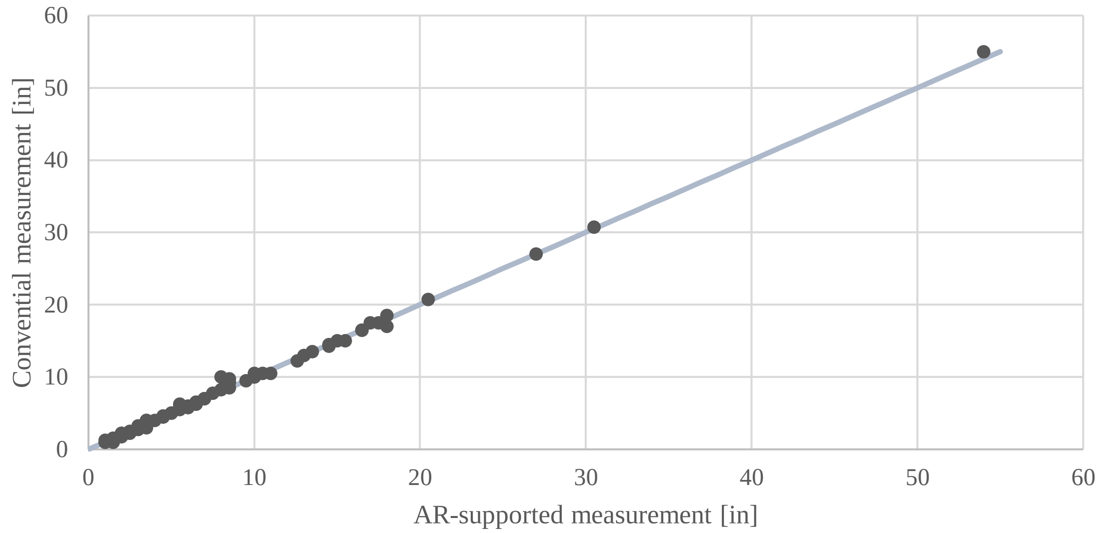


Figure 39: Sample 2 AR-supported Measures Compared to Conventional Measures (own figure, own data)

The light grey linear graph has a gradient of 1.0, hence the closer the datapoints are to the gradient, the smaller the deviation of digital and analog measure. All data points are aligned closely to the light grey graph, which implies that the difference between digital and analog measurements is small.

Justifying the accuracy of AR-supported measured values, next, the absolute deviation of each data point is displayed and analyzed. The sample shows almost all values in the range smaller than positive or negative 1.0 in deviation as Figure 40 displays.

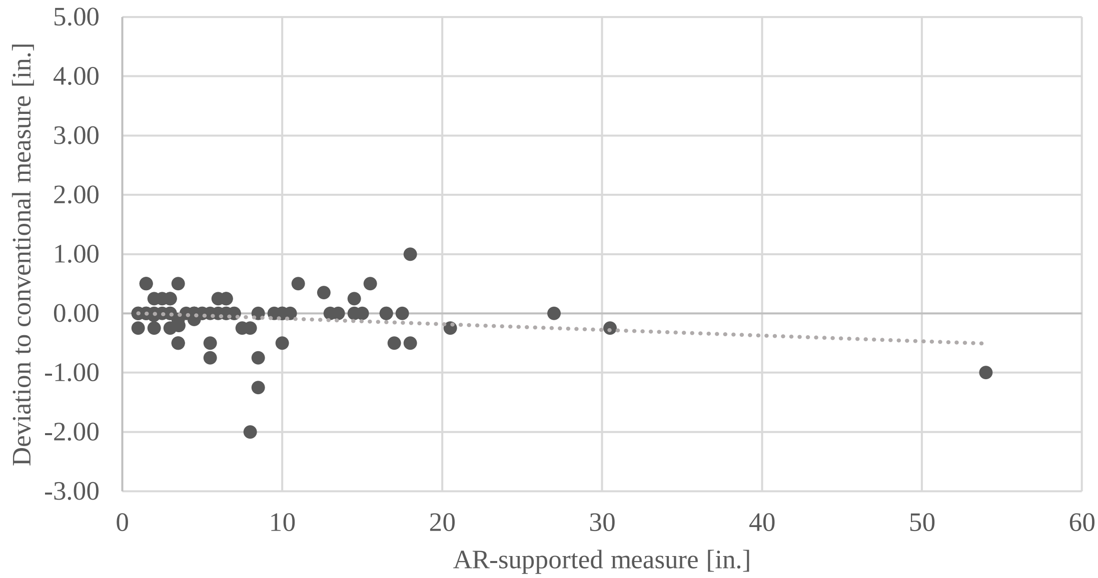


Figure 40: Sample 2 Absolute Deviation of AR supported Measures to conventional Measures (own figure, own data)

Four outliers are spotted: one outlier deviates by -2.0 in; two outliers deviate by positive 1.0 in respectively -1.0 in; and one outlier deviates by -1.25 in. The light grey trendline tends slightly to the negative side, which implies that AR-supported measurements tend to be smaller than the justification per inch rule.

The histogram in Figure 41 shows the deviation distribution of AR-supported measurements. It is proven that most digitally assessed values deviate within 0.5 in compared to the analog measurements. Furthermore, the tendency of digital measurements to be smaller than the analog justification by tape measure is confirmed.

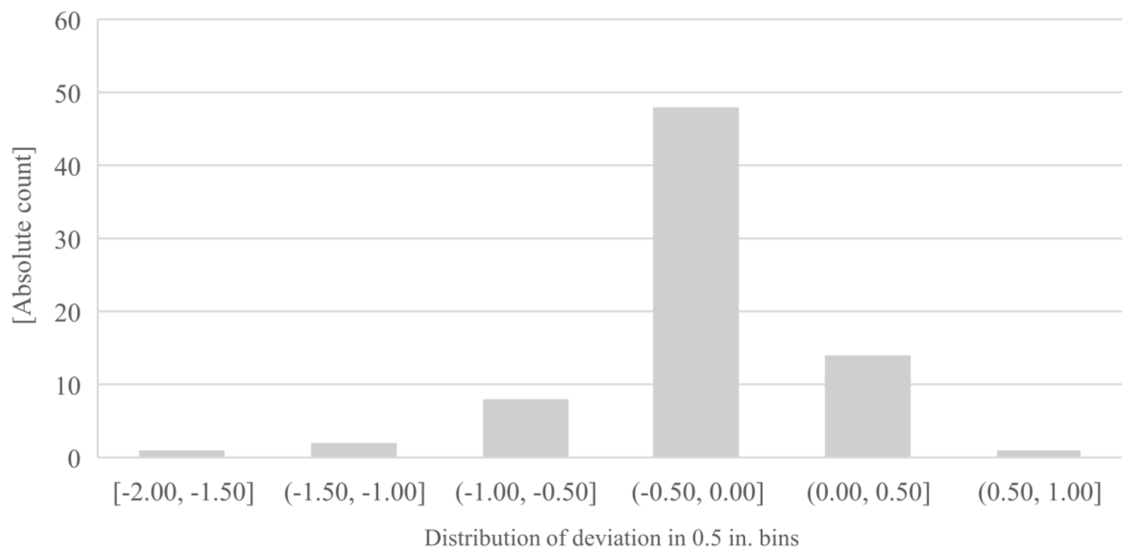


Figure 41: Sample 2 Histogram of Deviation Distribution (own figure, own data)

5.3 LIMITATIONS OF THE FINDINGS

Findings of this thesis based on the case study outcomes are limited to certain aspects. The limitations are separated into the following sections.

5.3.1 DATA SAMPLE

The size of the two data samples varies. The variance of the sample size is caused by the postprocessing of pictures, since only AR-measurements are considered which are explicit verifiable by analog measurements. Without any alignment of digital and analog measurement, the accuracy cannot be determined, hence these photos are neglected for the accuracy analysis. The process of verifying each defect by digital and analog measurements is not required once the accuracy of AR is further tested and calibrated.

The familiarity with the smartphone applications increased from the first to the second sample which might affected the measurement accuracy. Additionally, the familiarity with the bridge structure itself is increased from first to second data assessment. This also must be considered, when transferring the findings of this thesis to other bridges.

The data samples do not claim to be comprehensive inspection reports; hence they do not assess each element and defect at both events. The data collection focuses on testing the accuracy of AR-measurements on a broad scope of defects.

5.3.2 ACCURACY OF THE AR SOFTWARE

The available device for testing the BIDM and accuracy of AR-supported measurements was limited to an Apple iPhone 8 smartphone only. Limitations of the smartphone software as well as its camera capabilities must be respected. The Measure smartphone application is accurate up to 0.5 in which also limits the applicability of this method to larger defects only. Measuring defects e.g. width of cracks smaller than 0.5 in are not feasible with this application.

5.3.3 MODEL LIMITATION

The development of the BIDM did not include any software programming. Originally developed for design and construction management processes Trimble Connect is limited in its applicability to inspection purposes. But, the feasibility of this solution without any adaption of software codes is stated previous.

The Tekla Structures 2019i is equipped with a structural analysis tool which is not considered in this thesis. The created 3D-model does not allow structural analysis or calculation since provided construction plans are not eligible to recreate the required level of detail. If more detailed construction plans are available a more sophisticated model can be created which allows structural computation. The breakdown of the model into elements is based on the fragmentation taken in the 2018 inspection report. The more accurate the fragmentation is, the more detailed defects can be placed in the BIDM.

CHAPTER 6 - CONCLUSION

6.1 SUMMARY

To counter the progressive deterioration of bridges in the US and particularly in the state of Rhode Island, it is necessary to implement effective and efficient inspection procedures. Bridge inspections assess the structural condition hence they are the first entity in the process of maintaining bridges serviceable. Contributing the ambitious plans of the Rhode Island Department of Transportation to decrease the amount of bridges in fair and poor condition, and following the Transportation Research Board's statement to investigate Information Modeling and Augmented Reality for bridge inspection processes, this thesis developed a hands-on method to enhance visual bridge inspection by implementing digital methods.

First, the literature review emphasized the importance of Bridge Management Systems to track deterioration and deficiencies over time. These systems provide deterioration prediction models of bridges and give decision support to owners and engineers to extent a bridge's lifespan. The input data for Bridge Management Systems are the result of bridge condition ratings which are assessed by bridge inspections. Visual inspections are the predominant inspection technique to inspect bridges in the United States. The literature review shows that most defects of concrete and steel bridges are perceivable on the bridge surface. However, visual inspection still relies on engineering judgement and lacks objectivity, quantifiability and traceability.

Secondly, to address the shortcomings two promising technologies, Augmented Reality (AR) and Building Information Modeling (BIM) are investigated regarding their capabilities to enhance the visual bridge inspection processes. Comprising these two technologies, a Bridge Information Data Model (BIDM) is developed. It is a 3D-database for storing and accessing inspection data on an element level, which follows BIM principles. Bridge elements can be addressed separately allowing the review of inspection history and the linkage of new defects. The AR-technology investigated in this thesis is limited to measuring the defect extent quantifiably and therefore more objective than with current methods.

Testing the applicability of the developed BIDM, a case study is conducted. Two concrete bridges in southern Rhode Island are selected for the case study. It is found that the main capabilities of the BIDM are the enhanced comprehension of the bridge structure, since it displays the bridge as a 3D digital twin, the enhanced traceability of location and inspection history of specific defects and elements, and the ability to enhance collaboration of bridge stakeholders.

Within the framework of the BIDM, the accuracy of AR-supported measurements is investigated. Proving accuracy, AR-measurements are aligned with conventional measure tools used for bridge inspections. The performed case study comprises 141 measurement data pairs of which 88.65 % deviate less or equal to 0.5 inch, which is inside the deviation range for inspecting concrete structures. It can be stated that AR-supported measurements are as accurate as analog measurements. Therefore, they are applicable for inspecting concrete bridges.

The interaction of both techniques investigated in this thesis enhances the visual bridge inspection. It is proven that the human-centered approach is simply applicable to current inspection procedures.

6.2 OUTLOOK AND FURTHER STEPS

To implement the BIDM into the routine bridge inspection processes, it is required to test the accuracy of AR-supported measurements on different materials additionally. Investigating accuracy on steel structures is recommended to be part of following research to allow the applicability to most bridge structures in the US.

Furthermore, computer science departments should accompany further development to create 3D-models that allow a more detailed placement of defect data. The more accurate defects can be attached within the digital model, the more precise are their future traceability. Creating a finite element method model would allow accurate structural analysis and simulation of defects but might cause disproportionate labor in comparison to the yield for bridge management purposes.

It is recommended to test the developed BIDM method in combination with a head-mounted AR-device. This application is promising to be even more suitable for the use-case of bridge inspections. Trimble Connect provides an interface for the AR-glasses Microsoft HoloLens 2 called Trimble XR10 in its current mobile application. Due to its specific development of providing AR (respectively mixed reality) to construction sites, it promises to be even more feasible for this inspection approach. Its capabilities of superimposing digital layers on the real environment within the user's field of vision is recommended to be investigated next.

APPENDICES

Appendix **Page**

APPENDIX A – BMS ORGANIZATIONAL CHART AND RATING

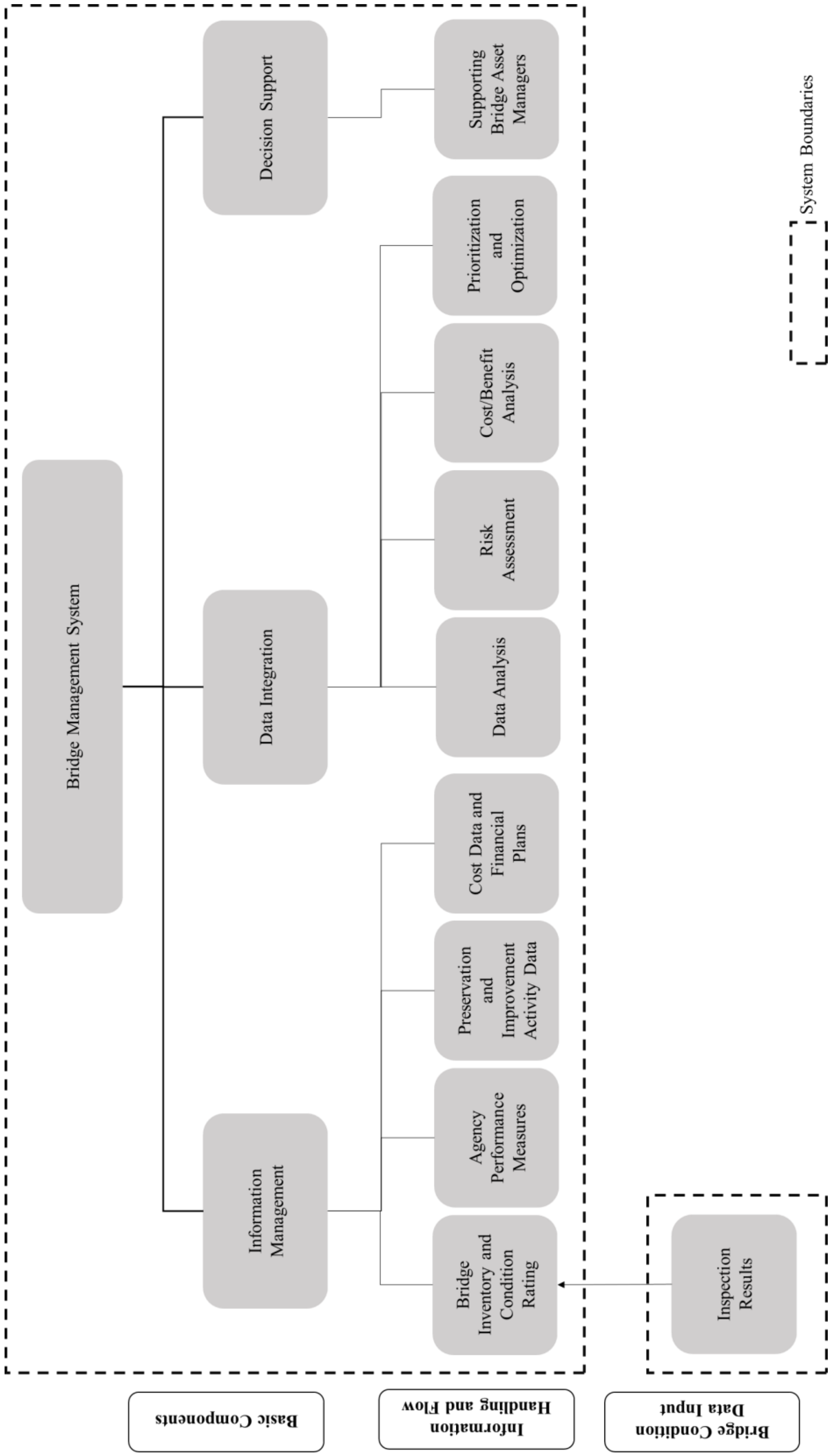


Figure 42: Organizational Chart of a BMS (own figure; cp. (AASHTO, 2018))

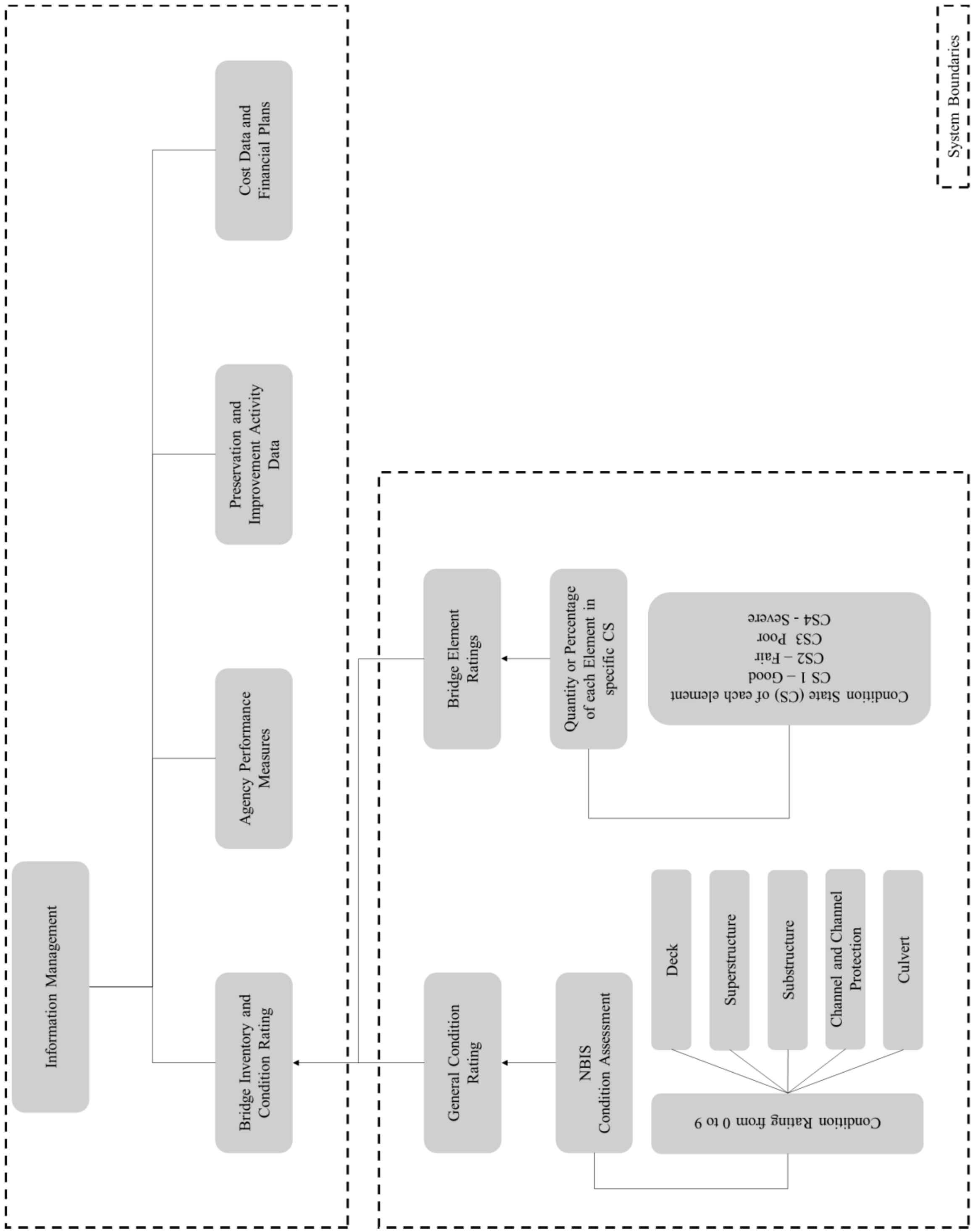


Figure 43: Component and Element Condition Rating with respect to BMS (own figure)

APPENDIX B – COMPONENT CONDITION RATING

Table 4: Component Rating Guidelines for Item 58, Item 59 and Item 60 (cp. (FHWA, 1995))

Code	Description
N	Not Applicable
9	Excellent Condition
8	Very Good Condition – No Problems noted
7	Good Condition – Some minor Problems
6	Satisfactory Condition – Structural Elements show some minor Deterioration
5	Fair Condition – All primary Structural Elements are sound but may have minor Section Loss, Cracking, Spalling or Scour
4	Poor Condition – Advanced Section Loss, Deterioration, Spalling or Scour
3	Serious Condition – Loss of Section, Deterioration, Spalling or Scour have seriously affected primary Structural Components. Local Failures are possible. Fatigue Cracks in Steel or Shear Cracks in Concrete may be present
2	Critical Condition – Advanced Deterioration of primary Structural Concrete may be present, or Scour may have removed Substructure Support. Unless closely monitored it may be necessary to close the Bridge until corrective Action is taken
1	“Imminent” Failure Condition – Major Deterioration or Section Loss present in critical Structural Components or obvious vertical or horizontal Movement affecting Structure Stability. Bridge is closed to Traffic, but corrective Action may put back in light Service
0	Failed Condition – Out of Service – Beyond corrective Action

APPENDIX C – BRIDGE ELEMENTS NBE AND BME

Table 5: National Bridge Elements for Concrete Bridges Part I (cp. (Ryan et al., 2012))

Material	Component	NBE No.	Description	Unit
RC	Decks/Slabs	12	Reinforced Concrete Deck	ft^2
PSC	Decks/Slabs	13	Prestressed Concrete Deck	ft^2
PSC	Decks/Slabs	15	Prestressed Concrete Top Flange	ft^2
RC	Decks/Slabs	16	Reinforce Concrete Top Flange	ft^2
RC	Decks/Slabs	38	Reinforced Concrete Slab	ft^2
PSC	Superstructure	104	Prestressed Concrete Closed Web/Box Girder	ft
RC	Superstructure	105	Reinforced Concrete Closed Web/Box Girder	ft
PSC	Superstructure	109	Prestressed Concrete Open Girder/Beam	ft
RC	Superstructure	110	Reinforced Concrete Open Girder/Beam	ft
PSC	Superstructure	115	Prestressed Concrete Stringer	ft
RC	Superstructure	116	Reinforced Concrete Stringer	ft
PSC	Superstructure	143	Prestressed Concrete Arch	ft
RC	Superstructure	144	Reinforced Concrete Arch	ft
PSC	Superstructure	154	Prestressed Concrete Floor Beam	ft
RC	Superstructure	155	Reinforced Concrete Floor Beam	ft

Table 6: National Bridge Elements for Concrete Bridges Part I (cp.(Ryan et al., 2012))

Material	Component	NBE No.	Description	Unit
PSC	Substructure	204	Prestressed Concrete Column	ea
RC	Substructure	205	Reinforced Concrete Column	ea
RC	Substructure	210	Reinforced Concrete Pier Wall	ea
RC	Substructure	215	Reinforced Concrete Abutment	ft
RC	Substructure	220	Reinforced Concrete Pile Cap/ Footing	ft
PSC	Substructure	226	Prestressed Concrete Pile	ea
RC	Substructure	227	Reinforced Concrete Pile	ea
PSC	Superstructure	233	Prestressed Concrete Pier Cap	ft
RC	Substructure	234	Reinforced Concrete Pier Cap	ft
RC	Culverts	241	Reinforced Concrete Culvert	ft
PSC	Superstructure	245	Prestressed Concrete Culvert	ft
PSC	Superstructure	320	Prestressed Concrete Approach Slab	ft^2
RC	Approach Slab	321	Reinforced Concrete Approach Slab	ft
RC	Railings	331	Reinforced Concrete Bridge Railing	ft

APPENDIX D – CRITERIA FOR HIGHWAY BRIDGES

Table 7: Item and Coding Criteria for Highway Bridges (cp. (FHWA, 1995))

Item	Code	Description
5a	1	Route carried on the Structure. Inventoried Route is carried on the Structure. Each Bridge Structure carrying Highway Traffic must have a Record identified with a Type Code = 1.
42a	1, 4, 5, 6, 7, 8	Type of Service on Bridge. (1) Highway; (4) Highway-railroad; (5) Highway-pedestrian. (6) Overpass Structure at an Interchange or second Level of a multilevel Interchange. (7) Third level (Interchange); (8) Fourth level (Interchange)
49	≥ 6.1 Meter or ≥ 20 Feet	The Structure Length of a Highway Bridge must be larger or equal to 6.1 Meter or 20 Feet. Length describes the minimum clear Widths between Backwalls of Abutments or between Paving Notches
112	Y	Yes, Length of Bridge is more than 6.1 Meter and therefore it is eligible for applying the National Bridge Inspection Standards.

