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Evaluating the Use of Drones for Timber Bridge Inspection

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Abstract

Bridge inspection using a drone, also referred to as an unpiloted aircraft system, has gained more interest in recent years among bridge owners, researchers, and stakeholders because of its efficiency and effectiveness. In fact, numerous bridges classified as structurally deficient in the United States that require more attention and effort for maintenance activities can be inspected using drones in an efficient manner. The primary goal of this project was to evaluate drones as supplemental bridge inspection tools for bridges that present accessibility challenges for inspectors. To accomplish this goal, an extensive literature review and technical survey were initially conducted to gain knowledge of the state-of-the-art and practices and critical considerations that should be accounted for while conducting inspections. Also, analysis of the drones was conducted and the most suitable drone for bridge inspections was selected. To recognize the drone-enabled inspection efficiency, preliminary inspections were conducted for structural damage identification in three structures, including a reinforced masonry building and two pedestrian timber deck bridges. With the knowledge and techniques established during the preliminary inspections, a six-stage recommended bridge inspection protocol using the drone was proposed and applied to two in-service highway timber bridges, including a timber arch bridge and a three-span timber girder bridge in South Dakota. Through the acquisition and analysis of image and video data, the effectiveness of the drone platform was evaluated in terms of image quality, damage identification and quantification, and comparisons with results from traditional inspections conducted on the bridges. This study details drone-enabled inspection advantages and challenges and provides conclusions and recommendations for future work. A key finding demonstrated throughout this project was that different types of structural damage on the bridges were efficiently identified using the drone.

Keywords: drone, bridge, inspection, condition rating, damage, deterioration, image analyses

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English unit	Conversion factor	SI unit
pound (lb)	0.45359	kilogram (kg)
foot (ft)	0.3048	meter (m)
square foot (ft^2)	0.092903	square meter (m^2)
foot candles (f-cd)	10.76	lux (lx)
miles per hour (mi/h)	1.6	kilometers per hour (km/h)
miles	1.6093	kilometers (km)

This study is part of the Research, Technology, and Education portion of the National Historic Covered Bridge Preservation (NHCBP) Program administered by the Federal Highway Administration. The NHCBP program includes preservation, rehabilitation, and restoration of covered bridges that are listed or are eligible for listing on the National Register of Historic places; research for better means of restoring and protecting these bridges; development of educational aids; and technology transfer to disseminate information on covered bridges in order to preserve the Nation's cultural heritage.

This study is conducted under a joint agreement between the Federal Highway Administration–Turner-Fairbank Highway Research Center and the Forest Service–Forest Products Laboratory.

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Executive Summary

This report summarizes the findings obtained while evaluating a drone as a bridge inspection tool. The use of drones has become more appealing to bridge owners, researchers, and stakeholders because of its efficiency and effectiveness to gather relevant data in shorter time and at a lower cost compared with traditional inspection methods. The primary objective of this project was to evaluate the efficiency of using a drone as supplemental inspection equipment for timber bridges that present accessibility issues for inspectors. In addition, conclusions and recommendations were made regarding the efficiency of drone-enabled inspection compared with conventional inspection methods.

During the initial stages of the project, a comprehensive literature review of the state-of-the-art and the practice of drone-enabled inspection technology of different types of structures, focusing on bridges, was completed. Additionally, a detailed discussion was performed with South Dakota Department of Transportation (SDDOT) bridge inspectors and a survey was sent to all 50 state departments of transportation (DOTs) to gather additional input on this technology used for bridge inspection. Based on the literature review and conversations with bridge inspectors from SDDOT, it was revealed that there is a need for a more efficient and cost-effective inspection methodology. Research completed by different state DOTs including Minnesota, Florida, and Alaska demonstrated an increasing interest in bridge inspection using drones. During the technical meeting with SDDOT bridge inspectors, it was determined that drone operation over traffic during drone-enabled bridge inspection was a concern.

Detailed drone comparisons and selections were made to provide a recommended drone to conduct bridge inspection duties. A total of seven considerations including flying time, additional cameras, camera resolution under low illumination, video resolution, payload capacity, additional lights, and remote range were evaluated to select a suitable drone. It was determined that the most suitable drone for inspection purposes was the senseFly Albris (senseFly SA, Lausanne, Switzerland), but because of the limited budget, a Da-Jiang Innovations (DJI) Phantom 4 (DJI, Shenzhen, China) was selected. The DJI Phantom 4 was selected because of additional technology such as obstacle avoidance. Another key consideration was the ability to fly without GPS signal, which enables the drone to inspect underneath a bridge without the problem of losing satellite connection.

To determine drone-enabled inspection efficiency, a preliminary inspection was conducted, especially for structural damage identification. Three different nearby structures, including a reinforced masonry building and two pedestrian timber deck bridges, were chosen for the inspection. To evaluate the images obtained during this stage, use of the proposed entropy–sharpness relationship aided the image quality assessment in determining high-quality images and providing more efficient damage identification. Other methods, such as the recommended pixel-based measurement and photogrammetry analysis, allowed for a thorough damage quantification procedure. Results obtained during the preliminary inspection of structures, such as the reinforced masonry building, demonstrated the capability of the drone to identify cracks under low illumination. Additionally, capturing damage such as buckling and cracking using the drone was possible while the drone was exposed to actual environmental effects. During the preliminary inspections, it was found that weather conditions must be considered to safely operate the drone. Other relevant findings include the capability of the drone to perform underside of deck inspection without GPS signal failure. The high-resolution camera mounted on the drone allowed for detailed damage identification under the deck while the drone was tilted up at an angle of 35°.

With the knowledge and techniques established during the preliminary inspections, a six-stage recommended bridge inspection protocol using the drone was proposed and applied to two in-service highway timber bridges, including a timber arch bridge and a three-span timber girder bridge in South Dakota. The drone efficiency was determined based on image quality, damage identification, and quality of results compared with traditional inspection methods. The proposed entropy–sharpness-based image assessment procedure was used to identify high-quality images. Then, using the image analysis software, a detailed damage quantification was conducted to determine the damage level rating based on the “Caltrans Bridge Element Inspection Manual” (Marshall 2016). Finally, a side-by-side comparison of the inspection reports provided by SDDOT and those obtained from the drone-enabled inspection for each of the Keystone Interchange Bridges confirmed the ability of the drone to effectively identify damage on the bridges.

After completion of the project and analysis of the findings, some recommendations for future generation inspections and research were developed. Further investigation of the recommended protocol with different types of bridges should be conducted. It was concluded that the proposed entropy–sharpness-based image quality assessment efficiently identified high-quality images. Further image quality parameters such as color uniformity should be studied to more efficiently select high-quality images. Recommendations for future research include finite-element-based structural analysis informed by damage identified by a drone. It is suggested that integrated finite element and drone technology be developed to predict bridge behavior considering the effect of damage states related to structural degradation and load-carrying capacity. Another area for future research could be integrating drones

and three-dimensional (3D) digital image correlation (DIC) to monitor long-term behavior of in-service bridges, specifically aging and deterioration.

1 Introduction

The American Society of Civil Engineers (ASCE) has investigated the structural integrity and performance of our nation's infrastructure including bridges (ASCE 2016). In December 2016, the ASCE report card for America's infrastructure indicated that approximately 9.1% of the nation's bridges were classified as structurally deficient. Although the percentage of structurally deficient bridges has slightly declined in past years, visual inspection for a significant number of such bridges needs to be performed to better identify damage and determine the appropriate retrofit methods. Because of the increasing costs and limited accessibility of bridge inspection with current inspection technology, the use of remote-controlled drones equipped with high-resolution cameras may be of interest for efficient and effective bridge inspection. Drone technology provides a more efficient tool for improving or enhancing current bridge inspection practices of timber bridges with visible damage and decay in inaccessible areas that could cause structural degradation.

To evaluate the effectiveness of drone-based bridge inspection, this project investigated the ability of a drone to efficiently identify damage. An extensive literature search on the state-of-the-art practices and a technical survey was conducted to gain knowledge of current drone-enabled inspection practices and relevant consideration to be studied prior to field inspections. Based upon the knowledge obtained from the literature review and technical survey, selection of a suitable drone for bridge inspections was made. Additionally, preliminary inspections of structures (reinforced masonry building and pedestrian timber deck bridges) were conducted to collect relevant information on how to operate the drone and best inspection practices. After all the preliminary data were collected, a proposed inspection protocol was developed and implemented for the Keystone Interchange Bridges in South Dakota for their efficient in-service inspection. Regulations from the Federal Aviation Administration (FAA) (i.e., part 107 certifications and regulations) and SDDOT (i.e., no flying over deck and use of propeller guards) were considered prior to conducting the in-service inspection. The imagery and video data obtained from the inspections was assessed by performing image quality analysis, damage identification and measurement, and comparisons with the historical inspection database from SDDOT. Finally, this project covered drone-enabled inspection merits, challenges, and conclusions, along with recommendations for future work.

2 Objectives and Scope

The primary objective of this project was to evaluate the efficiency of a drone as a supplemental inspection tool for timber bridges that present accessibility challenges for inspectors. In addition, conclusions and recommendations were made to determine the efficiency of drone-enabled inspection compared with conventional inspection approaches. The objectives were achieved with the following tasks:

1. Perform a technical meeting to receive input from local bridge inspectors
2. Complete an extensive literature review and survey to seek information on the current state-of-the-art and the practice in drone-based damage identification
3. Select two timber bridges in the State of South Dakota and the most suitable drone for bridge inspection
4. Perform a preliminary inspection of South Dakota State University (SDSU) facilities and bridges in the proximity of SDSU to identify damage by investigating imagery data gained from the drone
5. Complete field inspection of the selected bridges to evaluate efficiency of the drone to identify damage
6. Evaluate the quality of images obtained from the drone to select high-quality data for effective damage identification and quantification
7. Compare results with those from conventional access inspections to evaluate the performance of drone-enabled bridge inspection results

3 Background

An unpiloted aerial system (UAS), referred to as a drone, is an aircraft without an aviator aboard. The FAA defines small drones as UAS for commercial operations with the following restrictions: less than 55 lb, daylight operation, line of sight operation, under 100 mi/h, under 400 ft, class G airspace only, and may not fly over people or be operated from a moving vehicle. Drones are equipped with high-resolution cameras capable of capturing images and recording videos and have infrared vision to examine bridges, among other things (Eschmann and others 2012, Irizarry and Bastos 2016). They are capable of carrying additional attachments, such as flashlights or thermal cameras, to perform a wider variety of damage identification including delamination where higher temperatures are common (Vaghefi and others 2011). This emerging technology presents great potential for bridge inspection because these structures often present inaccessible areas for inspectors (Koonce and others 2011). To date, limited research regarding drone inspection compared with traditional inspection methods has been completed.

In the field of civil engineering, drone technology has been widely used for structural inspection, surveying, landscaping, and other things (Chan and others 2015, Irizarry and Bastos 2016, Kim and others 2015, Zink and Lovelace 2015, Otero and others 2015). In particular, several state DOTs and the USDA Forest Service have attempted to inspect bridges through drone technology. For example, the California Department of Transportation (Caltrans) developed a twin-motor, single-duct, electric-powered drone designed to carry cameras for visual inspection of bridges (Moller 2008). Similarly, Florida DOT (FDOT) and Otero and others (2015) used a multirotor helicopter-based drone with high-definition cameras to transmit video data of structural components of bridges, including timber bridges. Some stress cracks on bearing areas and guard rail supports were detected by investigating the high-resolution images captured from the drone. Recently, Minnesota DOT (MnDOT), in partnership with Lovelace and Zink (2015), performed a research project regarding visual inspection using drone technology on four different types of bridges in its state. A rotor aircraft drone with fixed wings was used for the bridge inspections. The research demonstrated the capability and advantages of the drone, enabling damage identification on critical areas in the selected bridges in a more cost-effective and safe manner. Region 10 of the USDA Forest Service (Alaska) also developed a drone system, and its associated inspection protocols were applied to the Placer River Trail Bridge located in the Alaskan Kenai Peninsula (Khaloo and others 2017). It was found that the drone was able to efficiently inspect the bridge using its high-resolution scans and 3D virtual model.

4 Literature Review and Survey

A complete literature review of the state-of-the art and practice on drone-enabled inspection technology of different types of structures focusing on bridges was completed herein. Additionally, a detailed discussion with SDDOT bridge inspectors and a survey sent to all state DOTs, were executed to gather additional practical input on applying this technology to bridges. Significant findings from the literature review, technical meeting, and survey are subsequently summarized.

4.1 Literature Review

The findings from the literature review demonstrated the effectiveness of drones to inspect bridges and other structures such as buildings, wind turbines, and industrial plants (Henriques and Roque 2015, Moranduzzo and Melgani 2014, Roca and others 2013). Different attachments, such as high-resolution cameras, thermal cameras, and orientation sensors, have proven to be effective means to collect visual data necessary for the identification of structural damage including corrosion and cracking (Irizarry and others 2012, Remondino and others 2012, Vaghefi and others 2011). Details on the drone technology that was applied to bridges and other structures are presented in the following subsections.

4.1.1 Bridges

A representative example of drone technology application to bridges is the demonstration project led by MnDOT partnered with Zink and Lovelace (2015), which used an Aeyron Skyranger (Aeryon Labs Inc., Waterloo, Ontario, Canada) drone to inspect four different types of bridges in the State of Minnesota. The selected bridges included a single-span prestressed concrete bridge, an open spandrel concrete arch bridge, a five-span steel underdeck truss bridge, and an arch truss bridge. MnDOT was able to identify defects, such as missing and damaged elements in the bridges, using the drone. Figure 1 shows a sample inspection picture depicting the details of a steel pin connection corroded with rust in the arch truss bridge.

Another example is the project performed by Florida Institute of Technology (FIT) and Otero and others (2015) in cooperation with FDOT. FIT and FDOT performed a proof of concept study to identify the most suitable drone considering maneuverability, adaptability, software compatibility, payload, size, and user controls for bridge inspections. Five different types of bridges were selected for the FDOT project and were inspected using the selected drone, an upgraded quad-copter. Figure 2a shows a steel connection with missing nuts in the selected steel truss bridge, and Figure 2b illustrates a stress crack on the underside of the selected timber bridge.

Recently, the USDA Forest Service Region 10, University of Alaska Fairbanks, and George Mason University collaborated to inspect an existing timber truss bridge using a drone in Alaska. Specifically, Khaloo and others (2017) used a hexacopter drone called Ptarmigan, which was built based on DJI S800 airframe with gyrostabilized Sony Nex7 (Sony Corporation, Minato, Japan) and GoPro cameras (Woodman Labs, Inc., San Mateo, California, USA). The drone was able to identify damage on the bridge components (e.g., gaps between end of kerf plate and sawn kerf in brace (Fig. 3a)). A 3D virtual model of the bridge in a dense 3D point cloud was created using the software PhotoScan (Agisoft LLC, St. Petersburg, Russia) informed by the imagery data from the drone with computationally expensive costs (Fig. 3b). The 3D model was able to check the detailed damage of the bridge.

4.1.2 Other Structures

More information on drone-based damage detection technology with other types of structures was obtained through the relevant literature review conducted for this project. For example, drones have frequently been used to inspect photovoltaic (PV) fields, better known as solar panels (Aghaei and others 2015). Such drones are typically equipped with infrared sensors and other attachments for this use. Thermographic assessment using a PLP610 Nimbus (Aerodyne-RC, Kent, Washington, USA) drone platform with a forward looking infrared radiometer (FLIR) A35 infrared imaging sensor was performed to examine the solar panels (Fig. 4).

Other common structures, such as dams, have also been inspected by drones. For instance, Henriques and Roque from the Laboratorio Nacional de Engenharia Civil (LNEC), or National Civil Engineering Laboratory, in Lisbon, Portugal, investigated the use of drones for dam inspection (Henriques and Roque 2015). They used an Octocopter SKY II drone (CIS-Associates, Valley Springs, California, USA) to check cracks on the surface of the dam. Previous methods included surveillance cameras and binoculars used from the base of the dam, but neither of those methods were effective because of the great distance and the low quality of the resulting images. The researchers concluded that the drone, accompanied with high-quality cameras, was an effective tool to inspect dams because they could obtain detailed images of critical sections in inaccessible areas.

Corrosion levels in industrial plants and their effect on overall structural performance have also been investigated (Moranduzzo and Melgani 2014). That investigation highlighted that the level of detail of the drone images was used for further computational analyses. However, the most common approach to identifying visual damage on other structures was the integration of simply obtaining photos from a drone and using imaging generation software such as PhotoScan to create a 3D point cloud model of the data. It is anticipated that different types of damage detection algorithms such as Morphological Link for Crack (Morphlink-C) may be used to measure crack thickness and corrosion growth and to detect defective structural components (Kim and others 2015).

4.2 Technical Meeting

More practical information was assembled during the technical conference call with some SDDOT bridge inspectors and engineers held on August 25th, 2016. During the call, a discussion regarding the use of drones to inspect bridges and restrictions imparted by SDDOT was conducted. Some of the information discussed involved the following:

- Safety precautions during the bridge inspection
- Concerns regarding traffic control and bridge damage that may occur during the inspection (e.g., not flying over traffic, use of propeller guards, and special traffic control required if inspectors are near roadway)
- Additional requirements (e.g., a full week notice prior to field inspection)

Furthermore, SDDOT indicated that visual data (i.e., photographs and videos) will be the most beneficial information for damage identification. A discussion of the survey distributed to different DOTs nationwide revealed that despite the fact that SDDOT has not previously used a drone for bridge inspections, they anticipate that this new technology will be promising for the near future of bridge maintenance.

4.3 Survey to DOTs

4.3.1 Overview

An online survey sent to all 50 state DOTs was conducted to gather additional hands-on information about the use of drones for bridge inspection. The survey form can be seen in Appendix A. Nineteen responses to the survey through an online version were received from different DOTs: Idaho, Iowa, Illinois, Missouri, Wyoming, Florida, Delaware, New York, Wisconsin (2), Alaska, Arkansas, Nevada, South Dakota (2), Kentucky, Arizona, and Colorado, along with Alaska Forest Service. It was reported that seven states, Florida, Iowa, Idaho, Kentucky, New York, Wisconsin, and Alaska, have used or planned to use drones for bridge inspection. This shows the increasing interest of states to use the drone technology.

4.3.2 Details

The survey questions and corresponding responses are detailed herein:

Question 1 asked “Does your state have use or is your state planning to use UAV for bridge inspection”. Additionally, if they answered yes to Question 1, it was enquired which drone has been used and what attachments have been used. Only one state (Alaska Forest Service), among those who answered the questions listed above, used a drone for bridge inspection, whereas six state DOTs were planning to inspect their own bridges using drones. A summary of the responses to the questions is presented in Table 1.

For Question 2, information related to drone techniques for bridge inspection was requested from the respondents. The question was “what techniques or data were or will be used to inspect bridges?” As expected, all the DOTs that responded to the first two questions mentioned that images and video are the most important pieces of information to detect damage. Figure 5 shows the results obtained. A total of eight state DOTs mentioned that imagery and video data are considered the most effective to identify damage on bridges. Among eight DOTs, five respondents (Wisconsin (2), Colorado, Idaho, and Iowa) believed that data gained from thermal cameras is the second most important resource for bridge inspection. Meanwhile, according to the feedback from Colorado DOT, displacement sensors will provide critical data necessary for damage identification. Alaska Forest Service responded that 3D site reconstruction photogrammetric software (e.g., structure from motion (SfM)) was important for detailed damage investigation.

Question 3 enquired about the most necessary data and challenges that drone technology may have for bridge inspection. Several challenges were mentioned about this technology by several state DOTs because of the relatively new appearance of this technology on the market for bridge inspection. The details for answers to Question 3 are listed in Table 2.

For Question 4, the research team enquired about main concerns when inspecting bridges using drones. Concerns regarding safety and regulations stood out. DOTs were skeptical of this new technology and how it will perform during field inspections. Responses to this question from different state DOTs are presented in Table 3.

Next, Question 5 enquired about DOTs having either past or ongoing research projects on unmanned aerial vehicle inspection techniques. Several state DOTs, including Arkansas, Arizona, Illinois, Missouri, Wyoming, Delaware, and New York, did not specify any ongoing research. The remainer of the state DOTs provided specifics of their ongoing research. A summary of the responses is presented in Table 4.

Finally, Question 6 enquired about future research plans related to drone techniques for inspecting bridges. Again, the same state DOTs as the previous question, with the inclusion of South Dakota and Alaska, did not have any future research plans on drone techniques. The responses from the remaining state DOTs are presented in Table 5.

The survey results provided insightful information regarding what states have used, what they plan to use, and what they think in regards to drone technology that may be used to inspect bridges in the future. The most common data necessary for bridge inspection were found to be images and videos. However, several state DOTs expressed some concerns about safety, traffic control, privacy, frequent changes in FAA regulations, and other things. Hence, these concerns were taken into consideration during the entire course of this project.

5 Drone and Structure Selection

For this project, an appropriate drone necessary for bridge inspection was first selected considering different factors, including flight time, upward viewing camera, camera resolution, video resolution, etc. Then, several structures were chosen to evaluate the efficiency of the drone as a supplemental inspection tool. Proper permissions were obtained before any evaluations began, and none of the structures were located on U.S. Forest Service lands.
The structures for the preliminary inspection included a reinforced masonry building at the SDSU campus and two pedestrian bridges at city parks in Brookings, South Dakota. For the full-scale inspection, the structures selected were the Keystone Interchange Bridges located near Keystone, South Dakota. It can be noted that the preliminary inspection of structures served not only to evaluate drone-enabled structure inspection efficiency but also to develop a protocol for more systematic and efficient inspection of highway bridges. Details of the drone and structure selection are subsequently presented.

5.1 Drone Selection

A suitable drone needed to be chosen for visual inspection of the selected structures. During the literature review, various drones were investigated to compare their capabilities in terms of data acquisition. Based on the knowledge from the literature review and the survey, the following considerations were made to select the most suitable inspection drone for this project:

(1) **Flying time more than 20 min:** A relatively long flying time is beneficial for a more efficient structure inspection by limiting the need of additional batteries and allowing for longer inspection times.

(2) **Additional camera on top of drone:** A second camera facing straight up to inspect underneath the bridge will allow for its comprehensive inspection.

(3) **Camera resolution with low illumination:** Low illumination reduces image quality, which results in small damage being challenging to detect. Additional flashlights can be attached to a drone to enhance illumination.

(4) **High-resolution video:** High-resolution video is required to visually observe details of damage.

(5) **Adequate payload capacity:** Sufficient payload capacity would be beneficial for potential attachments that might be required to be carried by a drone.

(6) **Drone lights:** Light-emitting diode (LED) lights attached to a drone will provide some extra illumination required for efficient damage observation underneath a bridge.

(7) **Remote range:** Some structures might not be relatively close to the pilot location. Long range modules for remote control will allow for inspection of structures at long distances.

With the required seven considerations, thirteen drones (Fig. 6) with a variety of prices, physical sizes, and manufacturers were identified and are listed in Table 6. The drones and each of their capabilities were compared in terms of the aforementioned considerations and rated from 1 (not suitable) to 5 (extremely suitable). Table 6 shows that the most appropriate drone was the senseFly Albris, which was rated 5 (Fig. 6). This is because (1) it is able to rotate the camera 180° and has an integrated flashlight, infrared camera, and wide-angle camera; (2) different flight modes (e.g., GPS-mapping and manual) allow the drone to program missions or fly under bridges where GPS signal is unavailable (during the survey, many state DOTs expressed issues with the low signal of the drones); and (3) its effectiveness for bridge inspection was previously demonstrated through the MnDOT project. However, the cost of the drone is close to $45,000, exceeding the allocated budget to purchase a drone.

Other options such as the DJI Matrice 100 (Fig. 6c), DJI S900 (Fig. 6g), DJI Phantom 3 pro (Fig. 6d), and DJI Phantom 4 (Fig. 6e) were deemed to be suitable for the project at a more affordable price compared with the senseFly Albris. Of these, the DJI Phantom 4 was selected because of its performance and versatility in meeting the aforementioned specifications at a reasonable cost. Adding obstacle avoidance technology would be beneficial for the drone to prevent damage to both bridge and drone components when the drone approaches a bridge. Another key consideration is the ability to fly without GPS signal. As stated before, this enables the drone to inspect underneath the bridge without the problem of losing satellite connection. Some attachments, such as a flashlight and second camera, could be added to the drone to overcome inspection challenges.

5.2 Preliminary Inspection Structure Selection

5.2.1 Reinforced Masonry Structure

During the initial stages of the project, a preliminary inspection of a reinforced masonry building called the Animal Science Arena at the SDSU campus (Fig. 7) permitted the pilot to become familiarized with drone operation. The building is a multipurpose 21,000-ft^2 building that provides a space to bring in livestock for SDSU students, and accordingly, the open space inside the building allows for safe drone operation. The structure is 104 by 192 ft and is composed of reinforced masonry walls with concrete columns supporting 33 lines of steel trusses at 5.25-ft spacing on center (o.c.) for the roof.

5.2.2 Pedestrian Timber Deck Bridges

Two pedestrian timber deck bridges at city parks in Brookings, South Dakota, were inspected using the drone. The main objective of performing the preliminary inspections of the bridges was to identify any damage and to evaluate flying conditions of the drone. The bridges met the requirements for structure availability and accessibility and for drone-based inspection. The inspection was performed in accordance with city park policies and FAA regulations.

The first bridge, located at Dakota Nature Park, has a single simply supported span with eight steel stringers spaced at 2 ft o.c. and a clear width of 16 ft. The bridge with timber decking has a 40-ft-long span and steel truss guardrails parallel to the superstructure (Fig. 8).

The second pedestrian bridge, located at Sexauer Park, has two continuous spans with three steel box stringers spaced at 2.5 ft o.c. and a clear width of 4.5 ft. The bridge with timber decking has a total length of 90 ft and steel truss guardrails parallel to the superstructure (Fig. 9).

5.3 Selection of Keystone Interchange Bridges for Full-Scale Inspection

For the full-scale inspection of bridges, the Keystone Interchange Bridges, which include a timber girder bridge and a timber arch bridge (Keystone Wye), were selected (Fig. 10). They are located on highways US16 and US16A in Pennington County, South Dakota. The timber girder bridge has three simply supported spans with four girders spaced at 7.5 ft o.c. and a clear width of 26 ft. The bridge has curved concrete decking and is 170 ft long with steel bridge railings parallel to the superstructure. The Keystone Wye timber arch bridge has three continuous spans near the approaches and two sets of four continuous spans over the arch with three stringers spaced at 10.25 ft o.c. and a clear width of 26 ft. The bridge has concrete decking and is 290 ft long with steel bridge railings parallel to the superstructure.

6 Image Analysis Approach

To identify high-quality images for damage quantification, image analysis based on the entropy–sharpness relationship was proposed. This approach involved damage quantification with different image analysis algorithms using ImageJ and Photoscan for photogrammetric processing of images. An overview of damage from different angles is thereby produced. The significance of the entropy–sharpness relationship, ImageJ, and PhotoScan is subsequently presented.

6.1 Entropy–Sharpness Relationship

To identify high-quality images out of a number of images from the drone, the relationship between entropy and sharpness of images should be better understood. Entropy can be used to evaluate the standard deviation of every color pixel per image based on a mathematical algorithm. The algorithm is based upon the sum of pixel color in grayscale from the histogram counts (range of color values) of the image to produce a single value based on the standard deviation of color from pixel to pixel. Conversely, sharpness is defined as an ability to display the boundary of an image and spatial resolution. To obtain the quantifiable value, an algorithm created by Tolga Birdal using MATLAB (The MathWorks, Inc., Natick, Massachusetts, USA) was executed. The original image was converted into a grayscale image and measured for color change boundaries to determine if the transition was gradual (blurry) or not (sharp). Then the algorithm quantified the sharpness by dividing the sum of all gradient norms (or magnitude of vectors along color change boundaries) by the number of pixels on the picture.

Sample images obtained from the inspection of one of the pedestrian bridges were taken as a reference to perform the pilot investigation of image quality. The study of the relationship using sample pictures gained from the drone is shown in Figure 11. Entropy determination of the two sample images in Figure 11a, b was completed using MATLAB (Moler 1984). This demonstrates the significance of entropy for the determination of high-quality images. Figure 11a has a similar relative entropy to that of Figure 11b but its image sharpness is significantly lower than that of Figure 11b. As a result of the comparison, the image in Figure 11b can be classified as a high-quality image.

To efficiently identify damage using the drone, blurry and low-quality images should be removed from the imagery data gained using the drone. Two example images (Fig. 11b (high-quality) and Fig. 11c (blurry)) were used to investigate how blurry images can be categorized as low-quality images using both entropy and sharpness. Figure 11c with an entropy of 7.42 and sharpness of 0.69 appears to be very blurry. The entropy and sharpness values of Figure 11c are similar and much lower than the respective ones of the image in Figure 11b. From this comparison, it can be concluded that blur does not significantly affect entropy and a high sharpness and entropy produces a high-quality image. In brief, the use of both entropy and sharpness produces an estimate of image quality and is a reasonable choice to eliminate either poor illumination or blurry images and therefore select high-quality images.

6.2 Damage Quantification Using ImageJ

After the high-quality images are identified, damage quantification can be completed via the image analysis software ImageJ (Rasband 1997). This software is able to perform length and area measurements based on a known scale specified by the user. When a scale is identified, the use of the measuring tool can be applied to measure distances for damages such as cracks. Further capabilities such as edge detection may be used to efficiently identify cracks. The edge detection function available in ImageJ applies the Sobel filter to identify sudden changes in color gradient (edges) typically seen in crack boundaries.

6.3 3D Virtual Modeling Using PhotoScan

The use of PhotoScan allowed for a more comprehensive overview of damage. Using aerial images, the computer software identifies unique features of each image and compares them to the entire image set to align them and produce a sparse point cloud as the first step of the reconstruction process. To produce a high-quality 3D virtual model, it is necessary to capture images with approximately 60% to 80% overlap between each subsequent picture. After the images are aligned correctly and the sparse point cloud is generated, a dense cloud with more spatial points is developed to better observe details of the 3D virtual model. The next step is to create a mesh between the points in the dense cloud for the surface reconstruction. PhotoScan uses a triangulation method defined as the connection of adjacent points in a triangular form to produce a solid surface. The triangulation method produces triangular shapes for the meshing, or creation of the object surface for the 3D virtual model, producing a solid surface of the object. The final step is to generate the texture of the virtual model to resemble the real target damage. The process as described is completed with information from the image set used to create the 3D virtual model.

7 Preliminary Inspection Using Drone

The reinforced masonry building and two pedestrian bridges were initially inspected prior to the full-scale inspection of the in-service highway Keystone Interchange Bridges. The information gathered during these preliminary inspections helped make critical decisions that needed to be contemplated for the in-service bridge inspection. The preliminary inspections also served as pilot training, drone flight recognition, and practice. To increase the drone-based inspection quality, image quality assessment was performed by analyzing the relationship between entropy and sharpness for images from the drone. Additionally, damage quantification for certain structural components was performed using ImageJ analysis, and corresponding damage levels were determined by following federal or state damage state documents such as “Caltrans Bridge Element Inspection Manual” (Marshall 2016). Finally, representative structural components with significant damage were generated in 3D virtual environments using PhotoScan, which permitted further review of the observed damage. The preliminary structure inspections are detailed in the following sections.

7.1 Reinforced Masonry Structure

During the inspection of the reinforced masonry structure, different structural components (e.g., concrete wall, concrete slab, and concrete columns) were inspected to perform image acquisition techniques to ensure the capture of high-resolution pictures during the aviation of the drone. A total of 119 images (2.2 GB) of different structural components were obtained during the drone operation. Sample images gained from this inspection can be seen in Figure 12a-d. Also, Figure 12e, f shows the operation of the drone by the remote pilots Luis Duque and Junwon Seo, respectively. The data were used for image quality analysis using the relationship of entropy and sharpness, as previously described. After taking several pictures under different drone movements (i.e., still and moving slowly across the structure), it was found that to obtain high-quality pictures and avoid distortion, the drone needs to be steady and stationary for a few seconds while taking the picture. Another point is that drone flight should be adjusted depending on each of the target structural components. For example, for the examination of a flat surface such as a slab, the drone should scan through it in a horizontal movement.

The damage identified and results for various structural components of the building are presented in the following sections, subdivided by component.

7.1.1 Slab

To investigate cracks on the slab, ten images were used. Instead of scanning the slab at the same altitude, the pictures were taken at different altitudes to explore if PhotoScan was able to recognize the pictures and align them properly. Entropy and sharpness were plotted on the same graph to identify blurry and low-quality images (Fig. 13a). They were plotted using two different scales to better recognize the trend of the image quality parameters. During visual review of the images, it was recognized that image number 2 and 4 correspond to low-quality images. This was confirmed by reviewing the entropy and sharpness values of each image. Image number 4 in Figure 13b validates the result.

The high-quality images selected from the image quality assessment procedure were used in PhotoScan to re-create the cracks on the slab in 3D virtual environment (Fig. 14a). The re-created slab with the cracks can be seen in Figure 14b. The investigation procedure of incorporating images from different altitudes helped identify high-quality images for more efficient crack detection on the slab. Additionally, the approximate length of the crack was estimated with the commercially available image analysis program ImageJ by using the edge detection function (Fig. 14c). The respective quantifiable results are presented in Table 7. Then, the results were compared with field measurements and quantified according to the Federal Emergency Management Agency (FEMA) standards for high-seismic zones. The rating scale includes destroyed, major damage, minor damage, affected, and inaccessible. The damage of the reinforced masonry structure was classified as "affected", meaning the damage of the building is not significant and the structure is habitable without repair (FEMA 2012). We should mention that although the building is not located in a high-risk seismic zone, the FEMA damage level rating was used to provide a rating of the damage results obtained.

Furthermore, an analysis of the entropy–sharpness relationship with variability in illumination was performed. It was found that as illumination decreased, both entropy and sharpness also decreased. This was caused by color blend at pixel boundaries, which causes the tone and color transition to be less noticeable. With the aid of EngineeringToolBox.com, an online tool with a variety of resources and fundamental information for engineering, it was found that the illumination level of the pictures taken for the cracks with sufficient illumination was approximately 13.94 f-cd (foot-candle). The illumination levels of the pictures gained for the cracks with insufficient illumination ranged from 1.86 to 4.65 f-cd, which was significantly lower. Twenty images were analyzed using the entropy–sharpness relationship, and the set of images for the cracks with insufficient illumination was found to be of high quality (Fig. 15a), despite the low sharpness of some images. Figure 15a shows a similar trend in both sharpness and entropy, meaning there are no blurry images. For practicality of damage detection, images with such low sharpness caused by low illumination (low entropy and low sharpness) are not suitable and consequently should be discarded. Image number 18 is presented in Figure 15b to demonstrate that despite its low sharpness it is not blurry.

The second investigation with low illumination images on the slab crack was made because this was necessary for identification of any damage underneath bridges during field inspections. The overall entropy and sharpness decreased as a result of the low illumination, but PhotoScan was able to identify the cracks and re-create them in a 3D virtual workspace. Figure 16a shows the low illumination images for the cracks on the slab, and Figure 16b displays the cracks on a 3D virtual model that was re-created using PhotoScan.