APPENDIX E – ANTICIPATED MODE OF DEFICIENCY

Table 8: Perceptibility of Deficiency on Concrete Surfaces (cp. (Ryan et al., 2012))

Material	Anticipated Mode of Deficiency	Perceptibility on Surface
Concrete	Cracking	Yes
Concrete	Scaling	Yes
Concrete	Delamination	Partly, sound Testing required
Concrete	Spalling	Yes
Concrete	Chloride Contamination	Partly
Concrete	Freeze-thaw	Yes, in further Process
Concrete	Efflorescence	Yes, to estimate Extent of contaminated Concrete NDE is necessary
Concrete	Alkali-Silica Reactivity (ASR)	Yes, but for early Confirmation of Presence Lab Testing is needed
Concrete	Ettringite Formation	No
Concrete	Honeycombs	Yes
Concrete	Pop-outs	Yes
Concrete	Wear	Yes
Concrete	Collision Damage	Yes
Concrete	Abrasion	Yes
Concrete	Overload Damage	Yes
Concrete	Internal Steel Corrosion	Partly, Yes
Concrete	Loss of Prestress	Partly
Concrete	Carbonation	No early Perceptibility
Concrete	Other Causes	Undefined

Table 9: Perceptibility of Deficiency on Steel Surfaces (cp. (Ryan et al., 2012))

Material	Anticipated Mode of Deficiency	Perceptibility on Surface
Steel	Corrosion	Yes
Steel	Fatigue Cracking	Yes
Steel	Overloads	Yes
Steel	Collision Damage	Yes
Steel	Heat Damage	Yes
Steel	Coating Failures	Yes

APPENDIX F – NBI ANALYSIS DATA

Table 10: Share of Main Design Material of Bridges listed in the NBI (data: (FHWA, 2020))

	Main Design Material [%]	
	Rhode Island	United States
Other Main Material Type	2.82%	0.60%
Wood or Timber	1.28%	2.94%
Steel	51.60%	28.49%
Steel Continuous	10.40%	8.28%
Steel	41.21%	20.22%
Concrete	44.29%	67.96%
Prestressed Concrete Continuous	0.90%	4.50%
Concrete Continuous	2.70%	12.75%
Prestressed Concrete	20.28%	21.90%
Concrete	20.41%	28.81%
Grand Total	100.00%	

Table 11: Share of Main Design Material and Average Daily Traffic, RI (data:(FHWA, 2020))

	Share of registered Bridges [%]	Average Daily Traffic [%]
Other Main Design Materials	2.82%	1.23%
Timber or Wood	1.28%	0.07%
Steel	51.60%	60.08%
Concrete	44.29%	38.61%
Grand Total	100.00%	100.00%

Table 12: Correlation of Construction Design Type and Average Daily Traffic, RI (data: (FHWA, 2020))

	Main Construction Design Type [%]	Average Daily Traffic [%]
Channel Beam	0.13%	0.01%
Orthotropic	0.13%	0.07%
Truss - Thru	1.20%	0.15%
Movable - Swing	0.13%	0.15%
Suspension	0.27%	0.21%
Segmental Box Girder	0.13%	0.21%
Girder and Floorbeam System	1.61%	0.75%
Arch - Thru	0.27%	1.13%
Tee Beam	2.68%	1.37%
Box Beam or Girders - Single or Spread	0.94%	1.58%
Slab	6.96%	2.18%
Frame	3.35%	3.95%
Arch - Deck	8.70%	6.05%
Culvert	5.22%	7.28%
Box Beam or Girders - Multiple	11.91%	7.97%
Stringer/Multi-Beam or Girder	56.36%	66.96%
Grand Total	100.00%	100.00%

Table 13: Correlation of Condition Rating, Material Type and Average Daily Traffic, RI (cp. (Ryan et al., 2012))

	Concrete		Steel		Total	
Condition Rating	Average Daily Traffic [%]	Bridge Condition [%]	Average Daily Traffic [%]	Bridge Condition [%]	Total Average Daily Traffic [%]	Total Bridge Condition [%]
0	0.00%	0.00%	0.00%	0.25%	0.00%	0.13%
1	0.00%	0.00%	0.06%	0.25%	0.06%	0.13%
2	0.04%	0.29%	0.27%	1.49%	0.31%	0.94%
3	0.47%	2.90%	2.27%	4.23%	2.74%	3.61%
4	4.38%	11.88%	14.23%	20.40%	18.61%	16.47%
5	12.85%	31.30%	24.06%	40.55%	36.91%	36.28%
6	15.20%	31.59%	12.58%	18.66%	27.79%	24.63%
7	5.87%	19.13%	7.14%	12.94%	13.02%	15.80%
8	0.31%	2.90%	0.27%	1.24%	0.57%	2.01%
Grand Total	39.12%	100.00%	60.88%	100.00%	100.00%	100.00%

APPENDIX G – INSPECTION ORGANIZATIONAL CHART

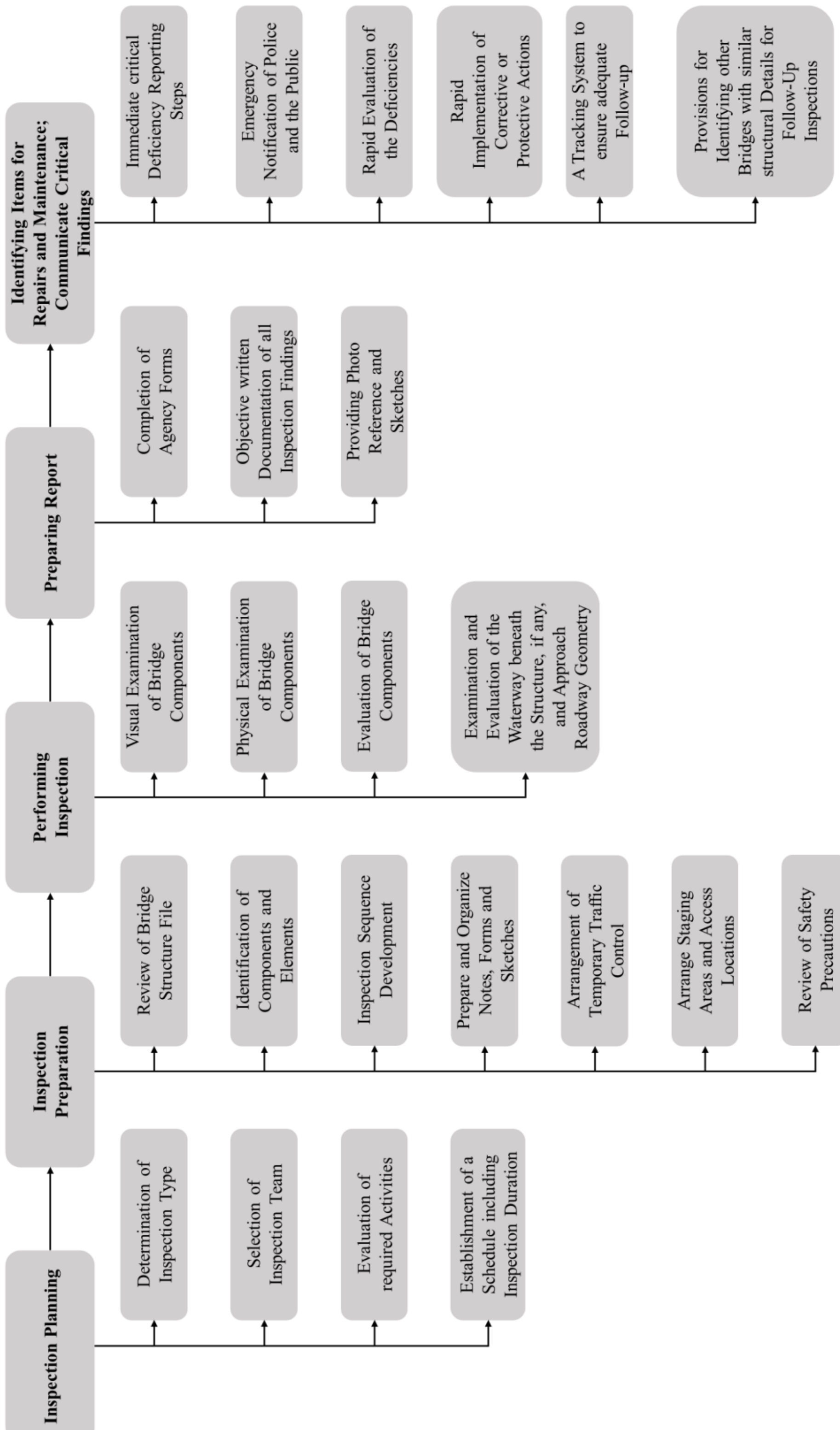


Figure 44: Inspection Organizational Chart (cp. (Ryan et al., 2012))

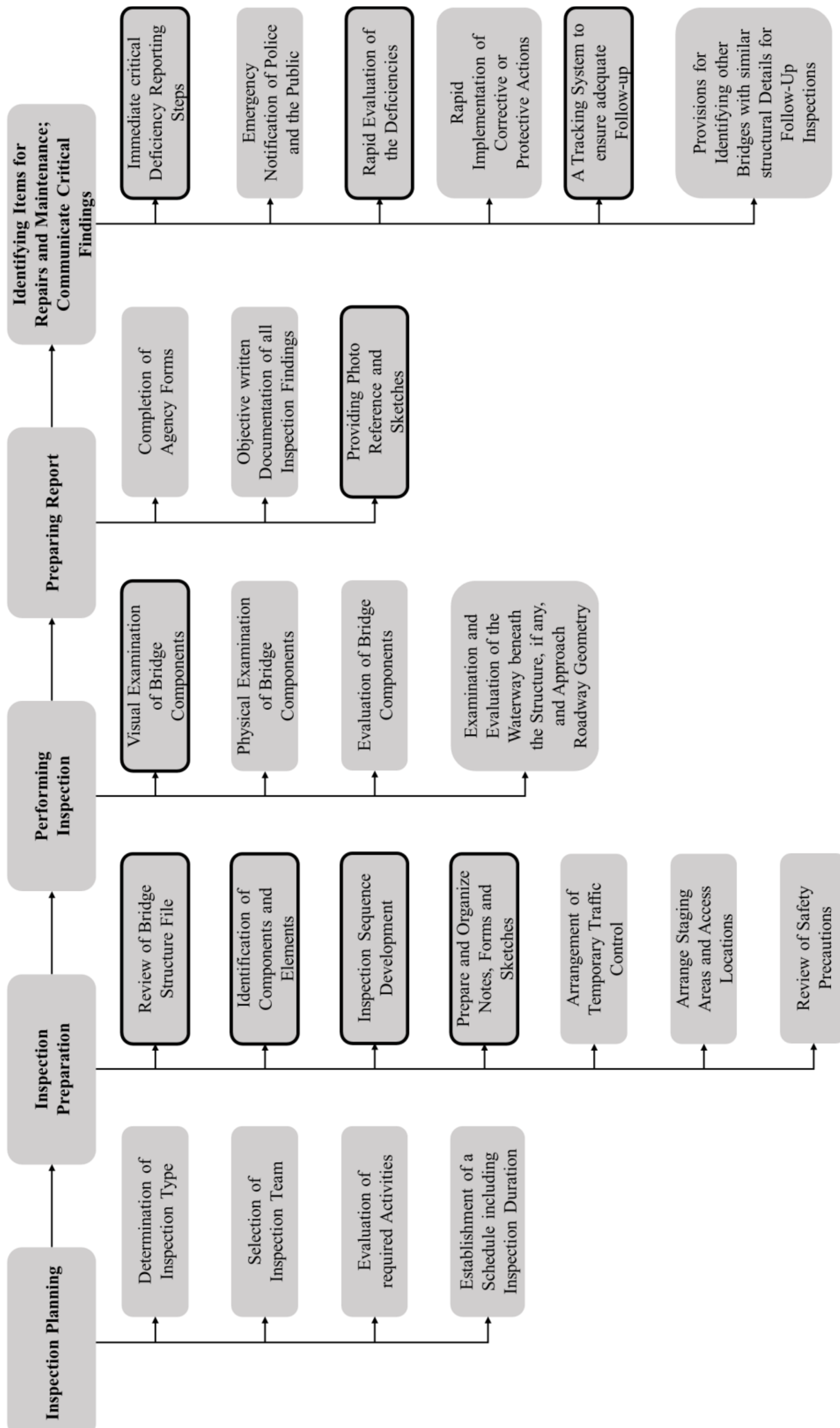


Figure 45: Inspection Organizational Chart - Enhanced Inspection Procedures highlighted (cp. (Ryan et al., 2012)**)**

APPENDIX H – CASE STUDY OVERVIEW

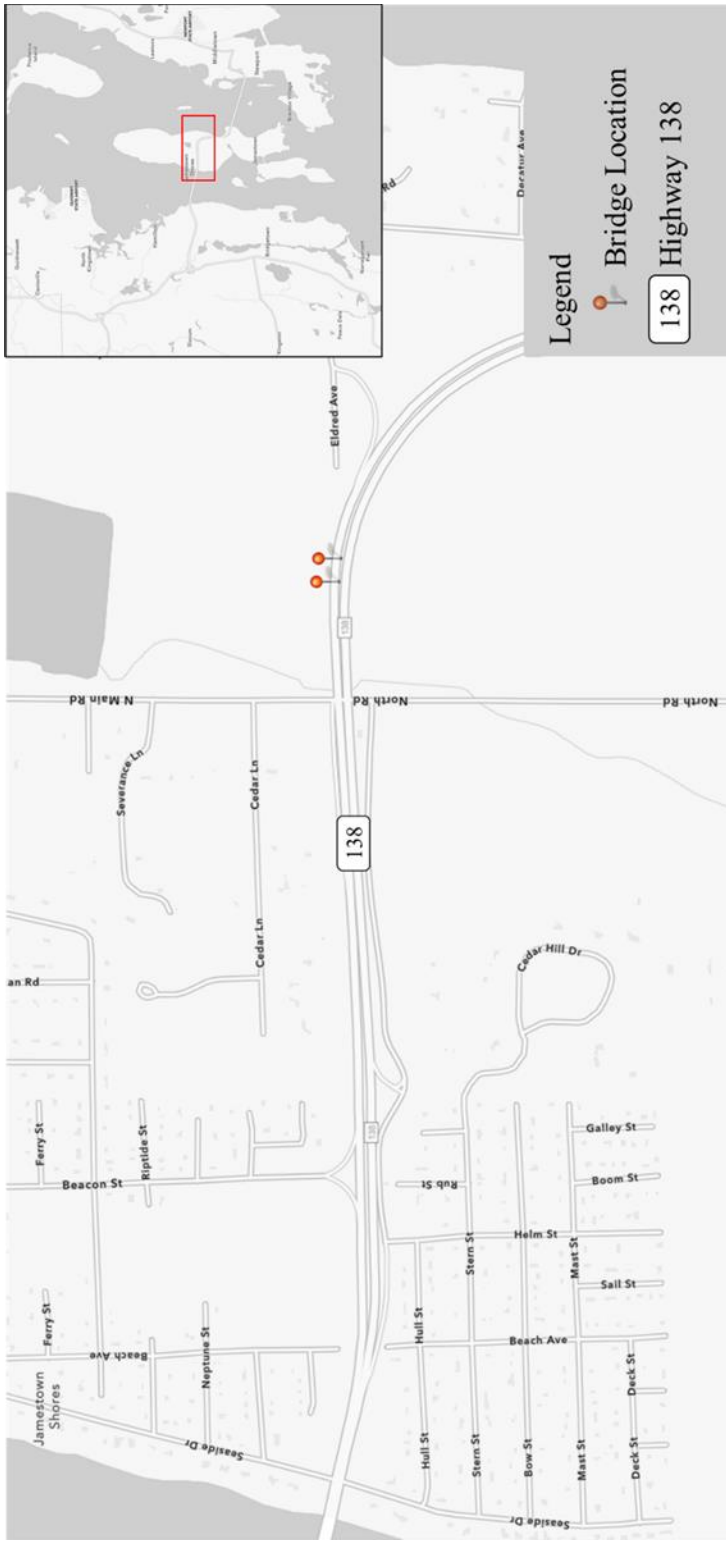


Figure 46: Enlarged Overview Bridges' Location in Southern Rhode Island (map: (ESRI, 2020))

Figure 47: Arch III View from North to South (own image)

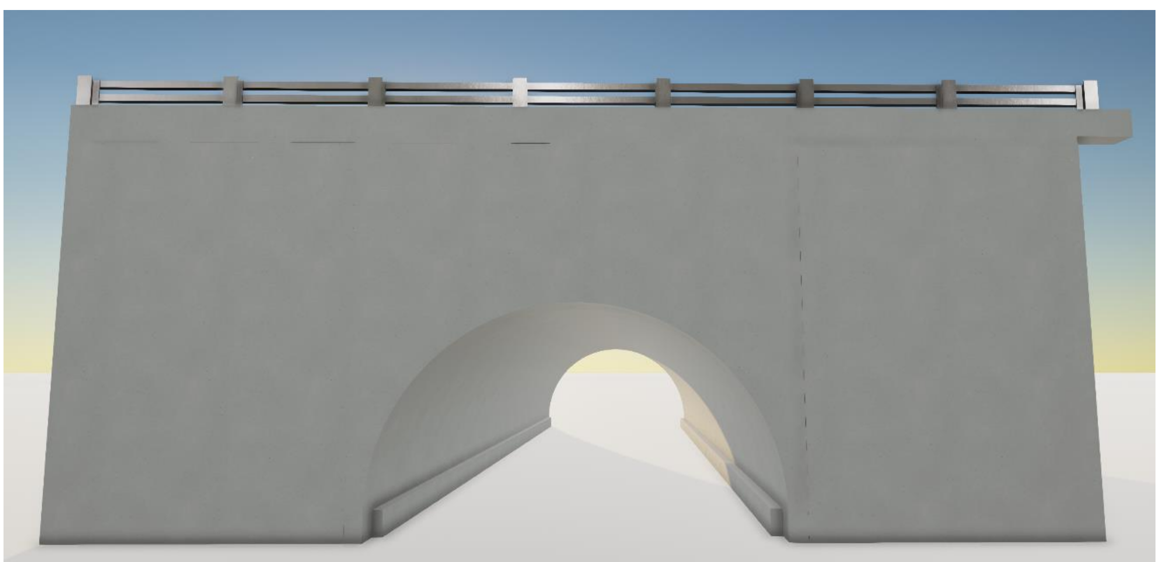


Figure 48: Arch III View at North Portal to South, Model Rendering (own image)

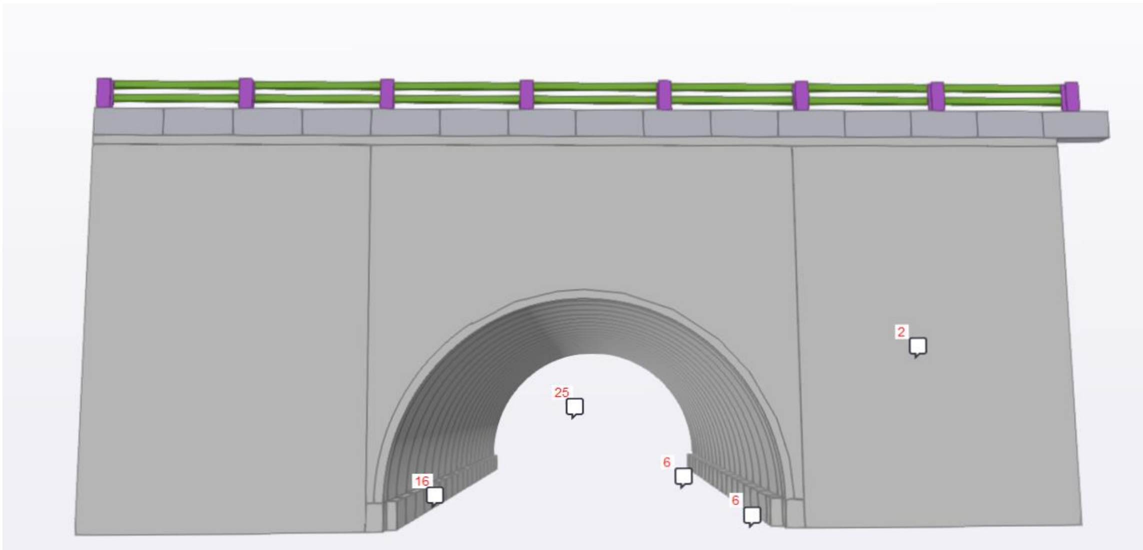


Figure 49: Arch III View at North Portal to South, Trimble Connect Model View with Defect Tags (own image)

Figure 50: Arch III View at the South Portal to North (own image)

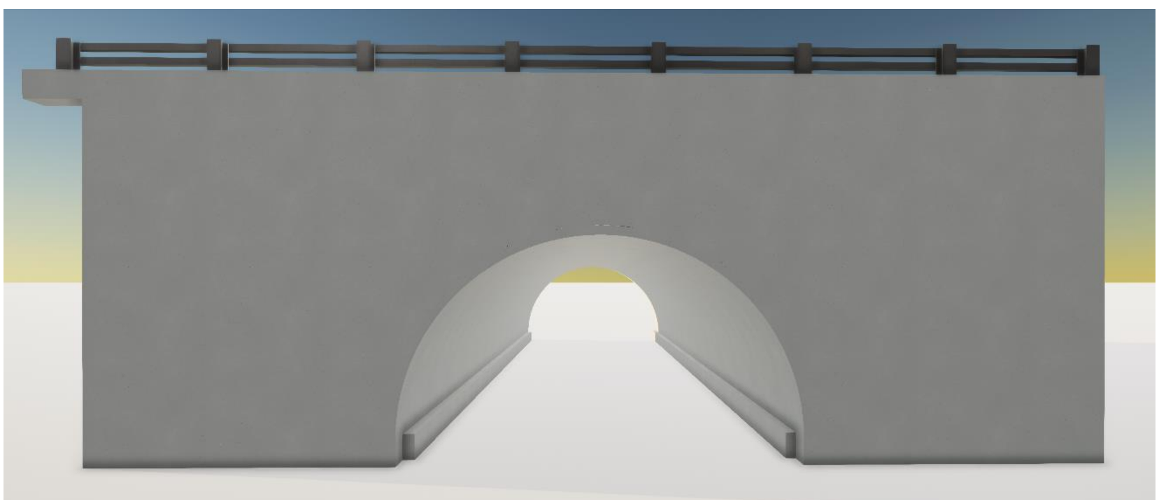


Figure 51: Arch III View at the South Portal to North, **Model Rendering** (own image)

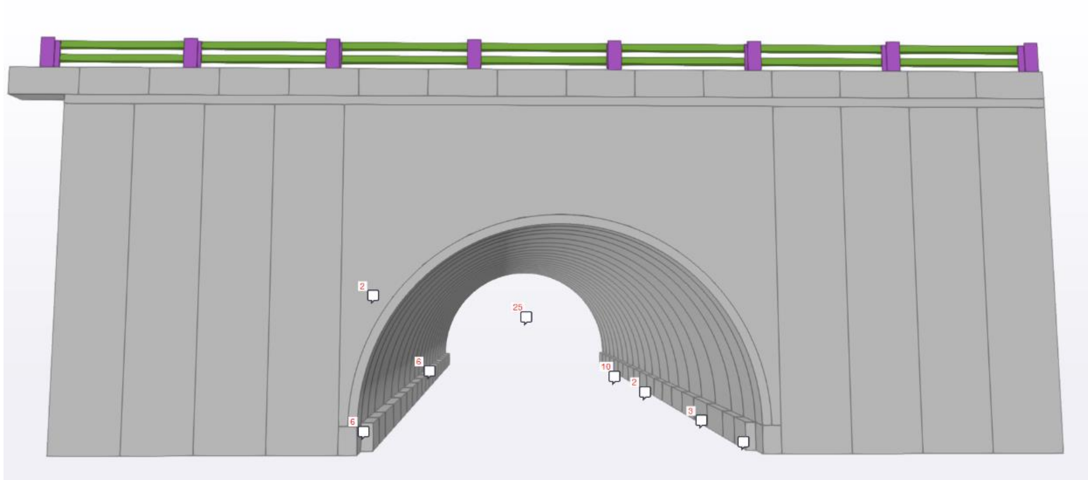


Figure 52: Arch III View at South Portal to North, Trimble Connect Model View with Defect Tags (own image)

Figure 53: Arch IV View at North Portal to East (own image)

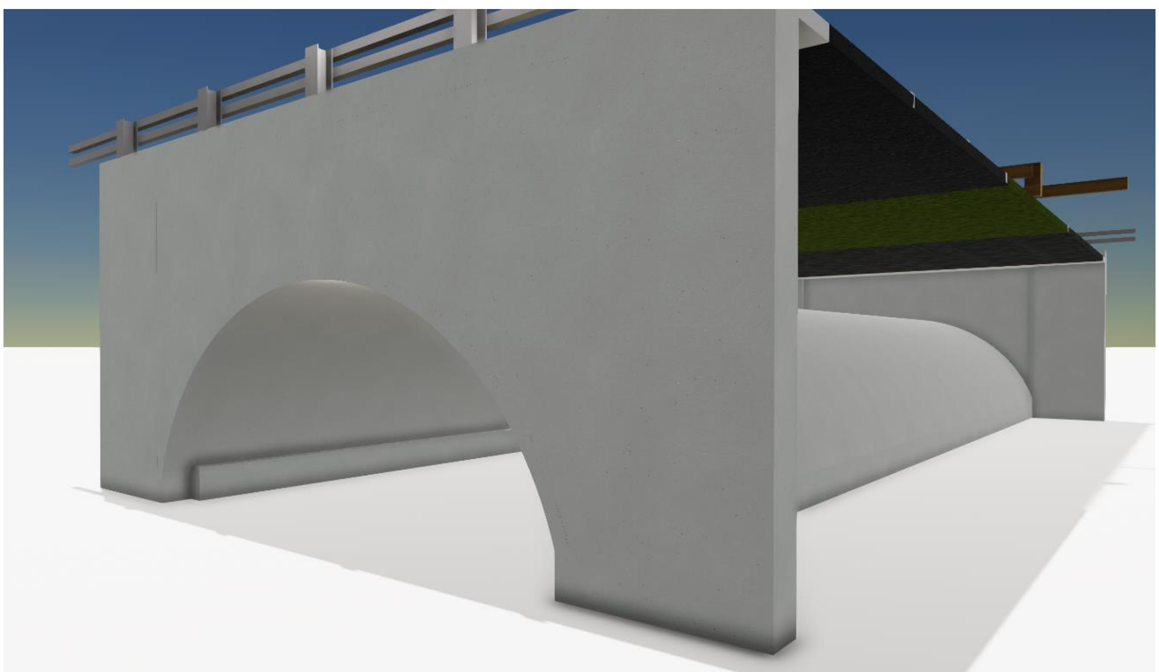


Figure 54: Arch IV View at North Portal to East, Model Rendering (own image)

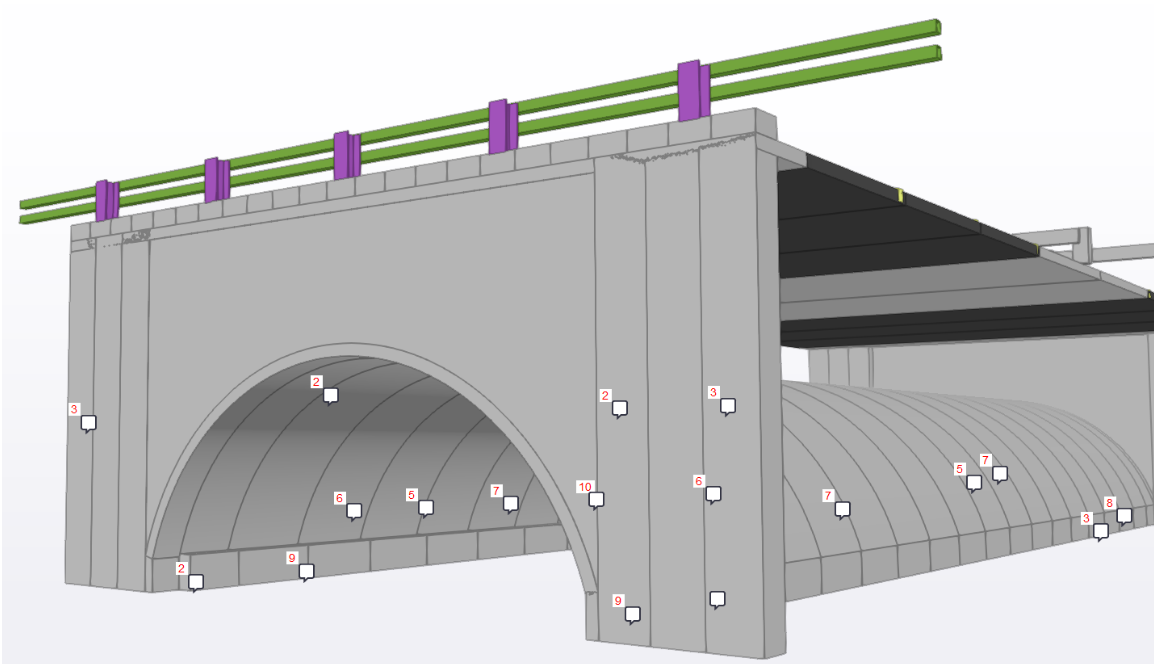


Figure 55: Arch IV View at North Portal to East, Trimble Connect Model View with Defect Tags (own image)

Figure 56: Arch IV View from South to North (own image)

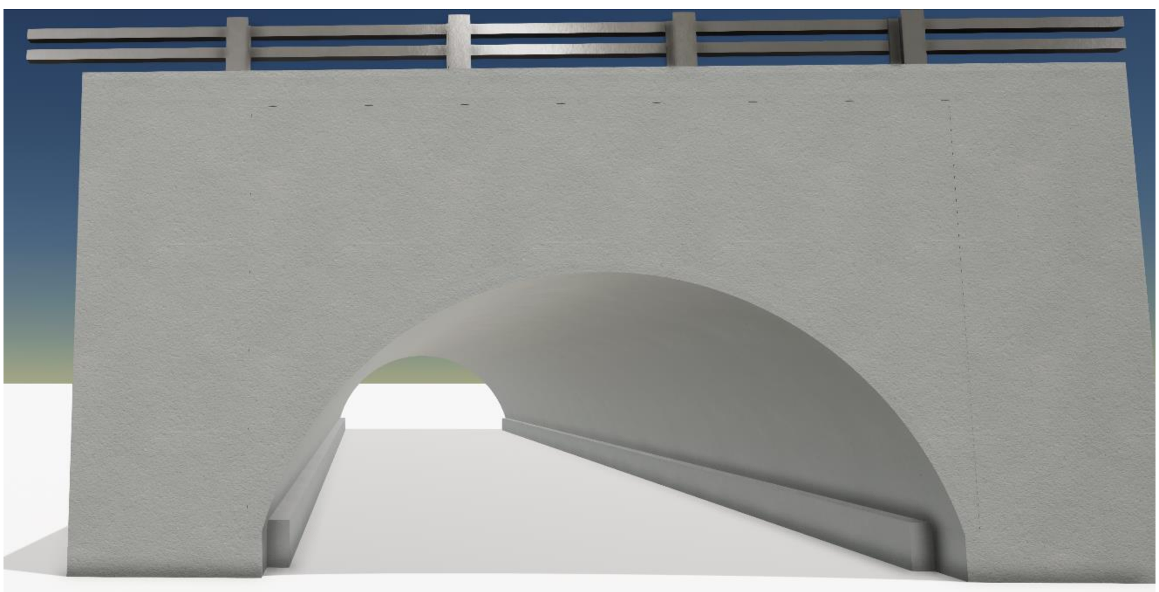


Figure 57: Arch IV View South to North, Model Rendering (own image)

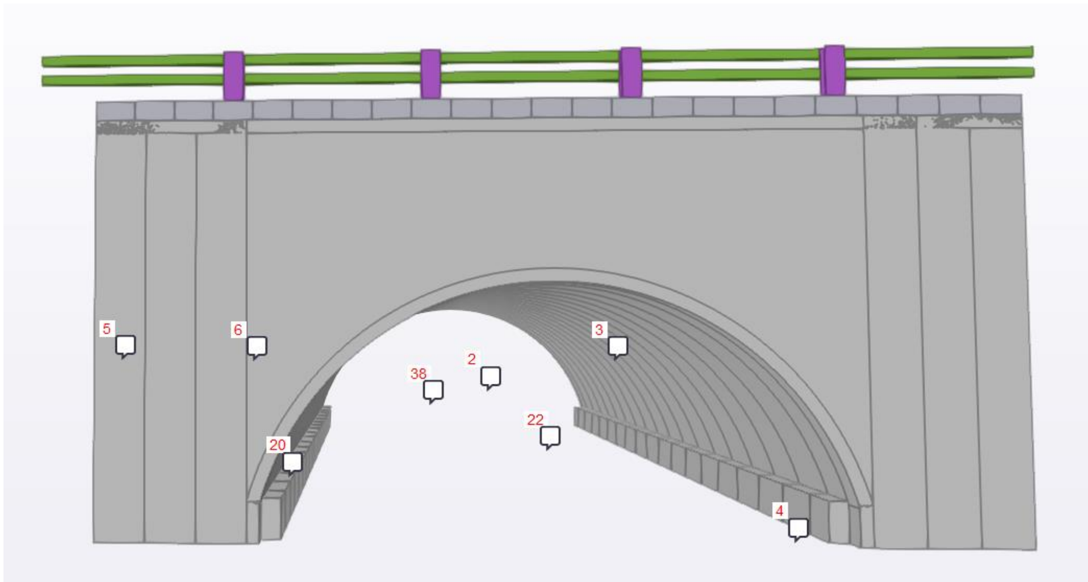


Figure 58: Arch IV View South to North, Trimble Connect Model View with Defect Tags (own image)

APPENDIX I – ARCH III MODEL CREATION

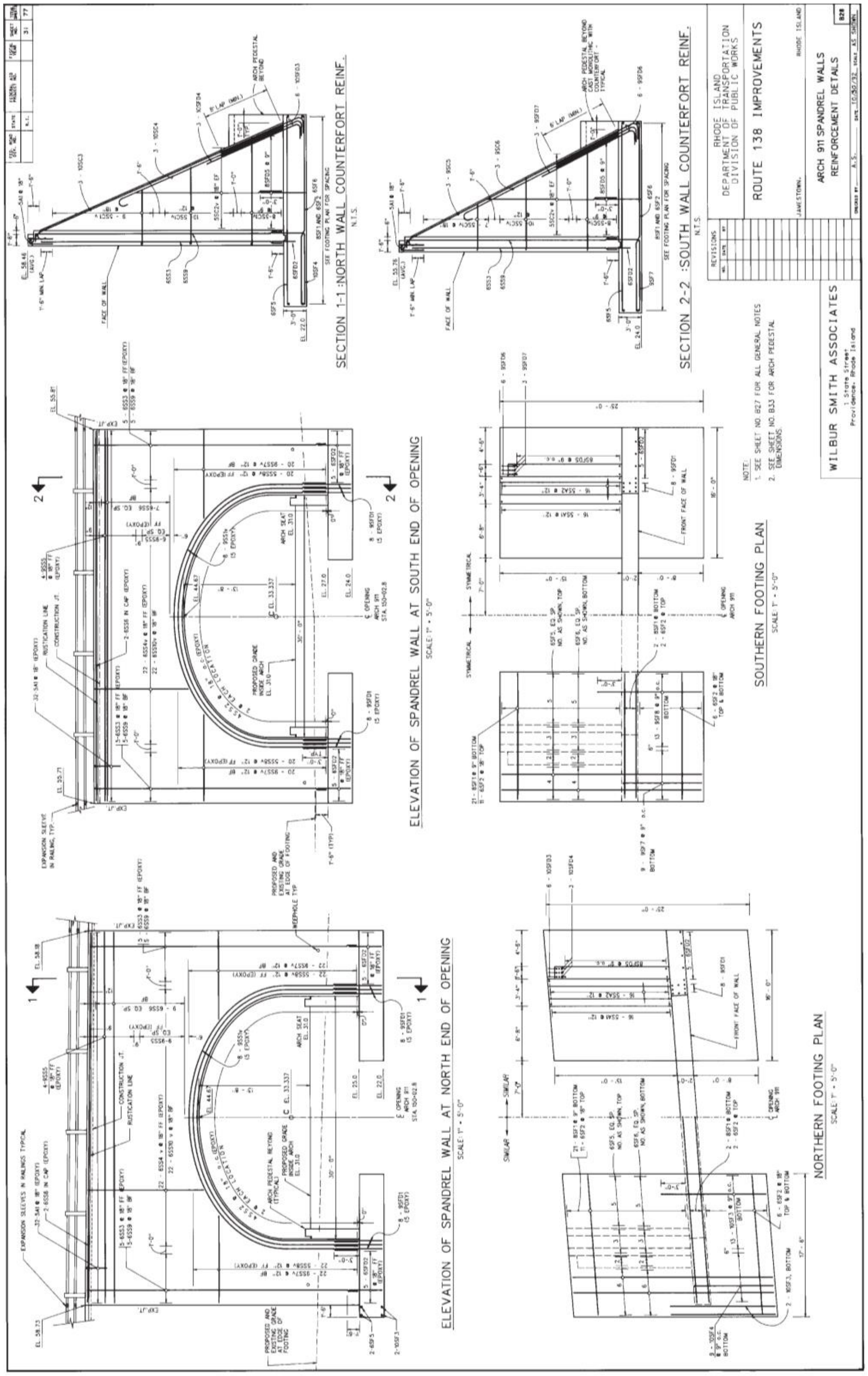


Figure 59: Arch III Construction Plan I (provided by RIDOT)

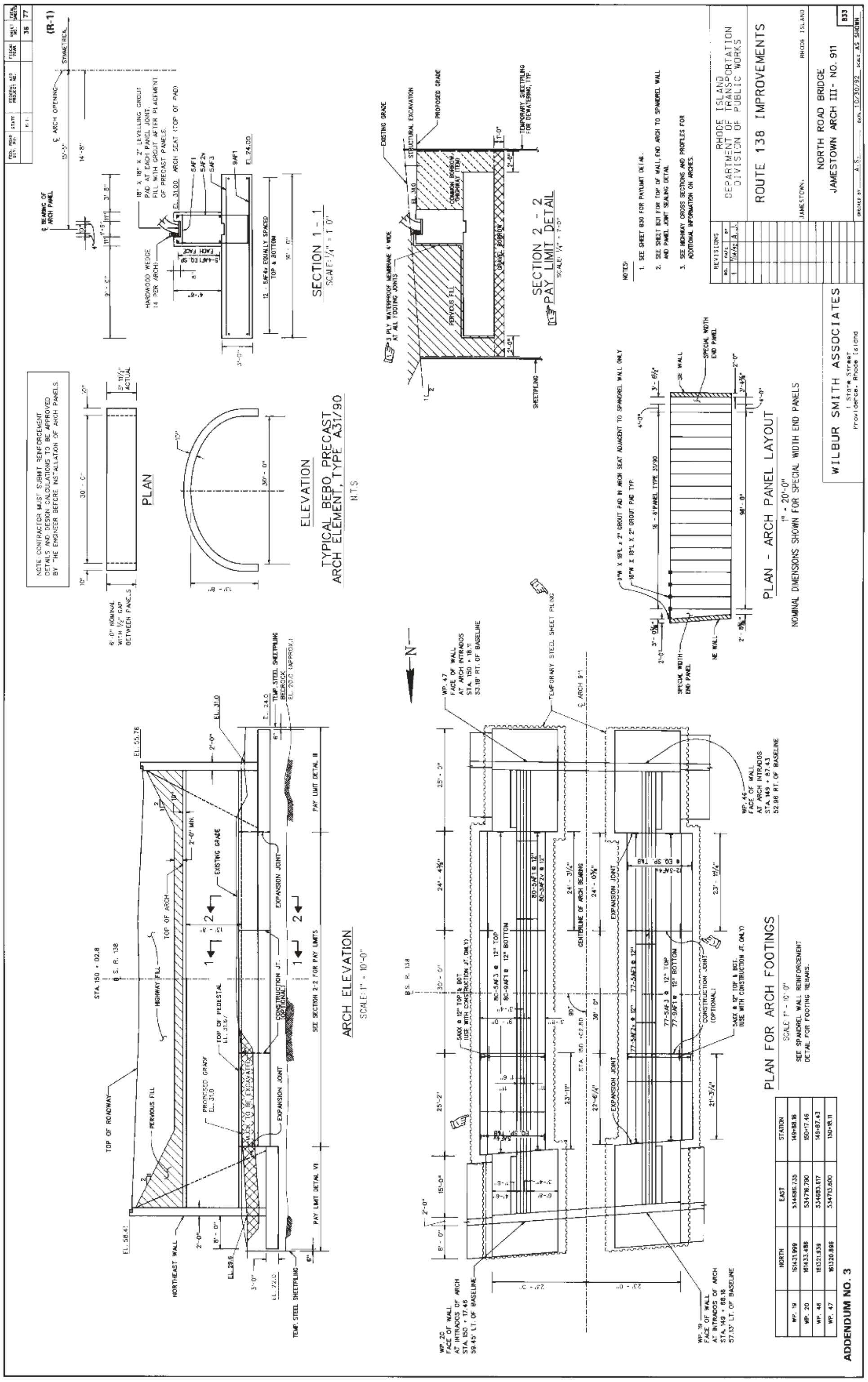


Figure 60: Arch III Construction Plan II (provided by RIDOT)