7.1.2 Columns

After completing the comparison of entropy and sharpness for the images on the cracked slab, image quality was determined for the tall and short columns of the building. Figure 17a, c show the entropy–sharpness relationship for the tall and short columns, respectively. Thirty-one images for the tall column were plotted to eliminate the low-quality pictures by comparing the entropy and sharpness of each of them (Fig. 17a).The entropy for the tall column with insufficient illumination ranged from 5.2 to 5.8, whereas that of the wall with sufficient illumination ranged from 6.8 to 7.7. When the plot of entropy and sharpness was analyzed, image number 10 and 11 were recognized as low-quality images because of a significant decrease in sharpness with an increase in entropy. Image number 21 was also recognized as a low-quality image because of poor illumination; both entropy and sharpness were decreased significantly. Image number 21 is shown in Figure 17b as an example of poor illumination.

Similarly, for the short column, the entropy and sharpness of the 37 pictures were determined and plotted in Figure 17c. The results demonstrate how illumination greatly affects the entropy and sharpness of the image because the short column was located at a corner of the building where illumination was the lowest. A total of 12 pictures could be classified as low-quality images. The images identified to be of lower quality are numbers 5, 15 through 22, and 31 through 33. It is important to note that there are no blurry images in this set. The low quality is attributed to insufficient illumination at the moment of the inspection using the drone. Image number 21 is presented in Figure 17d to demonstrate its low illumination.

3D virtual models for each of the columns under different image quality conditions were generated using

PhotoScan. Figure 18 includes original pictures for each component captured from the drone and corresponding 3D representation images generated from the program. Figure 18a shows a sample picture of the geometry of the tall column obtained using the drone, and Figure 18b displays its 3D virtual model. This demonstrates the effectiveness of the program to re-create the tall column under low illumination. Similarly, more evidence can be seen in Figure 18c, d for the short column. Based upon the image quality analysis and the program capability to reproduce each component with a range of image qualities and illumination, the program was effective in re-creating the 3D representations.

Recognition of damage under low illumination conditions is challenging during field inspection. To overcome this adversity, the image enhancement capabilities of ImageJ were studied for a sample low-illumination image identified from the image quality assessment. To conduct the image enhancement, the histogram equalization (color distribution) capabilities of ImageJ were utilized to improve the contrast of the image as shown in Figure 19. The original image is presented in Figure 19a with its respective histogram in Figure 19b, and the processed image is presented in Figure 19c with its corresponding histogram in Figure 19d. As seen in the histogram for the original image, the mean and standard deviation of its color pixels are 26.4 and 15.7, whereas those of the processed image are 109 and 64.9, respectively. It can be interpreted that the original image has the lower mean value, meaning that most of pixels are on the dark side of the color scale, whereas the processed image has the middle mean value, which means the majority of the pixels are located on the center of the scale. Another interpretation is that lower contrast of the original image is one of the causes of low standard deviation, which means lower entropy (poor illumination) as seen in Figure 19a. After this process was done, a small crack 14.7 in. long on the side of the column was successfully identified from the processed image (Fig. 19c) and measured using the proposed image analysis approach.

7.1.3 Wall

A wall of the building was also studied. The entropy–sharpness relationship for the wall is presented in Figure 20a. For the wall, a total of 21 images were analyzed and 5 were considered to be of low quality after the relationship of entropy and sharpness was reviewed. The low-quality images are image numbers 2, 3, 4, 7, and 18. The low quality was caused by significant drops in sharpness with relatively small changes in entropy, meaning the images are blurry. Image number 4 is presented in Figure 20b to demonstrate the blurry quality.

A 3D virtual model for the wall was generated using PhotoScan. Figure 21a, b represents the wall picture captured from the drone and corresponding 3D virtual model. Despite some images being blurry, the wall was re-created. Based upon the image quality analysis and the program capability to reproduce each structural component with a range of image qualities and illumination, the program was effective in re-creating the 3D representations.

7.1.4 Other Components

In addition to the previously mentioned major structural components inspected, an inspection of the lamp and roof joints or bracings (secondary component) using the drone was conducted. With the drone, corrosion was detected on one of the lamps in the building. The stable flight of the drone allowed it to approach the lamp closely (approximately 1.5 ft) to obtain detailed images. Sample images for two different sections that were captured using the drone can be seen in Figure 22. The drone was also able to inspect below and between the joists as shown in Figure 23. The drone gimbal was tilted upward 35° to capture images of the roof above the joints, and then images for further details between the joints were obtained when the drone was between them. A sample of the pictures can be seen in Figure 23a, b. Although several images were obtained during these inspections, generating high-quality 3D virtual models for the lamp and joints was not achievable because of complexity of the multiple components around them.

7.2 Pedestrian Timber Deck Bridges

The outdoor preliminary inspections of the two pedestrian bridges allowed for gathering imagery while the drone was exposed to actual environmental effects. For the bridge inspection, two main concerns were (1) keeping the drone steady while flying with varying wind speeds and (2) maintaining a GPS signal underneath the bridge. Details for each of the bridge inspections are presented in the following subsections.

7.2.1 Dakota Nature Park Pedestrian Bridge

The pedestrian bridge located at the Dakota Nature Park in Brookings, South Dakota, was studied. A total of 135 images (3.49 GB) were taken by the drone during the inspection. Images for several bridge components such as the deck and stringers can be seen in Figure 24a-d.

During the flight, the average and maximum wind speeds were 6 and 8 mi/h, respectively. The drone could be normally operated at these wind speeds, and the GPS signal under the bridge was good. However, the drone was unstable during certain wind gusts during the inspection. Sample pictures taken by the digital camera as well during the aviation of the drone can be seen in Figure 25. These inspection practices were timely and useful prior to performing the full-scale inspections for the Keystone Interchange Bridges. Overall, the flight was a success and relevant information was collected to be analyzed using the proposed image quality assessment.

The images were analyzed by investigating the relationship between entropy and sharpness to eliminate any low-quality images. The entropy and sharpness plots are presented in Figure 26a-c. Because of the large number of images, the 135 images were divided into three different sets showing the corresponding entropy and sharpness plots to better observe their fluctuations: the first plot shows the first set of 45 images (image number 1 through 45), the second plot presents the next 45 images (image number 46 through 90), and the final plot introduces the last 45 images (image number 91 through 135).

As shown in Figure 26a, the quality of the first set of 45 images was significantly high, with a sharpness range of 12 to 21 and entropy range of 5.5 to 7.7, because of sufficient illumination (about 100 f-cd), compared with the indoor flights in which the sharpness did not exceed the cutoff of 6.0 on the sharpness scale and illumination on average was about 13.94 f-cd. Different results can be observed on the second plot (Fig. 26b) with a sharpness range of 8.5 to 20.5 and entropy range of 6.8 to 7.6. Three images, image numbers 82 through 84, were identified as low quality because of excessive exposure caused by both the snow on the ground and the sun during the flight. The sudden drop in both sharpness and entropy from 9 to 3 and 5.8 to 4.5, respectively, reflects this condition.

The last set of 45 images is introduced in Figure 26c. Images 115, 118, 122, and 135 were identified as having low quality. The sharpness decreased with increasing entropy caused by minimal blurriness because of overexposure. Additionally, images 93, 96, and 136 were also identified as low-quality images because of a significant decrease of both sharpness and entropy caused by severe overexposure. During this flight, there were no highly blurry images but because of overexposure, the quality of some pictures was diminished causing difficulty observing damage per bridge component. Examples of such images are presented in Figure 26d, e. Lastly, a total of 10 images were classified as low-quality images, which represents only 7.4% of the 135 images analyzed and confirms the efficiency of the drone to capture high-quality imagery data.

By reviewing the high-quality images selected after the quality assessment, it was possible to identify a buckled steel rail in the bridge (Fig. 27a). This buckling was also identified by the re-creation of a 3D virtual rail model (Fig. 27b). Corrosion in most of the steel railing members was observed (Fig. 27c). Some images captured using the drone that hovered underneath the bridge allowed for the investigation of damage on the stringers and cross frames (Fig. 27d). It appearred that there was some corrosion in certain stringers. Most of the images obtained were of good quality and aided in identifying and quantifying different damage types for the bridge components.

The maximum vertical deflection of the buckled rail in Figure 27a and corrosion areas for the rail shown in Figure 27c were measured using the measuring tool available in ImageJ. The corresponding measurements are presented in Table 8. To verify the pixel-based measurements obtained using ImageJ, a field measurement of the buckled member was conducted and compared with it. No significant difference was shown. Meanwhile, the rail with some corrosion as indicated may be classified as fair for the condition state, based on steel railing rating matrix in the Caltrans bridge rating manual (Marshall 2016). Caltrans has four damage condition states specified as (1) good, (2) fair, (3) poor, and (4) severe. Detailed information on the Caltrans bridge rating manual can be found in Appendix B. A field measurement for the corroded area was not determined because of the shape irregularity, but the accuracy of the buckling measurement legitimizes the precision of the measurements that ImageJ can attain.

7.2.2 Sexauer Park Pedestrian Bridge

A second pedestrian steel stringer bridge with timber decking located in Sexauer Park in Brookings, South Dakota, was successfully inspected. A total of 193 images (908 MB) were taken by the drone during this inspection. Sample images of the bridge and its structural components, such as deck and chords, can be seen in Figure 28a-d.

This inspection allowed for sufficient imagery data collection, which supplements the information obtained from the pedestrian bridge located at the Dakota Nature Park. During the first pedestrian bridge inspection, a few concerns arose regarding how the drone would perform under severe weather conditions (e.g., exposure to high wind speeds or wind gusts). However, this inspection was completed without such issues (wind speeds averaged 10 to 12 mi/h). Some unstable conditions caused by wind funnels near enclosed sections (including between railings) and underneath the bridge did not significantly affect flight safety and inspection data quality. Sample pictures (including the pilot) taken by the digital camera during the aviation of the drone can be seen in Figure 29.

Prior to identification of any damage on the bridge, image quality analysis was performed to remove low-quality pictures. Because of the amount of data obtained, the pictures were distributed among four plots to better visualize the changes of entropy and sharpness: the first plot shows the first set of 49 images (pictures 1 through 49), the second plot introduces the next 49 images (pictures 50 through 98), the third plot presents the following 49 images (pictures 99 through 147), and the fourth plot shows the last 46 images (pictures 148 through 193). These four plots are presented in Figure 30a-d.

In the first set of 49 images presented in Figure 30a, four images were identified as low-quality images. These images, numbers 2, 27, 28, and 29, show a relative decrease in sharpness without a considerable change in entropy. The decrease in sharpness is attributed to the change in illumination during the flight because the inspection was conducted close to sunset. The next set of 49 images is presented in Figure 30b, in which the comparison between entropy and sharpness did not show a possibility of low-quality images. The relation between entropy and sharpness for this set of images is consistent throughout the plot, which represents high-quality images. Again, the bridge inspection was performed late in the afternoon, causing the sun to shine directly into the camera when inspecting certain areas of the bridge. The direct sunshine caused a decrease of sharpness ranging from 8 to 16 in the second set of images to a range from 4 to 12 in the next 49 pictures (third plot) (Fig. 30c). The majority of the pictures taken by the drone when inspecting the bridge and facing the sun simultaneously are included in the third plot. The direct sunlight caused overexposure and a decrease in overall sharpness. The pictures identified to be of low quality are image numbers 110 through 114 and 127 through 140.

The final set of 46 images are presented in Figure 30d. The pictures presented in this plot were taken at the end of the flight, and consequently a reduction of sharpness can be seen compared with the first two sets of pictures from Figure 30a, b. Image numbers 183 through 188 were considered to be low quality because of the decrease in sharpness with an increase in entropy. A total of 26 images were determined to be of low quality based upon the analysis of entropy and sharpness, which comprised only 13.4% of the total data gathered. Examples of the identified low-quality images are provided in Figure 30e, f. The quality of the identified low-quality images (low quality caused by low exposure or low illumination) can be enhanced by adjusting an image contrast ratio in commercially available image software such as ImageJ, as previously mentioned.

Based upon the observation and 3D virtual re-creation of the high-quality images, several damage types such as corrosion, concrete cracking, and missing bolt nuts were identified. For example, Figure 31a shows a bolt that was bent, and the bolt was represented in 3D virtual space as shown in Figure 31b. The drone hovered at a distance of about 2 ft from the surface of the bridge and identified missing bolt nuts (Fig. 31c). Corrosion was also identified on most railings and on some lateral bracings and stringers (Fig. 31d). Overall, the bridge presented several timber board separations and holes on the deck (Fig. 31e) and some concrete cracking at the abutment (Fig. 31f). A summary of the image-based and field measurements for the bent bolt, deck hole diameter, and crack length is presented in Table 9. Most of the images obtained were of high quality and enabled the identification of different damage types on the bridge components. Any damage rating information specific to the aforementioned damage was not specified in the Caltrans bridge rating manual (Marshall 2016).

8 Drone-Enabled Inspection Protocol

To systemically identify damage or defects on in-service highway bridges using a drone and to help support next-generation bridge inspection guidelines, a recommended six-stage inspection protocol was developed. The protocol was developed based on the findings from the literature review and preliminary inspections of the reinforced masonry building and pedestrian bridges prior to the field inspection of the Keystone Interchange Bridges. The drone-enabled bridge inspection procedure flowchart is shown in Figure 32. Each stage is detailed as follows:

Stage 1 is to perform a visual observation of surrounding areas within and beyond the perimeter of a bridge location. The inspection team needs to identify potential risks that may affect the flight safety (e.g., adjacent trees and traffic volume). The visual observation should be considered a necessary stage of the bridge inspection process in which critical information is gathered for flight safety and pilot risk minimization. This stage allows recognition of flight landing–takeoff zones to access critical sections of the bridge using the drone. Prior to the drone inspection, evaluating the current damage state of structural components of the bridge is recommended to ensure all existing damage areas are inspected. Additionally, any restrictions that may apply to the bridge location must be considered. These restrictions include, but are not limited to, FAA certifications, FAA airspace class restriction (e.g., flying within 5 miles of an airport), DOT flying restrictions, and DOT safety measures. Also, traffic must be controlled for the inspection on the right-of-way of any highway per DOT regulations by displaying warning signs and cones to guide approaching traffic away from work zones. Finally, liability insurance should be obtained to cover any damage to either the drone or bridge in the case of unexpected accidents.

Stage 2 is to complete the bridge information review. During this stage, technical documents such as as-built construction plans and historical inspection reports are referenced to ensure the target bridge is fully inspected. The review of construction plans permits a pilot to determine vital information such as dimensions and locations of structural elements, increasing the accessibility across its elements for the drone. For instance, locations of critical structural elements such as girders can be determined by reviewing the plans and this can help develop an efficient strategy for their inspection under limited and complicated approachability conditions using the drone. Also, review of the plans and inspection reports allows for efficient damage identification on structural components using the drone. These reports can serve as the basis to help detect different types of damage (e.g., cracks and spalling) on the bridge prior to drone operation.

Stage 3 is to perform the drone preflight setup. It is important to ensure the drone is in good condition and all safety precautions have been taken before take-off at the bridge site. Both the FAA and drone manufacturers recommend a preflight check for the first flight of the day to ensure satisfactory flying performance. This check list includes, but is not limited to, propeller and rotor inspection, full charging of all instruments (e.g., remote controller, storage batteries, and monitor), remote controller adjustments, gimbal inspection, and firmware updates. During the bridge inspection, the drone may lose GPS signal, especially while flying under the deck; thus, it is necessary to calibrate the compass to avoid an unanticipated signal failure and possible flyaway.

Stage 4 is to complete the drone-enabled bridge inspection. After the preflight planning and safety precautions have been completed, the bridge inspection with the drone can be conducted. For this stage, flight safety and planning should be considered according to FAA and DOT regulations. For example, weather conditions with wind speeds of 15 mi/h or higher should be considered unsatisfactory for the use of the drone in bridge inspections because these conditions can adversely affect the flight safety and drone accessibility to specific bridge elements. To appropriately inspect the bridge, it is recommended that its overall views be captured first and then detailed views of side sections of critical components, determined based on review of the plans and inspection reports, be taken using the drone. After imagery data for the sections are collected, inspection of the underside of decking and all sides of bents can be performed to obtain relevant, detailed images. Some limitations from DOT (e.g., restricted flight over traffic and required use of propeller guards) could make data gathering difficult because particular sections (e.g., sections located directly over roadways) cannot be approached closely. The pilot-in-command (PIC) should be continuously assisted by an observer as recommended by the FAA. The observer can either assist the PIC when flying close to structural components or observe the drone camera; thus, the PIC avoids distractions while inspecting the bridge using the drone.

Stage 5 is to perform an image quality assessment. After sufficient imagery data are gathered, identification of high-quality images is achieved by performing image quality assessment. The high-quality images are analyzed and evaluated to localize damage in certain bridge components. This assessment procedure in conjunction with various image quality parameters (i.e., entropy and sharpness) facilitates the selection of high-quality images because it provides an estimate of image quality. High-quality images are identified by analyzing the variation of two parameters, entropy and sharpness. There are two ways in which an image can be selected as high quality: (1) a significant increase of sharpness with no significant change in entropy or (2) a significant increase of both parameters caused by sufficient illumination for the image. After high-quality images are identified, damage can be quantified more efficiently with a reduced number of images. Other criteria such as blurriness can be used to determine if the images are low quality. Blurriness can be caused by moving objects near a structural component, such as trees moving because of strong wind or traffic crossing the bridge, while data are being gathered.

Stage 6 is to complete the damage quantification. To complete the bridge inspection, collected imagery data must be analyzed to determine the level of damage on each component for the bridge. Commercially available image analysis software coupled with mathematical algorithms (e.g., edge detection) can be implemented to provide measurement capabilities to identify and quantify damage. Additionally, 3D photogrammetric computer software (e.g., PhotoScan) can be used to detail different types of damage from various angles as a more efficient alternative to conventional 2D images. To efficiently measure each type of damage, image analysis software such as ImageJ could be used. For example, concrete crack lengths and thicknesses can be determined using ImageJ. The scale assignment function available in the software can be used to provide a known distance between edges of cracks on the image (e.g., 10 pixels equal to 1 inch) and the line tool can quantify overall length and thicknesses. ImageJ software also allows for measuring areas inside bounded crack lines and angles between two reference lines, which provides the ability to quantify corrosion or defective bolts.

9 Application of Protocol to Keystone Interchange Bridges

The following section presents information regarding the application of the inspection protocol to the in-service Keystone Interchange Bridges owned by SDDOT. Results related to the bridges are subsequently presented, subdivided by stages.

9.1 Stage 1

A visual observation of the bridges and their surroundings was conducted to identify potential threats to the flight safety and operation. Because of the location and configuration complexity of the bridges, two critical inspection areas for drone aviation near each bridge were initially identified (Fig. 33a). Prior to the inspection using a drone, challenging access areas to each of the bridges were also identified by performing a visual observation around the bridge sites. The critical inspection areas were defined as locations where the drone would not be able to be efficiently operated, such as between bridges and other objects (e.g., trees). Overall, the bridges were not in a high risk zone because there were not many trees or impediment elements (i.e., buildings or large structures) that may have unfavorably affected the flight safety and drone operation.

Additionally, specific restrictions imparted by SDDOT needed to be considered. Drone operations were not allowed over the decks and traffic, and liability insurance was required to cover any damage to the bridges in case of an accident. To meet these requirements for drone operation to inspect the bridges, liability insurance was purchased through Verifly Insurance Services, Inc. Also, traffic control was necessary to avoid any injury to the inspectors. Specifically, warning signs were placed 750 ft from the bridges, and cones were placed near inspection zones to warn approaching traffic as requested by SDDOT (Fig. 33b). Although the inspectors were located behind a barrier, some of the work was adjacent to the roadway, requiring channelizing devices and warning signs as detailed in Figure 33b. Specific FAA regulations (See Appendix C) did not apply for this bridge location because they are located more than five miles away from any adjacent airport. For example, if the target bridges were in the vicinity of any airport, authorization from the air traffic control tower must have been acquired to operate the drone. Other FAA regulations to be considered are the following:

- No restriction for Class G airspace (need air traffic control tower permission otherwise)
- Must keep the aircraft in sight (visual line-of-sight)
- Must fly under 400 ft
- Must fly during the day
- Must fly at or below 100 mi/h
- Must yield right of way to manned aircraft
- Must not fly over people
- Must not fly from a moving vehicle

9.2 Stage 2

For this stage, the bridge information review was performed. Construction plans for each bridge were provided by SDDOT for this project along with historical inspection reports to identify previous damage on both bridges. A brief description for each bridge is subsequently presented.

9.2.1 Timber Girder Bridge

- 170 ft long
- Glued-laminated timber
- Three-span, simply supported girders
- Two bents with four columns each
- Curved concrete deck

For ease of damage identification, each component of the bridge was numbered following the numbering system used in the SDDOT bridge plan (Fig. 34). Details for the component numbering on the plan and elevation views are shown in Figure 34a and b, respectively. Figure 34c shows an overall view of the bridge to show the components. Bents 1 and 4 correspond to abutment locations.

9.2.2 Keystone Wye Timber Arch Bridge

- 290 ft long
- Glued-laminated timber
- Main supporting arch
- Three-span continuous stringers near abutments
- Two sets of four-span continuous stringers over arch
- Three bents near abutments with three columns each
- Six spandrel timber column bents
- Straight concrete deck

The component numbering for this bridge was also based on the construction plans presented by SDDOT (Fig. 35). Figure 35a, b presents the layout of the bridge in plan and elevation views, respectively, with component numbering. Figure 35c shows the corresponding representative picture to visually establish the location of each component. Bents 1 and 15 correspond to the abutment locations.

Review of the construction plans coupled with the inspection reports was performed to determine critical sections across all structural components with and without existing damage to be inspected per bridge. For example, the inspectors were aware of the joints that were the most critical component because of damage caused by water leakage coming from the deck of each bridge. Based on this information, the joints were completely inspected by the drone. Other bridge components that had critical damage, such as underside of decks, girders, columns, and cross-frames, were inspected by the drone.

9.3 Stage 3

For the inspection of the bridge, as mentioned before, a DJI Phantom 4 (Fig. 36a) was selected as the most suitable drone based on the selection process previously presented. The specifications of the drone are documented in Appendix D. During the drone preflight setup, a thorough inspection was conducted on the drone. For example, rotors, propellers, batteries, computer, remote controller, gimbal, and software updates were checked to ensure good flight operation performance. There were no signs of damage or irregularities on the drone prior to the inspection of the bridges. The compass was successfully calibrated to ensure full GPS system support. To calibrate the compass, the drone needs to be rotated counter clockwise while being held horizontally. Then, this same process is performed once more vertically with the camera facing down as shown in Figure 36b. The drone setup was completed without any issues that could have a negative influence on the flight and inspection performance.

9.4 Stage 4

The drone-enabled bridge inspection was completed over the course of two days, February 16th and 17th, 2017. All precautionary actions were taken as detailed in Stages 1 through 3. The first inspection period on February 16th was divided into two sessions, morning and afternoon, because of battery capacity. Both sessions were conducted according to the preplanned scheme. Sample images taken by either the drone or digital camera during both sessions can be observed in Figure 37a-f. The inspection was conducted following the proposed approach of capturing overall section views (Fig. 37a, b) first and then proceeding to sections specific to each structural component per bridge. During this flight, the PIC was continuously assisted by an observer to ensure the flight was conducted safely. For both sessions, the drone was able to capture images of damage on each bridge (Fig. 37c, d). Figure 37c shows various types of damage of one of the girders in the timber girder bridge, whereas Figure 37d displays a damaged joint of the Keystone Wye bridge with corrosion and concrete spalling. From this inspection, it appears that there is a shear crack on the timber stringer in the Keystone Wye bridge. Figure 37e, f shows the drone aviation near structural components for the timber girder and Keystone Wye bridges, respectively.

During the second day of inspection, February 17th, the weather conditions were not as favorable as had been expected because of high wind speeds of 10 to 15 mi/h and wind gusts of 27 mi/h. Inspection was conducted during only one morning session. A limited amount of data were gathered using the drone during this inspection period. A different inspection approach was explored using video-based data acquisition to eliminate any unnecessary distractions from the picture-taking process while flying under such harsh weather conditions. Pictures containing sample damage were obtained from the videos (Fig. 38a, b). Figure 38a shows a damaged washer at the support of one of the glued-laminated (glulam) arches, while Figure 38b shows concrete cracks and high moisture resulting from water leakage at one of the abutments of the timber girder bridge. It has been proven that the video-based inspection was able to facilitate the acquisition of image information necessary for damage identification. Figure 38c, d shows the drone approaching components of the Keystone Wye arch bridge and timber girder bridges, respectively.

9.5 Stage 5

After the inspection and imagery data collection were completed, the image quality assessment was performed to select high-quality pictures required for damage quantification of each structural component. During the inspection of both bridges, a total of 133 images (656 MB) and 6 videos (2.21 GB) for the timber girder bridge and 110 images (542 MB) and 18 videos (11.4 GB) for the Keystone Wye bridge were obtained for this analysis. The images were analyzed by examining the relationship of entropy and sharpness, which was used to identify and discard low-quality images. The proposed image quality assessment process was applied to the two bridges, and the resulting findings, which were subdivided for each bridge, are subsequently presented.

9.5.1 Timber Girder Bridge

For an efficient image quality assessment, the 133 images were subdivided into two sets: a set composed of the first 65 images (image 1 through 65) and another set consisting of the next 68 images (image 66 through 133). Entropy and sharpness graphs for each set and corresponding sample low-quality pictures are presented in Figure 39a-d. Figure 39a shows entropy and sharpness graphs for the first set of 65 images. Several pictures were identified to be low quality because the sharpness decreased without a corresponding decrease of entropy. This was caused by poor illumination and overexposure. These images are numbers 41, 42, and 47 through 53. Image number 47 is presented in Figure 39b as an example of a low-quality image for the first set of images. Another entropy and sharpness graph for the second set of 68 images is presented in Figure 39c. From this set of images, image numbers 102 through 104, 115, 116, and 121 were classified as low-quality images because of a decrease in sharpness and a corresponding increase in entropy when comparing the overall trend of the plot. Image number 115 is given in Figure 39d as a sample of the low-quality images identified from the second set. Typically, these low-quality images occurred as a result of overexposure caused by illumination from the sun. A total of 15 images identified as low quality were eliminated; thus, the 118 high-quality images obtained from this process were used for damage identification in Stage 6.

9.5.2 Keystone Wye Timber Arch Bridge

To increase efficiency, the 110 images were subdivided into two different sets: a set containing the first 65 images (image 1 through 65) and a second set composed of the following 45 images (image 66 through 110). The plots containing entropy and sharpness curves for image sets and their correspondent low-quality sample pictures are presented in Figure 40a-d. The first set of 65 images is presented in Figure 40a. The images identified to have low quality are image numbers 12, 14 through 17, 40, 41, and 45. These images had a significant decrease of sharpness without a corresponding decrease of entropy, which was caused by overexposure. Image 14 is presented in Figure 40b to demonstrate a low-quality image for the first set of images. The second set of 45 images is illustrated in Figure 40c. From this set of images, image 77, 85 through 93, and 97 through 99 were identified to have low quality caused by overexposure from the sun's illumination. Image 99 is presented in Figure 40d as an example of a low-quality image for the second image set. A total of 21 images were identified to have low quality and were discarded. The remaining 89 high-quality images obtained during this process allowed for more efficient damage quantification in Stage 6.

9.6 Stage 6

After the high-quality images for each bridge were identified, detailed damage identification and quantification were performed to demonstrate the efficiency of the drone as a bridge inspection tool. Using the aforementioned computer software (i.e., PhotoScan and ImageJ), 3D virtual models of some bridge areas were generated and damage measurements on the high-quality images captured from the drone were performed to determine the damage level of bridge components. The damage levels were determined based on the "Caltrans Bridge Element Inspection Manual" (Marshall 2016) as was done in the preliminary inspections (see Section 7). Field measurements during the inspection of in-service bridges were not obtained because of inaccessibility issues to most damage. Visual images and descriptive information specific to damage for each component per bridge is subsequently reported.

9.6.1 Drone Image-Based Inspection Report for Timber Girder Bridge

Plan and elevation views for the timber girder bridge with damage identified using the drone are presented in Figure 41a, b, respectively.

9.6.1.1 Underside of Deck

- Bay 2 between Joints 1 and 2: white efflorescence
- Near Girder 4 at Joint 2: corroded exposed rebar, spalling, delamination, and efflorescence
- Along Joints 2 and 3: corrosion, spalling, delamination, and discoloration
- Near Girder 4 Parapet along entire deck: minor cracks and discoloration especially near railings
- Near Girder 1 Parapet along entire deck: minor cracks and spalling especially near railing
- Near Girders 1 and 4 at Joint 4: concrete cracking, spalling, exposed rebar, discoloration, and water damage
- Near Girders 1 and 4 at Joint 1: cracking and discoloration
- Near Girder 4 between Joints 1 and 2: water leakage

Overall, the deck had several water leakage areas causing moisture-related damage such as corrosion. Sample images of the damage are presented in Figure 42. Figure 42a corresponds to corrosion, spalling, and exposed rebar near Girder 4 at Joint 2, and Figure 42b shows efflorescence in Bay 2 between Joints 1 and 2. Additionally, the computer programs helped further quantify the damage. Using PhotoScan, a 3D virtual model of the damage near Girder 4 at Joint 2 was developed to better visualize it in 3D virtual space (Fig. 42c). Using ImageJ, the spalled and delaminated areas and the length of the exposed rebar at Joint 2 were measured (Fig. 42d); the results are summarized in Table 10. After quantifying each damage occurrence, the corresponding damage levels (or ratings) for reinforced concrete deck were determined based on the Caltrans bridge rating manual.

9.6.1.2 Abutments

- North Abutment near Girder 1: spalling and corroded exposed rebar
- North Abutment near Girder 4: spalling, efflorescence, rust stains, and water damage
- South Abutment near Girders 1 and 4: spalling, efflorescence, and moisture
- South Abutment on Bays 1 and 2: concrete spalling

The abutments were in good condition, despite some cracking and discoloration observed during the inspection. Figure 43a shows the damage on the south abutment near Girder 4 using the drone. Minor discoloration, spalling, and moisture caused by water coming from the deck at the north abutment near Girder 4 were also observed (Fig. 43b). The south abutment near Girder 1 was successfully re-created using PhotoScan to observe the damage from different angles (Fig. 43c). Using ImageJ, the spalled and discolored areas at the north abutment near Girder 4 (Fig. 43d) were measured; the results are tabulated in Table 11. After quantifying the damage for the abutments, the corresponding damage levels were determined based on the Caltrans bridge rating manual.

9.6.1.3 Girders

- Girders 3 and 4 at Joints 2 and 3: bottom surface on both girders has discoloration and stains caused by water leakage
- Girders 3 and 4 between Joints 2 and 3: stains at bottom of both girders
- Girder 4 between Joints 3 and 4: some moisture
- Girder 4 between Joints 1 and 2: some moisture

Overall, the girders were in good condition despite some moisture caused by water leakage coming from the deck. Some stains and discoloration were also apparent on some girders, possibly caused by calcium deposits and corrosion coming from the chemical reaction of the water with concrete and steel. Sample images of the damage identified on the girders are shown in Figure 44a, b. Figure 44a shows visible moisture corresponding to Girder 4 between Joints 1 and 2, and Figure 44b shows stains on Girder 3 at Joint 2 caused by corrosion of the steel connection bracket. PhotoScan effectively generated a 3D virtual representation of Girder 4 between Joints 3 and 4 (Fig. 44c). The approximate stain area on the bottom of Girder 3 (Fig. 44d) was measured using ImageJ; the quantified damage is listed in Table 12. Table 12 includes an appropriate damage level for the stained girder that was decided based on the timber girder matrix in the Caltrans bridge rating manual.

9.6.1.4 Diaphragms

The galvanized diaphragms inspected using the drone were in good condition. No major damage was found, excluding minor discoloration near certain joints caused by water leakage. Figure 45 shows diaphragms with discoloration at Joint 3. Because of the limited number of pictures of the diaphragm and its complicated configuration with other components, a 3D virtual model was not completed successfully. After identifying the minor discoloration on the diaphragms, the damage level was classified as good based on the steel protective coating–galvanization matrix in the Caltrans bridge rating manual (Table 13).

9.6.1.5 Columns

- Column 4 pedestal at Bents 2 and 3: minor spalling, cracking, and efflorescence
- Column 1 pedestal at Bent 3: minor spalling and exposed rebar
- Columns 2, 3, and 4 at Bent 2: minor cracks
- Column 4 at Bent 3: minor cracks and stains
- Column 4 at Bent 2: stains on top

The columns were generally in good condition except for minor damage. Figure 46 shows sample efflorescence on Column 4 Pedestal at Bent 2. The concrete pedestals are included as “concrete columns” based on the inspection report provided by SDDOT, and the concrete column matrix in the Caltrans bridge rating manual was used to determine the damage level, which was fair (Table 14). A 3D virtual model was not included because of insufficient number of relevant pictures for PhotoScan to re-create the column.

9.6.1.6 Railing

The steel railing inspected using the drone was found to be in fair condition. Some corrosion affected different areas of the railing causing the paint to fall off as shown in Figure 47. After identifying the damage, the Caltrans-manual-based damage level for bridge railing — metal was determined and is presented in Table 15. A 3D virtual model and an image analysis to measure rusting areas were not included because of insufficient imagery data for the railing.

9.6.2 Drone Image-Based Inspection Report for Keystone Wye Bridge

Plan and elevation views for the Keystone Wye bridge with damage found on each bridge component are presented in Figure 48a and b, respectively.

9.6.2.1 Underside of Deck

- Along the parapet near both Stringers 1 and 3: minor cracking
- Near Stringer 1 between Joints 2 and 3: stains and water leakage
- Near Stringer 1 at Joint 2: spalling, discoloration, and corrosion
- Along Joints 2 and 4: spalling and stains
- Near Stringers 1 and 3 at Joint 5: concrete cracking, exposed corroded rebar, efflorescence, and discoloration
- Near Stringer 1 at Joint 4: spalling and corroded exposed rebar
- Near Stringer 3 at Joint 2: spalling and stains
- Near Stringers 1 and 3 at Joint 1: spalling, cracking, and exposed corroded rebar
- Near Stringer 1 between Joints 3 and 4: minor moisture

The deck has been affected by moisture in several sections, especially along the joints. Sample images of the damage captured using the drone are displayed in Figure 49a, b. Figure 49a shows damage on the deck at Joint 5 near Stringer 1 where concrete cracking, exposed corroded rebar, stains, and moisture can be observed. Figure 49b presents concrete spalling and stains located at Joint 2, which was also successfully re-created in 3D virtual space using PhotoScan (Fig. 49c). Additionally, the approximate crack lengths and thicknesses and corroded areas on the deck at joint 5 near stringer 1 were measured using ImageJ as shown in Figure 49d and e, respectively; the results are summarized in Table 16. After quantifying different damage types, the corresponding damage levels according to the Caltrans bridge rating manual was determined.

9.6.2.2 Abutments

- North abutment on Bay 1: large transverse crack, water accumulation and leakage, spalling, and efflorescence
- North and south abutments: concrete spalling, cracks, and moisture
- Near Stringer 3 on south abutment: cracks under deck
- Near Stringer 1 on south abutment: cracks near bottom of deck

Several cracks were found on both abutments. For example, a transverse crack, spalling, water leakage, and efflorescence on Bay 1 at the north abutment can be seen in Figure 50a and water accumulation was noticeable on the north abutment as can be seen in Figure 50b. The damage on the north abutment (e.g., transverse crack and efflorescence) was re-created using PhotoScan (Fig. 50c) and is detailed for its quantification (Fig. 50d); the quantitative damages are listed in Table 17. Table 17 also includes the appropriate damage level for each damage occurrence, which was determined following recommendations from the Caltrans bridge rating manual.