Table 14: Nomenclature and Geometrical Data of Arch III. Part I/III

Nomenclature	Class	Volume (ft^3)	Net surface area (ft^2)
N-East Wingwall	IFCWALL	361.62	1159.27
N-West Wingwall	IFCWALL	410.32	1167.88
North Portal	IFCSLAB	290.96	971.98
North Spandrel	IFCPLATE	59.89	245.42
Pedestal 1A	IFCWALL	11.67	31.22
Pedestal 1B	IFCWALL	26.01	59.20
Pedestal 1C	IFCWALL	26.01	59.20
Pedestal 1D	IFCWALL	26.01	59.20
Pedestal 1E	IFCWALL	26.01	59.20
Pedestal 1F	IFCWALL	26.01	59.20
Pedestal 1G	IFCWALL	26.01	59.20
Pedestal 1H	IFCWALL	26.01	59.20
Pedestal 1I	IFCWALL	26.01	59.20
Pedestal 1J	IFCWALL	26.01	59.20
Pedestal 1K	IFCWALL	26.01	59.20
Pedestal 1L	IFCWALL	26.01	59.20
Pedestal 1M	IFCWALL	26.01	59.20
Pedestal 1N	IFCWALL	26.01	59.20
Pedestal 1O	IFCWALL	26.01	59.20
Pedestal 1P	IFCWALL	26.01	59.20
Pedestal 1Q	IFCWALL	26.01	59.20
Pedestal 1R	IFCWALL	17.34	41.98
Pedestal 1S	IFCWALL	15.36	37.67

Table 15: Nomenclature and Geometric Data of Arch III. Part II/III

Nomenclature	Class	Volume (ft^3)	Net surface area (ft^2)
Pedestal 2A	IFCWALL	20.43	48.44
Pedestal 2B	IFCWALL	24.39	57.05
Pedestal 2C	IFCWALL	24.39	57.05
Pedestal 2D	IFCWALL	24.39	57.05
Pedestal 2E	IFCWALL	24.39	57.05
Pedestal 2F	IFCWALL	24.39	57.05
Pedestal 2G	IFCWALL	24.39	57.05
Pedestal 2H	IFCWALL	24.39	57.05
Pedestal 2I	IFCWALL	24.39	57.05
Pedestal 2J	IFCWALL	24.39	57.05
Pedestal 2K	IFCWALL	24.39	57.05
Pedestal 2L	IFCWALL	24.39	57.05
Pedestal 2M	IFCWALL	24.39	57.05
Pedestal 2N	IFCWALL	24.39	57.05
Pedestal 2O	IFCWALL	24.39	57.05
Pedestal 2P	IFCWALL	24.39	57.05
Pedestal 2Q	IFCWALL	24.39	57.05
Pedestal 2R	IFCWALL	16.26	40.90
Pedestal 2S	IFCWALL	14.40	37.67
S-East Wingwall 1	IFCWALL	247.60	367.05
S-East Wingwall 2	IFCWALL	247.60	367.05
S-East Wingwall 3	IFCWALL	247.60	367.05
S-East Wingwall 4	IFCWALL	247.60	367.05
S-West Wingwall 1	IFCWALL	247.60	367.05
S-West Wingwall 2	IFCWALL	247.60	367.05
S-West Wingwall 3	IFCWALL	247.60	367.05
S-West Wingwall 4	IFCWALL	247.60	367.05

Table 16: Nomenclature and Geometrical Data Arch III. Part III/III

Nomenclature	Class	Volume (ft^3)	Net surface area (ft^2)
Segment A	IFCPLATE	115.48	416.56
Segment B	IFCPLATE	179.38	614.62
Segment C	IFCPLATE	179.38	614.62
Segment D	IFCPLATE	179.38	614.62
Segment E	IFCPLATE	179.38	614.62
Segment F	IFCPLATE	179.38	614.62
Segment G	IFCPLATE	179.38	614.62
Segment H	IFCPLATE	179.38	614.62
Segment I	IFCPLATE	179.38	614.62
Segment J	IFCPLATE	179.38	614.62
Segment K	IFCPLATE	179.38	614.62
Segment L	IFCPLATE	179.38	614.62
Segment M	IFCPLATE	179.38	614.62
Segment N	IFCPLATE	179.38	614.62
Segment O	IFCPLATE	179.38	614.62
Segment P	IFCPLATE	179.38	614.62
Segment Q	IFCPLATE	179.38	614.62
Segment R	IFCPLATE	119.59	429.48
Segment S	IFCPLATE	105.89	387.50
South Portal	IFCSLAB	237.07	804.06
South Spandrel	IFCPLATE	59.79	245.42

APPENDIX J – ARCH III DATA ACQUISITION

RIDOT Bridge Inspection Report

091101

Jamestown Arch III

Inspected By Inspector: [redacted]

Bridge Condition Good

Last Inspection Date 05/23/2018

IDENTIFICATION

Bridge ID:	091101
NBI Number:	Jamestown Arch III
Structure Name:	Jamestown Arch III
Location (9):	3.8 Mi E Jct US1A/RI138
Carries (7):	RI 138
Type of Service (42A):	1 Highway
Feature Crossed (6):	Wildlife Passage
Type of Service (42B):	0 Other
Placecode (4):	Jamestown
County (3):	Newport
State (1):	44 Rhode Island
Station:	NBI
Region (2):	District 5
Latitude (16):	41.53
Longitude (17):	-71.37
Owner (22):	31 State Toll Authority
Custodian (21):	31 State Toll Authority
Year Built (27):	1994
Year Recon (106):	
Historical (37):	5 Not eligible for NRHP

Border State: Not Applicable (P)
Border Number:
% Responsibility:

INSPECTION

Date of Inspection (90):	5/23/2018
Frequency (91):	24
Next Inspection:	5/23/2020

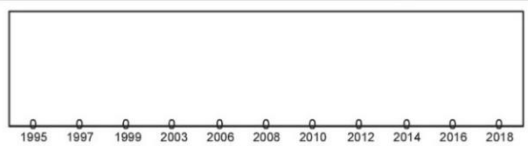
Inspection Type	Freq (92)	Last Insp (93)	Next Insp
Element	24	5/23/2018	5/23/2020
Fracture Critical (A)		1/1/1901	1/1/1901
Underwater (B)		1/1/1901	1/1/1901
Special Insp (C)		1/1/1901	1/1/1901

LOAD RATING AND POSTING

Posting Status (41)	A Open, no restriction
Posting % (70):	5 At/Above Legal Loads
Rating Date:	10/6/2011
Design Load (31):	5 MS 18 (HS 20)
Opr Method (63):	3 LRFR Load & Res. Fact
Opr Rating (64):	81.00 Tons
Inv Method (65):	3 LRFR Load & Res. Fact
Inv Rating (66):	62.00 Tons

DECK GEOMETRY

Deck Geometry (68):	7 Above Min Criteria
Deck Area:	3,287.40
Deck Type (107):	N N/A (NBI)
Wearing Surface (108A):	N N/A (no deck (NBI))
Membrane (108B):	N N/A (no deck (NBI))
Deck Protection (108C):	N N/A (no deck (NBI))
O. to O. Width (52):	109.58
Curb / Sidewalk Width L (50A):	0.25
Curb / Sidewalk Width R (50B):	0.25
Median (33):	3 Closed Med w/Barriers

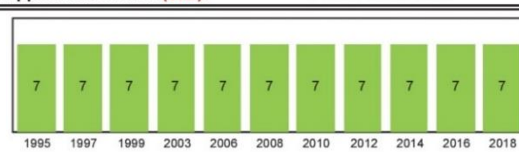


DECK CONDITION

Deck Rating (58):	N N/A (NBI)
Bridge Rail (36A):	0 Substandard
Transition (36B):	1 Meets Standards
Approach Rail (36C):	0 Substandard
Approach Rail Ends (36D):	1 Meets Standards

SUPERSTRUCTURE GEOMETRY

# of Main Spans (45):	1
# of Approach Spans (46):	0
Main Material (43 A):	1 Concrete
Main Design (43 B):	11 Arch-Deck
Max Span Length (48):	30.00
Structure Length (49):	30.00
NBIS Length (37):	Long Enough
Temp Structure (103):	Not Applicable (P)
Skew (34):	0
Structure Flared (35):	0 No flare
Parallel Structure (101):	No || bridge exists
Approach Alignment (72):	8 Equal Desirable Crit



SUPERSTRUCTURE CONDITION

Superstructure Rating (59):	7 Good
Structure Evaluation (67):	7 Above Min Criteria

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Figure 61: Arch III Inspection Report 2018 Page 1 (RIDOT, 2018a)

RIDOT Bridge Inspection Report

Driven to get you there

Bridge Condition Good

091101

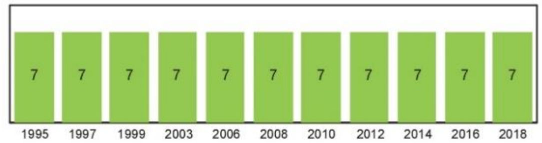
Jamestown Arch III

Inspected By Inspector: [redacted]

Last Inspection Date 05/23/2018

SUBSTRUCTURE GEOMETRY

Navigation Control (38):	NA-no waterway
Nav Vert Clearance (39):	0.00
Nav Horiz Clearance (40):	0.00
Pier Protection (111):	Not Applicable (P)
Lift Bridge Vertical Clearance (116):	
Scour Rating (113):	N Not Over Waterway
Waterway Adequacy (71):	N Not applicable



SUBSTRUCTURE CONDITION

Substructure Rating (59):	7 Good
Channel Rating (61):	N N/A (NBI)

ROUTE ON STRUCTURE: Route 138

ROADWAY LOCATION

Pos Prefix (5A):	Route On Structure
Kind of Hwy (5B):	3 State Hwy
Route Num (5D):	00138
LRS Route (13A/B):	4920-A/00
Milepost (11):	28.46 mi (45.80 km)
Suffix (5E):	0 N/A (NBI)
Lanes On (28A):	5
Detour Length (19):	1.90 mi (3.06 km)

ROADWAY CLASSIFICATION

Funct Class (26):	12 Urban Fwy/Expwy
Level Service (5C):	1 Mainline
NHS (104):	1 On the NHS
Defense Hwy (100):	0 Not a STRAHNET hwy
Toll Facility (20):	3 On free road
ADT (29):	26,700 Cars/Day
Pct Trucks (109):	10.00%
ADT Year (30):	2006

CLEARANCES

Vertical (10):	99.99	
Min Vert Over (53):	99.99	0.00
Vert Ref (54A):	N Feature not hwy or RR	
Horizontal (47):	46.58	
Min Lat Left (56):	0.00	
Min Lat Right (55B):	0.00	
Horiz Ref (55A):	N Feature not hwy or RR	
Underclearance (69):	N Not applicable (NBI)	

BRIDGE NOTES

The bridge is logged from west to east. The arch segments are labeled from north to south.

Equipment Used: Waders and ladder

Inspection Access: The structure is the third of four wildlife passages below RI 138 to the east of North Main Road. The structure was accessed from the southeast corner of nearby bridge 090201 carrying RI 138 over North Main Road .

Traffic Control: Single right lane closures on RI 138 EB and WB were used to inspect the top of deck. Traffic Control was provided by RITBA.

INSPECTION NOTES

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Figure 62: Arch III Inspection Report 2018 Page 2 (RIDOT, 2018a)

RIDOT Bridge
Inspection Report

091101
Jamestown Arch III

Inspected By
Inspector: [redacted]

Bridge Condition Good

Last Inspection Date 05/23/2018

Team Leader: [redacted]
Staff Inspector: [redacted]
Staff Inspector: [redacted]
Inspection Dates: May 22 and 23, 2018
Weather: 05/22: 68 degrees Fahrenheit, Cloudy, 05/23: 73 degrees Fahrenheit, Partly Sunny

Superstructure (Rating = 7): The underside of the reinforced concrete arch has a few small spalls up to 2" deep, an isolated hollow area, light leakage stains and moss growth throughout. The arch segments have random vertical cracks near the pedestals up to 4' long and isolated areas of superficial hairline map cracks. The segments at the crown have vertical misalignment up to 1" and gaps up to 1-1/4" wide. The joint between Segment 'S' and the south spandrel wall has vertical misalignment up to 2" with a 2" wide gap.

Substructure (Rating = 7): The reinforced concrete pedestals are exposed full length x up to 1.5' high with a few small spalls up to 3" deep. Both pedestals have full height vertical cracks open up to 1/16" wide and extend up to full width across the top with and without efflorescence. The pedestal segments have vertical misalignment up to 1" and horizontal misalignments up to 1-3/4".

Deflection and Vibration: There was no vibration noted at the time of inspection.

Curbs: North and south curbs have random areas of rust stains. Isolated curb joints have areas of deteriorated joint sealant between curb sections and between the curb and top of the spandrel walls (over the bridge and in the approaches). The north curb near Pedestal #2 has a full height vertical hairline crack that extends full width across the top of the North spandrel wall, (See Photos 27 through 29).

Average North and South Curb Reveals: RI 138 was being resurfaced at the time of inspection. The right lane/shoulde r in both directions have the first lift/course of bituminous wearing surface, the final course has not yet been placed.

Average North Curb Reveal = 7-1/2"
Average South Curb Reveal = 9-1/2"

Median: Vegetated median is located on the top of the bridge between the eastbound and westbound travel lanes, (S ee Photo 41).

Passageway: There were areas of ponding water up to full length x full width (worst along Pedestal #2) at the time of inspection, (See Photo 22).

Vegetation: The north and south entrances have moderate growth of vegetation and small trees, (See Photos 43 and 44).

ELEMENT CONDITION SUMMARY

Elm/Env	Description	Total Qty	% in 1	Qty. St. 1	% in 2	Qty. St. 2	% in 3	Qty. St. 3	% in 4	Qty. St. 4
144/3	Re Conc Arch	570.00	98%	550.00	1%	17.00	1%	3.00	0%	0.00
1080/3	Delamination/Spall/Patched Area	5.00	0%	0.00	25%	2.00	75%	3.00	0%	0.00
1130/3	Cracking (RC and Other)	65.00	100%	50.00	0%	15.00	0%	0.00	0%	0.00
8510/3	Wearing Surfaces Arch -Culvert	2,478.00	100%	2,478.00	0%	0.00	0%	0.00	0%	0.00
215/3	Re Conc Abutment	220.00	76%	162.00	23%	53.00	1%	5.00	0%	0.00
1080/3	Delamination/Spall/Patched Area	8.00	0%	0.00	33%	3.00	67%	5.00	0%	0.00
1120/3	Efflorescence/Rust Staining	20.00	0%	0.00	100%	20.00	0%	0.00	0%	0.00
1130/3	Cracking (RC and Other)	30.00	33%	10.00	67%	20.00	0%	0.00	0%	0.00
4000/3	Settlement	10.00	0%	0.00	100%	10.00	0%	0.00	0%	0.00
321/3	Re Conc Approach Slab	2,313.00	81%	2,313.00	19%	0.00	0%	0.00	0%	0.00
510/3	Wearing Surfaces	2,313.00	81%	2,313.00	19%	0.00	0%	0.00	0%	0.00
330/3	Metal Bridge Railing	91.00	100%	91.00	0%	0.00	0%	0.00	0%	0.00
515/3	Steel Protective Coating	364.00	100%	349.00	0%	15.00	0%	0.00	0%	0.00

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Figure 63: Arch III Inspection Report 2018 Page 3 (RIDOT, 2018a)

RIDOT Bridge Inspection Report

091101

Jamestown Arch III

Inspected By Inspector: [redacted]

Last Inspection Date 05/23/2018

Bridge Condition Good

Elm/Env	Description	Total Qty	% in 1	Qty. St. 1	% in 2	Qty. St. 2	% in 3	Qty. St. 3	% in 4	Qty. St. 4
8208/3	R/C Spandrel Wall	91.00	71%	65.00	29%	26.00	0%	0.00	0%	0.00
1080/3	Delamination/Spall/Patched Area	1.00	0%	0.00	100%	1.00	0%	0.00	0%	0.00
1120/3	Efflorescence/Rust Staining	10.00	0%	0.00	100%	10.00	0%	0.00	0%	0.00
1130/3	Cracking (RC and Other)	20.00	25%	5.00	75%	15.00	0%	0.00	0%	0.00
8335/3	Guardrail, Vehicular	600.00	95%	555.00	3%	40.00	2%	5.00	0%	0.00
515/3	Steel Protective Coating	1,600.00	90%	1,520.00	10%	80.00	0%	0.00	0%	0.00
1150/3	Check/Shake	20.00	50%	10.00	50%	10.00	0%	0.00	0%	0.00
1170/3	Split/Delamination (Timber)	15.00	100%	0.00	0%	10.00	0%	5.00	0%	0.00
7000/3	Damage	20.00	0%	0.00	0%	20.00	100%	0.00	0%	0.00

ELEMENT NOTES

STRUCTURE UNIT: 0

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
144	Re Conc Arch	3	570.00	ft	550.00	17.00	3.00	0.00

The superstructure is comprised of nineteen (19) pre-cast reinforced concrete arch segments labeled from North to South as Segments 'A' to SS', and cast-in-place concrete spandrel walls at the North and South ends of the arch. The underside of the reinforced concrete arch has light leakage staining and moderate moss growth throughout. The arch segments have superficial hairline map cracks near the crown, random vertical hairline cracks near the pedestals, a few spalls, and an isolated hollow area. The segments at the crown have vertical misalignment up to 1" and gaps up to 1-1/4" wide (maximum at the east end of joint between Segments 'P' and 'Q'). Isolated joints have efflorescence and soil leakage onto the pedestals. The joint between Segment 'S' and the South spandrel wall has gaps up to 2" wide with vertical misalignment up to 2", (See Photos 12 through 20 and 22).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1080	Delaminatton/Spall/Pattched Ar3		5.00	ffl	0.00	2.00	3.00	0.00

Segment 'C' at Pedestal #2 at the east end has a spall up to 6" high x 6" wide x 2" deep, (S ee Photo 13).

Segment 'D' at Pedestal #1 at the west end has a spall up to 16" high x 8" wide x 2" deep, (See Photo 14).

Segment 'I' at Pedestal #1 at the west end has a spall up to 16" high x 5" wide x 1" deep, (See Photo 15).

Segment 'P' at the west end has a hollow area up to 14" high x 4" wide with several vertical hairline cracks up to 4' long, (See Photo 16).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1130	Cracking (RC and Otther)	3	65.00	ffl	50.00	15.00	0.00	0.00

The arch segments near the pedestals have random vertical hairline cracks up to 4' long and superficial hairline map cracks at the crown up to 12' long x full segment width, (See Photos 12 and 16).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
8510	Wearing Surfflaces Arch -Culvert3		2,478.00	sq.ffl	2,478.00	0.00	0.00	0.00

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Figure 64: Arch III Inspection Report 2018 Page 4 (RIDOT, 2018a)

RI 138 was being resurfaced at the time of inspection.

The Eastbound right lane and shoulder have the first lift/course of bituminous wearing surface in place. The Eastbound left lane and shoulder have the final lift/course of wearing surface in place. The final wearing surface in the Eastbound left lane and shoulder has no notable deficiencies, (See Photos 4 through 7).

The Westbound lanes have the final lift/course of bituminous wearing surface in place in both travel lanes. The right shoulder has the first lift/course of bituminous wearing surface in place only; the final course has not yet been placed. The final wearing surface in the Westbound travel lanes has no notable deficiencies, (See Photos 8 through 11).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
215	Re Conc Abutment	3	220.00	ft	162.00	53.00	5.00	0.00

The reinforced concrete pedestals are exposed full length x up to 1.5' high and have a few spalls, and random transverse and vertical cracks. The pedestal segments have a few locations of vertical and/or horizontal misalignment and there is 15' long section at Pedestal #2 with active leakage through the construction joints, (See Photos 13 through 16 and 20 through 26).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1080	Delaminatton/Spall/Pattched Ar	3	8.00	ffl	0.00	3.00	5.00	0.00

Pedestal #1 has a spall below arch Segment 'D' up to 1' long x 4" wide x 3" deep, (See Photos 14 and 20).

Pedestal #2 has two (2) spalls below arch Segment 'E' up to 3" long x 2-1/2" wide x 1-1/2" deep, (See Photo 23).

Pedestal #2 has a spall below arch Segment 'G' up to 7" long x 3-1/2" wide x 1-1/2" deep, (See Photo 24).

Pedestal #2 has a spall below Segment 'H' up to 26" long x 5" wide x 1-1/2" deep, (See Photo 25).

Pedestal #2 has a spall below arch Segment 'I' up to 2' long x 4" wide x 1" deep, (See Photo 25).

Pedestal #2 has four (4) spalls below arch Segment 'J' up to 2-1/2" diameter x 1/2" deep.

Pedestal #2 has a spall below arch Segment 'K' up to 4" long x 1" wide x 1/2" deep.

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1120	Efflorescence/Rustt Sttaining	3	20.00	ffl	0.00	20.00	0.00	0.00

The reinforced concrete pedestals have several full height vertical hairline cracks with and without efflorescence, (See Photos 13, 20 through 22, and 26). Pedestal #2 near Segments 'G' and 'H' has a 15' long area of active leakage, (See Photos 24 and 25).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1130	Cracking (RC and Otther)	3	30.00	ffl	10.00	20.00	0.00	0.00

The reinforced concrete pedestals have full height vertical cracks open up to 1/16" wide that extend up to full width across the top with and without efflorescence, (See Photos 13, 16, 20 through 22, and 26).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
4000	Settlementt	3	10.00	ffl	0.00	10.00	0.00	0.00

The pedestal segments at the joints have vertical misalignment up to 1" (maximum below arch Segment 'D') and lateral misalignments up to 1-3/4" (maximum below arch Segments 'C' and 'P') (See Photos 13, 14, 22, and 26).

Figure 65: Arch III Inspection Report 2018 Page 5 (RIDOT, 2018a)

Table 17: Arch III Defect ID and Location Tags derived from Routine Inspection Report 2018

Defect ID	Tags
2018 144-1080	Segment D
2018 144-1080	Segment C
2018 144-1080	Segment I
2018 144-1080	Segment C
2018 144-1080	Segment D
2018 144-1080	Segment P
2018 144-1080	Segment I
2018 215-1080	Pedestal 2K
2018 215-1080	Pedestal 2J
2018 215-1080	Pedestal 2I
2018 215-1080	Pedestal 2H
2018 215-1080	Pedestal 2G
2018 215-1080	Pedestal 2E
2018 215-1080	Pedestal 1D
2018 215-1120	Pedestal 2G
2018 8208-1080	N-West Wingwall
2018 8208-1120	North Spandrel
2018 8208-1120	South Portal

Table 18: Arch III Defect ID and Location Tags assessed on May 21st, 2020

Defect ID	Tags
2020 144-1080	Segment D
2020 144-1080	Segment P
2020 144-1080	Segment R
2020 144-1080	Segment C
2020 144-1080	Segment I
2020 215-1080	Pedestal 2S
2020 215-1080	Pedestal 1D
2020 215-1120	Pedestal 1S
2020 215-1120	Pedestal 1A
2020 215-1130	Pedestal 2P
2020 215-1130	Pedestal 2P
2020 215-1130	Pedestal 1R
2020 215-4000	Pedestal 2P
2020 215-4000	Pedestal 2C
2020 215-4000	Pedestal 1P
2020 8208-1080	N-West Wingwall
2020 8208-1080	South Spandrel
2020 8208-1080	South Portal
2020 8208-1090	North Spandrel
2020 8208-1130	North Spandrel
2020 8208-1130	North Spandrel
2020 8208-1130	South Spandrel
2020 8208-1130	South Spandrel
2020 8208-4000	South Spandrel

Table 19: Arch III Defect ID and Location Tags assessed on June 5th, 2020

Defect ID	Tags
2021 144-1080	Segment C
2021 144-1080	Segment I
2021 144-1080	Segment D
2021 144-1130	Segment P
2021 215-1080	Pedestal 1Q
2021 215-1080	Pedestal 1D
2021 215-1120	Pedestal 2A
2021 215-1120	Pedestal 2C
2021 215-1120	Pedestal 2G
2021 215-1120	Pedestal 2D
2021 215-1120	Pedestal 1A
2021 215-1120	Pedestal 1S
2021 215-4000	Pedestal 1P
2021 215-4000	Pedestal 1D
2021 8208-1080	South Portal
2021 8208-1120	North Spandrel

APPENDIX K – ARCH IV MODEL CREATION

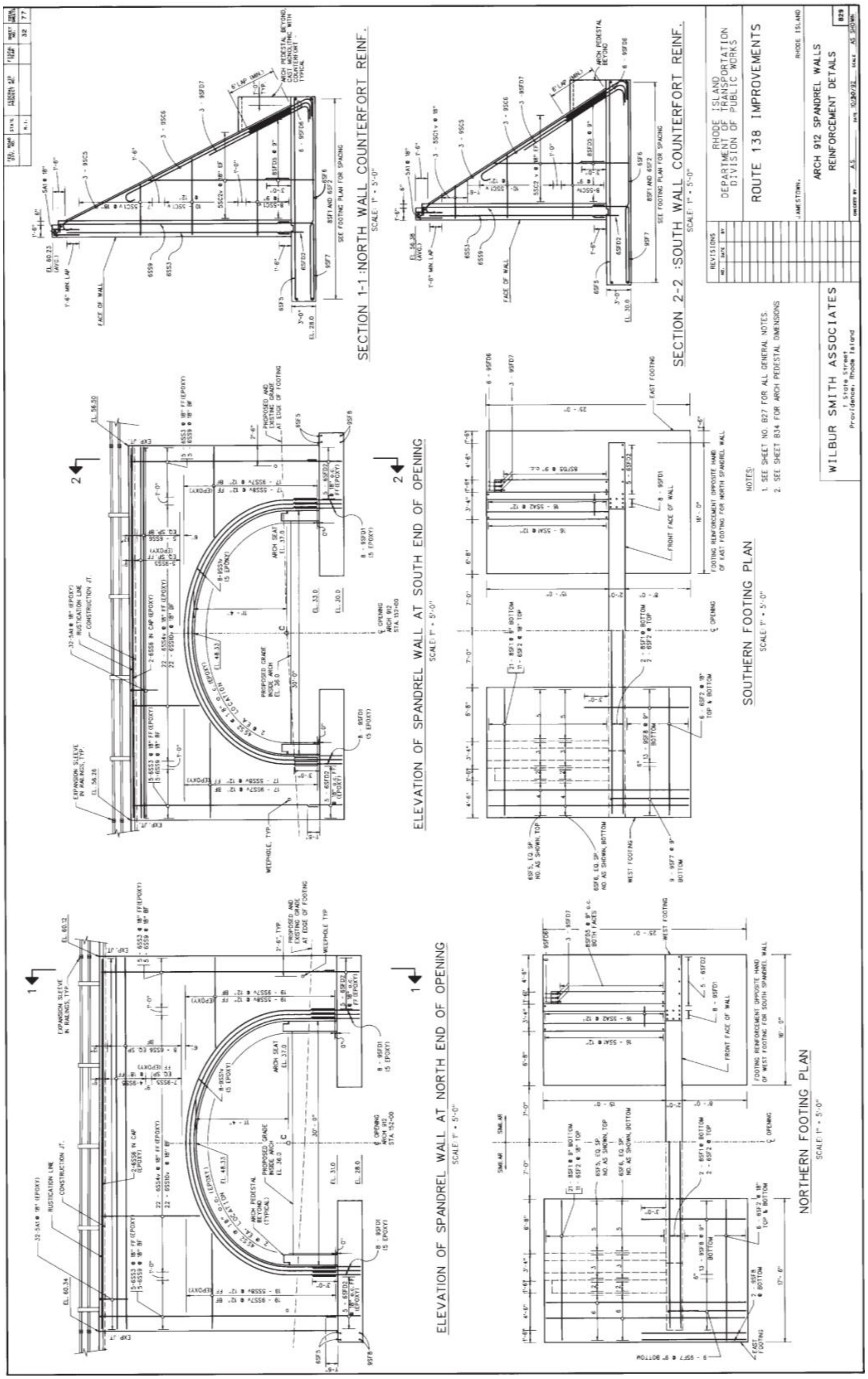


Figure 66: Arch IV Construction Plan I (provided by RIDOT)

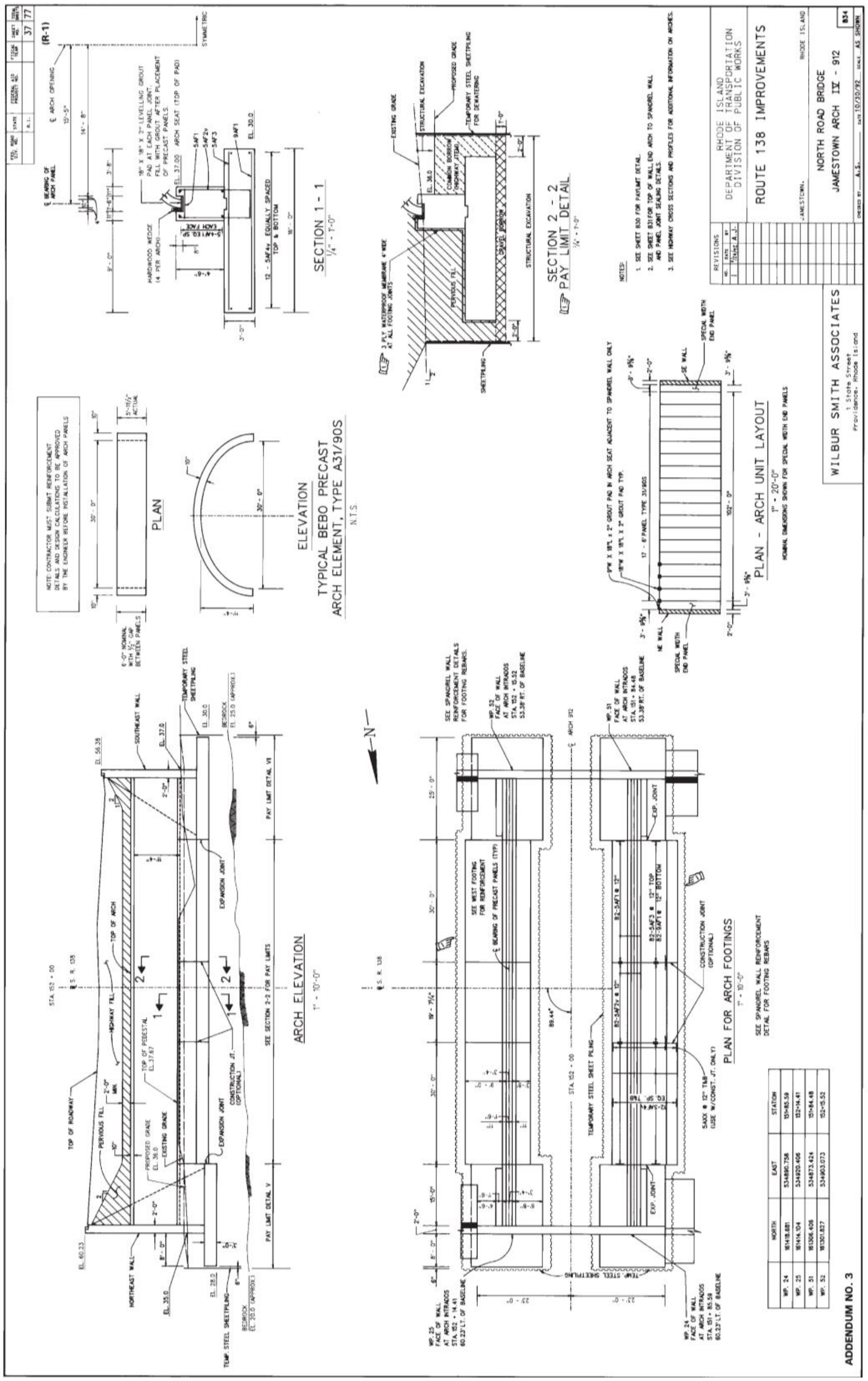


Figure 67: Arch IV Construction Plan II (provided by RIDOT)

Table 20: Nomenclature and Geometrical Data of Arch IV. Part I/III

Nomenclature	Class	Volume (ft³)	Net surface area (ft²)
N-East Wingwall1	IFCWALL	108.4	203.4
N-East Wingwall2	IFCWALL	108.4	203.4
N-East Wingwall3	IFCWALL	108.4	203.4
North Portal	IFCSLAB	213.5	723.3
North Spandrel	IFCPLATE	52.9	217.4
N-West Wingwall1	IFCWALL	108.4	203.4
N-West Wingwall2	IFCWALL	108.4	203.4
N-West Wingwall3	IFCWALL	108.4	203.4
Pedestal 1A	IFCWALL	7.9	28
Pedestal 1B	IFCWALL	12.5	40.9
Pedestal 1C	IFCWALL	12.5	40.9
Pedestal 1D	IFCWALL	12.5	40.9
Pedestal 1E	IFCWALL	12.5	40.9
Pedestal 1F	IFCWALL	12.5	40.9
Pedestal 1G	IFCWALL	12.5	40.9
Pedestal 1H	IFCWALL	12.5	40.9
Pedestal 1I	IFCWALL	12.5	40.9
Pedestal 1J	IFCWALL	12.5	40.9
Pedestal 1K	IFCWALL	12.5	40.9
Pedestal 1L	IFCWALL	12.5	40.9
Pedestal 1M	IFCWALL	12.5	40.9
Pedestal 1N	IFCWALL	12.5	40.9
Pedestal 1O	IFCWALL	12.5	40.9
Pedestal 1P	IFCWALL	12.5	40.9
Pedestal 1Q	IFCWALL	12.5	40.9
Pedestal 1R	IFCWALL	12.5	40.9
Pedestal 1S	IFCWALL	7.9	28

Table 21: Nomenclature and Geometrical Data of Arch IV. Part II/III

Nomenclature	Class	Volume (ft³)	Net surface area (ft²)
Pedestal 2A	IFCWALL	7.9	28
Pedestal 2B	IFCWALL	12.5	40.9
Pedestal 2C	IFCWALL	12.5	40.9
Pedestal 2D	IFCWALL	12.5	40.9
Pedestal 2E	IFCWALL	12.5	40.9
Pedestal 2F	IFCWALL	12.5	40.9
Pedestal 2G	IFCWALL	12.5	40.9
Pedestal 2H	IFCWALL	12.5	40.9
Pedestal 2I	IFCWALL	12.5	40.9
Pedestal 2J	IFCWALL	12.5	40.9
Pedestal 2K	IFCWALL	12.5	40.9
Pedestal 2L	IFCWALL	12.5	40.9
Pedestal 2M	IFCWALL	12.5	40.9
Pedestal 2N	IFCWALL	12.5	40.9
Pedestal 2O	IFCWALL	12.5	40.9
Pedestal 2P	IFCWALL	12.5	40.9
Pedestal 2Q	IFCWALL	12.5	40.9
Pedestal 2R	IFCWALL	12.5	40.9
Pedestal 2S	IFCWALL	7.9	28
S-East Wingwall1	IFCWALL	108.4	203.4
S-East Wingwall2	IFCWALL	108.4	203.4
S-East Wingwall3	IFCWALL	108.4	203.4

Table 22: Nomenclature and Geometrical Data of Arch IV. Part III/III

Nomenclature	Class	Volume (ft³)	Net surface area (ft²)
Segment A	IFCPLATE	100.7	364.9
Segment B	IFCPLATE	158.8	544.7
Segment C	IFCPLATE	158.8	544.7
Segment D	IFCPLATE	158.8	544.7
Segment E	IFCPLATE	158.8	544.7
Segment F	IFCPLATE	158.8	544.7
Segment G	IFCPLATE	158.8	544.7
Segment H	IFCPLATE	158.8	544.7
Segment I	IFCPLATE	158.8	544.7
Segment J	IFCPLATE	158.8	544.7
Segment K	IFCPLATE	158.8	544.7
Segment L	IFCPLATE	158.8	544.7
Segment M	IFCPLATE	158.8	544.7
Segment N	IFCPLATE	158.8	544.7
Segment O	IFCPLATE	158.8	544.7
Segment P	IFCPLATE	158.8	544.7
Segment Q	IFCPLATE	158.8	544.7
Segment R	IFCPLATE	158.8	544.7
Segment S	IFCPLATE	100.7	364.9
South Portal	IFCSLAB	213.5	723.3
South Spandrel	IFCPLATE	52.9	217.4
S-West Wingwall1	IFCWALL	108.4	203.4
S-West Wingwall2	IFCWALL	108.4	203.4
S-West Wingwall3	IFCWALL	108.6	203.4

RIDOT Bridge Inspection Report

091201

Jamestown Arch IV

Inspected By Inspector: [redacted]

Last Inspection Date 05/23/2018

Bridge Condition Good

IDENTIFICATION

Bridge ID:	091201
NBI Number:	Jamestown Arch IV
Structure Name:	Jamestown Arch IV
Location (9):	3.8 Mi E Jct US1A/RI138
Carries (7):	RI 138
Type of Service (42A):	1 Highway
Feature Crossed (6):	Wildlife Passage
Type of Service (42B):	0 Other
Placecode (4):	Jamestown
County (3):	Newport
State (1):	44 Rhode Island
Station:	NBI
Region (2):	District 5
Latitude (16):	41.53
Longitude (17):	-71.37
Owner (22):	31 State Toll Authority
Custodian (21):	31 State Toll Authority

Year Built (27):	1994	Border State: Not Applicable (P)
Year Recon (106):		Border Number:
Historical (37):	5 Not eligible for NRHP	% Responsibility:

INSPECTION

Date of Inspection (90):	5/23/2018
Frequency (91):	24
Next Inspection:	5/23/2020

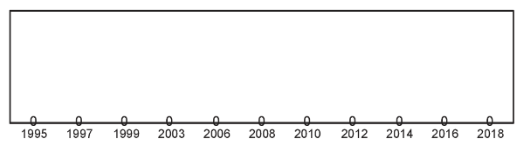
Inspection Type	Freq (92)	Last Insp (93)	Next Insp
Element	24	5/23/2018	5/23/2020
Fracture Critical (A)		1/1/1901	1/1/1901
Underwater (B)		1/1/1901	1/1/1901
Special Insp (C)		1/1/1901	1/1/1901

LOAD RATING AND POSTING

Posting Status (41)	A Open, no restriction
Posting % (70):	5 At/Above Legal Loads
Rating Date:	10/11/2011
Design Load (31):	5 MS 18 (HS 20)
Opr Method (63):	3 LRFR Load & Res. Fact
Opr Rating (64):	53.00 Tons
Inv Method (65):	3 LRFR Load & Res. Fact
Inv Rating (66):	41.00 Tons

DECK GEOMETRY

Deck Geometry (68):	9 Above Desirable Crit
Deck Area:	3,437.40
Deck Type (107):	N N/A (NBI)
Wearing Surface (108A):	N N/A (no deck (NBI))
Membrane (108B):	N N/A (no deck (NBI))
Deck Protection (108C):	N N/A (no deck (NBI))
O. to O. Width (52):	114.58
Curb / Sidewalk Width L (50A):	0.25
Curb / Sidewalk Width R (50B):	0.25
Median (33):	3 Closed Med w/Barriers

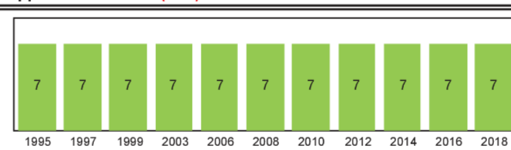


DECK CONDITION

Deck Rating (58):	N N/A (NBI)
Bridge Rail (36A):	0 Substandard
Transition (36B):	1 Meets Standards
Approach Rail (36C):	0 Substandard
Approach Rail Ends (36D):	1 Meets Standards

SUPERSTRUCTURE GEOMETRY

# of Main Spans (45):	1
# of Approach Spans (46):	0
Main Material (43 A):	1 Concrete
Main Design (43 B):	11 Arch-Deck
Max Span Length (48):	30.00
Structure Length (49):	30.00
NBIS Length (37):	Long Enough
Temp Structure (103):	Not Applicable (P)
Skew (34):	0
Structure Flared (35):	0 No flare
Parallel Structure (101):	No || bridge exists
Approach Alignment (72):	8 Equal Desirable Crit



SUPERSTRUCTURE CONDITION

Superstructure Rating (59):	7 Good
Structure Evaluation (67):	7 Above Min Criteria

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Figure 68: Arch IV Inspection Report 2018 Page 1 (RIDOT, 2018b)

RIDOT Bridge Inspection Report

091201

Jamestown Arch IV

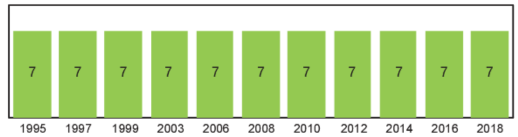
Inspected By Inspector: [redacted]

Last Inspection Date 05/23/2018

Bridge Condition Good

SUBSTRUCTURE GEOMETRY

Navigation Control (38):	NA-no waterway
Nav Vert Clearance (39):	0.00
Nav Horiz Clearance (40):	0.00
Pier Protection (111):	Not Applicable (P)
Lift Bridge Vertical Clearance (116):	
Scour Rating (113):	N Not Over Waterway
Waterway Adequacy (71):	N Not applicable



SUBSTRUCTURE CONDITION

Substructure Rating (59):	7 Good
Channel Rating (61):	N N/A (NBI)

ROUTE ON STRUCTURE: RI 138

ROADWAY LOCATION

Pos Prefix (5A):	Route On Structure
Kind of Hwy (5B):	3 State Hwy
Route Num (5D):	00138
LRS Route (13A/B):	4920-A/00
Milepost (11):	28.50 mi (45.86 km)
Suffix (5E):	0 N/A (NBI)
Lanes On (28A):	5
Detour Length (19):	1.90 mi (3.06 km)

ROADWAY CLASSIFICATION

Funct Class (26):	12 Urban Fwy/Expwy
Level Service (5C):	1 Mainline
NHS (104):	1 On the NHS
Defense Hwy (100):	0 Not a STRAHNET hwy
Toll Facility (20):	3 On free road
ADT (29):	26,700 Cars/Day
Pct Trucks (109):	10.00%
ADT Year (30):	2006

CLEARANCES

Vertical (10):	99.99	
Min Vert Over (53):	99.99	0.00
Vert Ref (54A):	N Feature not hwy or RR	
Horizontal (47):	51.58	
Min Lat Left (56):	0.00	
Min Lat Right (55B):	0.00	
Horiz Ref (55A):	N Feature not hwy or RR	
Underclearance (69):	N Not applicable (NBI)	

BRIDGE NOTES

The bridge is logged from west to east. The arch segments are labeled from north to south.

Equipment Used: Waders and ladders.

Inspection Access: The structure is the fourth of four wildlife passages below RI 138 to the east of North Main Road. The structure was accessed from the southeast corner of nearby bridge 090201 carrying RI 138 over North Main Road .

Traffic Control: Single right lane closures on RI 138 EB and WB were used to inspect the top of deck. Traffic Control was provided by RITBA.

INSPECTION NOTES

RIDOT Inspection Report (v2.7.4cn) Fri 05/22/2020 Page 2 of 8

Figure 69: Arch IV Inspection Report 2018 Page 2 (RIDOT, 2018b)

RIDOT Bridge Inspection Report

091201

Jamestown Arch IV

Inspected By
Inspector: [redacted]

Bridge Condition Good

Last Inspection Date 05/23/2018

Team Leader: [redacted]
Staff Inspector:
Staff Inspector:
Inspection Dates: May 22 and 23, 2018
Weather: 05/22: 68 degrees Fahrenheit, Cloudy, 05/23: 73 degrees Fahrenheit, Partly Sunny

Superstructure (Rating = 7): The reinforced concrete arch has isolated minor leakage stains, light moss growth, random vertical hairline cracks up to 3' long, small isolated spalls, and areas of graffiti. The segments have vertical misalignment up to 1/2" and gaps up to 3/4" wide.

Substructure (Rating = 7): The reinforced concrete pedestals are exposed full length x up to 20" high and have leakage stains, several full height vertical hairline cracks that extend for full width across the top, a small spall with exposed rebar, and scattered pop-outs up to 1/4" deep. The pedestals at the construction joints have vertical misalignment up to 1/2" and the south ends of both pedestals have leakage stains and efflorescence.

Deflection and Vibration: There was no significant vibration noted at the time of inspection.

Curbs: North and south curbs have isolated areas of rust stains. Isolated curb joints have areas of deteriorated joint sealant, (See Photos 24 and 25).

Average North and South Curb Reveals: RI 138 was being resurfaced at the time of inspection. The right lane/shoulde r in both directions have the first lift/course of bituminous wearing surface, the final course has not yet been placed.

Average North Curb Reveal = 8-1/2"
Average South Curb Reveal = 9"

Median: Vegetated median is located on the top of the bridge between the eastbound and westbound travel lanes, (S ee Photo 37 and 38).

Passageway: There were areas of ponding water up to full length x full width beneath the bridge (worst along Pedestal #2), (See Photos 12, 13 and 40).

Vegetation: The east end of the south spandrel wall has heavy growth of vegetation and an uprooted tree. The north entrance has light growth of vegetation and the south entrance has moderate growth of vegetation. There are three (3) up to 8" diameter trees growing from beneath the north end of the bridge, (See Photos 39 and 40).