9.6.2.3 Stringers

- Near supporting areas of each stringer at Joints 2 and 4: stains and decay
- Stringer 1 between Joints 3 and 4: noticeable stains
- Stringer 1 at Joint 2: salt deposits
- Stringer 1 at Joint 4: shear crack and discoloration

Stains near supporting areas of each stringer were caused by moisture resulting from water leakage from the deck, and corrosion of steel brackets was found at similar spots. One visible shear crack on Stringer 1 at Joint 4 was found as shown in Figure 51a. Figure 51b shows stains on Stringer 1 between Joints 3 and 4. A 3D virtual model of Joint 4 was generated using PhotoScan (Fig. 51c). The damage on Stringer 1 at Joint 4 was detailed for its quantification using ImageJ (Fig. 51d); the quantitative values for each damage occurrence are included in Table 18. Table 18 also includes the appropriate damage level per damage occurrence, which was determined following recommendations from the Caltrans bridge rating manual.

9.6.2.4 Diaphragms

The galvanized C-channel diaphragms in the bridge did not have any significant damage. Some minor stains near joints (e.g., Bay 2 at Joint 4) caused by water leakage were found (Fig. 52). After observing the damage, the corresponding damage level was decided in accordance with the Caltrans bridge rating manual (Table 19). A 3D virtual model of the diaphragms was not completed because of insufficient amount of imagery.

9.6.2.5 Columns

- Column 1 pedestal at Bent 4: corrosion and cracking
- Column 3 pedestal at Bent 4: cracking
- Column 1 pedestal at Bent 12: cracking, spalling, and corrosion
- Concrete pedestals of Columns 1 through 3 at Bents 13 and 14: minor cracking
- Column 1 at Bents 4 and 13: vertical cracks
- Column 2 at Bent 3: small scratch and discoloration

Overall, the columns were in good condition with minor stains and cracking. There was no significant damage on the columns, excluding the crack on the pedestal of Column 1 at Bent 12 (Fig. 53a). A successful 3D virtual representation of Column 4 at Bent 12 was generated using PhotoScan (Fig. 53b). As mentioned previously, the concrete pedestals were classified as “concrete columns”; thus, the rating matrix for concrete columns in the Caltrans bridge rating manual, with the damage (i.e., efflorescence and cracks) quantified using ImageJ, was used to determine the damage level (Table 20).

9.6.2.6 Arch

- Arch located below Girder 1 (Arch 1) between Bents 4 and 5: minor lam separation
- Arch 1 between Bents 5 and 6: small hole
- Arch located below Girder 3 (Arch 3) between Bents 4 and 5: minor cracks
- Arch 3 between Bents 12 and 13: minor cracks and discoloration

The arches were in good condition. Only minor damage was found, such as the small lam separation on Arch 1 between Bents 4 and 5 (Fig. 54). The lam separation was measured and rated based on the timber arch matrix in the Caltrans bridge rating manual; the result is summarized in Table 21. Because of insufficient images for the arch, a 3D virtual model was not re-created.

9.6.2.7 Railing

The steel railing inspected using the drone was found to be in good condition. Some corrosion affected different areas of the railing causing the paint to fall off as can be seen in Figure 55. Because of the limited amount of imagery, a 3D virtual model using PhotoScan was not generated. After identifying the damage, a rating based on the bridge railing — metal matrix in the Caltrans bridge rating manual was determined and is presented in Table 22.

10 Comparison with Conventional Inspection Procedures

After completing the inspection of the Keystone Interchange Bridges, a comparison with current inspection reports gained from SDDOT was performed to validate the results from the drone. The inspection report for the timber girder bridge is included in Appendix E, and the report for the Keystone Wye timber arch bridge is in Appendix F. The following sections summarize the comparative damage images and descriptions obtained from the drone and the conventional inspection techniques.

10.1 Timber Girder Bridge

To efficiently compare damage identified from the drone-enabled bridge inspection and from the conventional SDDOT inspection, a schematic of damage identified by the drone is presented in Figure 56, and Table 23 summarizes damage side-by-side for each component. Table 23 shows that the damage identified by the drone is numbered from 1 to 24, and the corresponding numbers are also included in the layout in Figure 56 to show the location and for completeness of results.

To explore visual details for the damage identified by SDDOT and using the drone, sample images and discussion are given for each component in the following subsections.

10.1.1 Underside of Deck

The drone was able to identify the damage underneath the deck that was identified in the SDDOT inspection report. Several areas of concrete spalling, delamination, and cracking were observed near joints and abutments. Figure 57 shows sample damage on the deck captured using the drone. A representative picture provided by SDDOT (Fig. 57a) is included to visually compare the quality of images between the SDDOT and the drone-enabled bridge inspection. It is apparent that the images are comparable and the damage is successfully identified. For example, water leakage under the deck between Joints 1 and 2 (Fig. 57c) and cracking, spalling, and exposed rebar (Fig. 57d) were identified using the drone.

10.1.2 Abutments

Using the drone, damage on the abutments (Fig. 58a) was identified that had been reported by SDDOT. Several occurrences of cracking, spalling, and discoloration were identified as shown in Figure 58b. Moisture coming from the deck at abutment locations was also found (Fig. 58c). No images related to the abutment damage were provided by SDDOT.

10.1.3 Girders

The damage detected on the girders using the drone coincided with the report provided by SDDOT. A picture provided by SDDOT (Fig. 59a) is included to visually compare with those taken by the drone. Several damaged areas caused by high moisture content were localized on the girders (Fig. 59b). For example, some moisture on Girder 4 between Joints 1 and 2 was identified as shown in Figure 59c. Girders damaged from high moisture levels were also recognized in other areas, especially near joints (Fig. 59d). SDDOT did not specify moisture-related damage of Girder 4 between Joints 1 and 2 and Girder 4 between Joints 3 and 4.

10.1.4 Diaphragms

On the diaphragms, the same issues that had been reported by SDDOT were observed using the drone. The diaphragms were in good condition other than minor discoloration near joints caused by water leakage (Fig. 60). Images related to damage on the diaphragms were not provided by SDDOT to be compared with the drone images.

10.1.5 Columns

The sample damage (Fig. 61a) on the columns identified by SDDOT and reported in their inspection report was confirmed by inspecting them using the drone. Stains caused by moisture were identified (Fig. 61b). There were no major differences in the damage reported by SDDOT and the damage identified by the drone. Visual comparisons of images from SDDOT and drone-enabled inspection were not made because relevant pictures were not available from SDDOT.

10.1.6 Railing

The railings were found to be rusted in different locations as shown in Figure 62. The damage found using the drone coincided with the damage reported by SDDOT. No comparison could be made to the drone images because images related to damage on the railing were not provided by SDDOT.

10.2 Keystone Wye Timber Arch Bridge

To compare damage identified from the drone-enabled bridge inspection and from the conventional SDDOT inspection in an efficient way, a schematic of damage identified by the drone is presented in Figure 63 and side-by-side damage for each component is summarized in Table 24. Table 24 numbers the damage identified by the drone from 1 to 29, and corresponding numbers are shown in Figure 63 to show the location of the damage and for completeness of results.

10.2.1 Underside of Deck

The damage from the SDDOT inspection report was successfully identified using the drone. Minor cracking along the parapet, especially near the railing, was recognized. Figure 64a, b shows images provided by SDDOT to compare with the corresponding images obtained using the drone. The images from the drone are of equal quality to those provided by SDDOT, which confirms the effectiveness of drone-enabled bridge inspection. For example, major damage near some joints such as spalling, cracking, and exposed rebar that was identified on the drawing (Fig. 64c) was observed as shown in Figure 64d, e. Some damage was not identified on sections over traffic (e.g, between Joints 2 and 4) because of SDDOT restrictions on flying over the deck with traffic.

10.2.2 Abutments

Most of the abutment damage reported by SDDOT was observed using the drone. The areas of damage identified using the drone are for the sections near Stringers 1 and 3 of the abutments because these sections were open for the drone to approach. Some critical damage such as a transverse concrete crack, spalling, moisture, and efflorescence at the north abutment on Bay 1 was captured (Fig. 65a). Figure 65b shows abutment cracking and spalling at the north abutment. The identified sample damage locations are included in the schematic of the partial bridge plan (Fig. 65c). Images associated with the abutment damage were not available from SDDOT for comparison purposes.

10.2.3 Stringers

The majority of damage identified from the SDDOT inspection report was also identified using the drone. A sample image related to shear cracking at the support of Stringer 1 at Joint 4 provided by SDDOT is presented in

Figure 66a, and its location and another damage location are included in the partial bridge plan shown in Figure 66b. Shear cracking was also identified using the drone (Fig. 66c). The glulam stringers had stains and salt deposits caused by water coming from the deck (Fig. 66d). The damage was located at Stringer 1 near Joints 3 through 4.

10.2.4 Diaphragms

The diaphragms inspected by SDDOT and the drone were found to be in good condition, other than minor stains near joints (e.g., Joints 2 and 4) caused by water leakage. A sample SDDOT image associated with minor stains on the connection of a diaphragm at Joint 4 on Bay 1 is presented in Figure 67a, and its location can be seen in Figure 67b. Figure 67c shows an image for this stain that was captured by the drone. In addition to this stain diagnosis, others on diaphragms across the bridge were identified using the drone at different joints.

10.2.5 Column

The drone was able to effectively identify the column damage reported by SDDOT. Several pedestals had cracking such as the pedestal at Bent 12 (Fig. 68a) and a relevant image taken by the drone can be seen in Figure 68b. Some minor cracks were also found on the timber columns, although those were not included in the SDDOT inspection report. No images related to the column damage were available from SDDOT.

10.2.6 Arch

The arches were found to be in good condition, other than some stains and discoloration as detailed by the SDDOT inspection report and the drone-enabled inspection report. For example, discoloration on the center arch on Bent 12 was reported, and a relevant image provided by SDDOT can be seen in Figure 69a. The discoloration location is included in the partial drawing (Fig. 69b). It was assumed that the discoloration on the arch was repaired because the discoloration on the same arch was not visible while inspecting it using the drone. However, a minor lam separation on Arch 1 between Bents 4 and 5 was observed using the drone (Fig. 69c). This separation damage was not included in the SDDOT inspection report.

10.2.7 Railing

The railings were found to have mild rusting as shown in Figure 70. The damage was found using the drone and was reported by SDDOT. The rusting that is located near Joint 4 along the railing (Fig. 70a) can be seen in Figure 70b. Relevant images were not available in the SDDOT inspection report.

11 Conclusions

This project was intended to evaluate drones as a supplemental inspection tool for bridges that present accessibility challenges for inspectors. To accomplish this goal, a comprehensive literature review and technical survey were conducted. This led to knowledge of the state-of-the-art, practice with drone-enabled inspection technologies, and awareness of critical considerations that should be accounted for while conducting such inspections. The literature review showed that there is need for a more efficient and cost-effective inspection methodology, and the survey results indicated that several state DOTs have interest in the drone technology for bridge inspection. With knowledge from the literature review and survey, the most suitable drone, DJI Phantom 4, was selected to conduct the preliminary and in-service bridge inspections. Preliminary inspections for several structures were conducted to gain knowledge of flying techniques using the drone and to help develop the six-stage bridge inspection protocol. After completion of the preliminary inspections, the techniques developed and the recommended inspection protocol incorporating image entropy–sharpness analysis were applied to two in-service highway bridges (a glulam timber girder bridge and the Keystone Wye glulam timber arch bridge) in South Dakota. Through the acquisition and examination of image and video data, the effectiveness of the drone platform was evaluated in terms of image quality, damage identification and quantification, and comparisons with results from traditional inspection reports on the bridges. Specifically, an element-to-element comparison of the results from the drone-enabled bridge inspection and those from the traditional inspections conducted by SDDOT were compared. Based on the results obtained, the following conclusions were made:

1. The proposed entropy–sharpness image quality assessment methodology helped identify high-quality images from the drone. These images were then used to efficiently identify damage.
2. The high-quality imagery data gathered using the drone coupled with image and photogrammetry analysis tools allowed for detailed damage identification and quantification. In detail, 3D virtual mapping of structural components created using commercially available photogrammetric software provided a comprehensive overview of damage for each components. Measurements of certain damage such as crack lengths and thicknesses were attained using the image analysis tool.
3. The capabilities of the drone to identify different types of damage were verified by conducting preliminary inspections. Inspection of a reinforced masonry building demonstrated the ability of the drone to visualize damage under low illumination, and additional pedestrian bridge inspections showed the efficiency of the drone to identify damage such as buckling, corrosion, and cracking of structural members while the drone was exposed to actual environmental effects such as wind. Other relevant findings include the capability of the drone to perform

under-deck inspections without GPS signal failure and the fact that the high-resolution camera mounted on the drone captured detailed damage under the deck while the drone was tilted up at an angle of 35°.

4. From the in-service bridge inspections, it was revealed that different types of damage, including cracking, spalling, and corrosion, for each of the Keystone Interchange Bridges were efficiently identified using the drone. Furthermore, using the pixel-based image analysis, the specific damage such as corrosion area was quantified and the corresponding damage level classification was determined according to the damage rating information provided in the Caltrans DOT bridge inspection manual.
5. A side-by-side comparison of the drone-based inspection for the Keystone Interchange Bridges and the traditional inspection reports provided by SDDOT further demonstrated the ability of the drone to effectively identify damage on the bridges.

12 Limitations of the Drone-Enabled Inspection

Some limitations of drone-enabled inspections were identified throughout this project. These limitations were mainly caused by weather conditions. Based on the findings and conclusions drawn from this project, the following limitations are identified.

1. Strong wind gusts can cause the drone to be unstable and consequently make safe control of the drone difficult for the PIC.
2. Sunny days and snow on the ground cause camera overexposure, which results in damage being challenging to observe.
3. Hands-on inspection procedures such as nondestructive testing cannot be replicated using a drone.
4. Drones are not effective when inspecting enclosed sections such as between closely spaced bents because of maneuverability limitations caused by wind gusts.
5. DOT regulations limit some inspection areas such as decks and sections above traffic lanes.
6. FAA regulations limit the operation of drones in some instances, which must be considered when selecting a structure.

13 Recommendations

Based upon the findings and conclusions obtained from the project, the following recommendations are made:

1. The proposed drone-enabled protocol was able to identify particular damage in the considered timber bridges more efficiently than conventional inspection methods. However, the protocol was only validated by performing the field inspection of the timber bridges. It is recommended that the protocol be applied to different bridge types to better validate the protocol’s effectiveness as an inspection tool and applicability in other bridge types.
2. The image quality assessment method incorporating two indicators (entropy and sharpness) was proposed to identify high-quality imagery from the drone during the preliminary and full-scale inspections. However, other image quality parameters may be better indicators to determine high-quality images. It is recommended that other parameters be further investigated to more efficiently select high-quality images.
3. The photogrammetry and image analysis tools implemented for the selected bridges allowed for efficient damage identification and quantification of their components. However, further exploration of advanced damage quantification methods is required to more precisely measure the amount of damage to the timber bridges.
4. No research has been performed on the finite element (FE) analysis and field monitoring of the timber bridges reflecting actual damage levels of particular structural components identified using a drone. To estimate actual load-carrying capacity and remaining structural capacity of the bridges, however, integrated FE analysis and field monitoring with drone technology is needed. It is suggested that a holistic framework integrating FE analysis, field monitoring, and drone technology be developed to predict bridge behavior and remaining bridge life considering the effect of damage states related to structural degradation and load-carrying capacity.
5. To improve current bridge inspection and maintenance practices, bridge inspectors and managers need to not only localize visual damage of a bridge but also better understand its long-term behavior resulting from aging and deterioration associated with dynamic vehicle loading. It is recommended that further studies be performed on drone-based bridge inspection in conjunction with 3D DIC systems that have the capabilities of measuring displacement and configuration profiles.
6. For automatic bridge inspection and efficient bridge maintenance decision making, it is recommended that radio-frequency identification technology be integrated with drone-based bridge inspection. This would enable automatic damage tracking and identification through readers, tags, and middleware.

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Table 1—Summary of responses for Question 1 of survey

	Questions		
Organization	Has your state or is your state planning to use any drone for bridge inspection?	Specify your drone type	Specify attachments
Alaska DOT[a]	No	—	—
Alaska USDA Forest Service	Yes, have used	Purpose-built hexacopter (based on DJI S800 airframe)	Gyro-stabilized SONY Nex7 and GoPro unit
Arizona DOT	No	—	—
Arkansas DOT	No	—	—
Colorado DOT	No	—	—
Delaware DOT	No	—	—
Florida DOT	Yes, planning to use	Not specified	—
Idaho DOT	Yes, planning to use	Coaxial Octocopter	—
Illinois DOT	No	—	—
Iowa DOT	Yes, planning to use	Aibotix	—
Kentucky DOT	Yes, planning to use	Rotor UAV[b]	GoPro camera
Missouri DOT	No	—	—
Nevada DOT	No	—	—
New York DOT	Yes, planning to use	Not specified	—
South Dakota DOT	No	—	—
Wisconsin DOT	Yes, planning to use	Not specified	—
Wyoming DOT	No	—	—

[a]DOT, Department of Transportation.
[b]UAV, unmanned aerial vehicle.

Table 2—Summary of responses for Question 3 of survey

	Questions	
Organization	Necessary data	Inspection challenges
Alaska DOT[a]	—	—
Alaska USDA Forest Service	High-definition imagery along with a replicable inspection pattern–process	Weather (wind), payload limitations, battery life, safe stand-off distances and collision avoidance, lighting conditions for under-bridge viewing
Arizona DOT	—	—
Arkansas DOT	—	—
Colorado DOT	—	—
Delaware DOT	—	—
Florida DOT	Images are the most important. Data from video and thermal cameras may be important. Displacement sensors are probably only useful in rare instances.	—
Idaho DOT	—	Issues related to the platform, autonomous control of UAVs[b], postprocessing of acquired data
Illinois DOT	—	—
Iowa DOT	High-quality images are necessary.	Regulations have been the biggest challenge.
Kentucky DOT	Video data would be most necessary.	A challenge would be losing signal underneath a bridge.
Missouri DOT	—	—
Nevada DOT	—	—
New York DOT	—	—
South Dakota DOT	—	—
Wisconsin DOT	Data will be to quantify condition and change in condition.	FAA rules have been the biggest obstacle.
Wyoming DOT	—	—

[a]DOT, Department of Transportation.
[b]UAV, unmanned aerial vehicle.

Table 3—Summary of responses from Question 4 of survey

	Question
Organization	What are your main concerns about inspecting bridges using UAV[a]?
Alaska DOT[b]	The drone had difficulty flying closer than 3 ft to the bridge structure. Also, in many instances, the camera on the drone was not able to see known cracks that were photographed by the inspector at arm's length.
Alaska USDA Forest Service	Transport and set-up time of equipment for remote sites, ability to ascertain imagery in real-time, airframe stability with upward looking cameras, low-light conditions, and maintaining Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) signals throughout under-bridge inspection, among others
Arizona DOT	We have no experience with UAV on bridge inspection at this time.
Arkansas DOT	Operation over traffic creating a distraction
Colorado DOT	Interfacing with the traveling public. UAS can be distracting and there is a fear that a UAS could fail, fall, land in a lane of traffic. That would make it difficult for us to use moving forward.
Delaware DOT	FAA regulations–practicality
Florida DOT	Can we obtain the same information as a normal inspection event? FAA limitations on use may limit the use of UAV.
Idaho DOT	Federal Highway Administration (FHWA) inspection protocol is 1) visual, 2) physical, and 3) advanced. We see it as a potential tool for "visual inspection" to be used by inspectors in lieu of or in combination with Under Bridge Inspection Truck (UBIT) for targeted areas if it can be efficient and accurate.
Illinois DOT	FHWA stating that drones cannot be used for bridge inspection. The use of drones around traffic.
Iowa DOT	High-quality images are necessary. Regulations have been the biggest challenge.
Kentucky DOT	The UAV impacting or falling on persons or vehicles
Missouri DOT	Costs, liability
Nevada DOT	—
New York DOT	Capability of UAVs to produce data that are compatible in quality with what we collect now. Policy changes required to be able to use UAVs.
South Dakota DOT	I think thermal imaging has the potential to overcome the difficulties of finding deficiencies like concrete delamination that aren't visually obvious and are otherwise only found through contact by the inspector. The other major concern would be inspection over traffic. Bridges over water are great candidates at this time, but a large number of bridges are over the traveling public. The FAA regulations do not allow operation of UAVs over the traveling public and people who are not involved in UAVs, and that causes a major challenge in determining drone inspection bridge candidates.
Wisconsin DOT	Understanding how to best leverage. Also what FHWA will accept for NBIS inspections.
Wyoming DOT	Cost, FAA requirements, and amount of data needing review and archiving.

[a]UAV, unmanned aerial vehicle.
[b]DOT, Department of Transportation.

Table 4—Summary of responses from Question 5 of survey

Organization	Question: Does your state have either past or ongoing research projects on UAV[a] inspection techniques? If yes, please detail the project (e.g., website, research report, etc.).
Alaska DOT[b]	In the Summer of 2015 after AKDOT&PF inspectors conducted a Fracture Critical Inspection on the Gerstle River Bridge #520 in conformance with the National Bridge Inspection Standards (NBIS), a supplementary examination of the bridge was conducted in coordination with our Research Division and the University of Alaska – Fairbanks by a UAF drone to demonstrate the capabilities and limitations of this equipment.
Alaska USDA Forest Service	Placer River Trail Bridge sUAS Inspection (demonstration project) 2015 performed in collaboration with University of Alaska-Fairbanks and George Mason University.
Arizona DOT	—
Arkansas DOT	—
Colorado DOT	Recently submitted a statement of work for UAV use across multiple areas of the organization (bridge inspections were omitted). The hope is that we will go out to request for proposal in the near future.
Delaware DOT	—
Florida DOT	We completed a proof of concept study with the Florida Institute of Technology. We have an on-going project in early stages with the University of Florida. This project will compare sUAV inspections with normal inspections on bridges and high mast light poles. Cost comparisons will also be performed.
Idaho DOT	Ongoing with Utah State. One test we are completing is to see if the drone can efficiently fly to a known defect (fatigue crack in a steel bridge) and then compare to see if data collection of the crack by the drone is consistent with what an inspector may have found completing visual inspection up close in a basket. Then we will compare to see if the drone was more efficient than mobilizing a UBIT.
Illinois DOT	—
Iowa DOT	Ongoing research to evaluate use. No reports available at this time.
Kentucky DOT	Yes, a research project is on-going to determine the best methods and practices for UAVs.
Missouri DOT	—
Nevada DOT	We are currently in procurement for a research project involving UAV.
New York DOT	—
South Dakota DOT	Current SDSU project which this survey is part of.
Wisconsin DOT	Yes, just starting.
Wyoming DOT	—

[a]UAV, unmanned aerial vehicle.
[b]DOT, Department of Transportation.

Table 5—Summary of responses from Question 6 of survey

	Question
Organization	What is the research plan for UAV[a] techniques to inspect bridges in the future?
Alaska DOT[b]	In the Summer of 2015 after AKDOT&PF inspectors conducted a Fracture Critical Inspection on the Gerstle River Bridge #520 in conformance with the National Bridge Inspection Standards (NBIS), a supplementary examination of the bridge was conducted in coordination with our Research Division and the University of Alaska – Fairbanks by a UAF drone to demonstrate the capabilities and limitations of this equipment.
Alaska USDA Forest Service	Presently working through development of agency guidance on future use of UAV as a tool for bridge and other infrastructure inspection.
Arizona DOT	—
Arkansas DOT	—
Colorado DOT	At this moment, we are only discussing.
Delaware DOT	—
Florida DOT	After the current research project is finished, we will determine how we want to use them and proceed.
Idaho DOT	Ongoing with Utah State. One test we are completing is to see if the drone can efficiently fly to a known defect (fatigue crack in a steel bridge) and then compare to see if data collection of the crack by the drone is consistent with what an inspector may have found completing visual inspection up close in a basket. Then we will compare to see if the drone was more efficient than mobilizing a UBIT.
Illinois DOT	—
Iowa DOT	Ongoing with Utah State.
Kentucky DOT	Use of an UAV on an as-needed basis or for an emergency to get a quick look at something on the bridge. Have in-house staff qualified to operate UAV and purchased system for use by in-house staff.
Missouri DOT	—
Nevada DOT	Develop software, acquire a drone, test it with 2 to 3 bridge inspections.
New York DOT	—
South Dakota DOT	Current SDSU project which this survey is part of.
Wisconsin DOT	To align with FHWA requirements and quantify cost savings and safety improvements. Also identify what can and cannot be accomplished with UAS.
Wyoming DOT	—

[a]UAV, unmanned aerial vehicle.
[b]DOT, Department of Transportation.

Table 6—Comparison of identified drone specifications

Drone	Price (US$)	Approximate fly time (min)	Upward camera view	Camera resolution with low illumination	Video resolution	Payload capacity (g)	Another source of light	Remote range (ft)	Satisfactory rating[a]
(a) DJI Inspire 1 (Da-Jiang Innovations, Shenzhen, China)	2,000	18	94-degree vertical range	Optional flashlight attachment will improve quality	4k/1080p	1,700	Drone has red LED lights	6,562	3
(b) Voyager 3 (Walker Technology Co.)	2,000	25	Facing upward at an angle	Optional flashlight attachment will improve quality	1080p	320	Drone has red and blue LED lights	3,281	2
(c) DJI Matrice 100	2,800 to 3,300 + 750 for camera	40	Need to buy camera	Optional flashlight attachment will improve quality	1080p	1,000	Drone has green LED lights	16,404	4
(d) DJI Phantom 3 Pro	1,200 + 499 for GoPro Camera	23	94-degree vertical range[b]	Optional flashlight attachment will improve quality	4k/1080p	462	Drone has red and yellow LED lights	16,404	4
(e) DJI Phantom 4	1,800 + 499 for GoPro Camera	28	94-degree vertical range[b]	Optional flashlight attachment will improve quality	4k/1080p	462	Drone has red and yellow LED lights	16,404	4
(f) Yuneec Typhoon H (Yuneec International Co., Ltd., Jinxi, Kunshan, China)	1,600	25	Facing upward at an angle	Optional flashlight attachment will improve quality	4k/1080p	600	Drone has green, red, and blue LED lights	3,281	3
(g) DJI S900 airframe	3,000 + 750 to 1,300 for camera	20	Optional attachment	Optional flashlight attachment will improve quality	4k/1080p	4,300	No LED lights	3,281	4
(h) Yuneec Typhoon 4K	1,100	25	115-degree vertical range	Optional flashlight attachment will improve quality	1080p	600	Drone has red and yellow LED lights	2,625	3
(i) Blade Chroma (Blade, Horizon Hobby, Champaign, Illinois, USA)	700	30	Facing upward at an angle	Optional flashlight attachment will improve quality	4k/1080p	200	Drone has green, red, and blue LED lights	1,312	2
(j) Autel Robotics X-Star Premium (Autel Robotics, Bothell, Washington, USA)	900	25	108-degree vertical range	Optional flashlight attachment will improve quality	4k/1080p	180	No LED lights	6,562	2

Table 6—Comparison of identified drone specifications—con.

Drone	Price (US$)	Approximate fly time (min)	Upward camera view	Camera resolution with low illumination	Video resolution	Payload capacity (g)	Another source of light	Remote range (ft)	Satisfactory rating[a]
(k) SenseFly eBee (SenseFly, Lausanne, Switzerland)	25,000	50	No	Optional flashlight attachment will improve quality	1080p	NA	No LED lights	9,843	1
(l) SenseFly albris	45,000	22	Yes	Flashlight included	4k/1080p	NA	Drone has green, red, and blue LED lights	6,562	5
(m) Topcon Sirius Pro (Topcon, Tokyo, Japan)	53,000	55	No	Optional flashlight attachment will improve quality	1080p	NA	No LED lights	9,843	1

[a]Rated 1 to 5 with 5 being the most satisfactory.
[b]Attachments: GoPro camera to look straight up, US$499, total weight approximately 200 g including mount. GoPro camera mount to attach to drone. (Included with camera or additional mount can be bought for US$29.99.)

Table 7—Sample measurements for cracked slab in masonry structure using ImageJ

	Crack length (ft)		
	Pixel-based measurement	Field measurement	FEMA[a] damage level classification
Crack 1	6.81	6.91	Affected
Crack 2	10.4	10.2	
Crack 3	3.11	3.19	
Crack 4	4.43	4.4	

[a]FEMA, Federal Emergency Management Agency.

Table 8—Sample damage measurements of Dakota Nature Park pedestrian bridge

Damage	Pixel-based measurement	Field measurement	Caltrans[a] damage level classification
Buckling deflection	0.62 in.	0.59 in.	No rating available
Corrosion	125.2 in^2	—[b]	Fair

[a]Caltrans, California Department of Transportation.
[b]Measurement not obtained.

Table 9—Sample damage measurements for Sexauer Park pedestrian bridge

Identified damage	Pixel-based measurement	Field measurement	Caltrans[a] damage level classification[b]
Bent bolt	15.3°	15.1°	—
Timber hole diameter	2.9 in.	3 in.	—
Crack length on abutment	5.2 in.	5 in.	—

[a]Caltrans, California Department of Transportation.
[b]Damage ratings were not available.

Table 10—Damage quantification for deck near Girder 4 at Joint 2 of Keystone Interchange timber girder bridge

Identified damage	Pixel-based measurement and observation	Caltrans[a] damage level classification
Length of exposed rebar 1	2.1 in.	Poor
Length of exposed rebar 2	1.1 in.	Poor
Length of exposed rebar 3	Unmeasurable	Fair
Spalled and delaminated (Area 1)	282.9 in^2 (approximately 11 in. in diameter)	Poor
Efflorescence (Area 2)	White surface with some rust stains	Fair

[a]Caltrans, California Department of Transportation.

Table 11—Damage quantification for north abutment near Girder 4 of Keystone Interchange timber girder bridge

Identified damage	Pixel-based measurement	Caltrans[a] damage level classification
Spalling area	77.4 in^2 (approximately 7 in. in diameter)	Poor
Efflorescence–rust stains	Slight white surface with minor rust stains	Fair

[a]Caltrans, California Department of Transportation.

Table 12—Damage quantification for Girder 3 support at Joint 2 of Keystone Interchange timber girder bridge

Identified damage	Pixel-based measurement	Caltrans[a] damage level classification
Stain area	Approximately 20 in^2 (<10% of member section)	Fair

[a]Caltrans, California Department of Transportation.

Table 13—Damage quantification for Diaphragm at Joint 3 of Keystone Interchange timber girder bridge

Identified damage	Observation	Caltrans[a] damage level classification
Stain	No effect on steel protective coating	Good

[a]Caltrans, California Department of Transportation.

Table 14—Damage quantification for Column 4 pedestal at Bent 2 of Keystone Interchange timber girder bridge

Identified damage	Observation	Caltrans[a] damage level classification
Efflorescence	White surface without accumulation	Fair

[a]Caltrans, California Department of Transportation.

Table 15—Damage quantification for railing between Joints 3 and 4 near Girder 4 of Keystone Interchange timber girder bridge

Identified damage	Observation	Caltrans[a] damage level classification
Rusting	Paint has spalled away from the railing	Fair

[a]Caltrans, California Department of Transportation.

Table 16—Results from measurements obtained using ImageJ of Keystone Wye arch bridge

Identified damage	Pixel-based measurements and observation	Caltrans[a] damage level classification
Crack length 1	38.6 in.	—[b]
Crack length 2	34.9 in.	—
Crack length 3	12.2 in.	—
Crack thickness 1	0.083 in.	Poor
Crack thickness 1	0.065 in.	Poor
Exposed rebar corroded area 1	28.7 in^2	Fair
Exposed rebar corroded area 2	1.25 in^2	Fair
Exposed rebar corroded area 3	11.6 in^2	Fair
Efflorescence	White surface without major accumulation	Fair

[a]Caltrans, California Department of Transportation.
[b]Damage rating not available.

Table 17—Damage quantification for north abutment of Keystone Wye arch bridge

Identified damage	Pixel-based measurements and observation	Caltrans[a] damage level classification
Transverse crack length	139.3 in.	—[b]
Crack thickness 1	0.56 in.	Poor
Crack thickness 2	0.82 in.	Poor
Crack thickness 3	0.69 in.	Poor
Spalling	Spalling along bay width	Poor
Efflorescence	White surface with accumulation and rust stains	Poor

[a]Caltrans, California Department of Transportation.
[b]Damage rating not available.

Table 18. Damage quantification for Stringer 1 at Joint 4 of Keystone Wye arch bridge

Identified damage	Pixel-based measurement	Caltrans[a] damage level classification
Crack (timber split)	12.3 in.	Fair
Stain area 1	15.3 in^2	Fair
Stain area 2	32.6 in^2	Fair
Stain area 3	10 in^2	Fair

[a]Caltrans, California Department of Transportation.

Table 19—Damage quantification for diaphragm on Bay 2 at Joint 4 of Keystone Wye arch bridge

Identified damage	Observation	Caltrans[a] damage level classification
Stains	No effect on steel protective coating	Good

[a]Caltrans, California Department of Transportation.

Table 20—Damage quantification for Column 4 at Bent 12 of Keystone Wye arch bridge

Identified damage	Pixel-based measurements and observation	Caltrans[a] damage level classification
Crack length	34 in.	—[b]
Crack thickness 1	0.10 in.	Poor
Crack thickness 2	0.14 in.	Poor
Efflorescence and rust stain	White surface without accumulation	Fair

[a]Caltrans, California Department of Transportation.
[b]Damage rating not available.

Table 21—Damage quantification for Arch 1 between Bents 4 and 5 of Keystone Wye arch bridge

Identified damage	Pixel-based measurement	Caltrans[a] damage level classification
Lam separation	19.6 in. (< member depth)	Fair

[a]Caltrans, California Department of Transportation.

Table 22—Damage quantification for railing near Stringer 1 at Joint 4 of Keystone Wye arch bridge

Identified damage	Observation	Caltrans[a] damage level classification
Rusting	Paint has spalled away from the railing	Fair

[a]Caltrans, California Department of Transportation.