ELEMENT CONDITION SUMMARY

Elm/Env	Description	Total Qty	% in 1	Qty. St. 1	% in 2	Qty. St. 2	% in 3	Qty. St. 3	% in 4	Qty. St. 4
144/3	Re Conc Arch	570.00	99%	562.00	1%	8.00	0%	0.00	0%	0.00
1080/3	Delamination/Spall/Patched Area	3.00	100%	0.00	0%	3.00	0%	0.00	0%	0.00
1130/3	Cracking (RC and Other)	10.00	50%	5.00	50%	5.00	0%	0.00	0%	0.00
8368/3	Graffiti	237.00	0%	0.00	100%	237.00	0%	0.00	0%	0.00
8510/3	Wearing Surfaces Arch -Culvert	2,628.00	100%	2,628.00	0%	0.00	0%	0.00	0%	0.00
215/3	Re Conc Abutment	230.00	84%	184.00	15%	45.00	0%	1.00	0%	0.00
1080/3	Delamination/Spall/Patched Area	1.00	0%	0.00	100%	1.00	0%	0.00	0%	0.00
1090/3	Exposed Rebar	1.00	0%	0.00	0%	0.00	100%	1.00	0%	0.00
1120/3	Efflorescence/Rust Staining	10.00	0%	0.00	100%	10.00	0%	0.00	0%	0.00
1130/3	Cracking (RC and Other)	25.00	40%	10.00	60%	15.00	0%	0.00	0%	0.00
4000/3	Settlement	10.00	0%	0.00	100%	10.00	0%	0.00	0%	0.00
321/3	Re Conc Approach Slab	2,453.00	87%	2,453.00	13%	0.00	0%	0.00	0%	0.00
510/3	Wearing Surfaces	2,453.00	87%	2,453.00	13%	0.00	0%	0.00	0%	0.00
330/3	Metal Bridge Railing	91.00	100%	91.00	0%	0.00	0%	0.00	0%	0.00
515/3	Steel Protective Coating	364.00	100%	349.00	0%	15.00	0%	0.00	0%	0.00

RIDOT Inspection Report (v2.7.4cn)

Fri 05/22/2020
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Figure 70: Arch IV Inspection Report 2018 Page 3 (RIDOT, 2018b)

RIDOT Bridge Inspection Report

091201

Jamestown Arch IV

Inspected By Inspector: [redacted]

Bridge Condition Good

Last Inspection Date 05/23/2018

Elm/Env	Description	Total Qty	% in 1	Qty. St. 1	% in 2	Qty. St. 2	% in 3	Qty. St. 3	% in 4	Qty. St. 4
8208/3	R/C Spandrel Wall	91.00	93%	85.00	7%	6.00	0%	0.00	0%	0.00
1090/3	Exposed Rebar	1.00	0%	0.00	100%	1.00	0%	0.00	0%	0.00
1120/3	Efflorescence/Rust Staining	5.00	0%	0.00	100%	5.00	0%	0.00	0%	0.00
1130/3	Cracking (RC and Other)	20.00	100%	20.00	0%	0.00	0%	0.00	0%	0.00
8368/3	Graffiti	95.00	0%	0.00	100%	95.00	0%	0.00	0%	0.00
8335/3	Guardrail, Vehicular	600.00	98%	575.00	2%	20.00	0%	5.00	0%	0.00
515/3	Steel Protective Coating	1,600.00	100%	1,560.00	0%	40.00	0%	0.00	0%	0.00
1150/3	Check/Shake	20.00	50%	10.00	50%	10.00	0%	0.00	0%	0.00
1170/3	Split/Delamination (Timber)	15.00	100%	0.00	0%	10.00	0%	5.00	0%	0.00

ELEMENT NOTES

STRUCTURE UNIT: 0

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
144	Re Conc Arch	3	570.00	ft	562.00	8.00	0.00	0.00

The superstructure is comprised of nineteen (19) pre-cast reinforced concrete arch segments labeled from North to South as Segments 'A' to 'S', and cast-in-place concrete spandrel walls at the North and South ends of the arch. The underside of the reinforced concrete arch light leakage staining, moderate moss growth, areas of graffiti, and random vertical hairline cracks. The joints between the arch segments have isolated areas of efflorescence leakage. There are a few small edge spalls at the crown between Segments 'C' and 'D'. The segments have vertical misalignment up to 1/2" and gaps up to 3/4" wide (maximum at the east end of Segments 'E' through 'H'), (See Photos 12 through 18).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1080	Delaminatton/Spall/Pattched Ar3		3.00	ffl	0.00	3.00	0.00	0.00

The joint between Segments 'C' and 'D' at the crown has two (2) small spalls, (See Photo 15).

Segment 'Q' near Pedestal #1 has a spall 2-1/2" wide x 10" high x 1" deep, (See Photo 18).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1130	Cracking (RC and Otther)	3	10.00	ffl	5.00	5.00	0.00	0.00

The reinforced concrete arch segments at the base have random vertical hairline cracks up to 3' long, (See Photos 14 and 17).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
8368	Graffltt	3	237.00	ffl	0.00	237.00	0.00	0.00

The east end on the north side of the arch between Segments 'A' and 'D' has a 72 square foot area of graffiti, (See Photo 13). The west end on the north side of the arch between Segments 'A' and 'H' has a 165 square foot area of graffiti, (See Photo 14).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
8510	Wearing Surfflaces Arch -Culvert8		2,628.00	sq.ffl	2,628.00	0.00	0.00	0.00

RI 138 was being resurfaced at the time of inspection.

The Eastbound right lane and shoulder have the first lift/course of bituminous wearing surface in place. The Eastbound left lane and shoulder have the final lift/course of wearing surface in place. The final wearing surface in the Eastbound left lane and shoulder has no notable deficiencies, (See Photos 4 through 7).

The Westbound lanes have the final lift/course of bituminous wearing surface in place in both travel lanes. The right shoulder has the first lift/course of bituminous wearing surface in place only; the final course has not yet been placed. The final wearing surface in the Westbound travel lanes has no notable deficiencies, (See Photos 8 through 11).

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Figure 71: Arch IV Inspection Report 2018 Page 4 (RIDOT, 2018b)

RIDOT Bridge Inspection Report

091201
Jamestown Arch IV

Bridge Condition: Good

Inspected By
Inspector: [redacted]
Last Inspection Date 05/23/2018

STRUCTURE UNIT: 0

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
215	Re Conc Abutment	3	230.00	ft	184.00	45.00	1.00	0.00

The reinforced concrete pedestals are exposed full length x up to 20" high and have several full height vertical hairline cracks with and without efflorescence; a few cracks extend for full width across the top. The pedestals have scattered shallow pop-outs up to 2" diameter x 1/4" deep and Pedestal #2 has a spall with exposed rebar. The pedestals at the construction joints have vertical misalignment up to 1/2", (See Photos 19 through 23). The south ends of both pedestals have leakage stains and efflorescence (See Photos 20 and 23) and Pedestal #2 below Segment 'C' has active water leakage through the joint, (See Photos 13 and 21).

1080	Delaminatton/Spall/Pattched Ar3		1.00	ffl	0.00	1.00	0.00	0.00

Both pedestals have random scattered pop-outs up to 2" diameter x 1/4" deep, (See Photo 19, 21, and 22).

1090	Exposed Rebar	3	1.00	ffl	0.00	0.00	1.00	0.00

Pedestal #2 below arch Segment 'C' has a 7" long x 6" high x 10" wide x 3" deep corner spall with exposed rebar, (See Photos 13 and 22).

1120	Efflorescence/Rustt Sttaining	3	10.00	ffl	0.00	10.00	0.00	0.00

The reinforced concrete pedestals have several full height vertical hairline cracks with efflorescence, (See Photos 19 and 21). The south ends of both pedestals have leakage stains and efflorescence, (See Photos 20 and 23).

1130	Cracking (RC and Otther)	3	25.00	ffl	10.00	15.00	0.00	0.00

The reinforce concrete pedestals have several full height vertical hairline cracks with and without efflorescence, a few extend for full width across the top, (See Photo 19 and 21).

4000	Settlementt	3	10.00	ffl	0.00	10.00	0.00	0.00

The pedestal segments have vertical misalignment up to 1/2", (See Photo 17).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
321	Re Conc Approach Slab	3	2,453.00	sq.ft	2,453.00	0.00	0.00	0.00

This element is used to document the condition of the approach pavements.

510	Wearing Surfflaces	3	2,453.00	sq.ffl	2,453.00	0.00	0.00	0.00

RI 138 was being resurfaced at the time of inspection.

The Eastbound right lane and shoulder have the first lift/course of bituminous pavement in place at both approaches. The Eastbound left lane and shoulder have the final course in place along both approaches. The final approach pavement in the Eastbound left lane and shoulder has no notable deficiencies, (See Photos 4 through 7).

The Westbound lanes have the final lift/course of bituminous approach pavement in place in both travel lanes. The right shoulder has the first lift/course of bituminous pavement in place only; the final course has not yet been placed. The final approach pavement in the Westbound travel lanes has no notable deficiencies, (See Photos 8 through 11).

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Figure 72: Arch IV Inspection Report 2018 Page 5 (RIDOT, 2018b)

RIDOT Bridge Inspection Report

091201
Jamestown Arch IV

Inspected By
Inspector: [redacted]
Last Inspection Date 05/23/2018

Bridge Condition Good

STRUCTURE UNIT: 0

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
330	Metal Bridge Railing	3	91.00	ft	91.00	0.00	0.00	0.00

The metal bridge railing consists of two painted steel rails mounted to steel posts which are a continuation of the approach guardrails at all four corners. The steel bridge railings have minor impact scrapes, (See Photos 24 and 25)
.

515	Stteel Prottecttve Coattng	3	364.00	sq.ffl	349.00	15.00	0.00	0.00

The steel protective coating has minor impact scrapes, (See Photos 24 and 25).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
8208	R/C Spandrel Wall	3	91.00	ft	85.00	6.00	0.00	0.00

The underside of the reinforce concrete spandrel walls have isolated shallow rebar spalls, random areas of shrinkage cracks and full width transverse hairline cracks with and without efflorescence. The tops of the spandrel walls have up to full width transverse hairline cracks. Between the south spandrel wall and arch Segment 'S', there is a gap up to 2-1/2" wide. Between the spandrel walls and the west retaining walls, there is lateral misalignment up to 1-1/2". The South spandrel wall at the east end has vine growth along the construction joint and the North spandrel wall has an area of graffiti, (See Photos 26 through 36).

1090	Exposed Rebar	3	1.00	ffl	0.00	1.00	0.00	0.00

The underside of the north spandrel wall near the crown has a spall up to 10" long x 3" wide x 1/2" deep with exposed rebar, (See Photo 32).

1120	Efflorescence/Rustt Sttaining	3	5.00	ffl	0.00	5.00	0.00	0.00

The underside of the spandrel walls have full width transverse hairline cracks with and without efflorescence that extend up to 6' long into the vertical face, (See Photos 26, 27, 31 and 32).

1130	Cracking (RC and Otther)	3	20.00	ffl	20.00	0.00	0.00	0.00

The underside of the spandrel walls have random areas of shrinkage cracks, full width transverse hairline cracks with and without light efflorescence that extend up the vertical face up to 6' high, The tops of the spandrel walls have up to full width transverse hairline cracks (See Photos 26 through 28 and 30 through 35).

8368	Grafftt	3	95.00	ffl	0.00	95.00	0.00	0.00

The east end of the North spandrel wall has graffiti up to 10' wide x 8' high, (See Photo 34).
The west end of the North spandrel wall has graffiti up to 3' wide x 5' high (See Photo 35).

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
8335	Guardrail, Vehicular	3	600.00	(LF)	575.00	20.00	5.00	0.00

The two metal rail vehicular approach guardrails at all corners are continuous over the arch and have minor chips and impact scrapes, (See Photos 4 through 11). The median guardrails consist of timber rails mounted to timber posts. The timber median guardrails have several checks up to 1/4" wide, splits up to 1/2" wide, and random areas of minor splintered edges, (See Photos 37 and 38).

515	Stteel Prottecttve Coattng	3	1,600.00	sq.ffl	1,560.00	40.00	0.00	0.00

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Figure 73: Arch IV Inspection Report 2018 Page 6 (RIDOT, 2018b)

Table 23: Arch IV Defect ID and Location Tags derived from Routine Inspection Report 2018 Part I/II

Defect ID	Tags
2018 144-1080	Pedestal 1Q, Segment Q
2018 144-1080	Segment R
2018 144-1080	Segment J
2018 144-1080	Segment E
2018 144-1080	Segment D, Segment C
2018 144-1080	Segment D, Segment C
2018 144-1130	Segment R
2018 144-1130	Segment H, Segment F, Segment G, Segment R
2018 144-4000	Segment J
2018 144-4000	Segment G
2018 144-8368	Segment G
2018 144-8368	Segment D, Segment H, Segment C, Segment A, Segment F, Segment E, Segment B, Segment G
2018 144-8368	Segment D, Segment C, Segment A, Segment B
2018 144-8386	Segment C
2018 215-1080	Pedestal 2C
2018 215-1080	Pedestal 2C
2018 215-1080	Pedestal 1A
2018 215-1090	Pedestal 2C
2018 215-1120	Pedestal 2S
2018 215-1120	Pedestal 2C
2018 215-1120	Pedestal 1S
2018 215-1120	Pedestal 1C
2018 215-1130	Pedestal 2C, Pedestal 2B
2018 215-1130	Pedestal 1B
2018 215-4000	Pedestal 1Q
2018 8208-1080	S-West Wingwall 1

Table 24: Arch IV Defect ID and Location Tags derived from Routine Inspection Report 2018 Part II/II

Defect ID	Tags
2018 8208-1090	North Spandrel
2018 8208-1120	South Spandrel
2018 8208-1120	North Spandrel, North Portal
2018 8208-1130	South Spandrel, South Portal
2018 8208-1130	N-East Wingwall 3
2018 8208-1130	North Spandrel, North Portal
2018 8208-4000	S-West Wingwall 3
2018 8208-4000	N-West Wingwall 3
2018 8208-4000	South Spandrel
2018 8208-8368	N-West Wingwall 1
2018 8208-8368	N-East Wingwall 3

Table 25: Arch IV Defect ID and Location Tags assessed on May 21st, 2020

Defect ID	Tags
2020 215-1120	Pedestal 1S
2020 215-1120	Pedestal 2S
2020 215-4000	Pedestal 1R
2020 215-1130	Pedestal 2Q
2020 215-1090	Pedestal 2C
2020 215-1130	Pedestal 2C, Pedestal 2B
2020 215-1080	Pedestal 2A
2020 215-1080	Pedestal 1S
2020 215-1130	Pedestal 1Q
2020 215-1080	Pedestal 1A
2020 215-1120	Pedestal 1A
2020 215-1080	Pedestal 1A
2020 215-1130	Pedestal 1B
2020 8208-4000	S-West Wingwall 3
2020 8208-1080	S-West Wingwall 2
2020 144-1080	Segment Q
2020 215-1130	Segment L
2020 144-4000	Segment D
2020 144-8368	Segment C
2020 8208-1080	N-West Wingwall 3
2020 8208-4000	N-West Wingwall 3
2020 8208-1090	North Spandrel
2020 8208-1130	North Spandrel
2020 8208-8368	N-West Wingwall 1
2020 8208-1130	South Spandrel
2020 8208-1080	South Spandrel

Table 26: Arch IV Defect ID and Location Tags assessed on June 5th, 2020

Defect ID	Tags
2021 215-1090	Pedestal 2C
2021 215 1120	Pedestal 1S
2021 215-1120	Pedestal 1A
2021 215-1120	Pedestal 2S
2021 8202-4000	S-West Wingwall 3
2021 8206-1080	S-West Wingwall 2
2021 215-1130	Pedestal 1R
2021 8208-1080	South Spandrel
2021 215-4000	Pedestal 1R
2021 215-1080	Pedestal 1B
2021 144-4000	Segment D
2021 215-1130	Pedestal 1B
2021 215-1130	Pedestal 2A
2021 8208-1080	N-East Wingwall 2
2021 8208-1120	North Spandrel

APPENDIX M – DATA HANDLING AND WORKFLOW

The following three examples display the data handling and workflow enhancements for bridge inspections provided by the BIDM.

EXAMPLE I

The first example shows how the BIDM enhances the quantifiability of defect extent and the traceability within the 3D-structure and over time. The differences of both methods for this specific defect of Pedestal 1S are displayed in Table 27.

Figure 74 shows the defect information assessed in 2018 and Figure 75 displays the photo documentary for this specific defect. The conventional inspection report does not provide any quantified information for this defect.

The BIDM user-interface is displayed in Figure 76 with the 3D-model on the left side and the defect information with attached photo documentary on the right side. The selected element is highlighted with yellow edges and the dropdown menu shows the inspection history. Figure 77 and Figure 78 display the defect at Pedestal 1S with the quantified extent verified by the AR-supported measurement.

Table 27: Comparison of the conventional Inspection Report to BIDM, Example I

Conventional Inspection Report	BIDM
Report shows only qualitative Assessement of Defect, no quantified Extent measured.	Defect Extent is quantified by the digital Measurement. Multiple Distances are displayed in one Picture.
Inspection Report and Photos must be aligned and compared.	BIDM stores the Information digitally at one Location.
Multiple Documents are necessary to retrace the Inspection History.	Inspection History is stored at the linked Element. History is accessable at this Location.
Additional Documents are necessary to determine the Defect Location.	BIDM provides the Defect Location within the 3D-model.

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1120	Efflorescence/Rustt Sttaining	3	10.00	ffl	0.00	10.00	0.00	0.00

The reinforced concrete pedestals have several full height vertical hairline cracks with efflorescence, (See Photos 19 and 21). The south ends of both pedestals have leakage stains and efflorescence, (See Photos 20 and 23).

Figure 74: Cutout from the 2018 Inspection Report Arch IV, Example I (RIDOT, 2018b)

Figure 75: Arch IV Pedestal 1S, Conventional Inspection Report (RIDOT, 2018b)

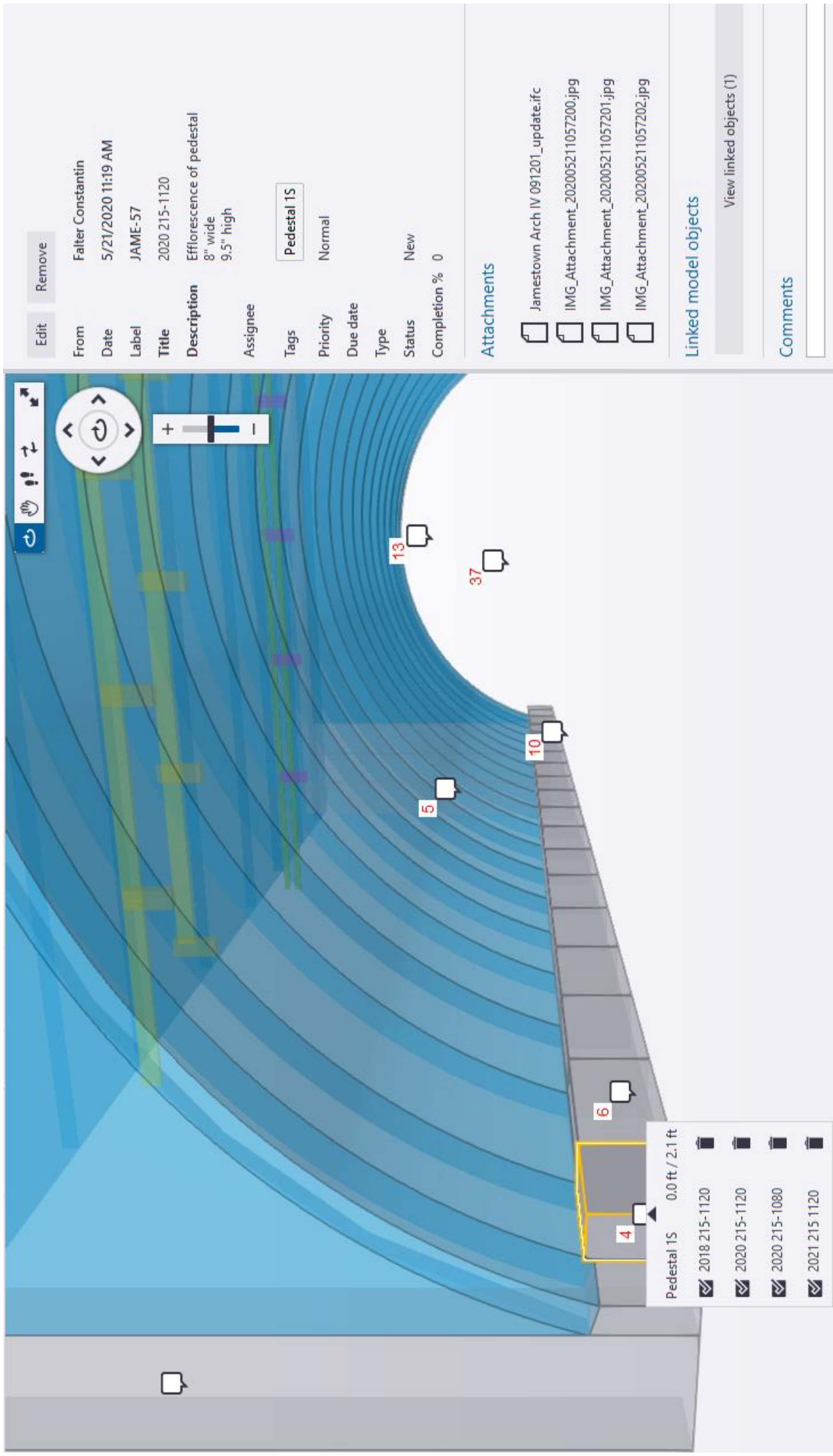

Figure 76: Arch IV Pedestal 1S ID: 2020 215-1120, BIDM Desktop View (own figure)

Figure 77: Arch IV Pedestal 1S, ID 2020 215-1120 Quantified Extent Width (own photo)

Figure 78: Arch IV Pedestal 1S, ID 2020 215-1120, Quantified Extent Height (own photo)

The Trimble Connect mobile application as it is used on site is displayed below in Figure 79 to Figure 82. The mobile application allows to address each element as the desktop version. Each defect can be addressed, reviewed and additional information attached.

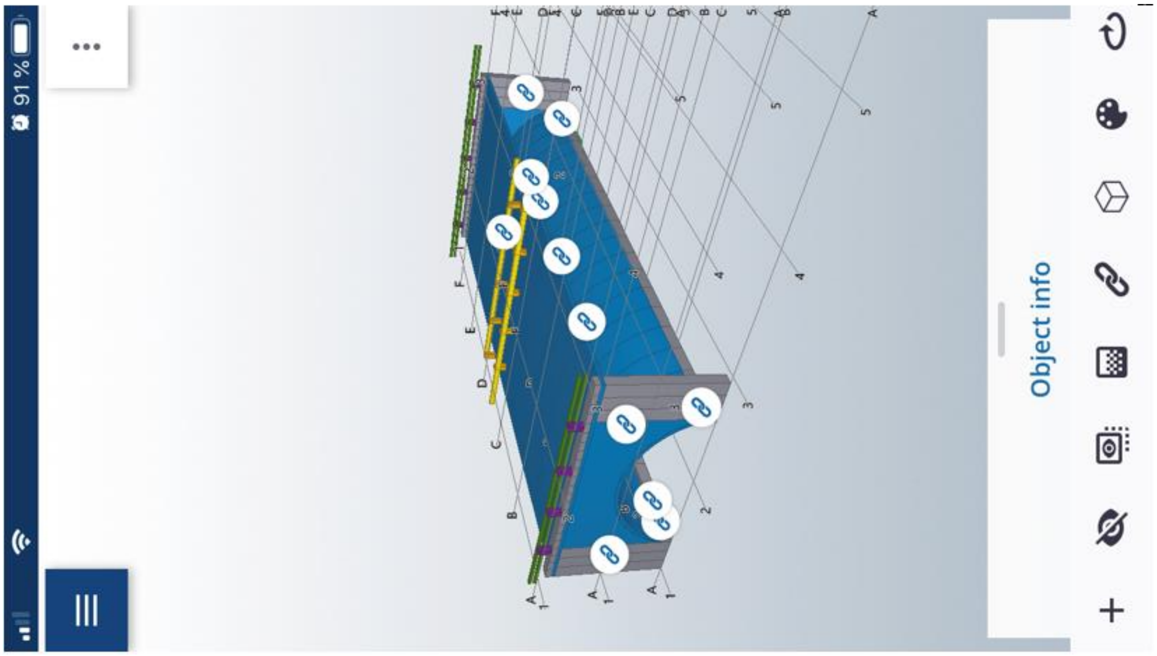

Figure 79: Trimble Connect Mobile Application, Arch IV Overview (own figure)

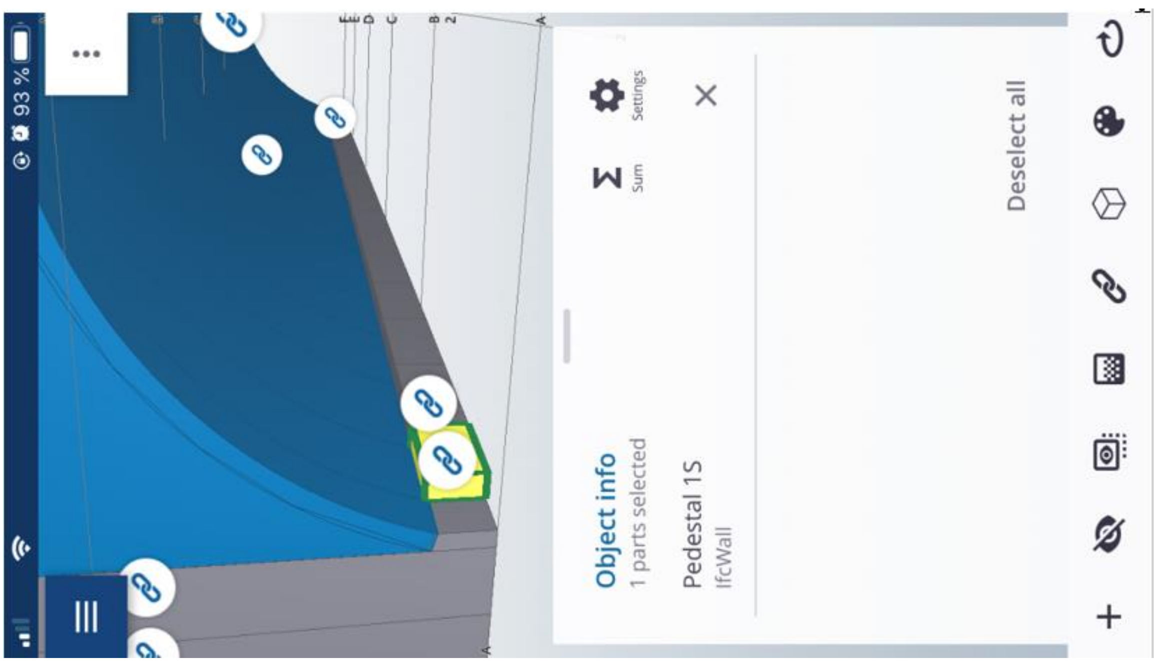

Figure 80: Trimble Connect Mobile Application, Arch IV Pedestal 1S Selected (own figure)

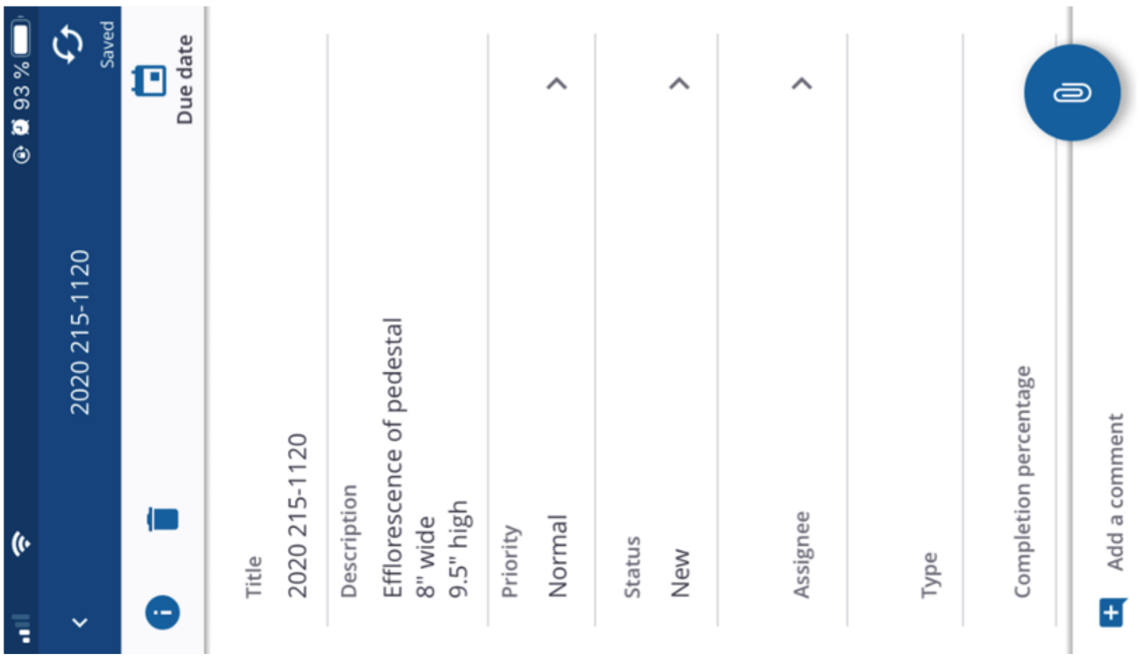

Figure 81: Trimble Connect Mobile Application, Arch IV Pedestal 1S ID: 2020-215-1120 Part I (own figure)

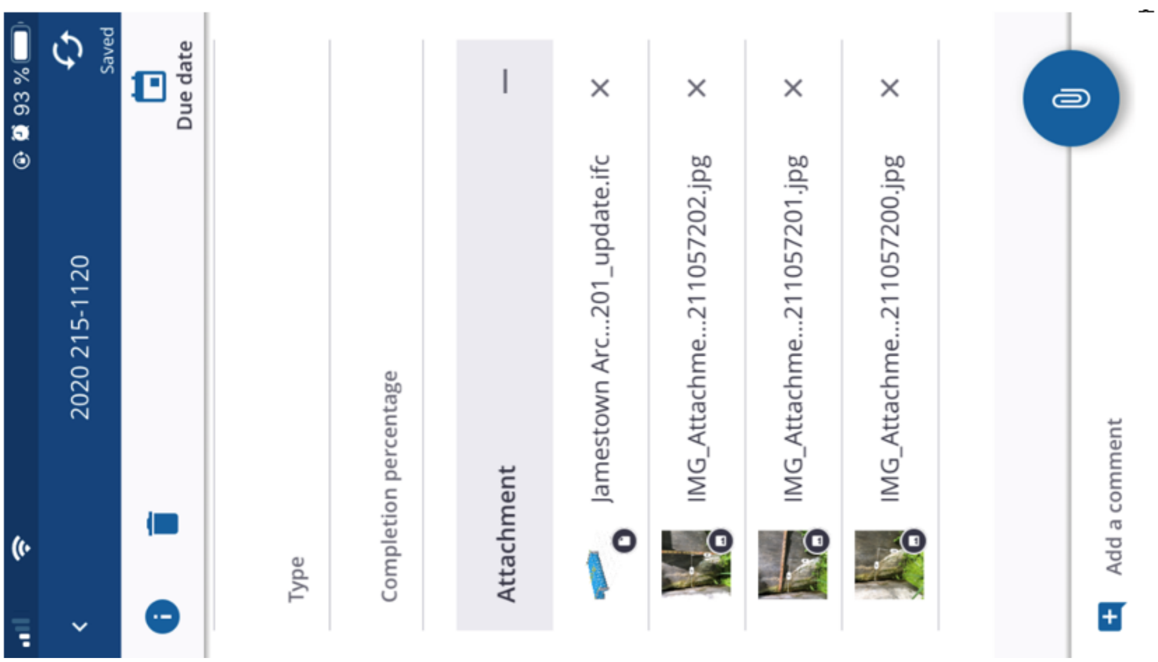

Figure 82: Trimble Connect Mobile Application, Arch IV Pedestal 1S ID: 2020-215-1120 Part II (own figure)

EXAMPLE II

The second example shows how the BIDM enhances the traceability of defects within the 3D-structure and over time. The differences of both methods for this specific defect of Pedestal 1S are displayed in Table 27.

Figure 83 shows the defect information assessed in the 2018 inspection report and Figure 84 displays the photo documentary for this specific defect. The defect is quantified by the inspector, but the measurement is not traceable. Therefore, review of this defect assessment is difficult.

The BIDM user-interface is displayed in Figure 85 with the 3D-model on the left side and the defect information with attached photo documentary on the right side. The selected element is highlighted with yellow edges and the dropdown menu shows the inspection history. The verification of the measured defect is retraceable as Figure 86, Figure 87 and Figure 88 display. However, the exposed rebar is not identifiable.

Table 28: Comparison of the conventional Inspection Report to BIDM, Example II

Conventional Inspection Report	BIDM
Report shows qantified Information about Defect Extent. However, measurement of Extent is not traceable with the provided Photo.	Defect Extent is quantified by the digital Measurement. Multiple Distances are displayed in one Photo.
Inspection Report and Photos must be aligned and compared.	BIDM stores the Information digitally at one Location.
Multiple Documents are necessary to retrace the Inspection History.	Inspection History is stored at the linked Element. History is accessable at this Location.
Additional Documents are necessary to determine the Defect Location.	BIDM provides the Defect Location within the 3D-model.
	Photo Documentary shows no Rebar Exposure.

ELEM	ELEMENT NAME	ENV	QUANTITY	UNITS	QTY CS 1	QTY CS 2	QTY CS 3	QTY CS 4
1090	Exposed Rebar	3	1.00	ffl	0.00	0.00	1.00	0.00

Pedestal #2 below arch Segment ‘C’ has a 7” long x 6” high x 10” wide x 3” deep corner spall with exposed rebar, (See Photos 13 and 22).

Figure 83: Cutout from the 2018 Inspection Report 2018, Example II (RIDOT, 2018b)

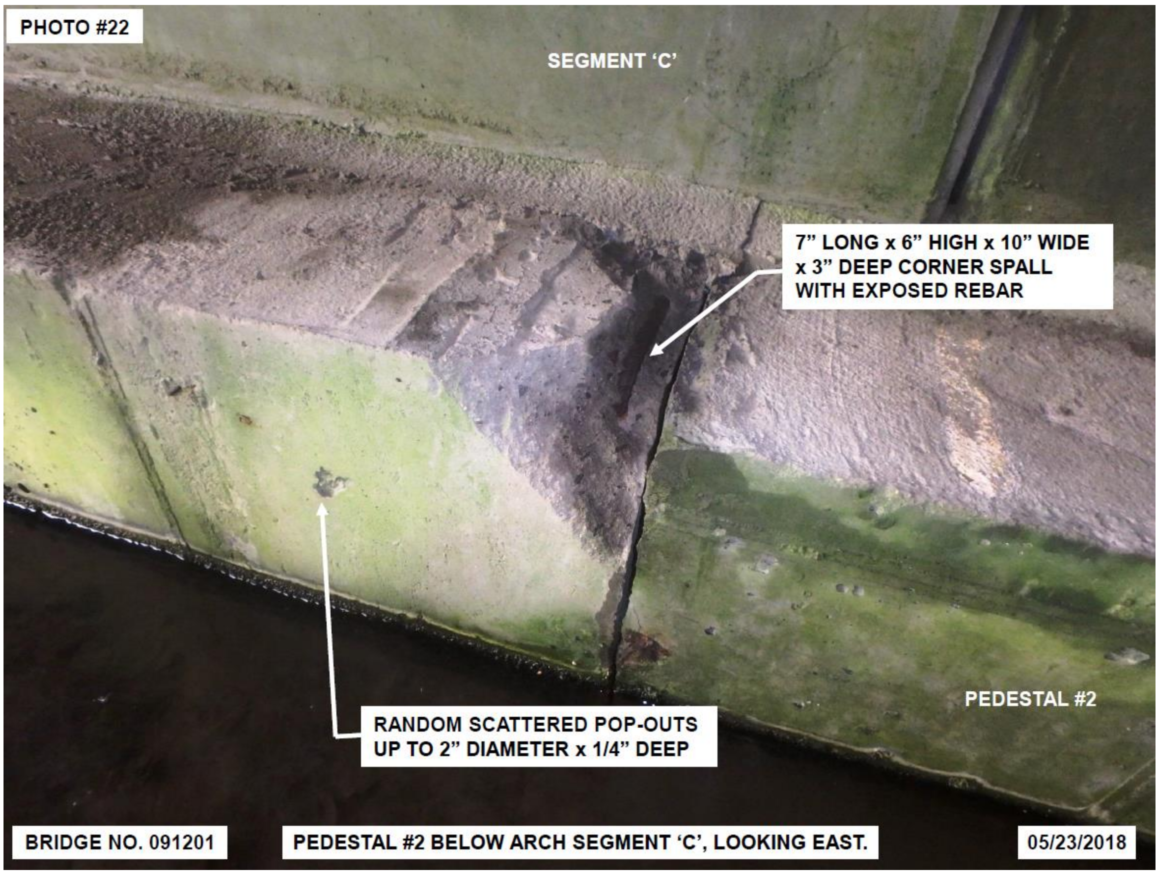

Figure 84: Arch IV Pedestal 2C, Conventional Inspection Report (RIDOT, 2018b)

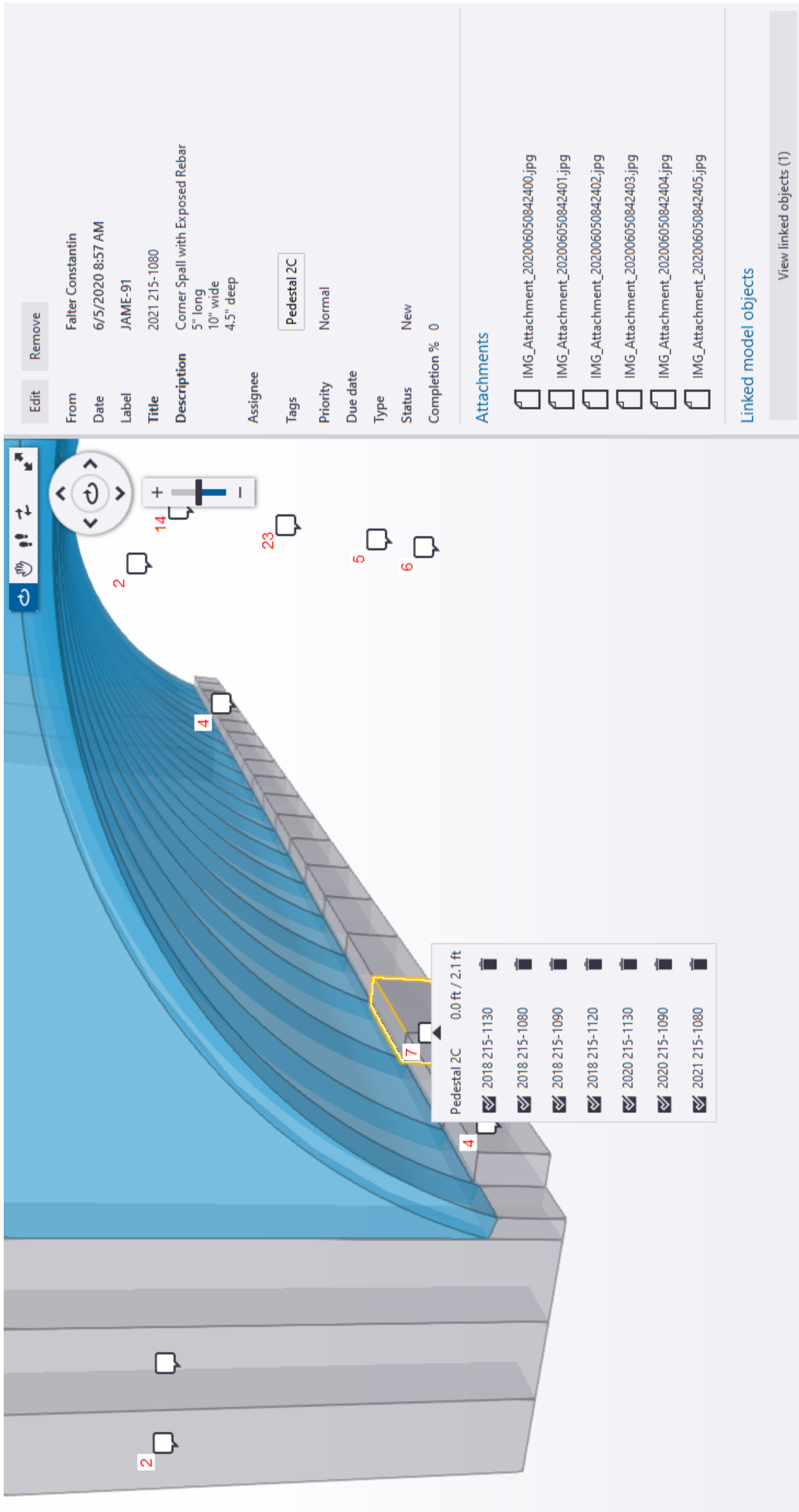

Figure 85: Arch IV Pedestal 2C, ID 2021 215-1090, BIDM Desktop View (own figure)

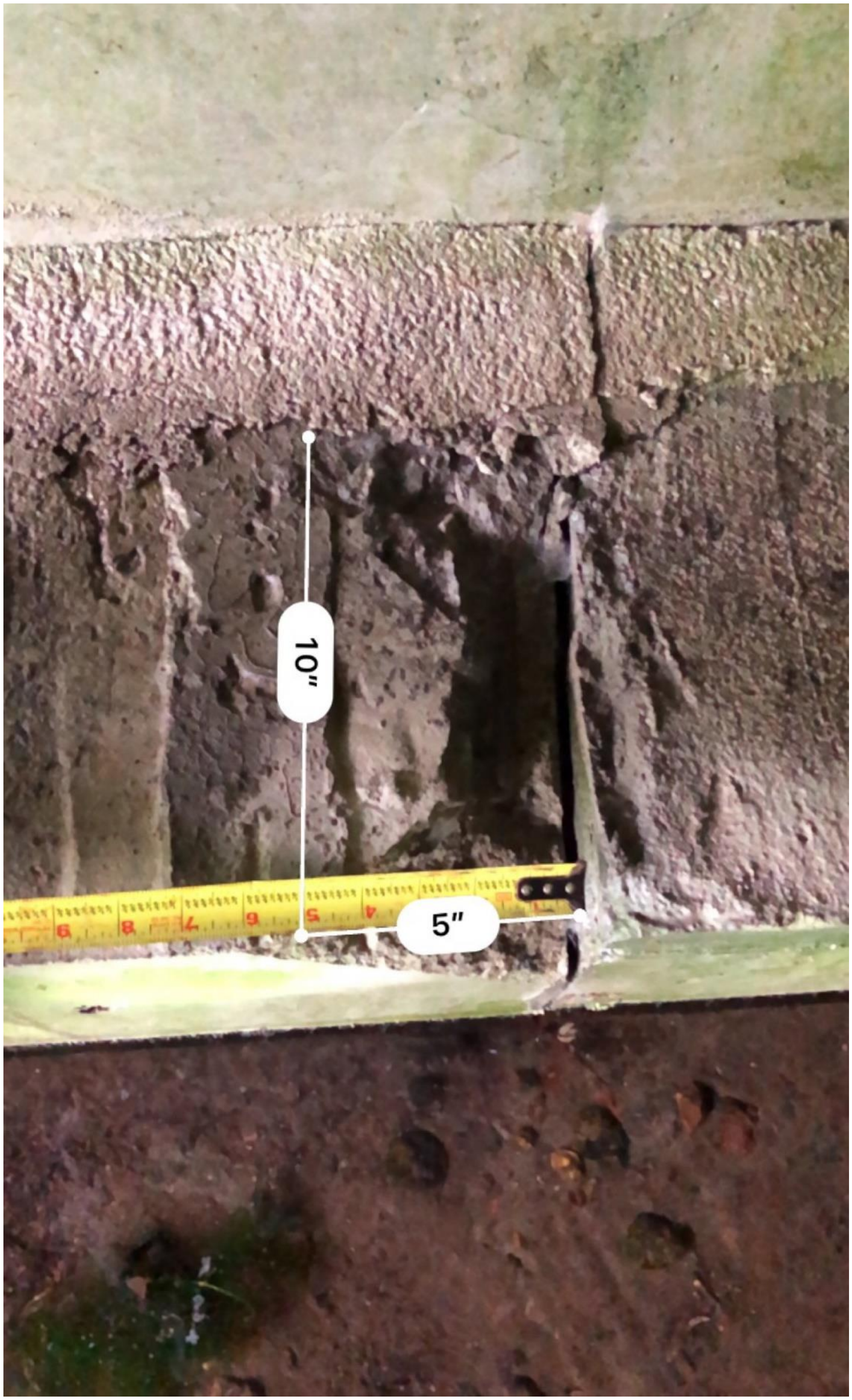

Figure 86: Arch IV Pedestal 2C, ID: 2021 215-1090, Defect Length (own photo)

Figure 87:Arch IV Pedestal 2C, ID 2021 215-1080, Defect Width (own photo)