Table 23—Comparison of South Dakota Department of Transportation (SDDOT) inspection report and drone-enabled inspection report for Keystone Interchange timber girder bridge

Structural component	SDDOT inspection report	Drone-enabled inspection report[a]	Comparison
Underside of deck	Near Stringer 1 at Joint 2: cracking delamination, and discoloration	(1) Bay 2 between Joints 1 and 2: white efflorescence	There were no major differences between the damage reported by SDDOT and the drone-enabled inspection report. Minor differences include water damage between spans captured using the drone and not reported by SDDOT.
	Bays 2 and 3 at Joint 2: joint cracking and minor scaling	(2) Near Girder 4 at Joint 2: corroded exposed rebar, spalling, delamination, and efflorescence	
	Bays 2 and 3 at Joint 3: joint scaling, cracking, and delamination	(3) Along Joints 2 and 3: corrosion, spalling, delamination, and discoloration	
	Near Girder 1 parapet along entire deck: cracking and discoloration	(4) Near Girder 4 parapet along entire deck: minor cracks and discoloration especially near railings	
	Near Girder 4 parapet along entire deck: scaling, cracking, delamination, and efflorescence	(5) Near Girder 1 parapet along entire deck: minor cracks and spalling especially near railings	
	Near Girder 4 at Joint 4: spalling and exposed rebar	(6) Near Girders 1 and 4 at Joint 4: concrete cracking, spalling, exposed rebar, discoloration, and water damage	
	Near Girder 4 at Joint 1: cracking, discoloration, and efflorescence	(7) Near Girders 1 and 4 at Joint 1: cracking and discoloration	
	Bay 2 at Joint 4: scaling, delamination, and efflorescence in Bay 2	(8) Near Girder 4 between Joints 1 and 2: water leakage	
Abutment	North abutment near Girder 1: spalled off and has exposed rebar	(9) North abutment near Girder 1: spalling and corroded exposed rebar	There are no major differences between the damage reported by SDDOT and the drone-enabled inspection report.
	North abutment near Girder 1: spalling	(10) North abutment near Girder 4: cracking, efflorescence, rust stains, and water damage	
	South abutment near Girder 4: efflorescence, scaling, and spalling	(11) South abutment near Girders 1 and 4: spalling, efflorescence, and moisture	
	South abutment on Bays 1 and 2: scaling and spalling	(12) South abutment on Bays 1 and 2: concrete spalling	
Girder	At supports at Joints 2 and 3: bottom of girders has discoloration and decay caused by trapped water and debris	(13) Girders 3 and 4 at Joints 2 and 3: bottom surface on both girders has discoloration and stains caused by water leakage	Moisture damage between bents was identified using the drone but not reported by SDDOT.
	Girder 3 at Joint 3: surface scratch	(14) Girders 3 and 4 between Joints 2 and 3: stains at bottom of both girders	
	N/A[b]	(15) Girder 4 between Joints 3 and 4: some moisture	
	N/A	(16) Girder 4 between Joints 1 and 2: some moisture	

Table 23—Comparison of South Dakota Department of Transportation (SDDOT) inspection report and drone-enabled inspection report for Keystone Interchange timber girder bridge—con.

Structural component	SDDOT inspection report	Drone-enabled inspection report[a]	Comparison
Diaphragm	Diaphragms have slight discoloration where water has been present	(17) No major issues were found apart from minor discoloration near joints caused by water leakage	No difference.
Column	Pedestals at Bent 2: horizontal crack along Bay 2 pedestal wall and crack along top of left side of Column 3 pedestal	(18) Column 4 pedestal at Bents 2 and 3: minor spalling, cracking, and efflorescence	No major differences other than minor cracks observed on the columns, which were not included in the SDDOT report.
	Pedestals at Bent 3: spalling with expose rebar on right side of pedestal and vertical cracks at top left side of Column 3 and left side of Column 4	(19) Column 1 pedestal at Bent 3: minor spalling and exposed rebar	
	Column 4 pedestal at Bent 2: horizontal crack	(20) Columns 2, 3, and 4 at Bent 2: minor cracks	
	Pedestal wall Bay 2 at Bent 2: longitudinal crack on top	(21) Column 4 at Bent 3: minor cracks and stains on top	
	N/A	(22) Column 4 at Bent 2: stains on top	
Railing	Paint is peeling because of heavy rust in locations throughout, especially on the railing near Girder 4.	(23) Heavy rusting on railing at different sections near Girder 4 (24) Mild rusting on railing near Girder 1	No difference.

[a]Numbering of drone-enabled inspection report corresponds to damage location in Figure 56.
[b]N/A, not applicable.

Table 24—Comparison of South Dakota Department of Transportation (SDDOT) inspection report and drone-enabled inspection report for Keystone Wye arch bridge

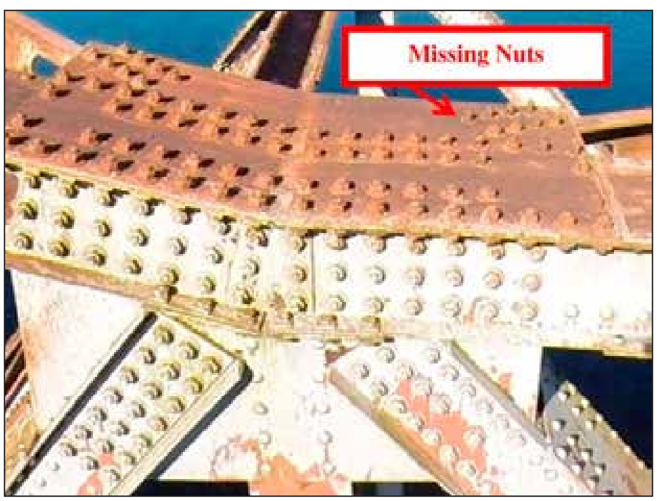
Structural component	SDDOT inspection report	Drone-enabled inspection report[a]	Comparison
Underside of deck	Parapets along deck: longitudinal, transverse, and random cracks	(1) Along the parapet near both Stringers 1 and 3: minor cracking	There were no major differences between the damage reported by SDDOT and the damage identified using the drone. The damage identified by SDDOT between Joints 2 and 4 were not fully observed because of restrictions of flying over deck.
	Near Stringer 1 between Joints 2 and 3: leakage and cracking	(2) Near Stringer 1 between Joints 2 and 3: stains and water leakage	
	Near Stringer 1 at Joint 2: spalling and cracking	(3) Near Stringer 1 at Joint 2: spalling: discoloration, and corrosion	
	Bays 1 and 2 at Joint 4: spalling	(4) Along Joints 2 and 4: spalling and stains	
	Joint 1: spalling	(5) Near Stringers 1 and 3 at Joint 5: concrete cracking, exposed corroded rebar, efflorescence, and discoloration	
	Joint 4: exposed rebar and spalling	(6) Near Stringer 1 at Joint 4: spalling and corroded exposed rebar	
	Near Stringer 3 at Joint 2: minor deterioration	(7) Near Stringer 3 at Joint 2: spalling and stains	
	Joint 5: spalling, cracking, and rust stains	(8) Near Stringers 1 and 3 at Joint 1: spalling, cracking, and exposed corroded rebar	
	Near Stringer 3 at Joint 3: cracking, scaling, and delamination	(9) Near Stringer 1 between Joints 3 and 4: minor moisture	
	Between Joints 3 and 4: transverse cracks with efflorescence	N/A[b]	
Abutment	North abutment on Bay 1: horizontal crack	(10) North abutment on Bay 1: large transverse crack, water accumulation and leakage, spalling, and efflorescence	Major abutment damage reported by SDDOT was identified.
	North and south abutments: spalling and horizontal and vertical cracks	(11) North and south abutments: concrete spalling, cracks, and moisture	
	Near Stringer 3 at south abutment: diagonal cracks near deck	(12) Near Stringer 3 on south abutment: cracks under deck	
	Near Stringer 1 at south abutment: horizontal crack near bottom of deck	(13) Near Stringer 1 on south abutment: cracks near bottom of deck	
	Bay 3 at south abutment: vertical cracks on sill	N/A	
	Near Stringer 3 at north abutment: cracks on sill	N/A	

Table 24—Comparison of South Dakota Department of Transportation (SDDOT) inspection report and drone-enabled inspection report for Keystone Wye arch bridge—con.

Structural component	SDDOT inspection report	Drone-enabled inspection report[a]	Comparison
Stringer	Joints 2 and 4: stains, discoloration, and decay at end of stringers due to water	(14) Near supporting areas of each stringer at Joints 2 and 4: stains and decay	Most damage was observed on stringers as detailed by SDDOT.
	Stringer 1 at Joint 2: salt deposits on top of stringer	(15) Stringer 1 between Joints 3 and 4: noticeable stains	
	Water damage on stringer at deck leakage locations	(16) Stringer 1 at Joint 2: salt deposits	
	Stringer 1 in Spans 2 and 3: horizontal cracking	(17) Stringer 1 at Joint 4: shear crack and discoloration	
	Stringer 1 in Span 5: horizontal crack	N/A	
	Stringer 3 in Span 13: horizontal crack	N/A	
	Stringer 1 in Span 10: partially sealed cracks	N/A	
Diaphragm	Diaphragms are in good condition	(18) Good condition with some minor stains at joints caused by water leakage	No difference other than minor stains observed with drone.
Column	Column 1 pedestal at Bent 4: 3 cracks on top	(19) Column 1 pedestal at Bent 4: corrosion and cracking	The damage reported by SDDOT was identified with additional damage such as minor vertical cracks and discoloration on columns.
	Column 3 pedestal at Bent 4: 2 cracks on top	(20) Column 3 pedestal at Bent 4: cracking	
	Column 1 pedestal at Bent 12: cracking, discoloration, and spalling	(21) Column 1 pedestal at Bent 12: cracking, spalling, and corrosion	
	Column pedestals at Bent 14: cracking	(22) Concrete pedestals of Columns 1 through 3 at Bents 13 and 14: minor cracking	
	Column pedestals at Bent 13: cracking	(23) Column 1 at Bents 4 and 13: vertical cracks	
	Column 3 pedestal at Bent 3: crack	(24) Column 2 at Bent 3: small scratch and discoloration	
	Column 1 and 3 pedestal at Bent 2: crack	N/A	
Arch	Arches are in good condition except some stains and deterioration	(25) Arch located below Girder 1 (Arch 1) between Bents 4 and 5: minor lam separation	Drone inspection detected additional damage such as minor cracks and lam separation not reported by SDDOT.
	N/A	(26) Arch 1 between Bents 5 and 6: small hole	
	N/A	(27) Arch located below Girder 3 (Arch 3) between Bents 4 and 5: minor cracks	
	N/A	(28) Arch 3 between Bents 11 and 12: minor cracks and discoloration	
Railing	Near Stringer 1 rail: top tube is scrapped and rusty for most of length	(29) Near Stringer 1 rail: Mild rusting at different locations	Heavy rusting was not seen because of heavy wind.
	Some heavy rust, particularly on rail posts	N/A	

[a]Numbering of drone-enabled inspection report corresponds to location in Figure 63.
[b]N/A, not applicable.

Figure 1. Sample inspection picture taken by the Aeyron Skyranger of a pin connection on a truss bridge (Zink and Lovelace 2015).



(a)

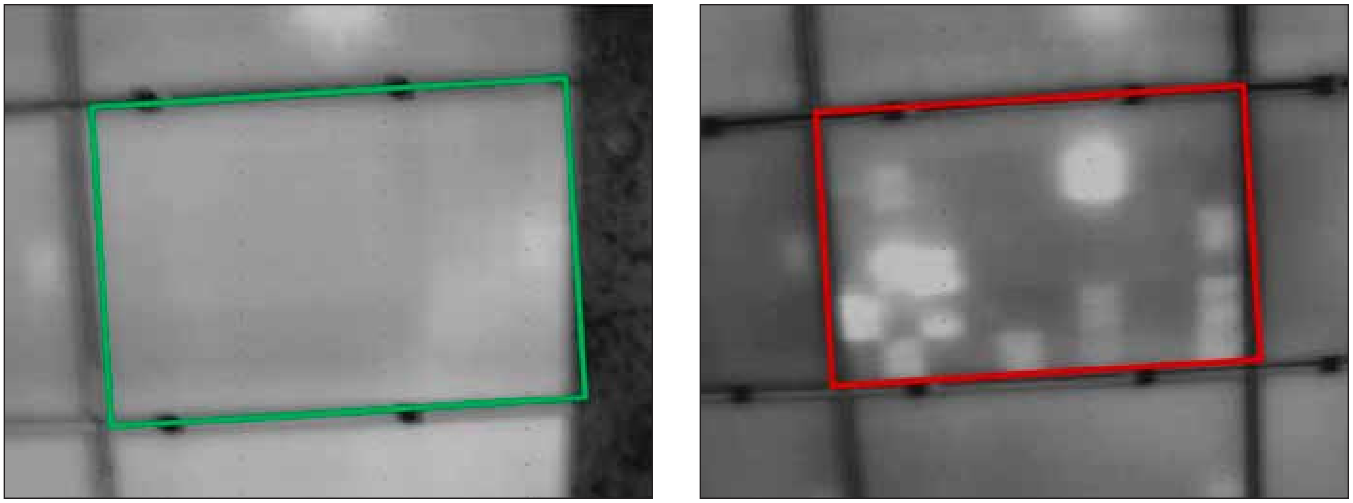
(b)

Figure 2. Sample inspection pictures: (a) steel connection with missing nuts; (b) stress crack on timber beam (Otero and others 2015).

(a)

(b)

Figure 3. Representative inspection data: (a) gap between end of kerf plate and sawn kerf in brace; (b) 3D dense point cloud representation of the selected bridge using Photoscan (Khaloo and others 2017).



(a) (b)

Figure 4. Solar panel inspection using thermal camera: (a) solar panel; (b) defective panel (Aghaei and others 2015).

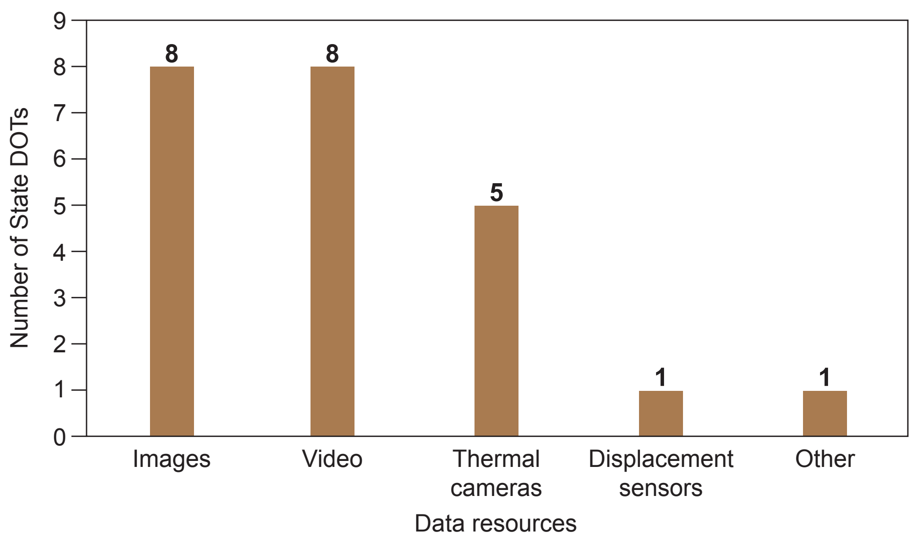


Figure 5. Responses to Question 2 of survey.

Figure 6. Investigated drones: (a) DJI Inspire 1; (b) Voyager 3; (c) DJI Matrice 100; (d) DJI Phantom 3 pro; (e) DJI Phantom 4; (f) Yuneec Typhoon H; (g) DJI S900 airframe; (h) Yuneec Typhoon 4K; (i) Blade Chroma; (j) Autel Robotics X-Star Premium; (k) SenseFly eBee; (l) SenseFly albris; (m) Topcon Sirius Pro.

Figure 7. Selected reinforced masonry structure.

Figure 8. Overview of selected pedestrian bridge at Dakota Nature Park in Brookings, South Dakota (photo captured with drone).

Figure 9. Overview of selected pedestrian bridge at Sexauer Park in Brookings, South Dakota (photo captured with drone).

Figure 10. Overview of the selected bridges (photo captured with drone).

(a)

(b)

(c)

Figure 11. Image quality comparison using entropy and sharpness relationship: (a) poor illumination caused by overexposure, entropy 6.43 and sharpness 4.68; (b) high-quality image, entropy 7.76 and sharpness 15.859; (c) blurry image, entropy 7.42 and sharpness 0.69.

(a)

(b)

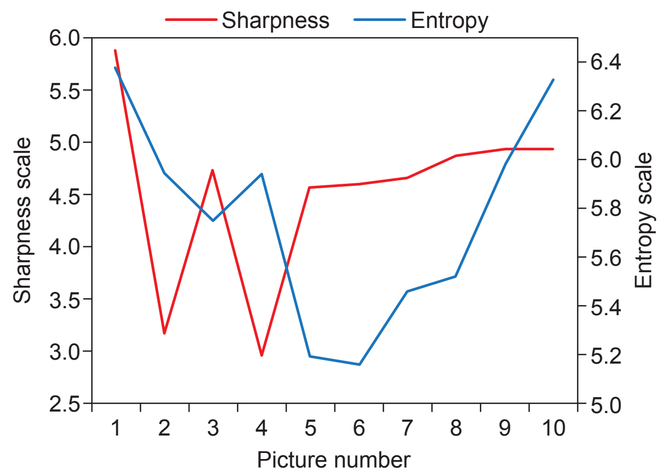
(c)

(d)

(e)

(f)

Figure 12. Sample images obtained during inspection of the building using the drone: (a) concrete wall; (b) concrete slab with cracks; (c) tall concrete column (because of underexposure, this image was lightened); (d) short concrete column (because of underexposure, this image was lightened); (e) Luis Duque flying the drone; (f) Junwon Seo flying the drone.



(a)

(b)

Figure 13. Image quality assessment for crack with sufficient illumination: (a) plot of entropy and sharpness for crack with sufficient illumination; (b) image number 4 with blur.

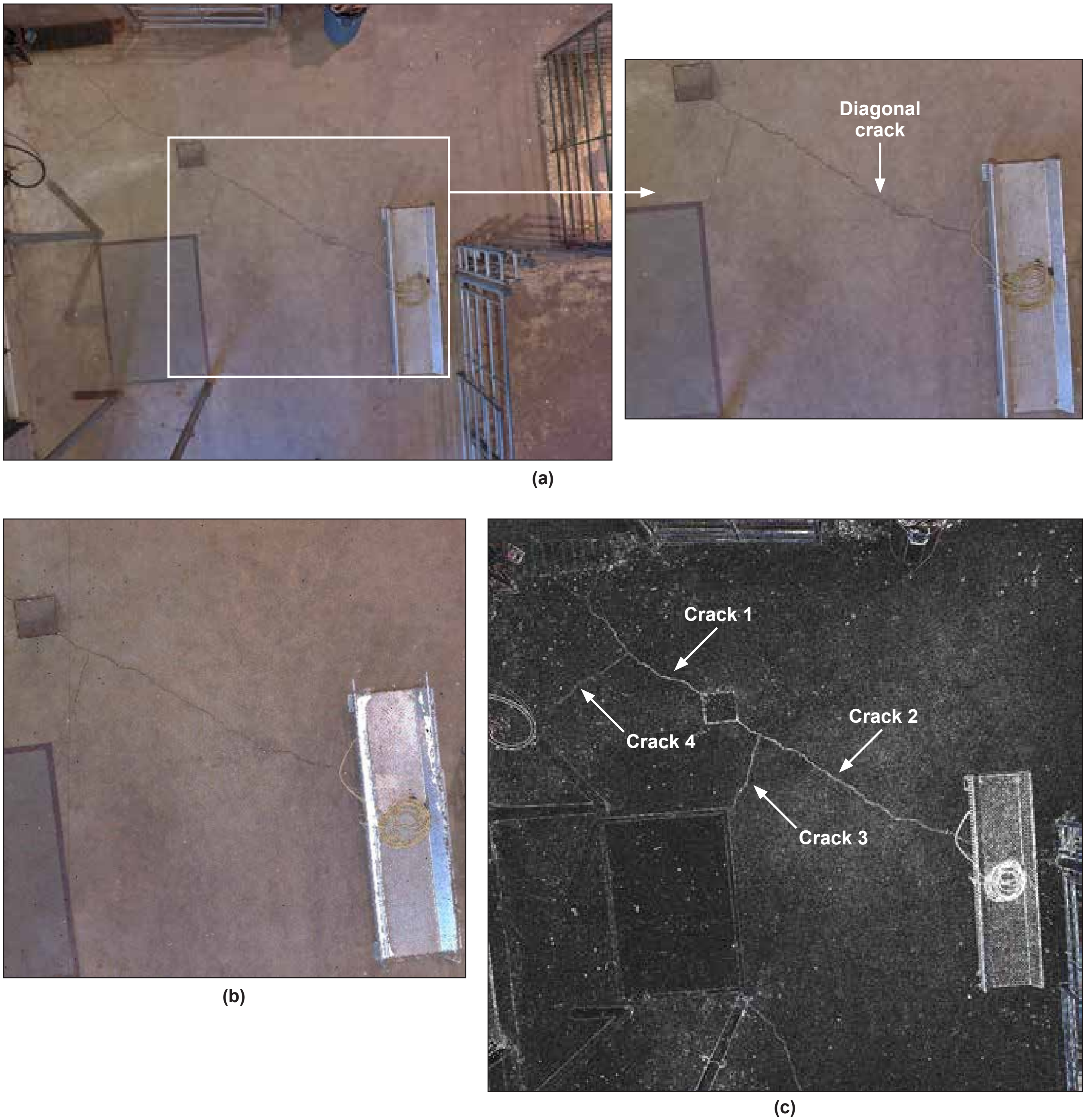
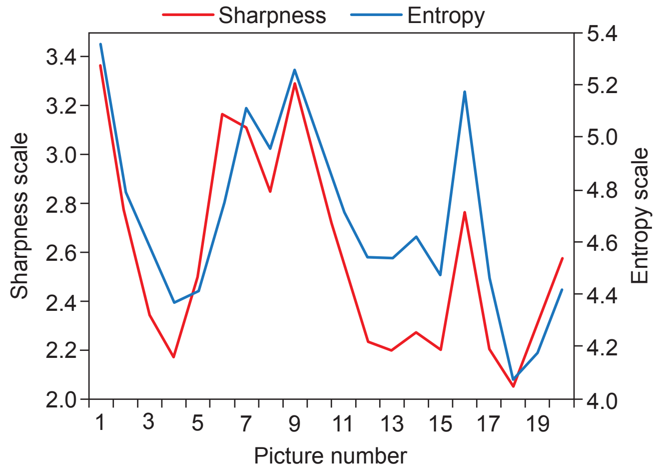


Figure 14. Crack on the slab: (a) images from drone; (b) 3D representation from PhotoScan; (c) processed image for edge detection from ImageJ to better visualize crack (because of underexposure, this image was lightened).



(a)

(b)

Figure 15. Image quality assessment for crack with insufficient illumination: (a) plot of entropy and sharpness for crack with insufficient illumination; (b) low-quality image number 18.

Figure 16. Crack on the slab using low illumination images: (a) image from drone; (b) 3D representation from PhotoScan.

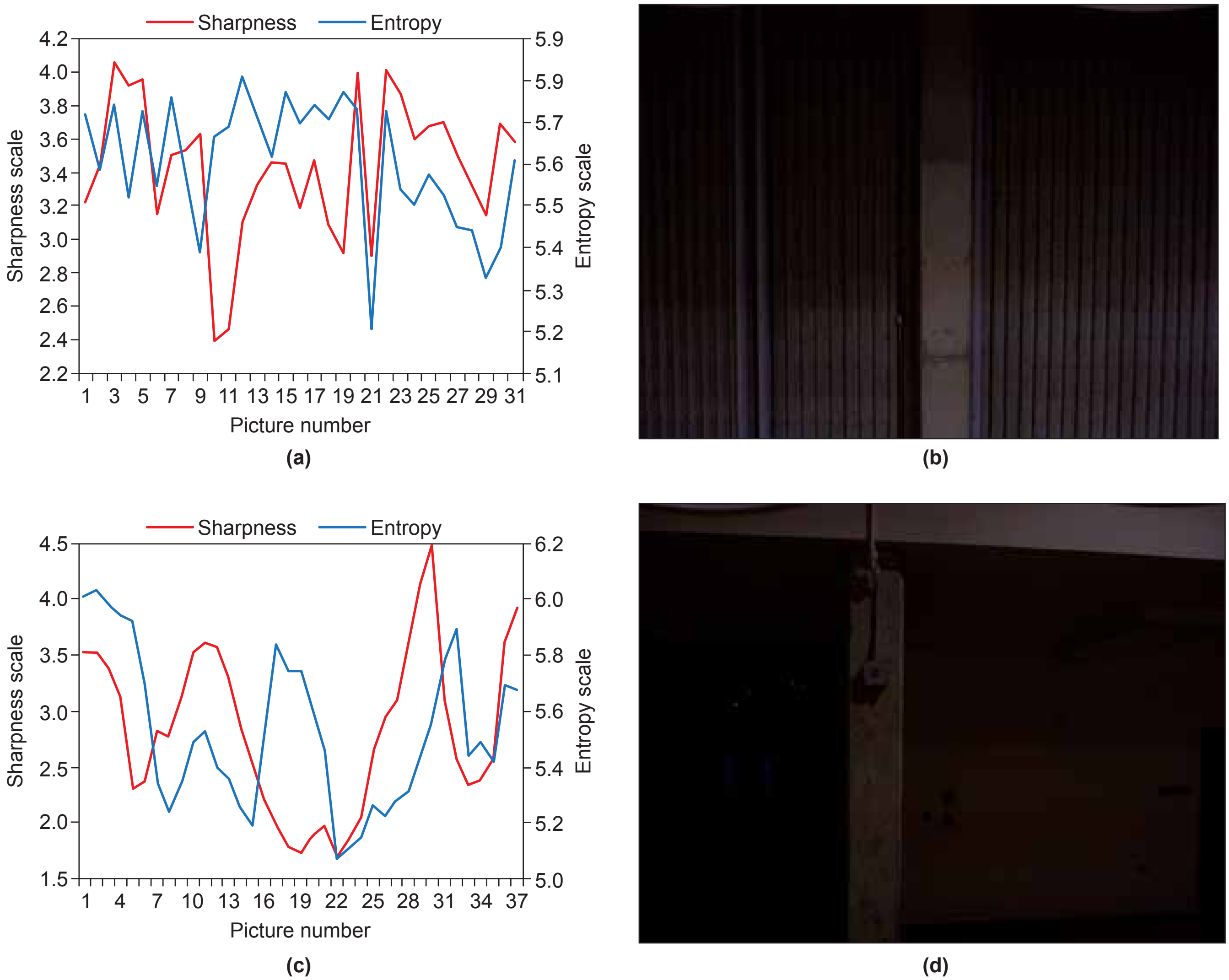


Figure 17. Image quality assessment of columns: (a) plot of entropy and sharpness for tall column; (b) representative low-quality image for tall column; (c) plot of entropy and sharpness for short column; (d) representative low-quality image for short column.

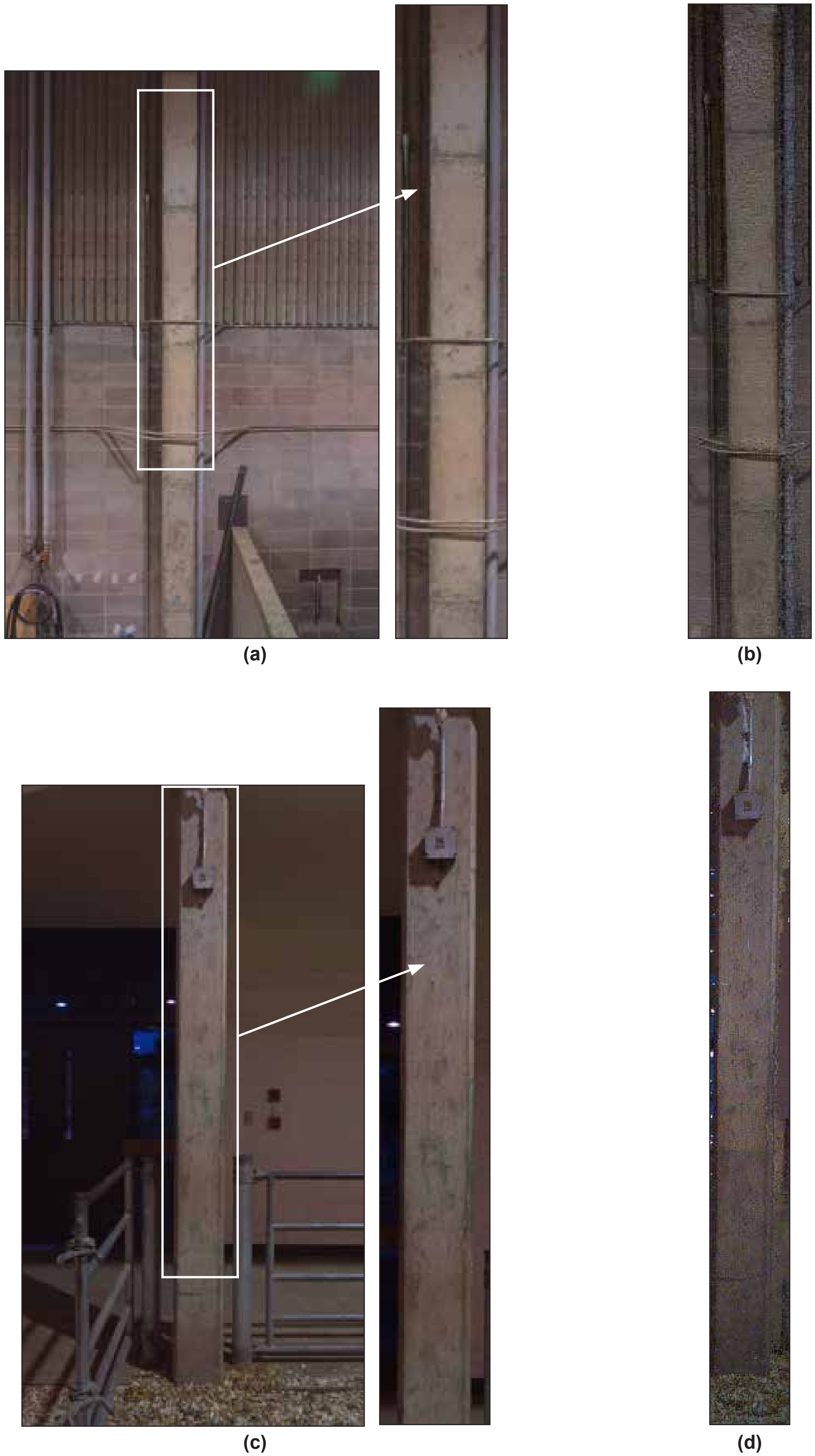
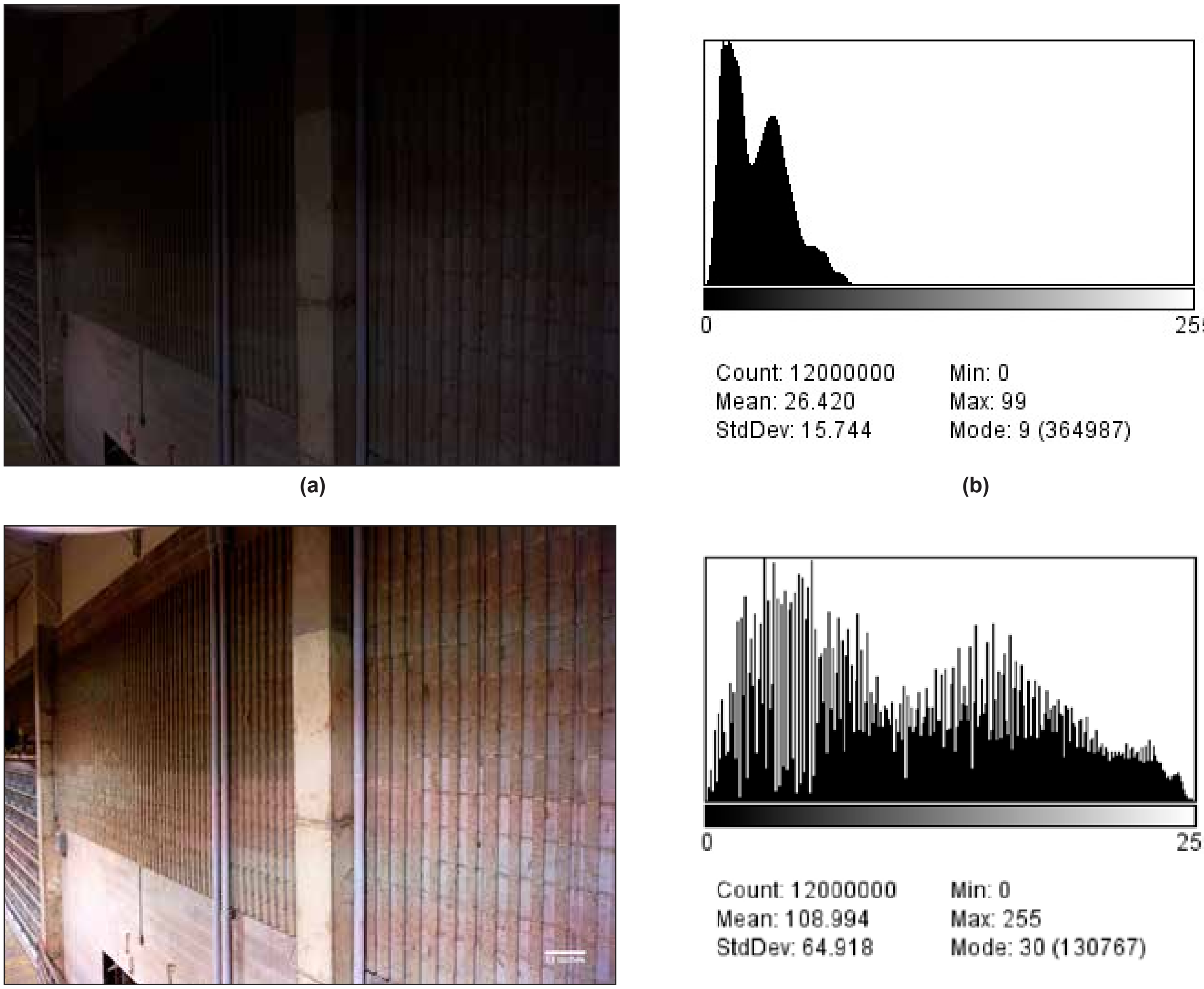


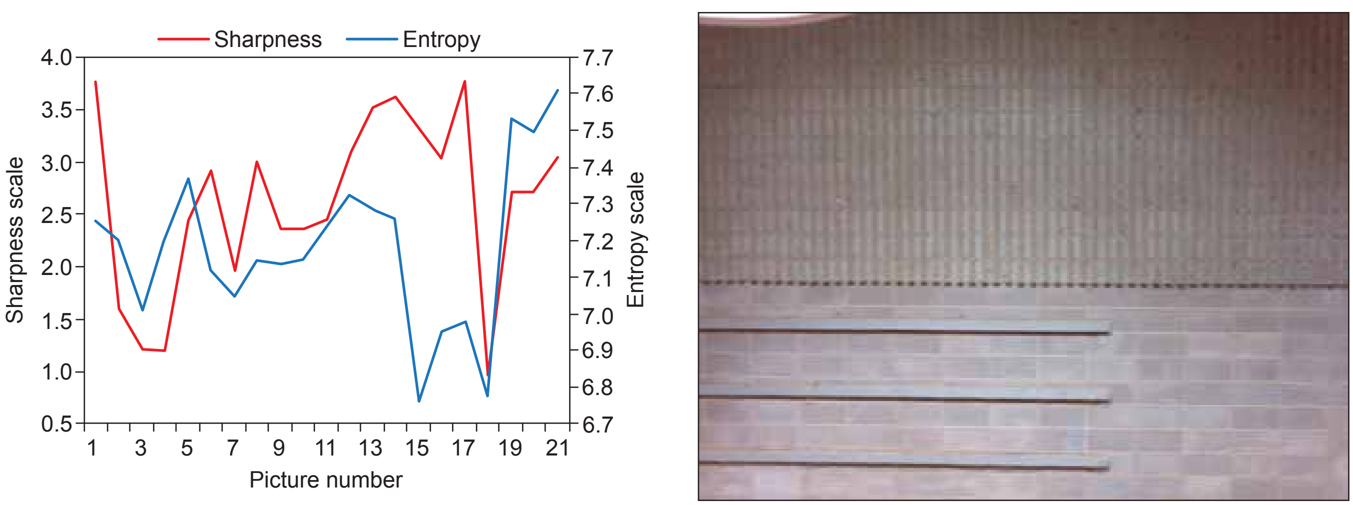
Figure 18. Columns recreated using PhotoScan: (a) tall column; (b) tall column 3D representation; (c) short column; (d) short column 3D representation (because of underexposure, these images were lightened).