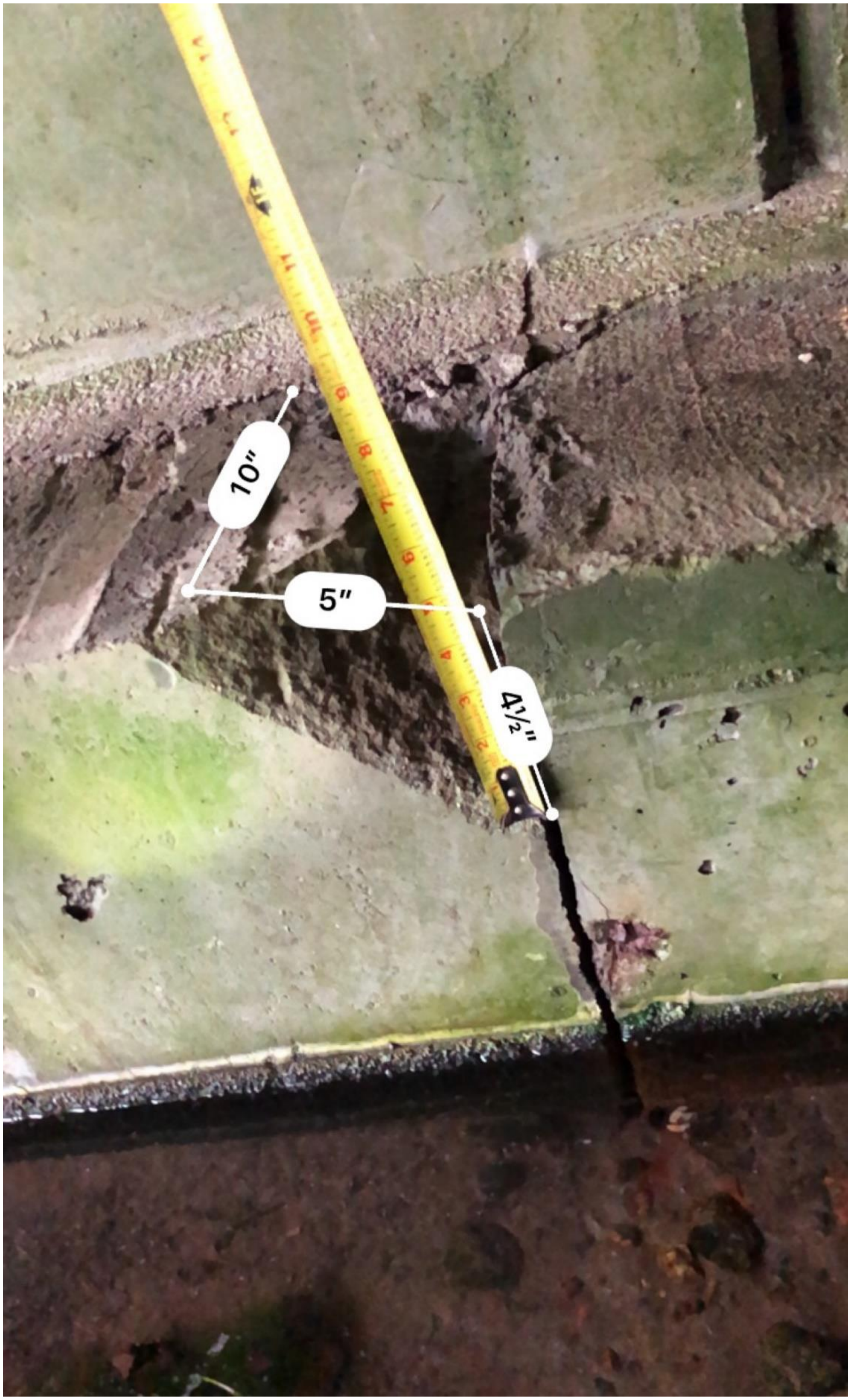

Figure 88: Arch IV Pedestal 2C, ID 2021 215-1090, Defect Height (own photo)

EXAMPLE III

The third example shows the capability of the BIDM to display the defect distribution within the bridge structure. Addressing all concrete arches (NBE-144) with defect 1080 leads to the following two views of the 3D-model. Figure 89 shows the affected arch elements in the Trimble Connect mobile application, the specific elements are listed by clicking on “Object info”. The desktop version as displayed in Figure 90 shows more detailed information on one screen. The task bar on the right side displays the affected elements; Segment C, D, I, P, and R. The inspection history of each element is displayed by clicking on the Segment description to expand the task bar. The visualization on the left side shows the distribution of arches in the structure.

Reviewing previous inspections and the overall condition of the bridge is enhanced by these views. Conventional inspection reports do not provide comparable views of the defect distribution within the structure.

Figure 89: Trimble Connect Mobile Application, ID: 144-1080 Distribution (own figure)

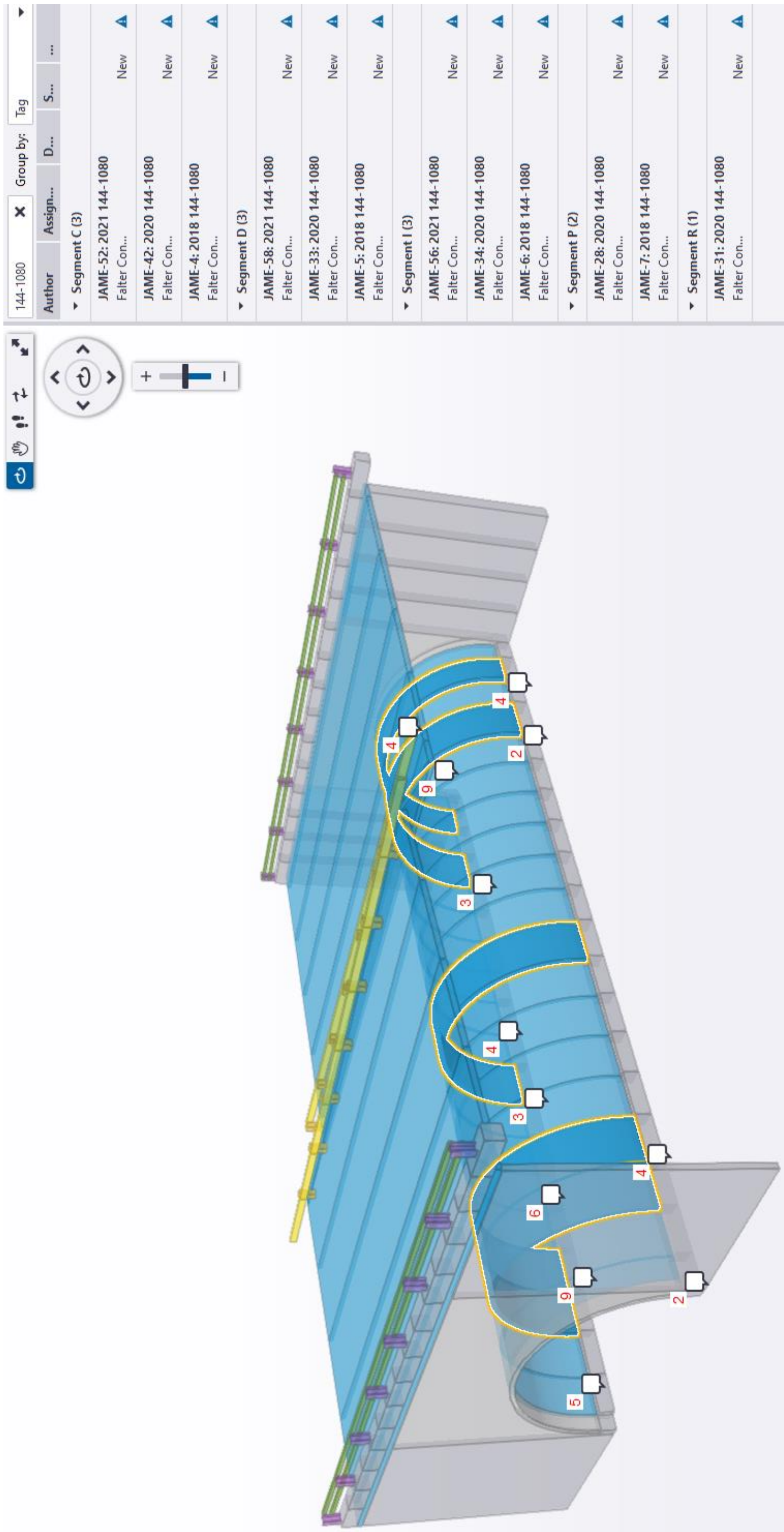

Figure 90: Trimble Connect Desktop Version, ID 144.1080 Distribution (own figure)

APPENDIX N – DATA FOR ACCURACY ANALYSIS

DATA SAMPLE I

The first data sample was assessed on May 21st, 2020 between 9:30AM and 11:30AM. The total photo documentation comprises 165 photos, but only 67 photos are eligible for the accuracy analysis. Each of these photos documents the superposition of digital and analog measurements, hence 67 data pairs were compared. The photos that were not considered are either of bad quality or the accuracy cannot be stated, since the photo shows an AR-measurement without an analog justification. The photos documenting the measurements are not attached to this thesis but can be made accessible for further processing and research.

Table 29: Measurements of Data Sample 1 used for the Accuracy Analysis Part I/IV

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202005211005262.jpg	12.50	16.50		32%	-4.00
IMG_Attachment_202005211005530.jpg	10.00	13.00		30%	-3.00
IMG_Attachment_202005210958271.jpg	11.00	13.00		18%	-2.00
IMG_Attachment_202005211018232.jpg	14.50	16.00		10%	-1.50
IMG_Attachment_202005211020280.jpg	12.00	13.00		8%	-1.00
IMG_Attachment_202005211040060.jpg	13.50	14.50		7%	-1.00
IMG_Attachment_202005210947570.jpg	14.50	15.50		7%	-1.00
IMG_Attachment_202005210954182.jpg	16.00	17.00		6%	-1.00
IMG_Attachment_202005211051077.jpg	17.00	18.00		6%	-1.00
IMG_Attachment_202005211118183.jpg	40.00	41.00		3%	-1.00
IMG_Attachment_202005210938374.jpg	1.00	1.50		50%	-0.50
IMG_Attachment_202005210956374.jpg	3.50	4.00		14%	-0.50
IMG_Attachment_202005211051072.jpg	4.00	4.50	IMG_Attachment_202005211051073.jpg	13%	-0.50
IMG_Attachment_202005211018231.jpg	5.00	5.50		10%	-0.50
IMG_Attachment_202005211027122.jpg	5.00	5.50		10%	-0.50
IMG_Attachment_202005211051076.jpg	5.00	5.50		10%	-0.50
IMG_Attachment_202005211111313.jpg	5.50	6.00		9%	-0.50

Table 30: Measurements of Data Sample 1 used for the Accuracy Analysis Part II/IV

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202005210942592.jpg	6.00	6.50		8%	-0.50
IMG_Attachment_202005211057202.jpg	9.00	9.50		6%	-0.50
IMG_Attachment_202005211107240.jpg	9.00	9.50		6%	-0.50
IMG_Attachment_202005211118184.jpg	9.50	10.00		5%	-0.50
IMG_Attachment_202005210950020.jpg	10.00	10.50		5%	-0.50
IMG_Attachment_202005210956373.jpg	10.00	10.50		5%	-0.50
IMG_Attachment_202005211040062.jpg	11.50	12.00		4%	-0.50
IMG_Attachment_2020052111353212.jpg	13.50	14.00		4%	-0.50
IMG_Attachment_202005211029311.jpg	14.00	14.50		4%	-0.50
IMG_Attachment_202005210942591.jpg	14.50	15.00		3%	-0.50
IMG_Attachment_202005210938370.jpg	16.00	16.50		3%	-0.50
IMG_Attachment_202005211105240.jpg	16.50	17.00	IMG_Attachment_202005211105251.jpg	3%	-0.50
IMG_Attachment_2020052111353210.jpg	17.50	18.00		3%	-0.50
IMG_Attachment_202005211111311.jpg	20.00	20.50		3%	-0.50
IMG_Attachment_202005210951360.jpg	1.00	1.25		25%	-0.25
IMG_Attachment_202005210931280.jpg	1.50	1.75		17%	-0.25
IMG_Attachment_202005210931571.jpg	3.00	3.25		8%	-0.25

Table 31: Measurements of Data Sample 1 used for the Accuracy Analysis Part III/IV

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202005210938372.jpg	3.00	3.25		8%	-0.25
IMG_Attachment_202005211111312.jpg	9.00	9.25		3%	-0.25
IMG_Attachment_202005211113391.jpg	1.00	1.00	IMG_Attachment_202005211113392.jpg	0%	0.00
IMG_Attachment_202005211135327.jpg	1.00	1.00		0%	0.00
IMG_Attachment_202005211120241.jpg	2.00	2.00		0%	0.00
IMG_Attachment_202005210946570.jpg	2.50	2.50		0%	0.00
IMG_Attachment_202005211135325.jpg	2.50	2.50		0%	0.00
IMG_Attachment_202005210946571.jpg	3.00	3.00		0%	0.00
IMG_Attachment_202005211102112.jpg	3.00	3.00		0%	0.00
IMG_Attachment_202005211107242.jpg	3.00	3.00		0%	0.00
IMG_Attachment_202005211135322.jpg	3.50	3.50		0%	0.00
IMG_Attachment_202005211005261.jpg	4.00	4.00		0%	0.00
IMG_Attachment_202005211135321.jpg	4.00	4.00		0%	0.00
IMG_Attachment_202005211051071.jpg	4.50	4.50	IMG_Attachment_202005211051073.jpg	0%	0.00
IMG_Attachment_202005211027120.jpg	6.00	6.00		0%	0.00
IMG_Attachment_202005210958270.jpg	7.50	7.50		0%	0.00

Table 32: Measurements of Data Sample 1 used for the Accuracy Analysis Part IV/IV

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202005211057201.jpg	8.00	8.00		0%	0.00
IMG_Attachment_202005211027371.jpg	11.50	11.50		0%	0.00
IMG_Attachment_202005211037301.jpg	12.00	12.00		0%	0.00
IMG_Attachment_202005211122452.jpg	14.00	14.00		0%	0.00
IMG_Attachment_202005210954183.jpg	16.00	16.00		0%	0.00
IMG_Attachment_202005211042141.jpg	18.00	18.00	IMG_Attachment_202005211044040.jpg	0%	0.00
IMG_Attachment_202005211636461.jpg	19.00	19.00		0%	0.00
IMG_Attachment_202005211102110.jpg	3.00	2.75		8%	0.25
IMG_Attachment_202005211118182.jpg	10.50	10.25		2%	0.25
IMG_Attachment_202005211131073.jpg	1.50	1.00		33%	0.50
IMG_Attachment_202005211139263.jpg	2.00	1.50		25%	0.50
IMG_Attachment_202005210954181.jpg	6.00	5.50		8%	0.50
IMG_Attachment_202005211047102.jpg	7.00	6.50	IMG_Attachment_202005211047100.jpg	7%	0.50
IMG_Attachment_202005211047100.jpg	8.50	8.00	IMG_Attachment_202005211047101.jpg	6%	0.50
IMG_Attachment_202005211023361.jpg	12.00	11.50		4%	0.50
IMG_Attachment_202005211023360.jpg	12.50	12.00		4%	0.50
IMG_Attachment_202005211100273.jpg	16.00	15.50		3%	0.50

DATA SAMPLE II

The second data sample was assessed on June 5th, 2020 between 7:30AM and 10:30AM. The total photo documentation comprises 129 photos, but only 74 photos are eligible for the accuracy analysis. Each of these photos documents the superposition of digital and analog measurements, hence 74 data pairs were compared. The photos that were not considered are either of bad quality or the accuracy cannot be stated, since the photo shows an AR-measurement without an analog justification. The photos documenting the measurements are not attached to this thesis but can be made accessible for further processing and research.

Table 33: Measurements of Data Sample 2 used for the Accuracy Analysis Part I/V

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202006050915526.jpg	8.00	10.00		25%	-2.00
IMG_Attachment_202006050800542.jpg	8.50	9.75		15%	-1.25
IMG_Attachment_202006050837113.jpg	54.00	55.00		2%	-1.00
IMG_Attachment_202006050906280.jpg	8.50	9.25		9%	-0.75
IMG_Attachment_202006050852392.jpg	5.50	6.25		14%	-0.75
IMG_Attachment_202006050916452.jpg	5.50	6.00		9%	-0.50
IMG_Attachment_202006050941262.jpg	17.00	17.50		3%	-0.50
IMG_Attachment_202006051452594.jpg	3.50	4.00		14%	-0.50
IMG_Attachment_202006050800543.jpg	18.00	18.50		3%	-0.50
IMG_Attachment_202006050813062.jpg	10.00	10.50		5%	-0.50
IMG_Attachment_202006050846280.jpg	3.50	4.00		14%	-0.50
IMG_Attachment_202006050920301.jpg	30.50	30.75		1%	-0.25
IMG_Attachment_202006050938230.jpg	1.00	1.25		25%	-0.25
IMG_Attachment_202006050944450.jpg	7.50	7.75		3%	-0.25
IMG_Attachment_202006050946540.jpg	3.00	3.25		8%	-0.25
IMG_Attachment_202006050952253.jpg	2.00	2.25		13%	-0.25
IMG_Attachment_202006050751291.jpg	8.00	8.25		3%	-0.25

Table 34: Measurements of Data Sample 2 used for the Accuracy Analysis Part II/V

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202006050831031.jpg	20.50	20.75		1%	-0.25
IMG_Attachment_202006050846284.jpg	3.54	3.75		6%	-0.21
IMG_Attachment_202006050751294.jpg	3.50	3.60		3%	-0.10
IMG_Attachment_202006050906281.jpg	4.50	4.60		2%	-0.10
IMG_Attachment_202006050747290.jpg	1.97	2.00	IMG_Attachment_202006050747291.jpg	2%	-0.03
IMG_Attachment_202006050908420.jpg	4.50	4.50		0%	0.00
IMG_Attachment_202006050908422.jpg	10.00	10.00		0%	0.00
IMG_Attachment_202006050915521.jpg	1.50	1.50		0%	0.00
IMG_Attachment_202006050915522.jpg	16.50	16.50		0%	0.00
IMG_Attachment_202006050915525.jpg	1.50	1.50		0%	0.00
IMG_Attachment_202006050916451.jpg	4.50	4.50		0%	0.00
IMG_Attachment_202006050920300.jpg	1.50	1.50		0%	0.00
IMG_Attachment_202006050923051.jpg	27.00	27.00	IMG_Attachment_202006050923050.jpg	0%	0.00
IMG_Attachment_202006050923052.jpg	7.00	7.00		0%	0.00
IMG_Attachment_202006050935012.jpg	2.50	2.50		0%	0.00
IMG_Attachment_202006050938232.jpg	15.00	15.00		0%	0.00
IMG_Attachment_202006050938233.jpg	10.50	10.50		0%	0.00

Table 35: Measurements of Data Sample 2 used for the Accuracy Analysis Part III/V

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202006050944451.jpg	13.50	13.50		0%	0.00
IMG_Attachment_202006050946541.jpg	9.50	9.50		0%	0.00
IMG_Attachment_202006050948030.jpg	1.00	1.00		0%	0.00
IMG_Attachment_202006050952240.jpg	5.00	5.00		0%	0.00
IMG_Attachment_202006050952251.jpg	5.50	5.50		0%	0.00
IMG_Attachment_202006050952252.jpg	16.50	16.50		0%	0.00
IMG_Attachment_202006050952254.jpg	3.00	3.00		0%	0.00
IMG_Attachment_202006050952255.jpg	2.00	2.00		0%	0.00
IMG_Attachment_202006051452595.jpg	7.00	7.00		0%	0.00
IMG_Attachment_202006051455000.jpg	6.50	6.50		0%	0.00
IMG_Attachment_202006051455003.jpg	17.50	17.50		0%	0.00
IMG_Attachment_202006050803434.jpg	3.00	3.00		0%	0.00
IMG_Attachment_202006050813060.jpg	4.00	4.00		0%	0.00
IMG_Attachment_202006050813063.jpg	10.00	10.00		0%	0.00
IMG_Attachment_202006050813065.jpg	1.00	1.00		0%	0.00
IMG_Attachment_202006050813411.jpg	1.00	1.00		0%	0.00
IMG_Attachment_202006050817540.jpg	8.50	8.50		0%	0.00

Table 36: Measurements of Data Sample 2 used for the Accuracy Analysis Part IV/V

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_202006050817542.jpg	6.00	6.00		0%	0.00
IMG_Attachment_202006050831032.jpg	14.50	14.50		0%	0.00
IMG_Attachment_202006050842401.jpg	10.00	10.00		0%	0.00
IMG_Attachment_202006050842402.jpg	5.00	5.00		0%	0.00
IMG_Attachment_202006050842404.jpg	4.50	4.50		0%	0.00
IMG_Attachment_202006050846282.jpg	13.00	13.00		0%	0.00
IMG_Attachment_202006050852390.jpg	6.50	6.50		0%	0.00
IMG_Attachment_202006050856421.jpg	4.50	4.50		0%	0.00
IMG_Attachment_202006050935011.jpg	3.00	2.75		8%	0.25
IMG_Attachment_202006050938234.jpg	3.00	2.75		8%	0.25
IMG_Attachment_202006050941261.jpg	6.50	6.25		4%	0.25
IMG_Attachment_202006051455001.jpg	6.00	5.75		4%	0.25
IMG_Attachment_202006050747291.jpg	2.00	1.75		13%	0.25
IMG_Attachment_202006050803430.jpg	2.50	2.25		10%	0.25
IMG_Attachment_202006050837111.jpg	14.50	14.25		2%	0.25
IMG_Attachment_202006051529121.jpg	6.50	6.25		4%	0.25
IMG_Attachment_202006050846283.jpg	12.60	12.25		3%	0.35

Table 37: Measurements of Data Sample 2 used for the Accuracy Analysis Part V/V

File Name	AR Measure [in]	Analog Measure [in]	Connected File Name	Difference [%]	Total Difference [in]
IMG_Attachment_20200605093501 3.jpg	1.50	1.00		33%	0.50
IMG_Attachment_20200605094654 2.jpg	11.00	10.50		5%	0.50
IMG_Attachment_20200605145259 3.jpg	15.50	15.00		3%	0.50
IMG_Attachment_20200605080343 3.jpg	3.50	3.00		14%	0.50
IMG_Attachment_20200605152600 1.jpg	1.50	1.00		33%	0.50
IMG_Attachment_20200605084628 1.jpg	18.00	17.00		6%	1.00

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