(a) (b)

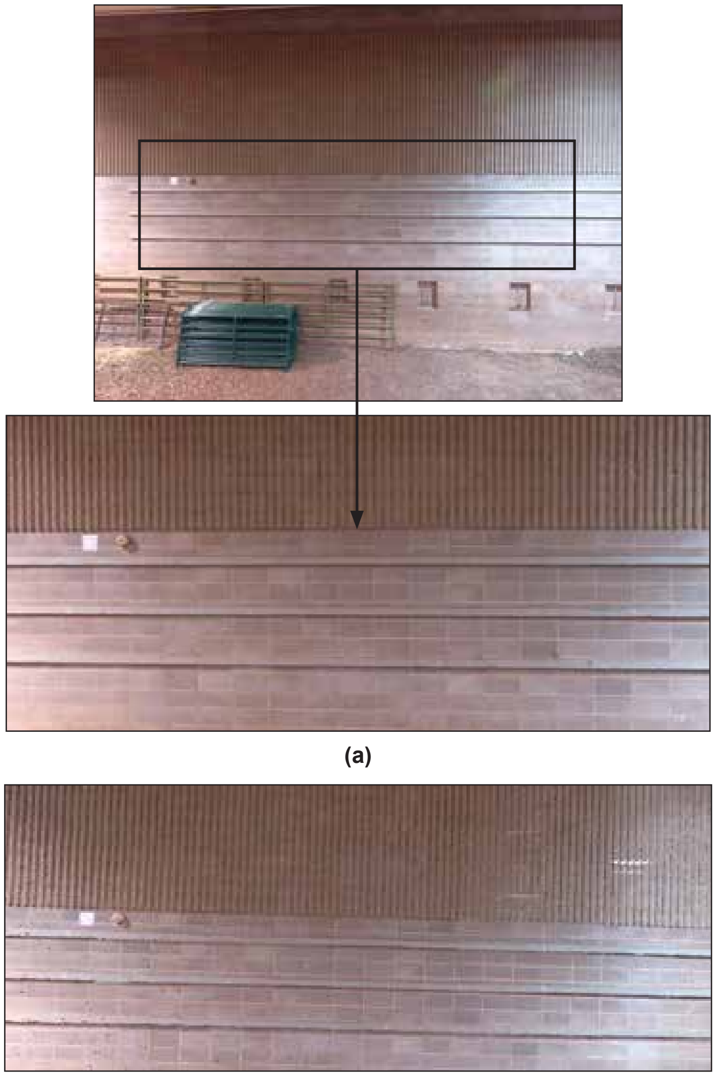
(c) (d)

Figure 19. Image analysis of tall column with insufficient illumination using ImageJ: (a) original image; (b) histogram of original image; (c) computer-enhanced image; (d) histogram of enhanced image.



(a) (b)

Figure 20. Image quality assessment of wall: (a) plot of entropy and sharpness for wall; (b) representative low-quality image for wall.



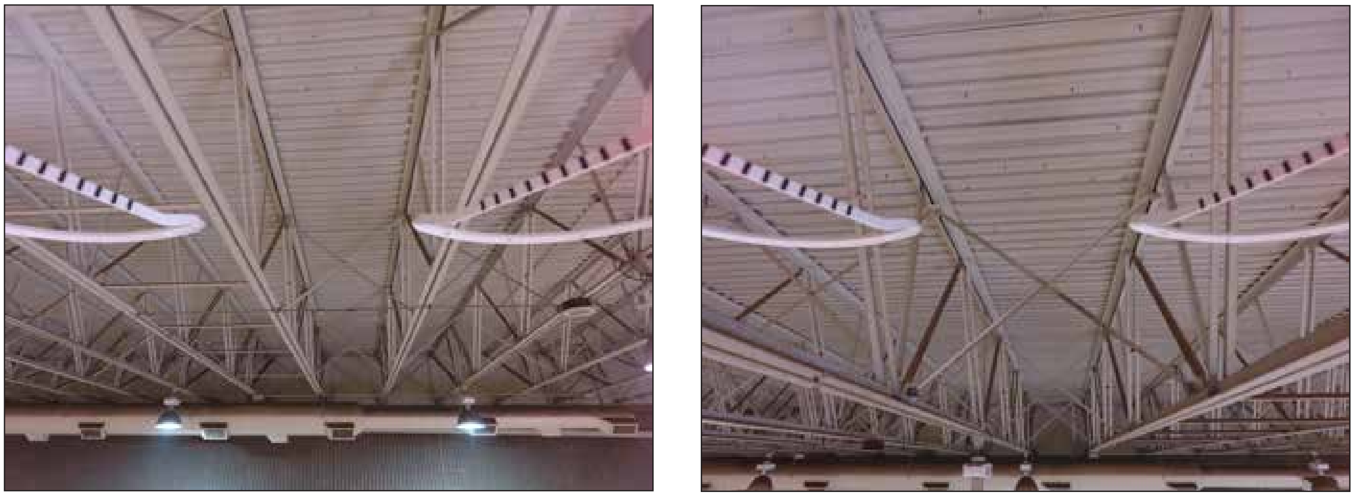
(a)

(b)

Figure 21. Wall recreated using PhotoScan: (a) wall; (b) wall 3D representation.

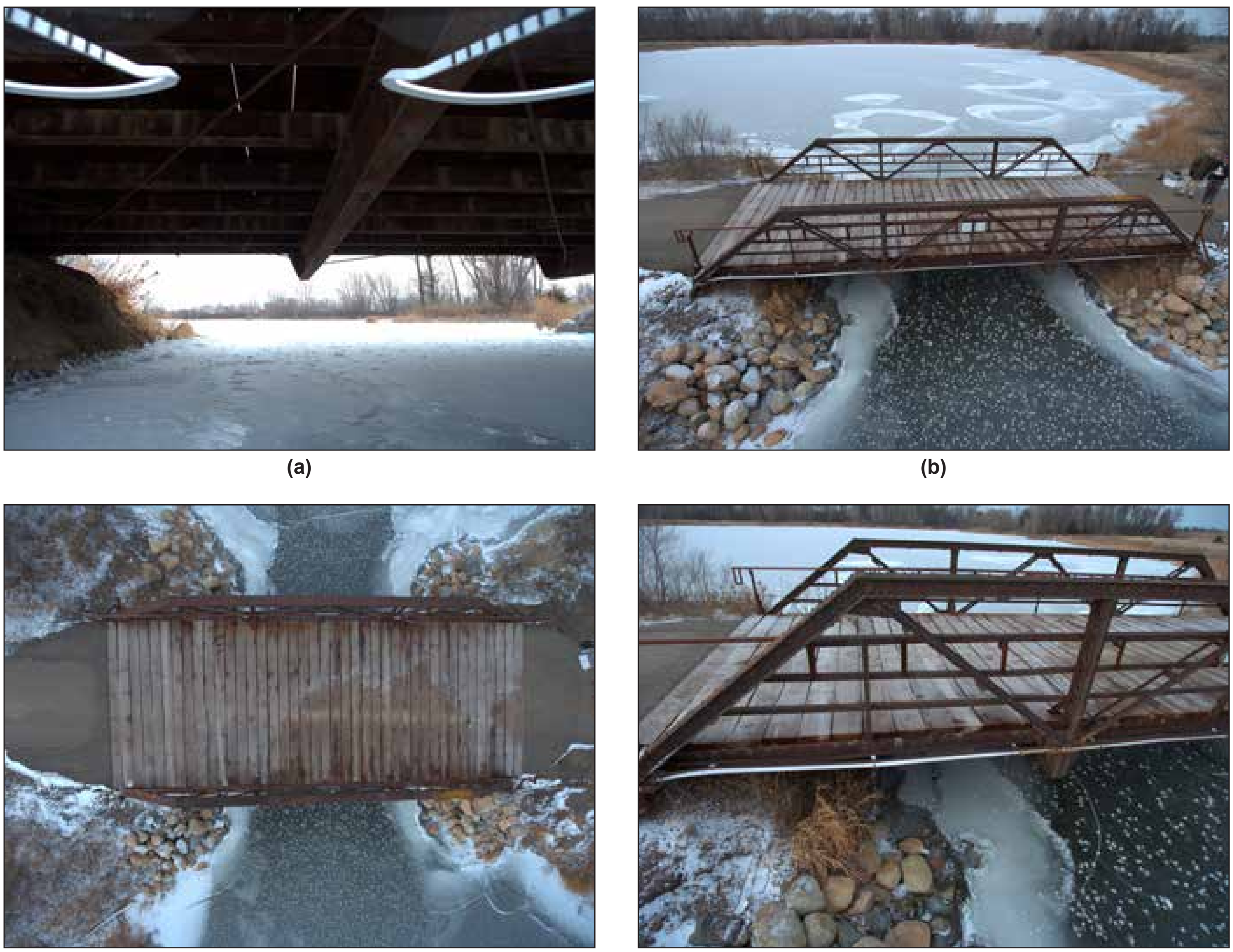
(a) (b)

Figure 22. Corroded lamp images taken from different angles using the drone: (a) camera directly pointing at corrosion; (b) camera pointing to the side of the corrosion.



(a) (b)

Figure 23. Image comparison for camera angle above horizontal: (a) image taken from the drone below joints with gimbal tilted 35° upward; (b) image from the drone flying between the joints.



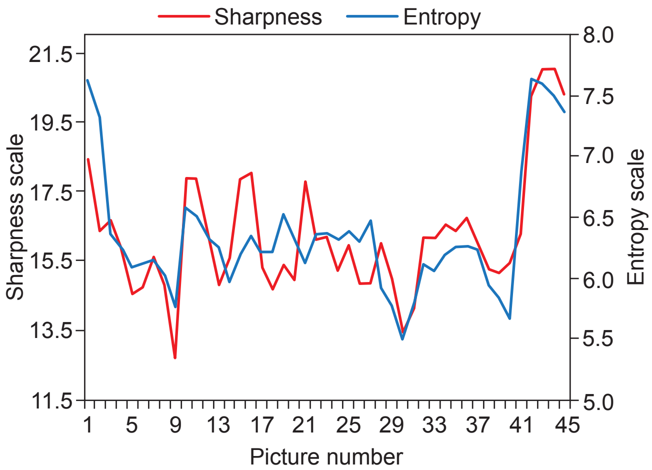
(a) (b) (c) (d)

Figure 24. Sample pictures obtained during inspection of the Dakota Nature Park pedestrian bridge: (a) underneath deck; (b) bridge overview; (c) timber decking; (d) steel railing.

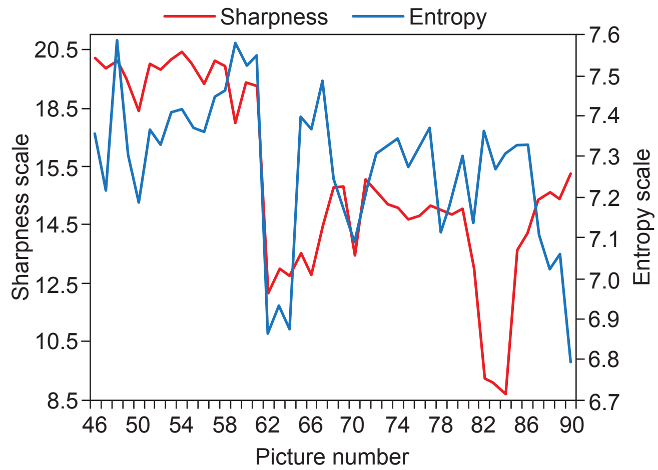
(a)

(b)

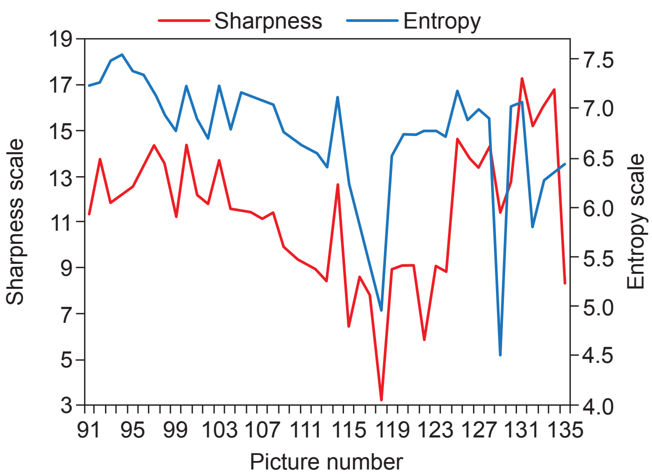
Figure 25. Sample flight pictures from digital camera: (a) the drone flying to take overall view of the bridge; (b) the drone flying to inspect stringers underneath the bridge.



(a)



(b)



(c)

(d)

(e)

Figure 26. Image quality assessment for bridge at the Dakota Nature Park using entropy and sharpness: (a) graph for images 1 to 45; (b) graph for images 46 to 90; (c) graph for images 91 to 135; (d) low-quality image with overexposure; (e) low-quality image with partial overexposure.

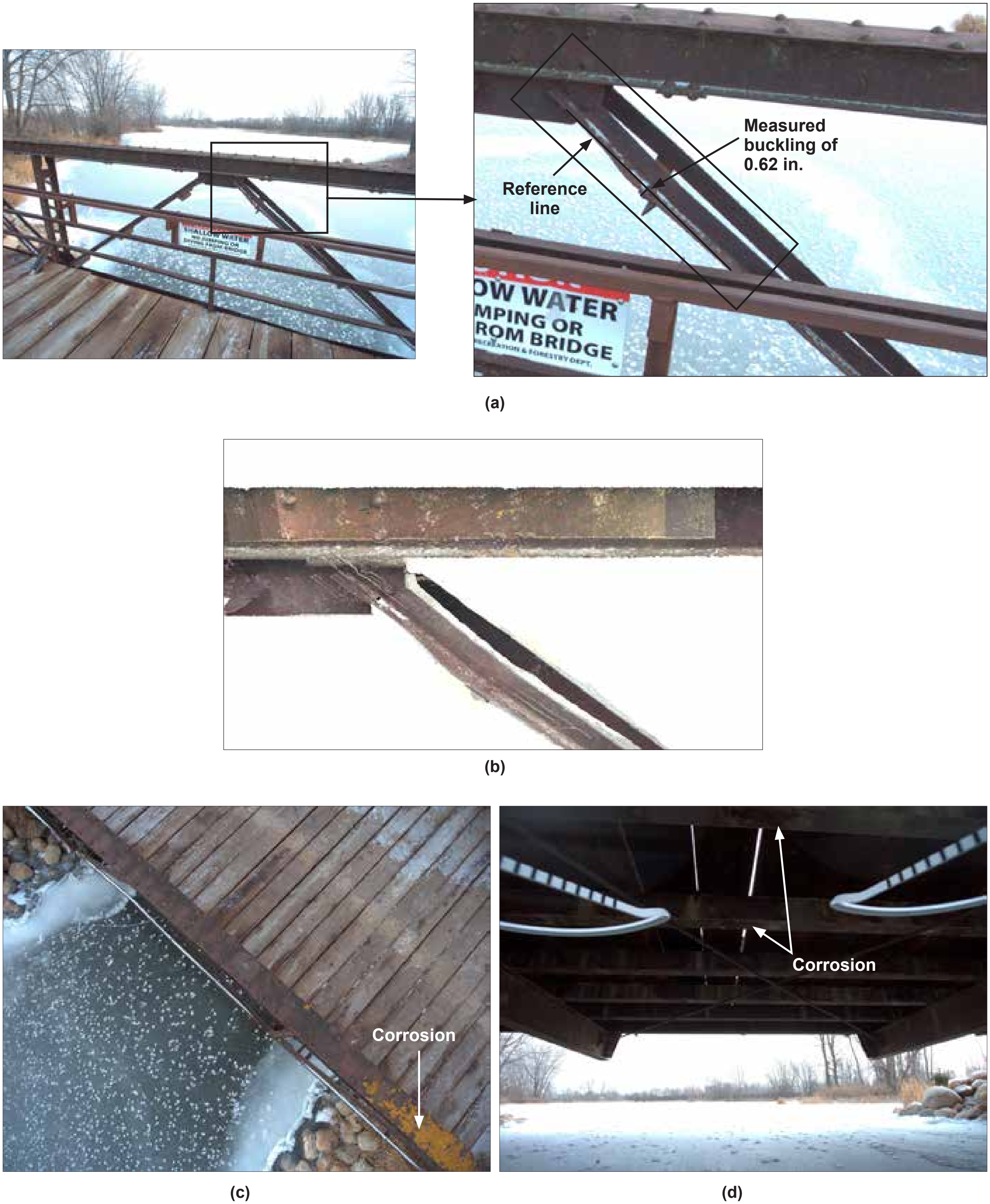


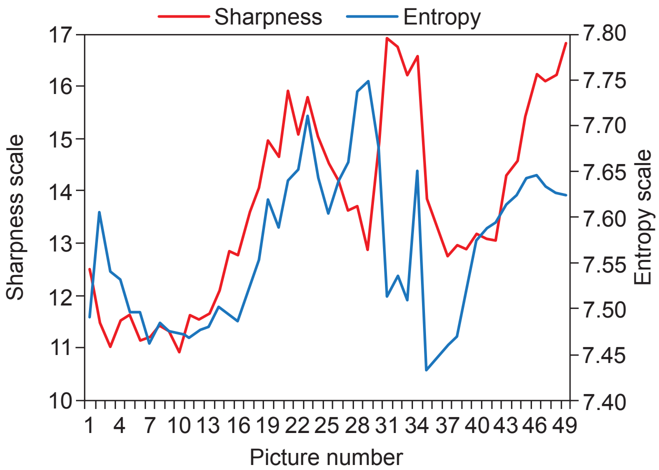
Figure 27. Damage detected using the drone during the outdoor flight: (a) steel truss member buckling; (b) steel truss member corrosion; (c) corrosion on stringers underside of bridge; (d) corrosion on stringers and cross frames.

(a) (b) (c) (d)

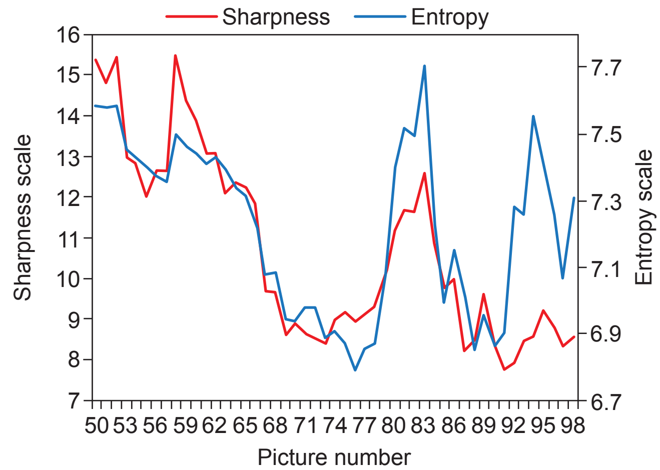
Figure 28. Sample pictures obtained during the outdoor flight: (a) overview; (b) timber decking; (c) lower chords and lateral bracings; (d) railing and abutment.

(a) (b)

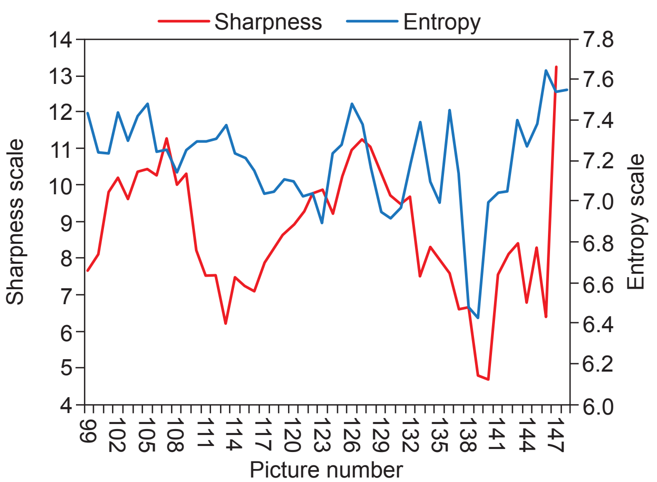
Figure 29. Sample outdoor flight pictures from digital camera: (a) the drone inspecting stringers and cross-frames underneath the deck; (b) the drone taking side view images of the bridge.



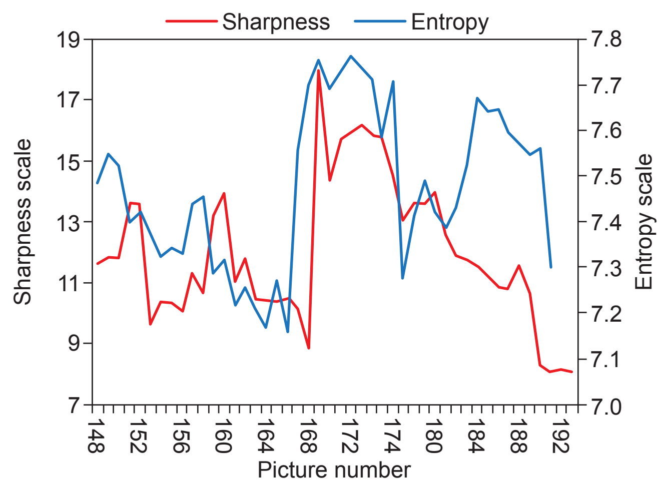
(a)



(b)



(c)



(d)

(e)

(f)

Figure 30. Image quality assessment for bridge at Sexauer Park using entropy and sharpness: (a) graph for images 1 to 49; (b) graph for imagea 50 to 98; (c) graph for images 99 to 147; (d) graph for images 148 to 193; (e) image number 89 representing low-quality image; (f) image number 140 representing low-quality picture.

Figure 31. Damage detected using the drone during the outdoor flight: (a) bended bolt; (b) 3D virtual representation of bended bolt; (c) missing bolt nuts; (d) steel truss member corrosion; (Figure 31 continued next page)

(e) (f)

Figure 31. (e) deck hole and timber board separation; (f) abutment crack.

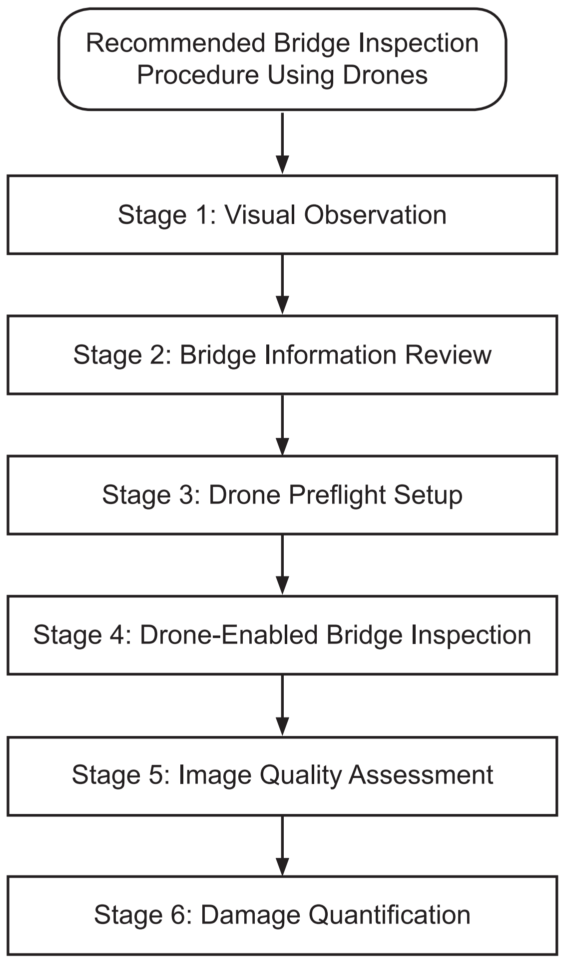
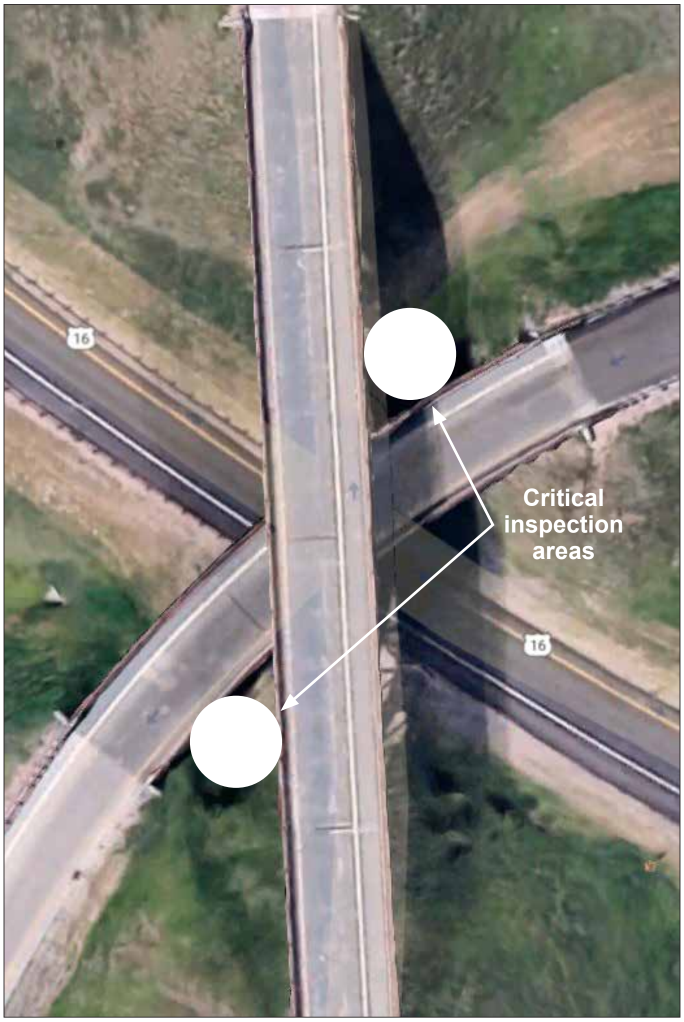
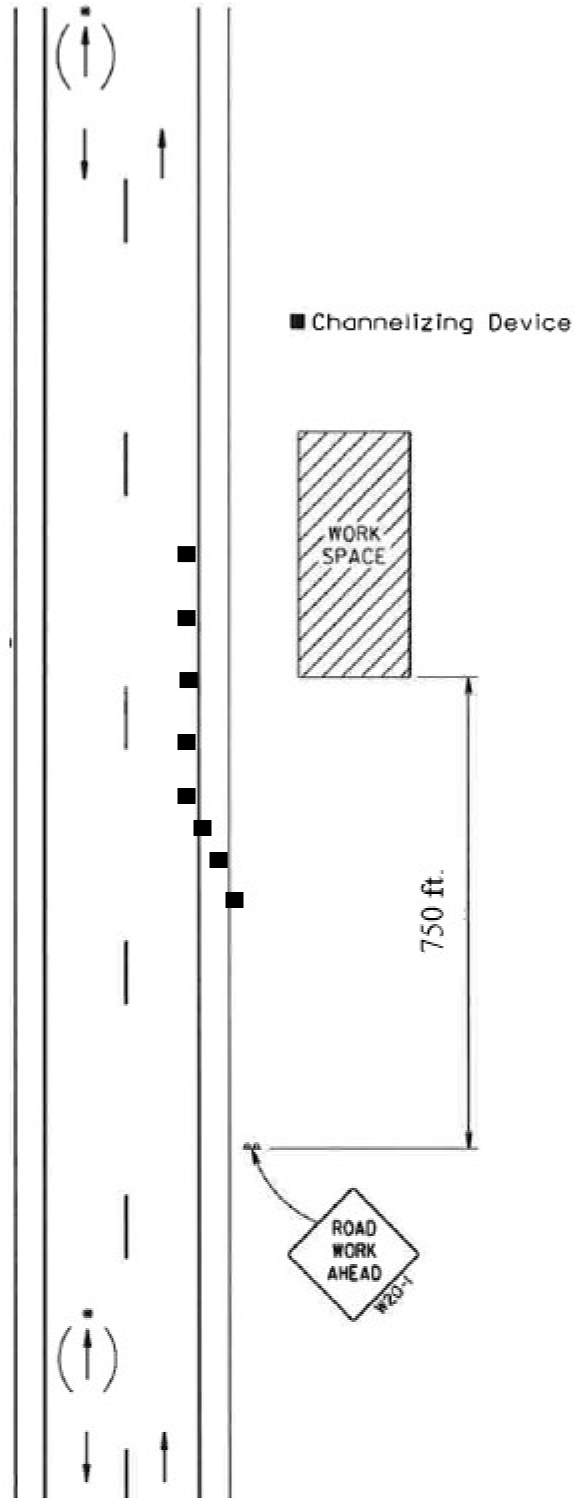


Figure 32. Recommended six-stage bridge inspection protocol.

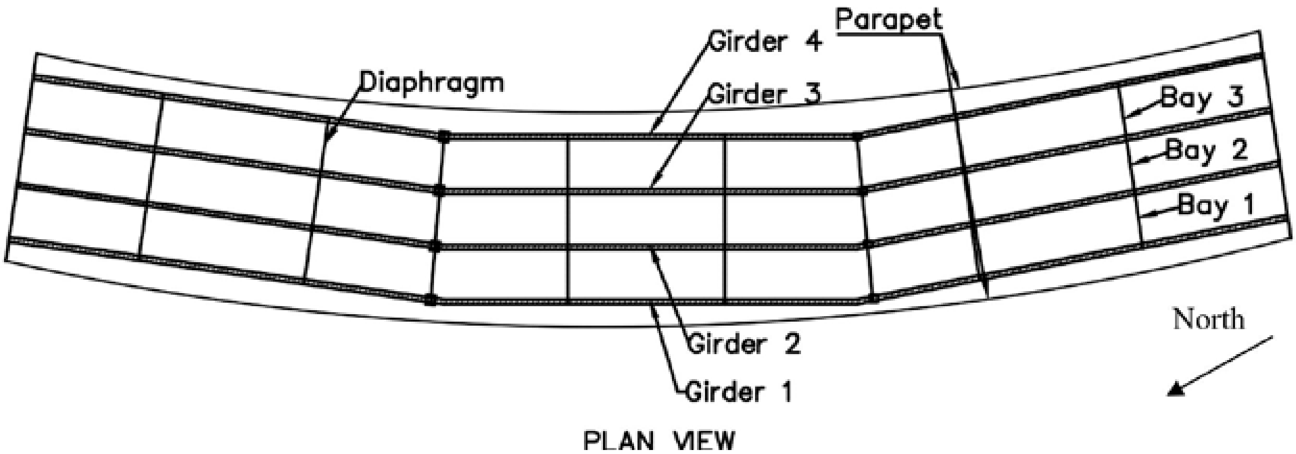


(a)

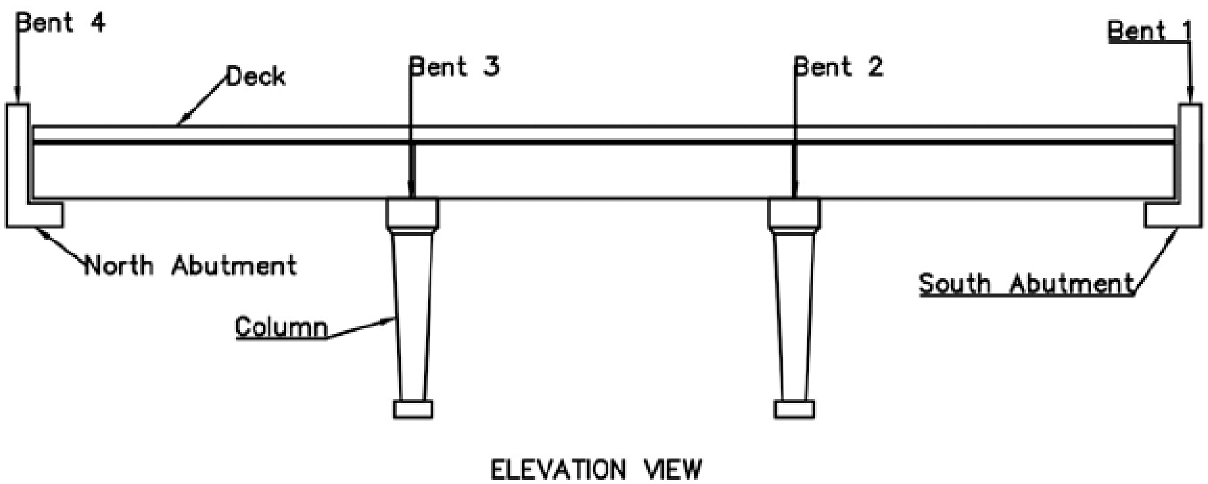


(b)

Figure 33. Bridge inspection layout: (a) critical inspection areas (image extracted from Google Maps); (b) location of traffic control signs and channelizing devices (used with permission from South Dakota Department of Transportation).



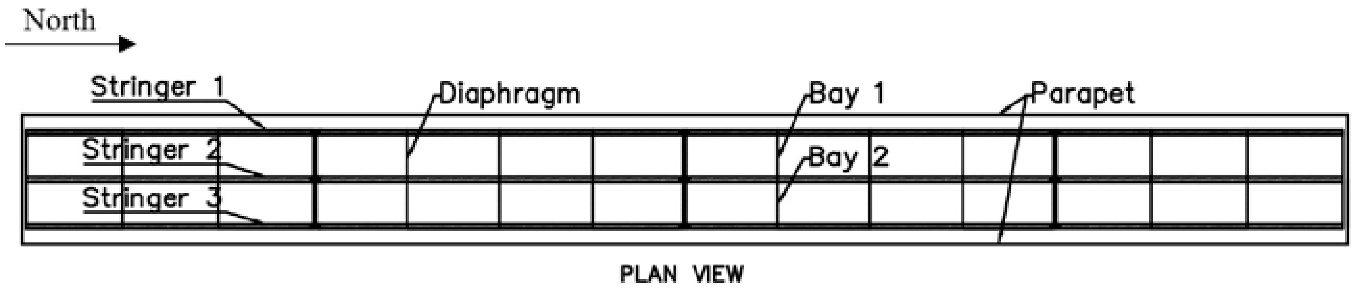
(a)



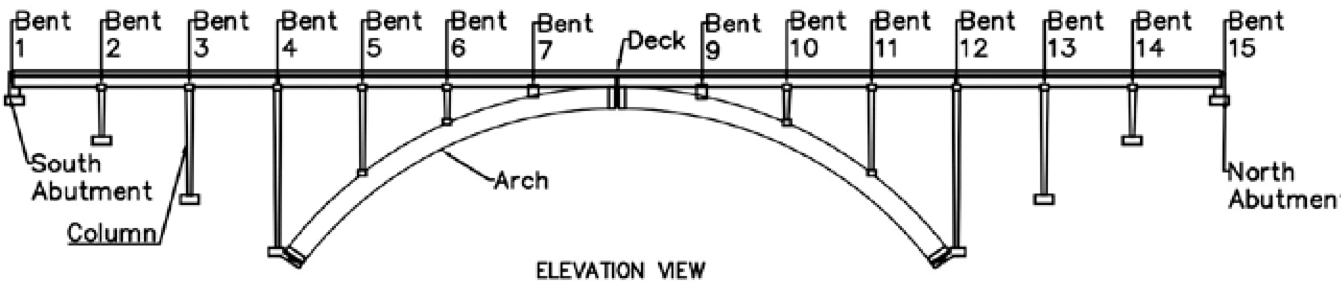
(b)

(c)

Figure 34. Bridge overview and components numbering: (a) component numbering on plan view; (b) component numbering on elevation view; (c) overview photo.



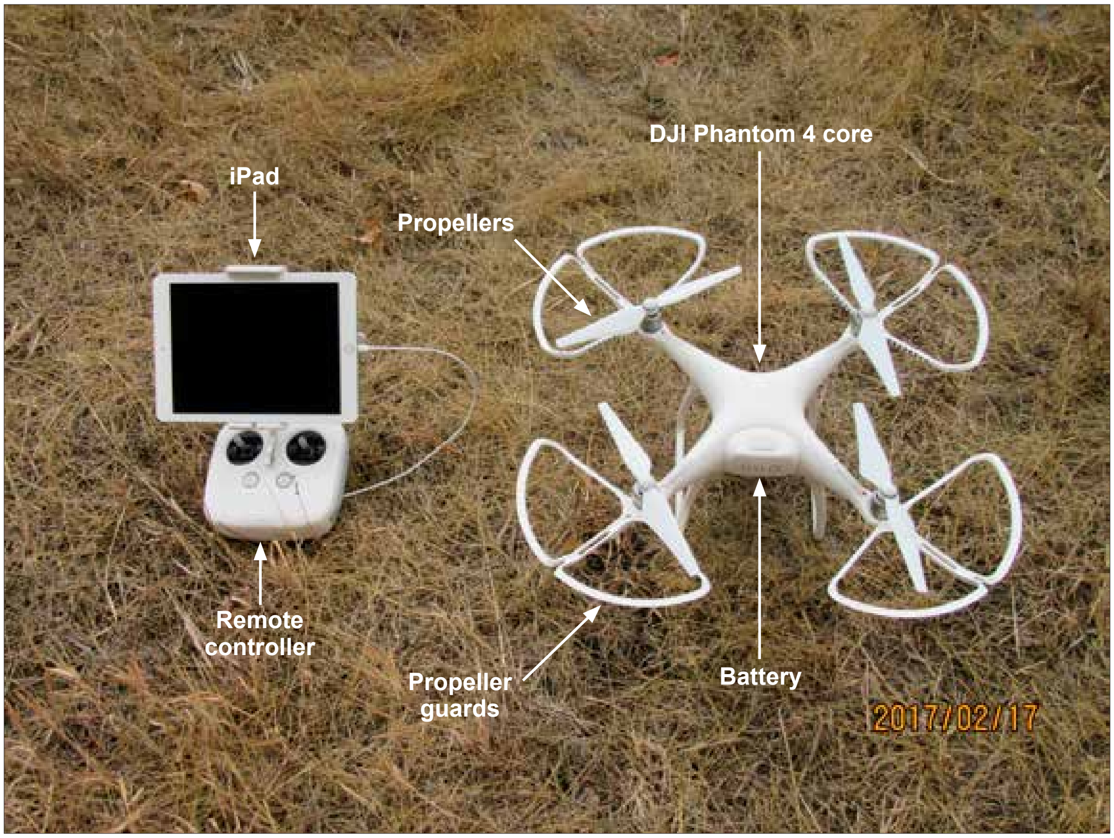
(a)



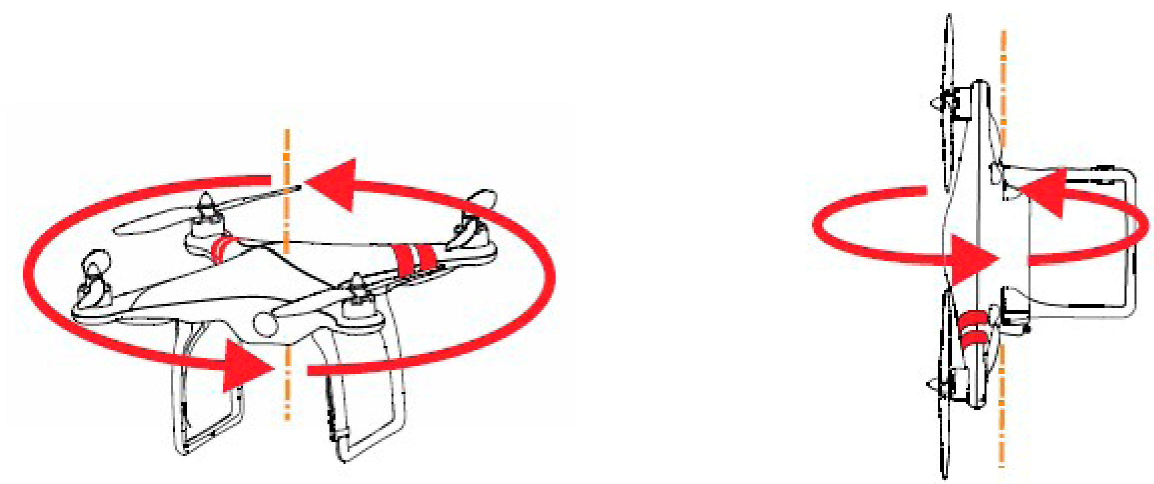
(b)

(c)

Figure 35. Bridge overview and components numbering: (a) component numbering on plan view; (b) component numbering on elevation view; (c) overview photo.



(a)



(b)

Figure 36. DJI Phantom 4 preflight setup: (a) DJI Phantom 4, remote controller, and iPad equipment; (b) calibration of compass demonstration.

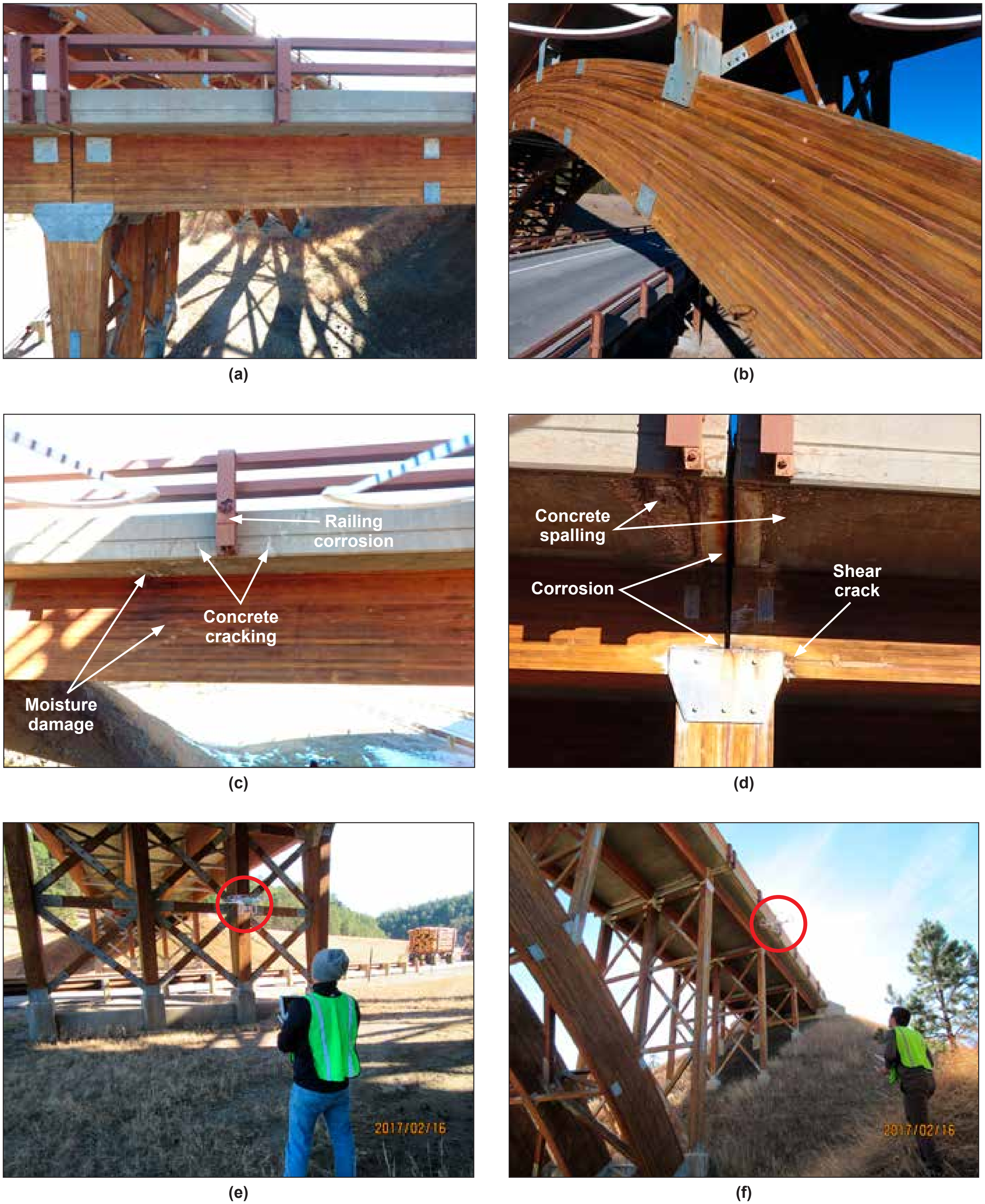


Figure 37. Sample images obtained from the full-scale bridge inspection on February 16th, 2017: (a) glulam girder; (b) glulam arch; (c) damage on timber girder bridge; (d) damage on joint of Keystone Wye arch bridge; (e) drone flying near column of timber girder bridge; (f) drone flying near column of Keystone Wye arch bridge.

Figure 38. Sample images obtained from the full-scale bridge inspection on February 17th, 2017: (a) damaged washer near glulam arch support; (b) concrete cracking and water leakage at abutment location of timber girder bridge; (c) drone capturing overview of Keystone Wye arch bridge; (d) drone approaching timber girder bridge.

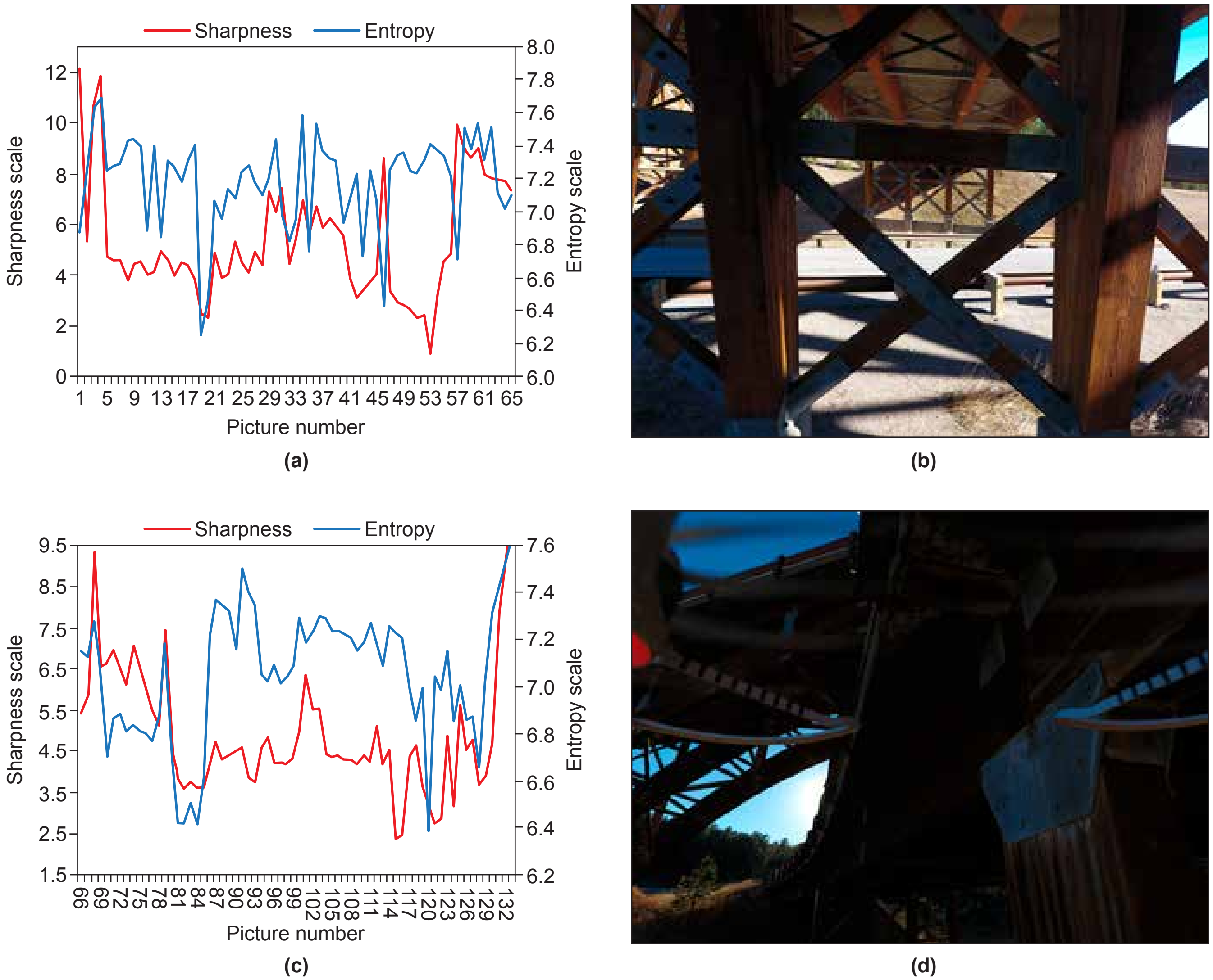
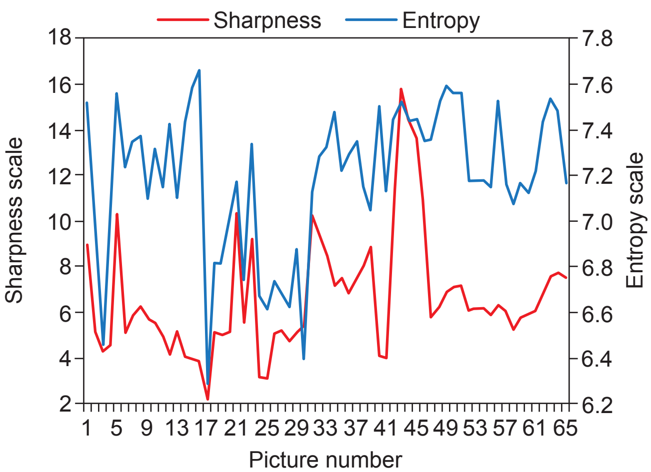
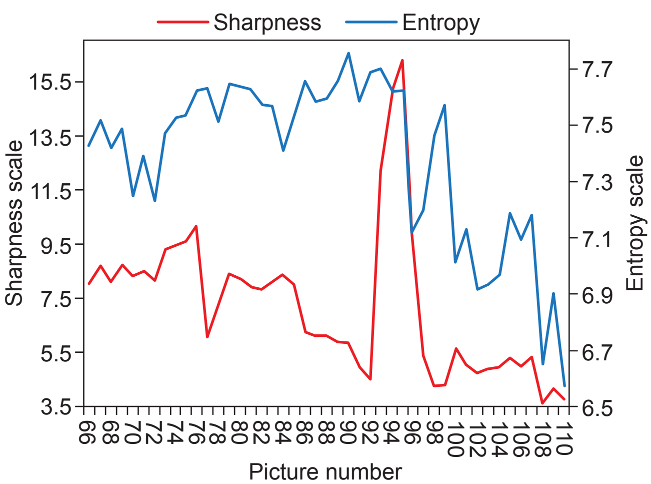


Figure 39. Image quality assessment for timber girder bridge inspection using entropy and sharpness: (a) graph for images 1 to 65; (b) image 47 representing low-quality image; (c) graph for images 66 to 133; (d) image 115 representing low-quality image.



(a)

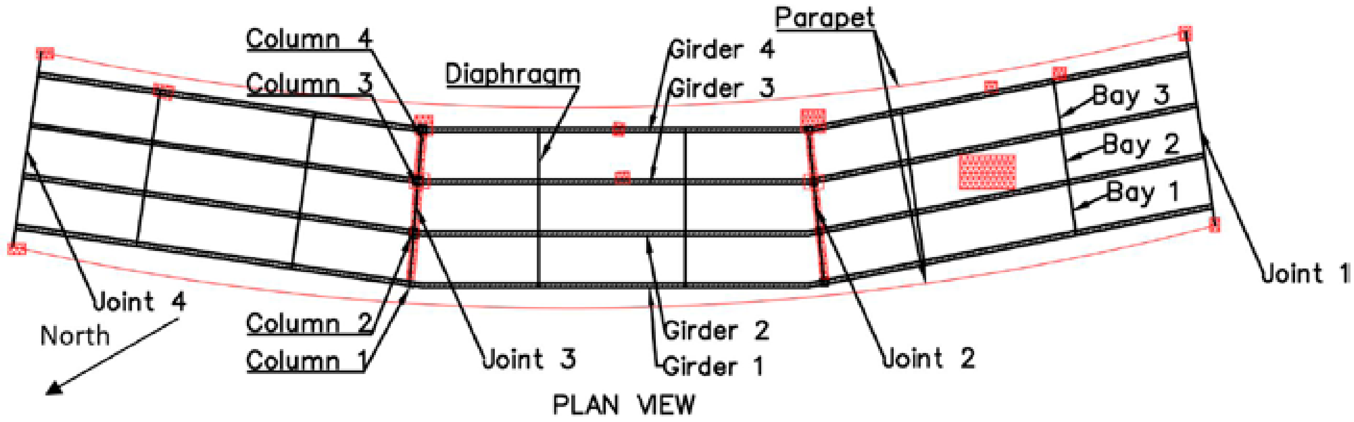
(b)



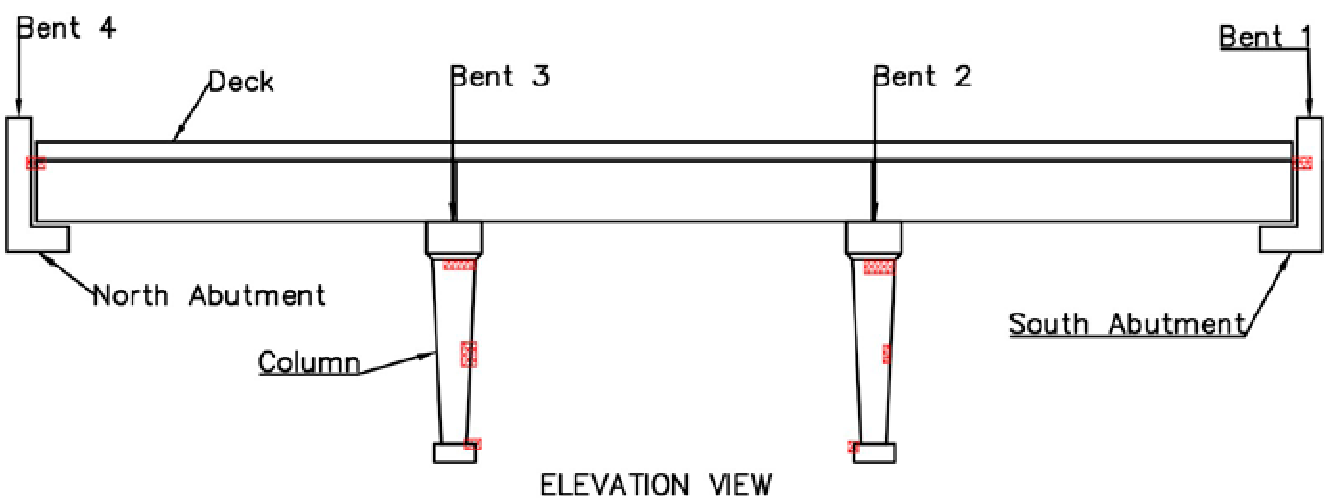
(c)

(d)

Figure 40. Image quality assessment for Keystone Wye arch bridge inspection using entropy and sharpness graphs: (a) graph for images 1 to 65; (b) image 14 representing low-quality image; (c) graph for images 66 to 110; (d) image 99 representing low-quality image.



(a)



(b)

Figure 41. Timber girder bridge layout with identified damage: (a) damage on plan view; (b) damage on elevation view. (Red rectangles in plan and elevation views indicate damage, and red lines in plan view denote minor cracks along the parapet and rusting in railing in a longitudinal direction.)

Figure 42. Underside of deck damage detected using drone: (a) concrete spalling and corrosion with exposed rebar at Joint 2 near Girder 4; (b) efflorescence in Bay 2 between Joints 1 and 2; (c) 3D virtual model of Joint 2 near Girder 3 using PhotoScan; (d) quantified damage for Joint 2 near Girder 4.

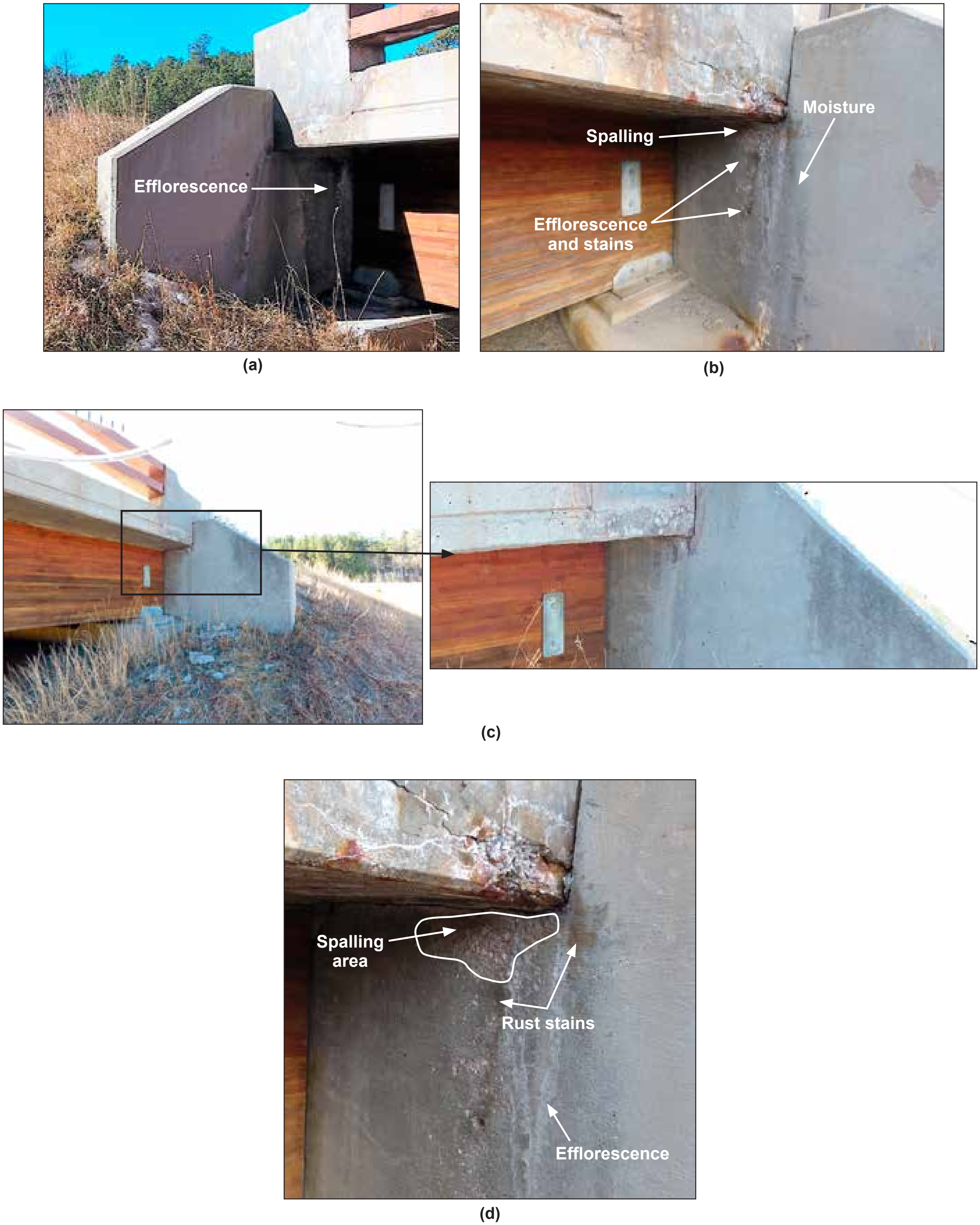


Figure 43. Abutment damage detected using drone: (a) efflorescence at south abutment near Girder 4; (b) spalling and discoloration of concrete caused by moisture at north abutment near Girder 4; (c) 3D virtual representation of south abutment near Girder 1; (d) quantified damage for north abutment near Girder 4.

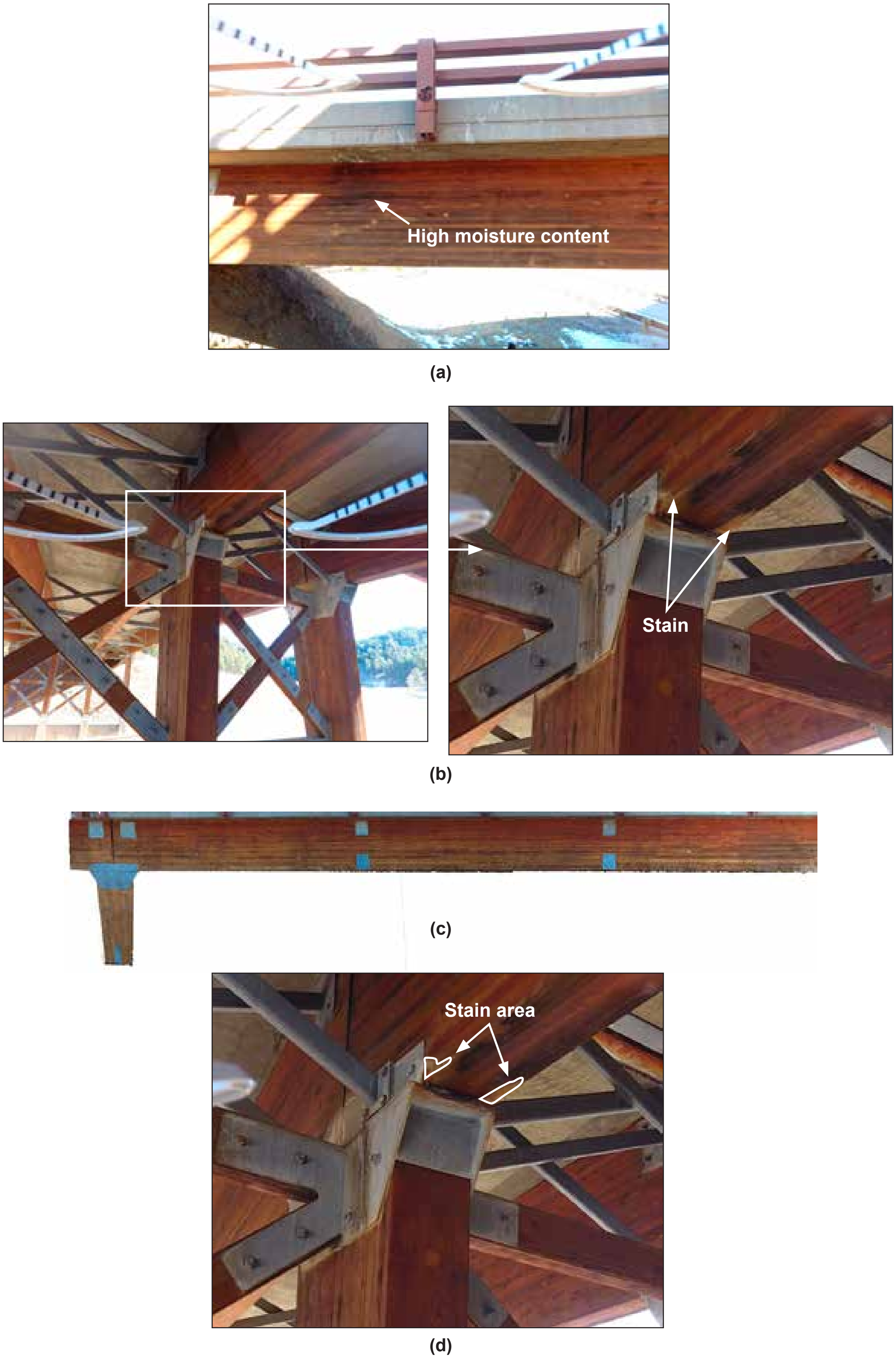


Figure 44. Girder damage detected using the drone: (a) moisture damage on the side of Girder 4 between Joints 1 and 2; (b) stains under Girder 3 at Joint 2; (c) PhotoScan representation of Girder 4 between Joints 3 and 4; (d) damage quantification for Girder 3 support at Joint 2.

Figure 45. Minor visible discoloration of diaphragms caused by water leakage from the deck at Joint 3.

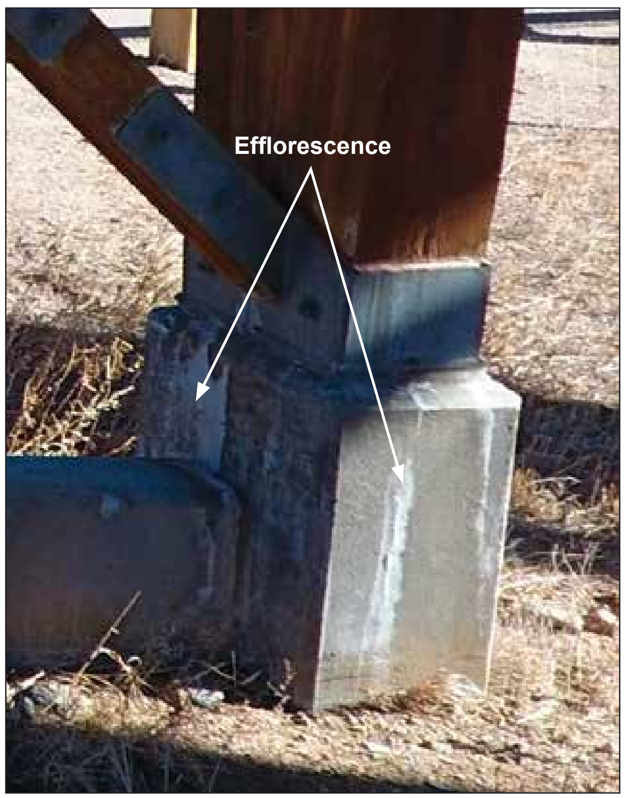
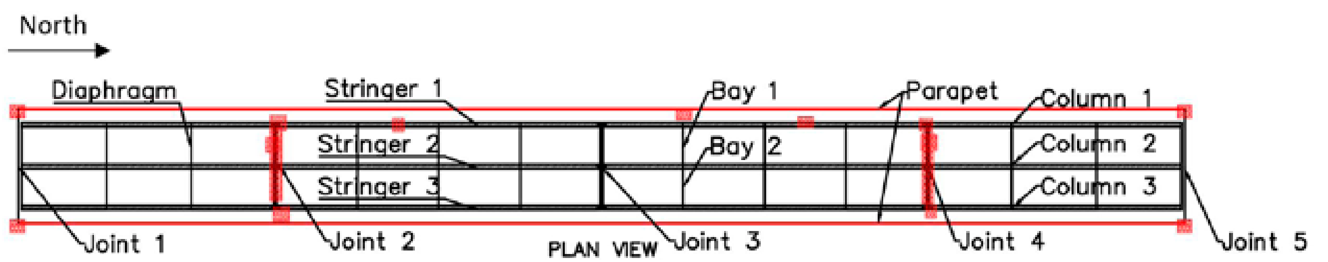
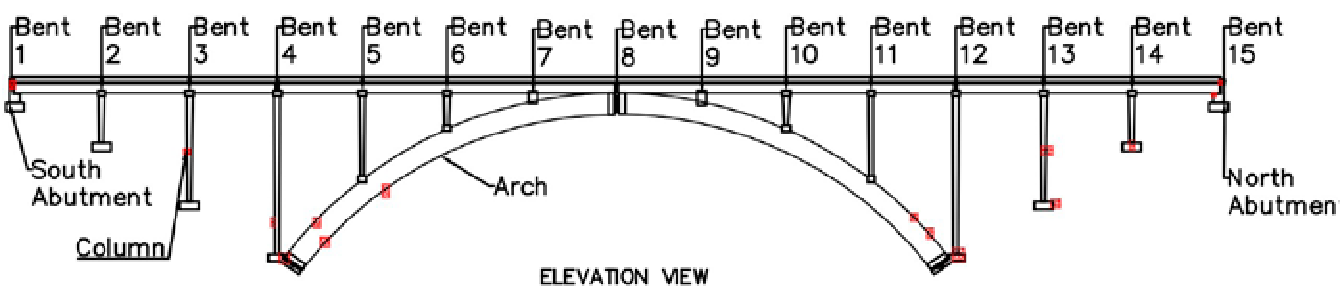


Figure 46. Sample efflorescence on Column 4 Pedestal at Bent 2 detected using the drone.

Figure 47. Sample damage on railing between Joints 3 and 4 near Girder 4.

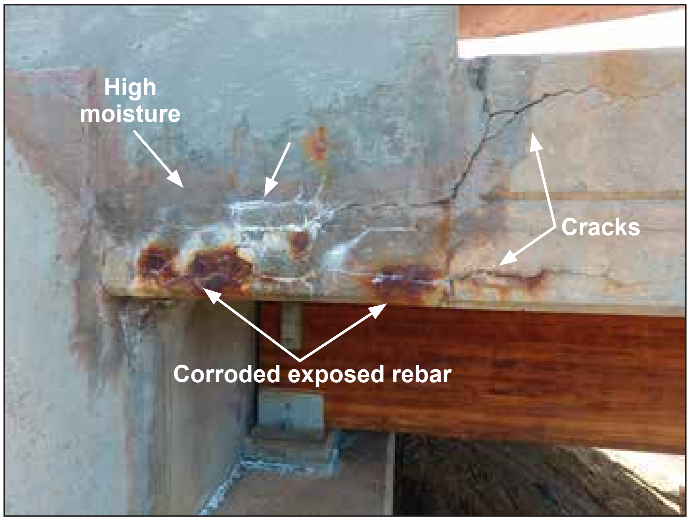


(a)



(b)

Figure 48. Keystone Wye bridge layout with identified damage: (a) damage on plan view; (b) damage on elevation view. (Red rectangles in plan and elevation views indicate damage, and red lines in plan view denote minor cracks along the parapet and rusting in railing in a longitudinal direction.)

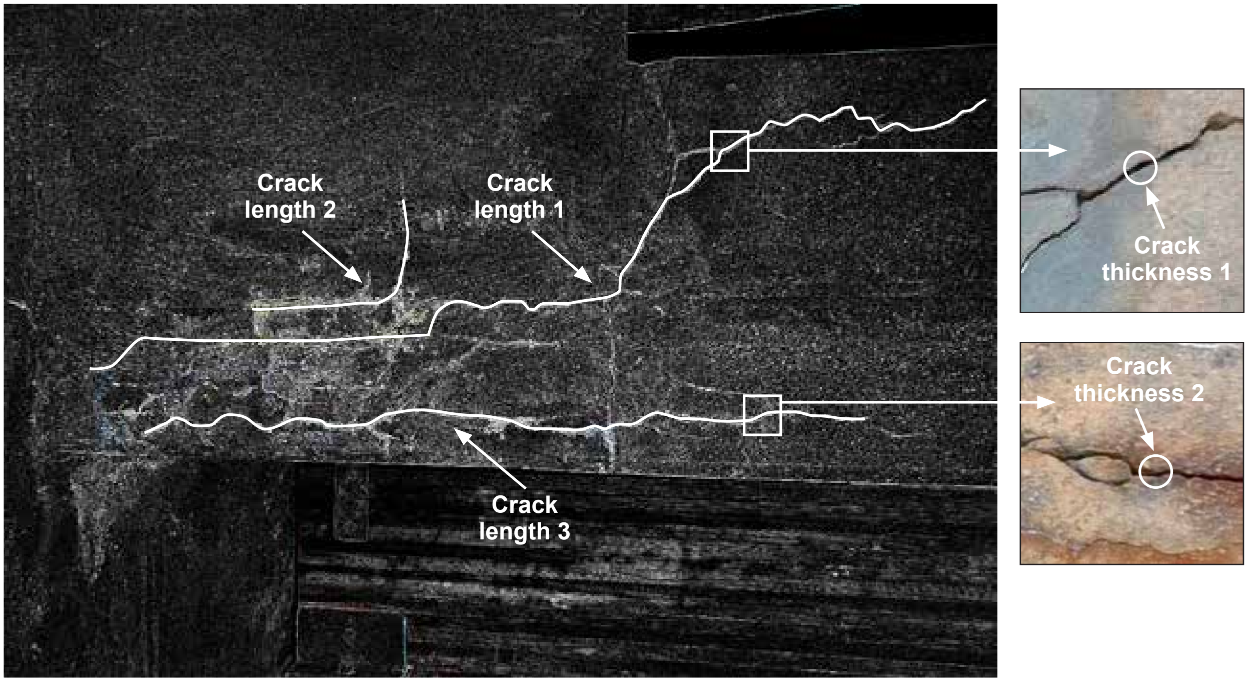

High
moisture
Cracks
Corroded exposed rebar

(a)

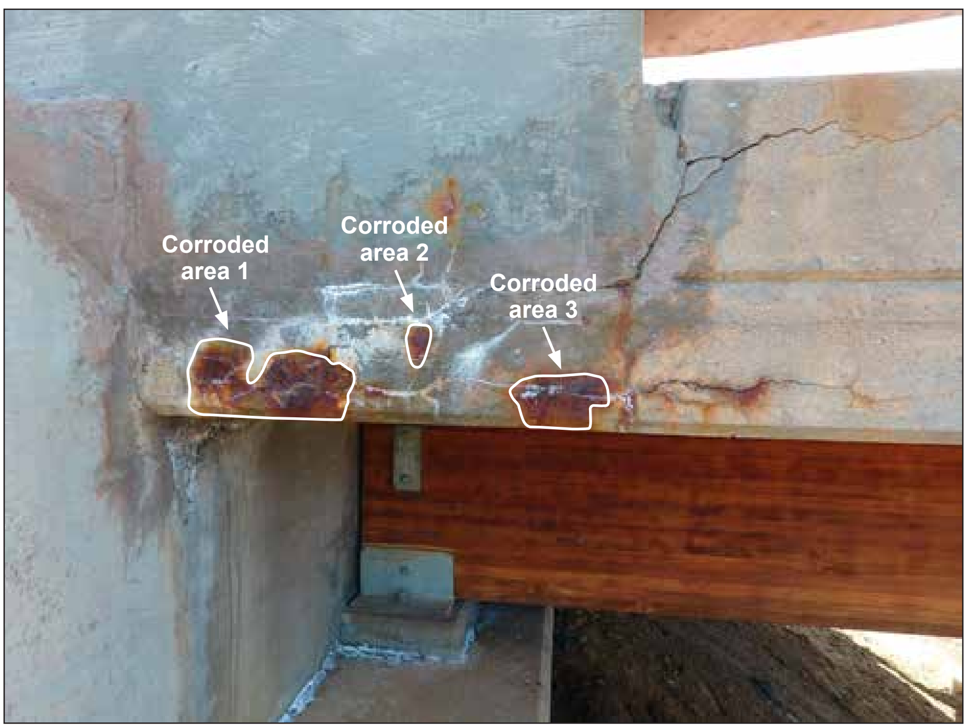

Spalling
Stains

(b)

(c)



(d)



(e)

Figure 49. Deck damage identified using drone: (a) concrete cracks, stains, corroded exposed rebar, and moisture of deck near Stringer 1 at Joint 5; (b) concrete spalling and stains at Joint 2; (c) PhotoScan representation of Joint 2 damage; (d) edge detection using ImageJ to better visualize identified cracks and sample crack thicknesses; (e) identified corroded areas.

Figure 50. Sample abutment damage detected using drone on Bay 1 at north abutment: (a) transverse concrete crack, visible water leakage, efflorescence, and spalling; (b) water accumulation over crack; (c) PhotoScan 3D virtual representation of north abutment transverse crack; (d) quantified damage on north abutment on Bay 1.

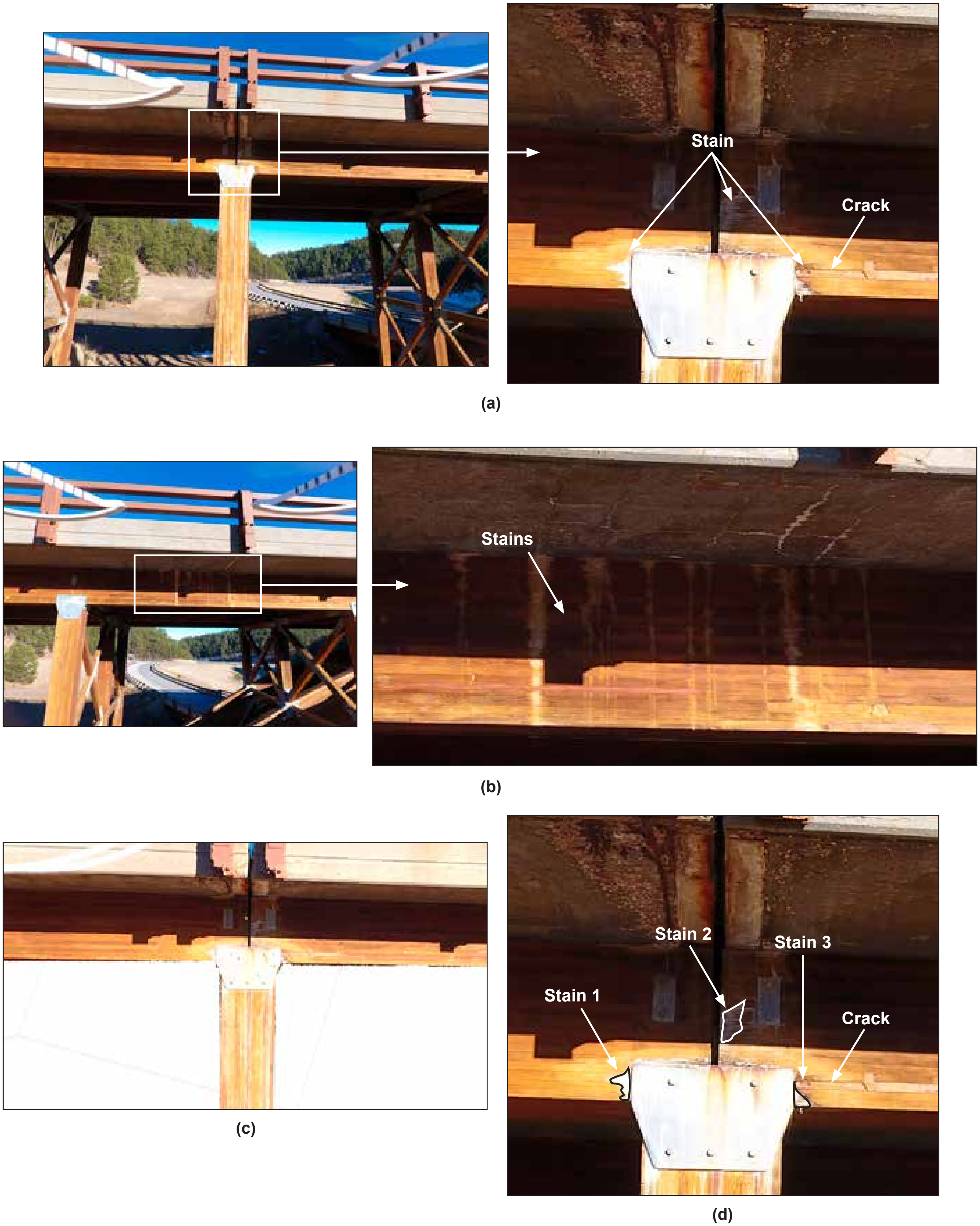


Figure 51. Example stringer damage detected using the drone: (a) discoloration caused by moisture coming from Joint 4 and a shear crack on Stringer 1 at Joint 4; (b) stains caused by water leakage coming from the deck on Stringer 1 between Joints 3 and 4; (c) 3D virtual representation of Stringer 1 at Joint 4 using PhotoScan; (d) quantified damage on Stringer 1 at Joint 4.

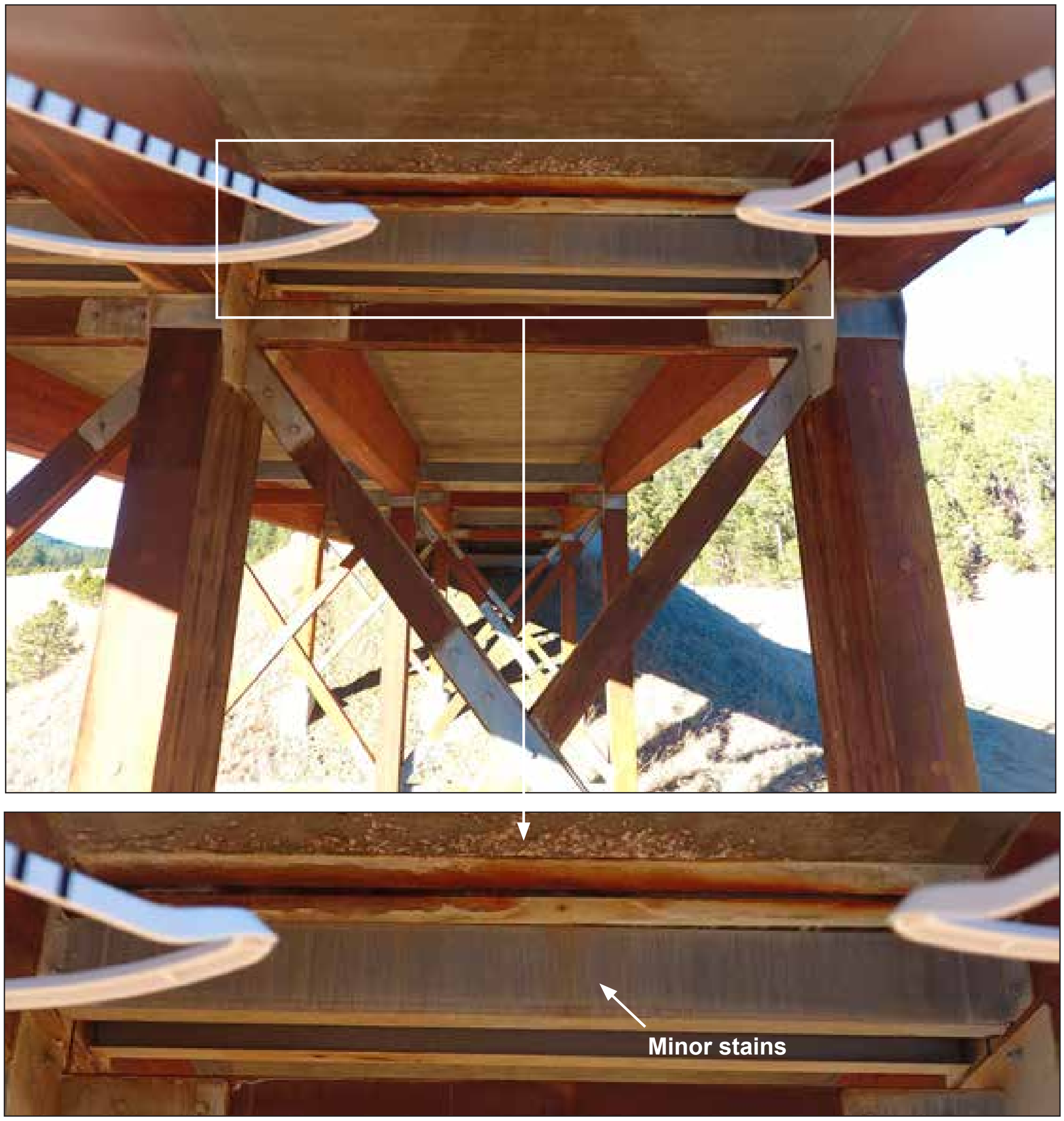


Figure 52. Minor stains on diaphragm on Bay 2 at Joint 4.

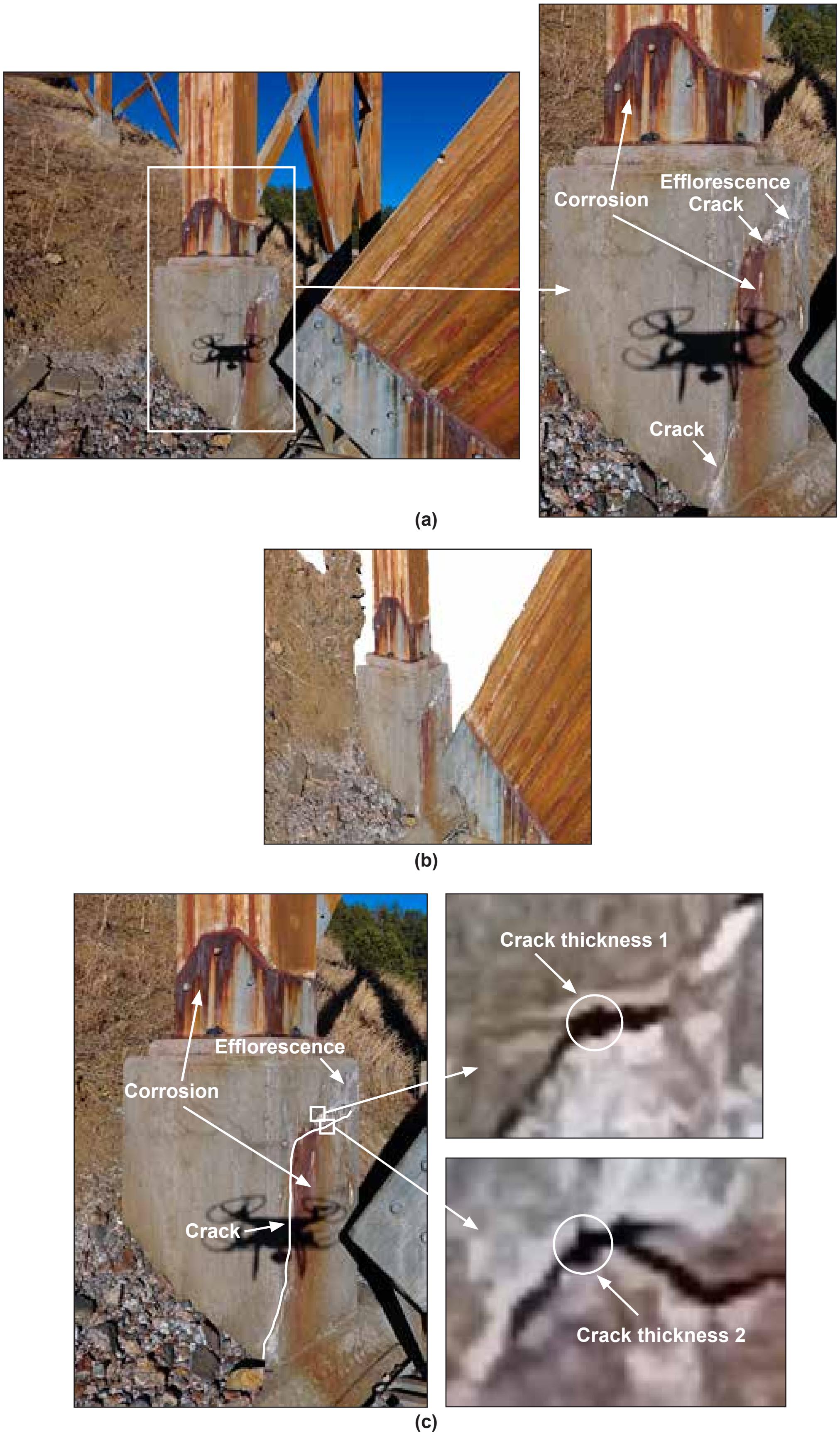


Figure 53. Sample damage on Column 4 at Bent 12 detected using the drone: (a) damage on column; (b) 3D virtual representation of column; (c) detailed column damage for quantification.

Figure 54. Example arch damage detected using the drone: slight lam separation on Arch 1 between Bents 4 and 5.

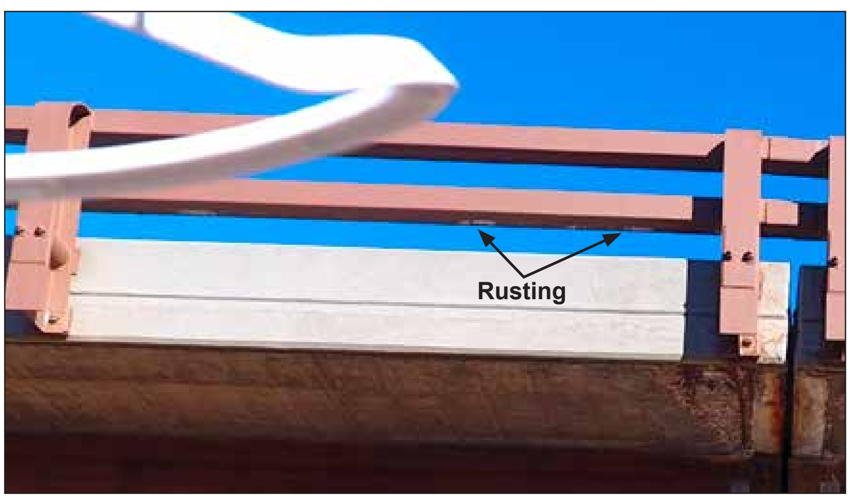


Figure 55. Sample damage on railing near Stringer 1 at Joint 4.

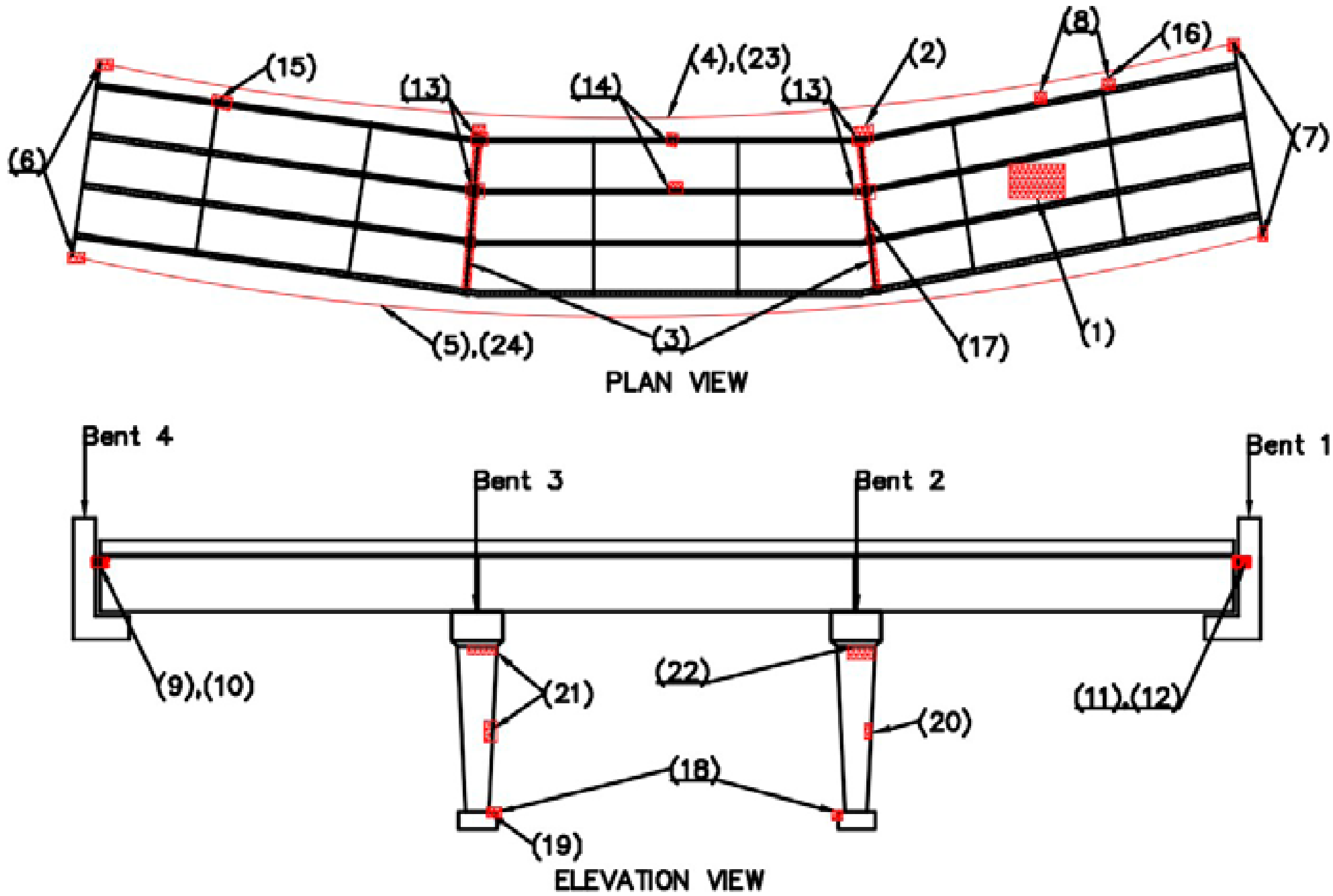


Figure 56. Schematic of damage location on timber girder bridge. (Red rectangles in plan and elevation views indicate damage, and red lines in plan view denote minor cracks along the parapet and rusting in railing in a longitudinal direction. Numbering corresponds to damage summarized in Table 23.)

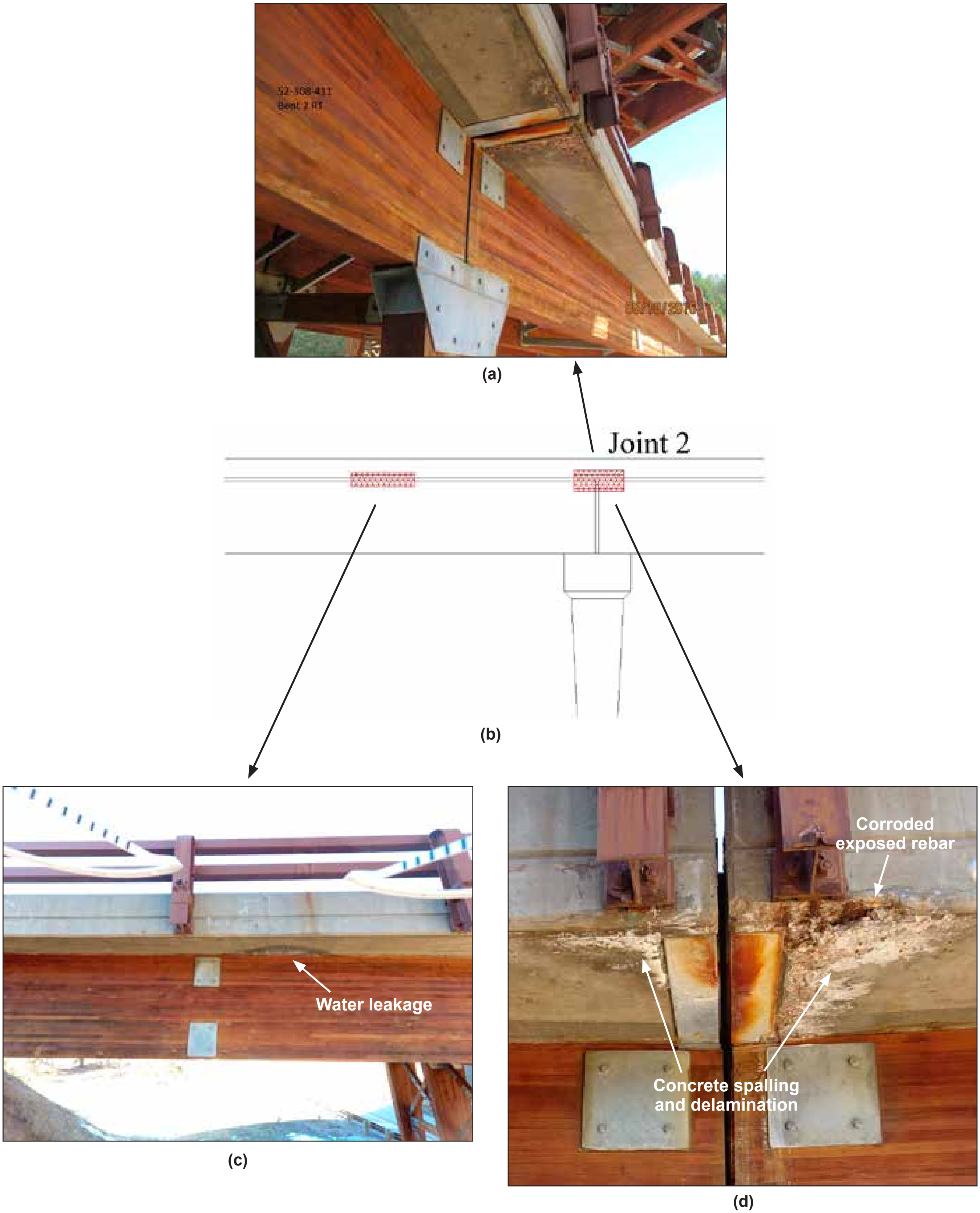


Figure 57. Sample damage on deck near Girder 4: (a) reference image taken during conventional inspection (used with permission from South Dakota Department of Transportation); (b) damage locations on girder; (c) water leakage under deck between Joints 1 and 2; (d) concrete spalling and corrosion with exposed rebar near Girder 4 at Joint 2.

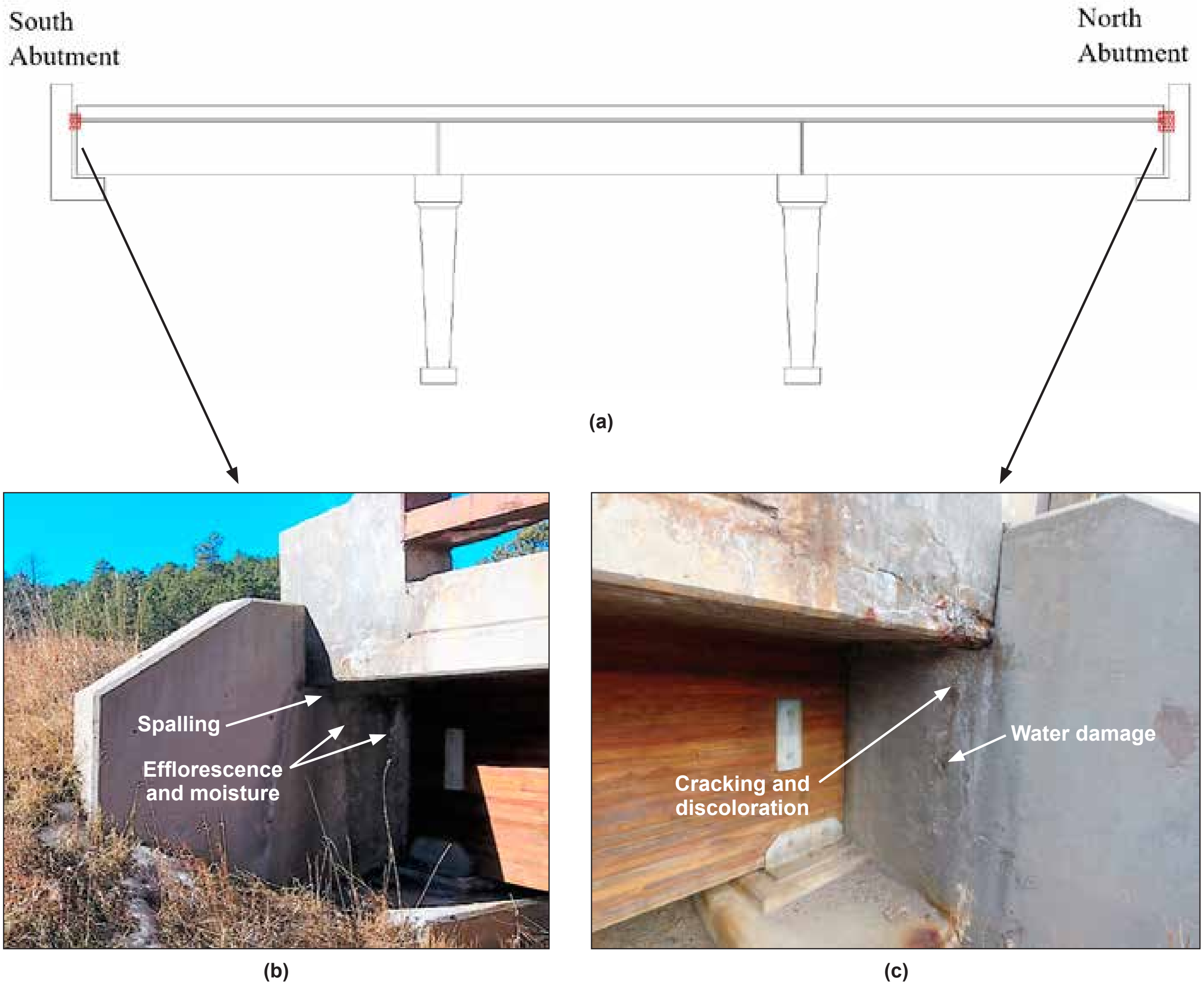


Figure 58. Sample damage on abutment: (a) damage location on abutment; (b) spalling, efflorescence, and moisture on south abutment near Girder 4; (c) cracking, discoloration, and water damage at north abutment near Girder 4.

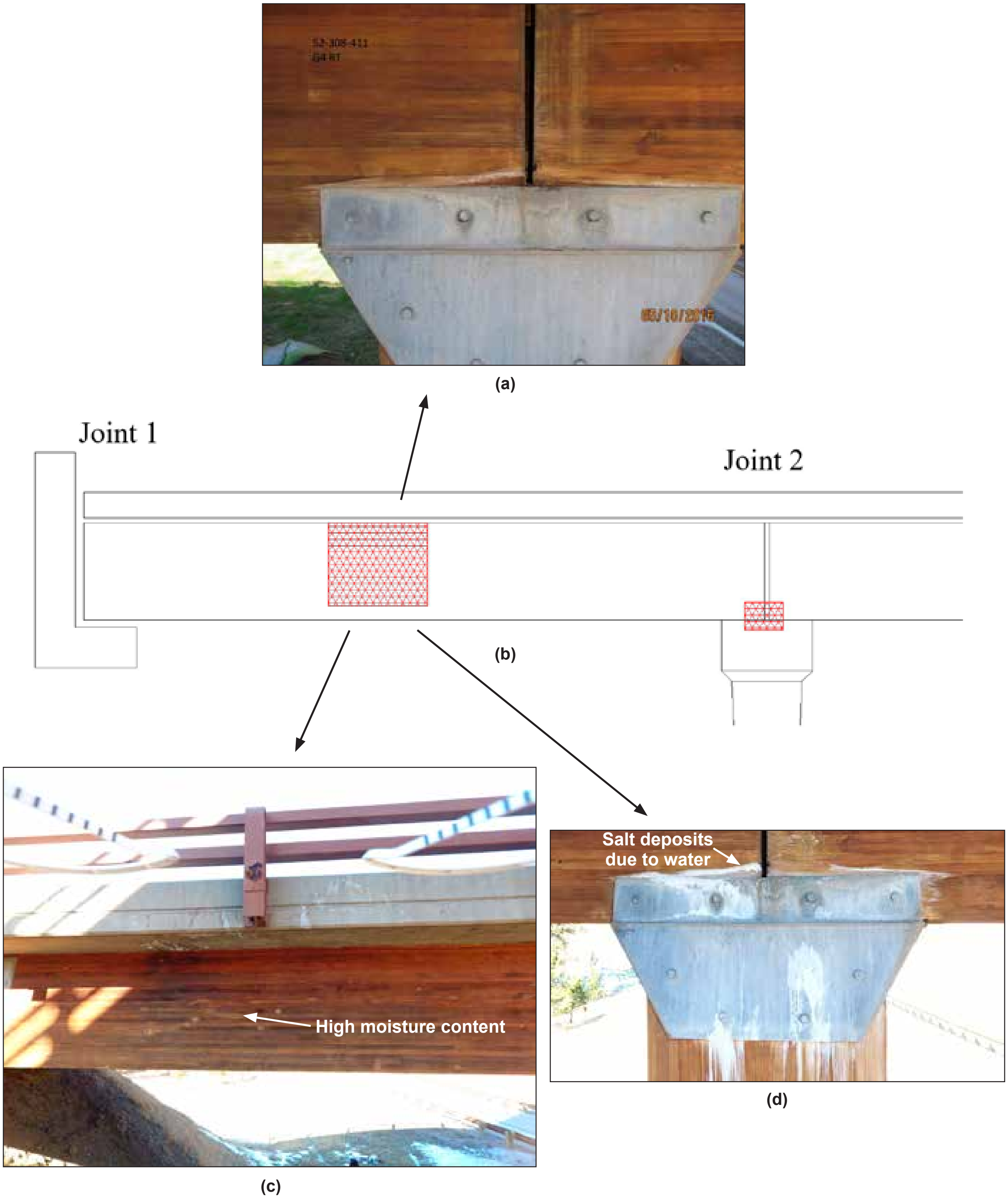


Figure 59. Sample damage on girder: (a) reference image taken during conventional inspection (used with permission from South Dakota Department of Transportation); (b) damage location; (c) some moisture on the side of Girder 4 between Joints 1 and 2; (d) salt deposits caused by water coming from deck at support of Girder 4 at Joint 2.

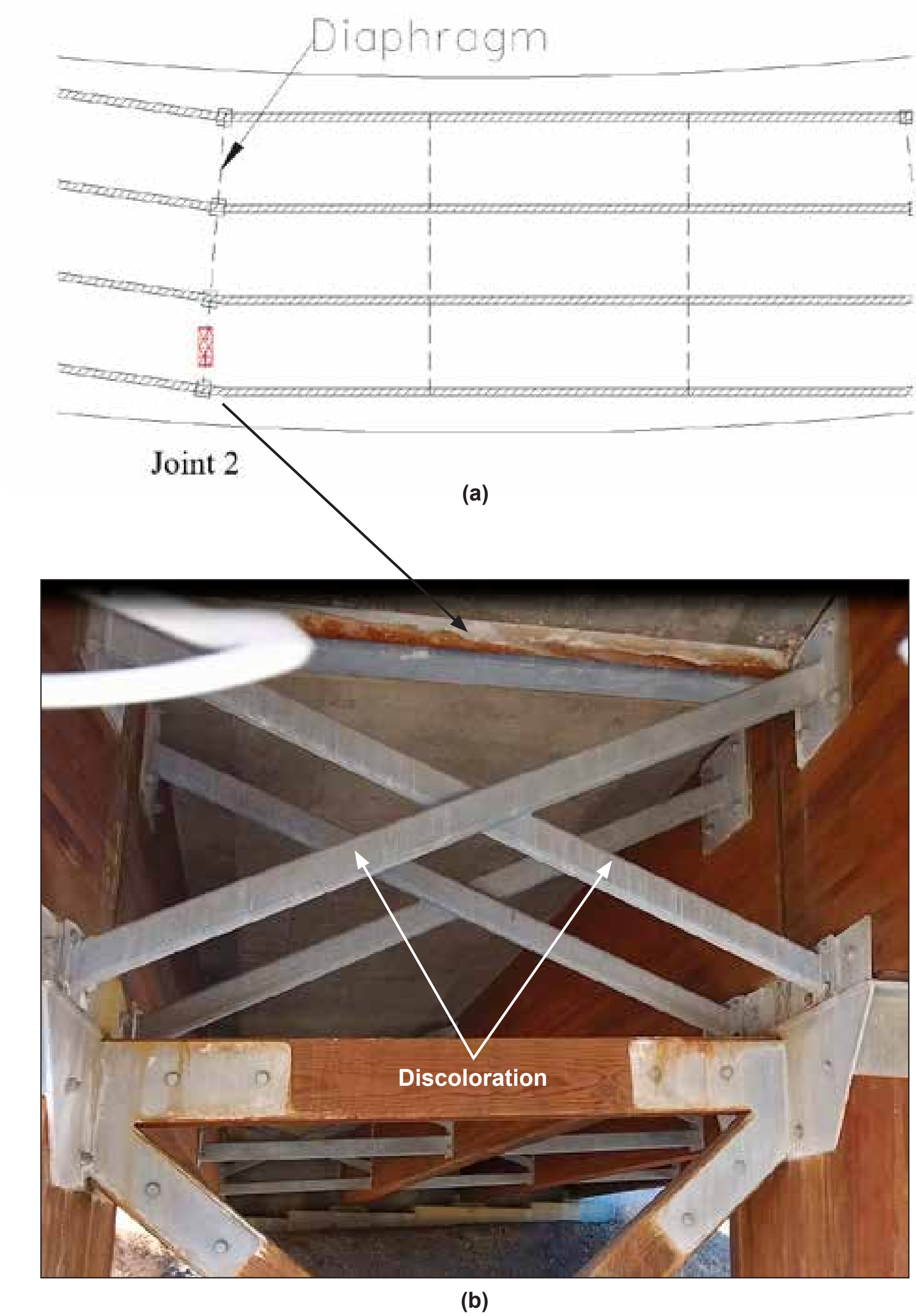


Figure 60. Sample damage on diaphragm: (a) damage location; (b) discoloration of diaphragm at Joint 2.

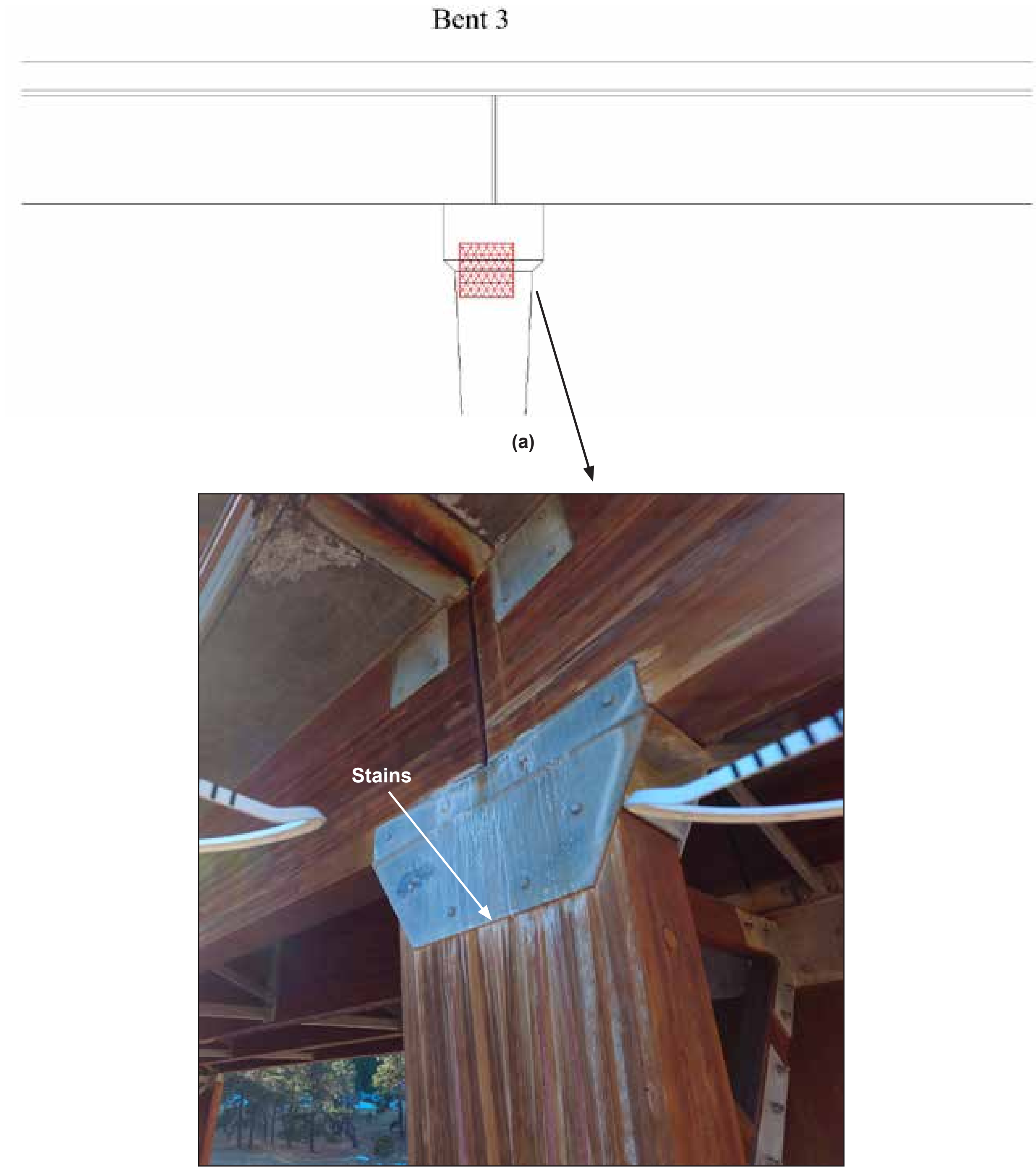
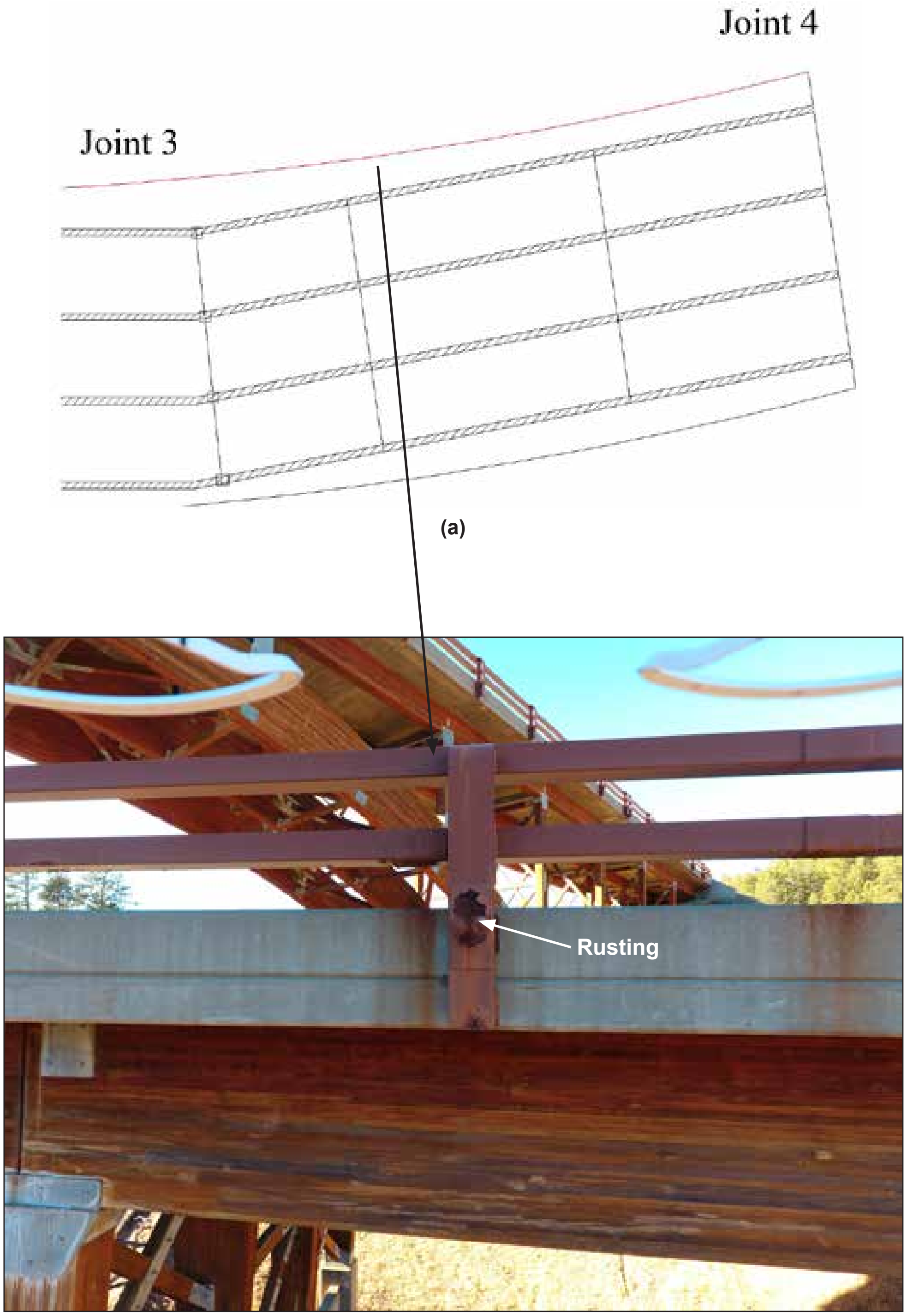


Figure 61. Sample column damage: (a) damage location; (b) stains on top of Column 4 at Bent 3.



(b)

Figure 62. Sample damage on railing: (a) damage location; (b) rusting between Joints 3 and 4 near Girder 4.

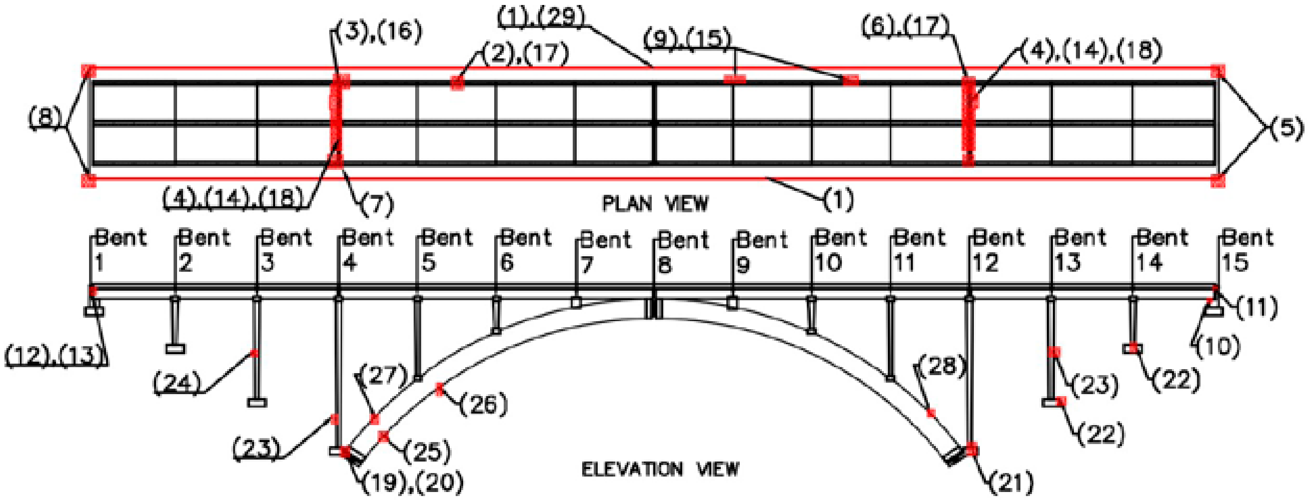


Figure 63. Damage location on Keystone Wye arch bridge. (Red rectangles in plan and elevation views indicate damage, and red lines in plan view denote minor cracks along the parapet and rusting in railing in a longitudinal direction. Numbering corresponds to damage summarized in Table 24.)

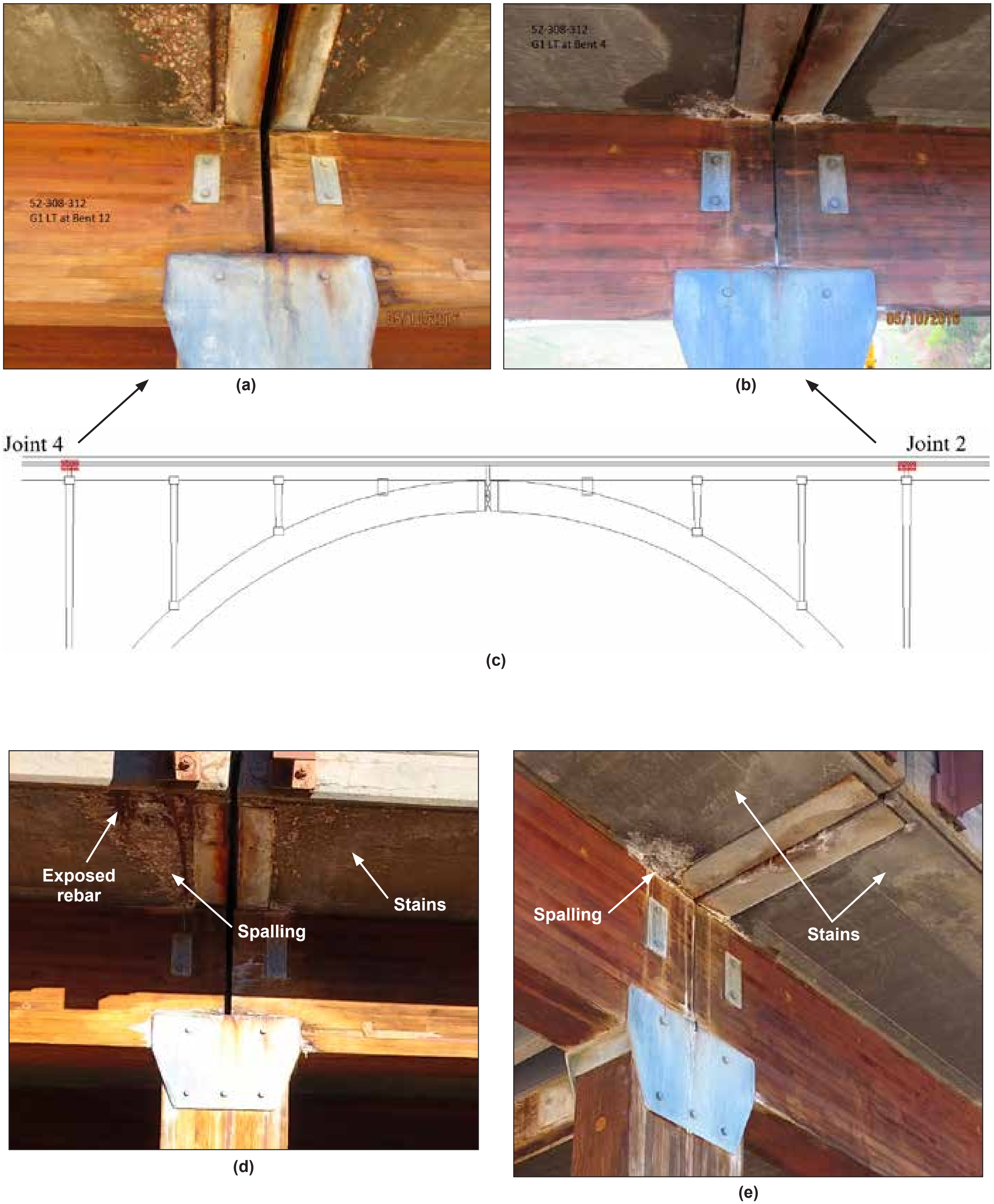


Figure 64. Sample damage on deck at Joints 2 and 4 on Stringer 1: (a) reference image of Joint 4 taken during conventional inspection (used with permission from South Dakota Department of Transportation (SDDOT)); (b) reference image of Joint 2 taken during conventional inspection (used with permission from SDDOT); (c) damage location; (d) concrete spalling, stains, and exposed corroded rebar near Stringer 1 at Joint 4; (e) concrete spalling and stains near Stringer 1 at Joint 2.

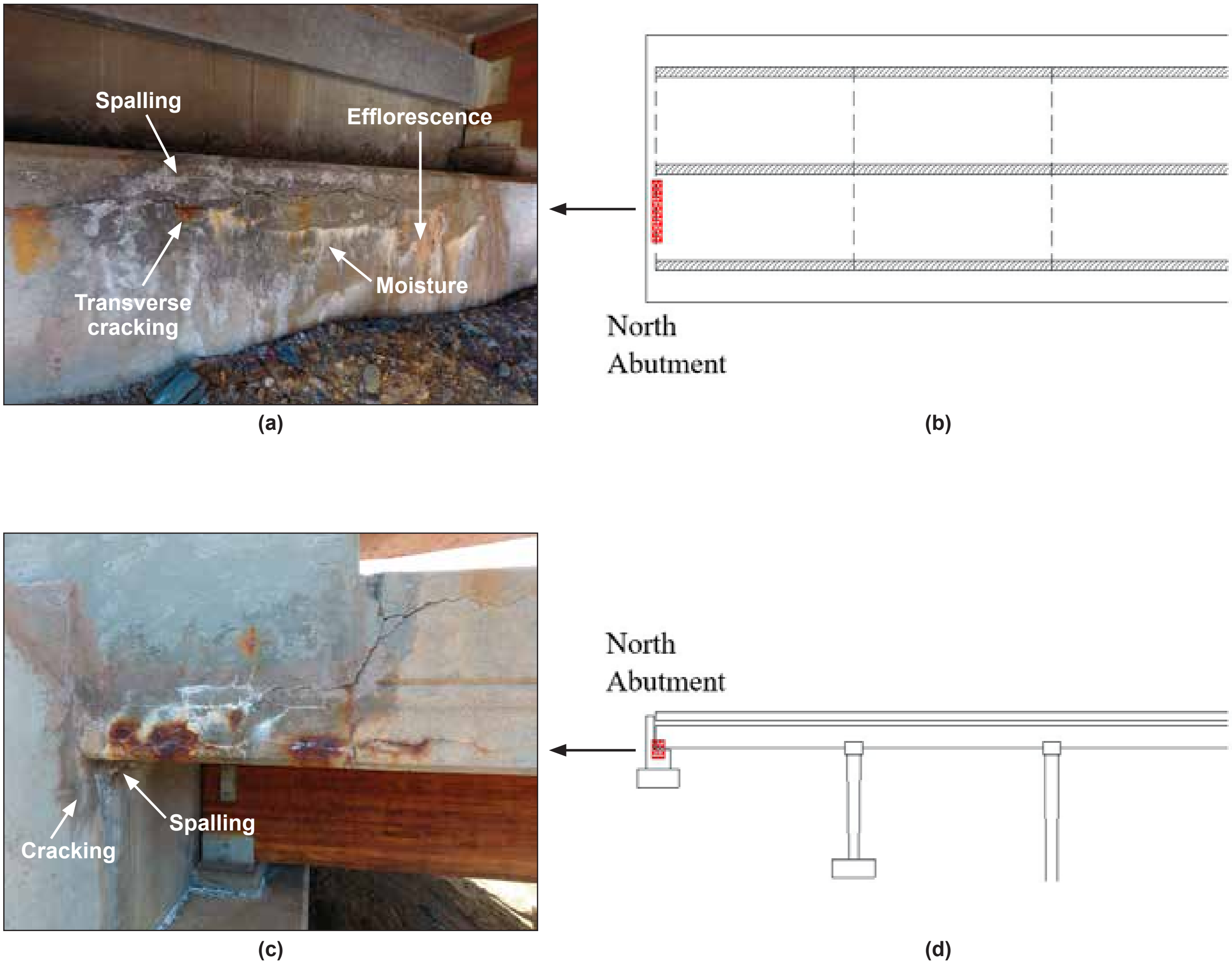


Figure 65. Sample damage on north abutment: (a) transverse concrete crack, spalling, efflorescence, and moisture on Bay 1; (b) damage location on plan view; (c) concrete cracking and spalling near Stringer 1; (d) damage location in elevation view.

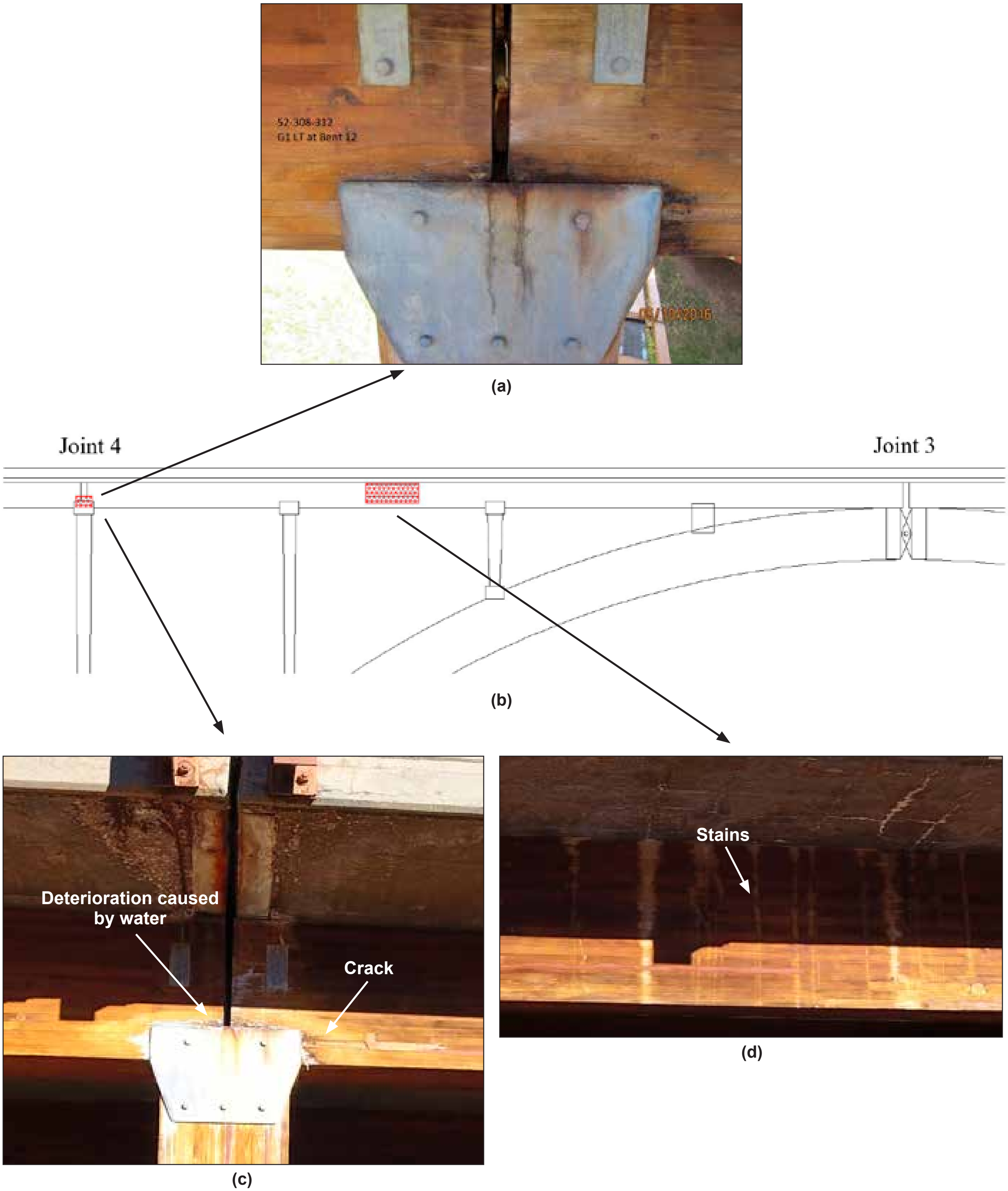


Figure 66. Sample damage on Stringer 1: (a) reference image taken during conventional inspection (used with permission from South Dakota Department of Transportation); (b) damage location; (c) shear crack and deterioration caused by water on Stringer 1 at Joint 4; (d) stains on Stringer 1 between Joints 3 and 4.

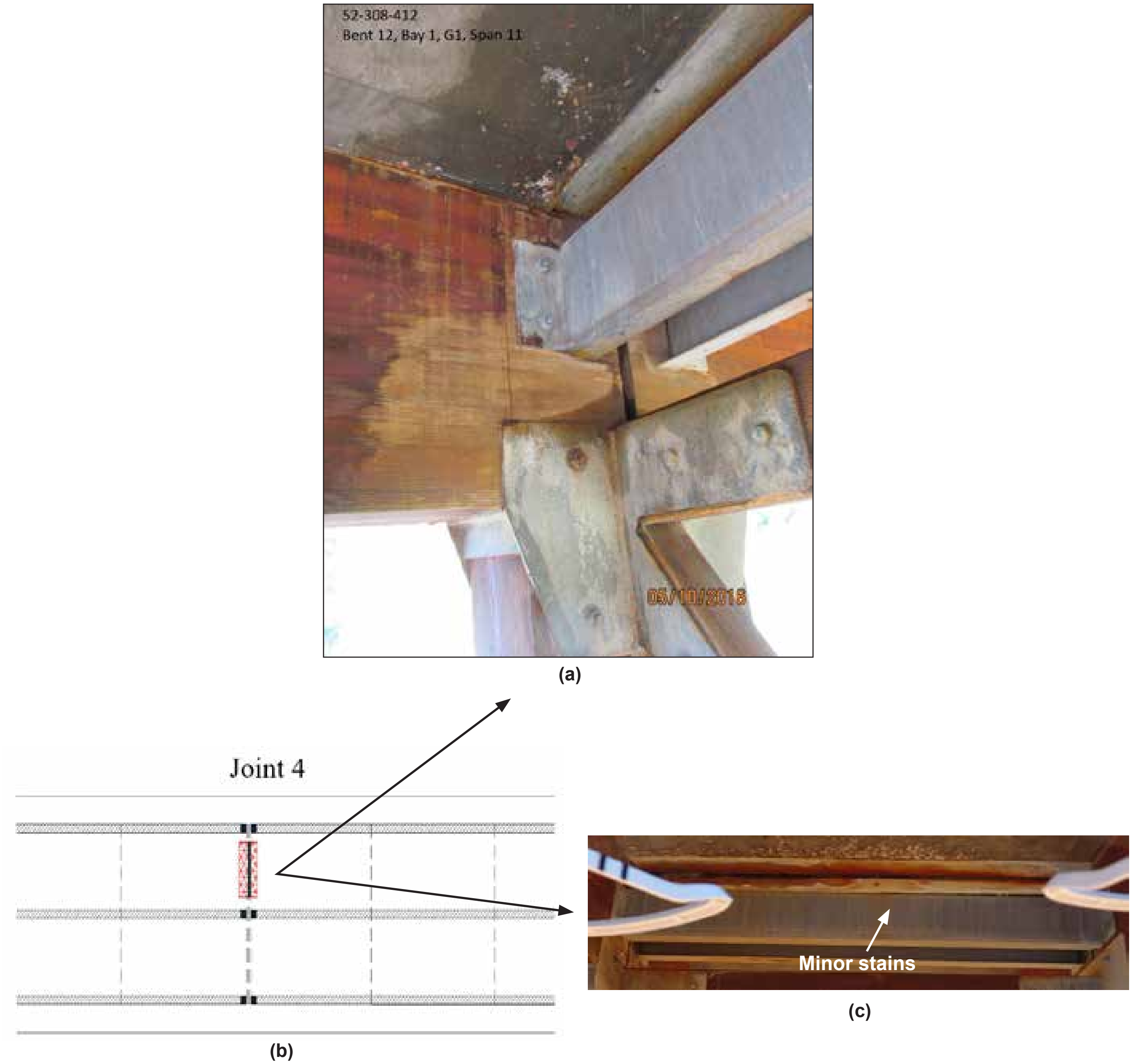
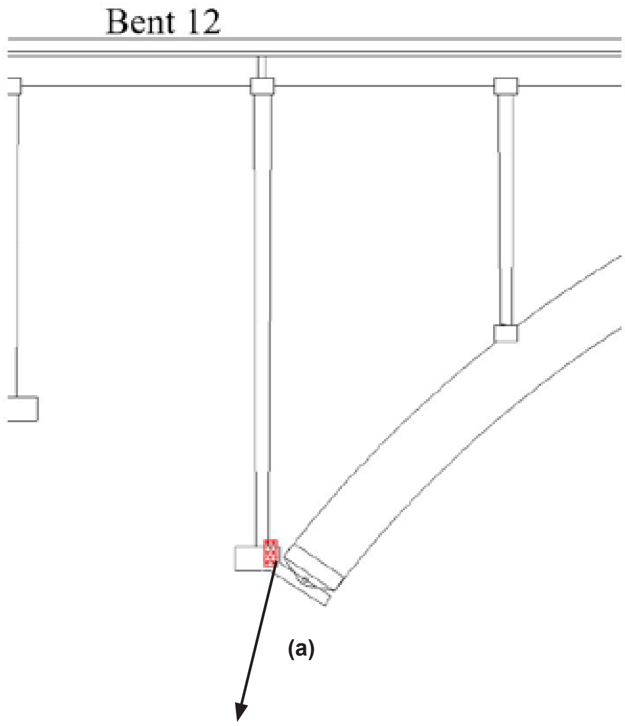
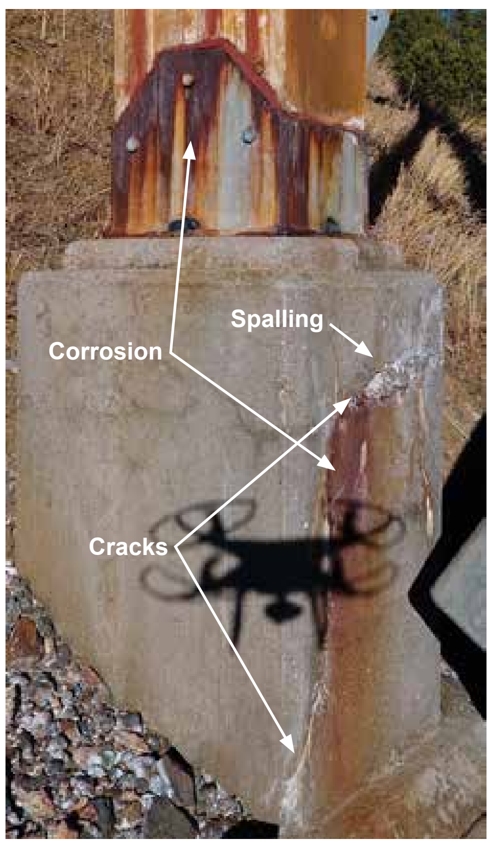


Figure 67. Sample damage on diaphragm at Joint 4: (a) reference image taken during conventional inspection (used with permission from South Dakota Department of Transportation); (b) damage location; (c) minor stains on diaphragm on Bay 1 at Joint 4.



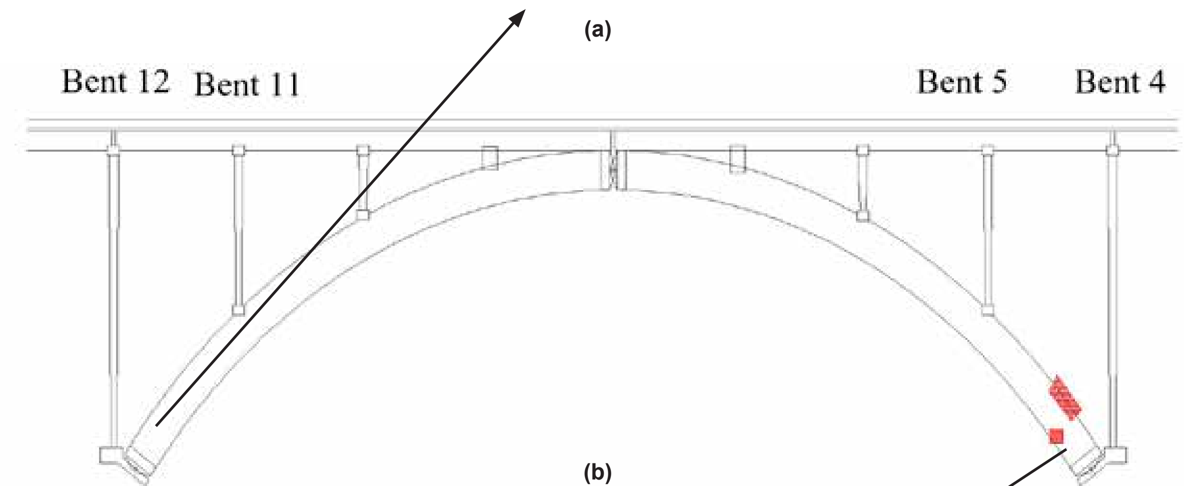
(a)



(b)

Fig. 68. Sample damage on Column 1 at Bent 12: (a) schematic of bridge; (b) concrete cracks, spalling, and corrosion on Column 1 Pedestal at Bent 12.

(a)



(b)

(c)

Figure 69. Sample damage on Arch 1: (a) reference image taken during conventional inspection (used with permission from South Dakota Department of Transportation); (b) damage location; (c) minor lam separation on Arch 1 between Bents 4 and 5.

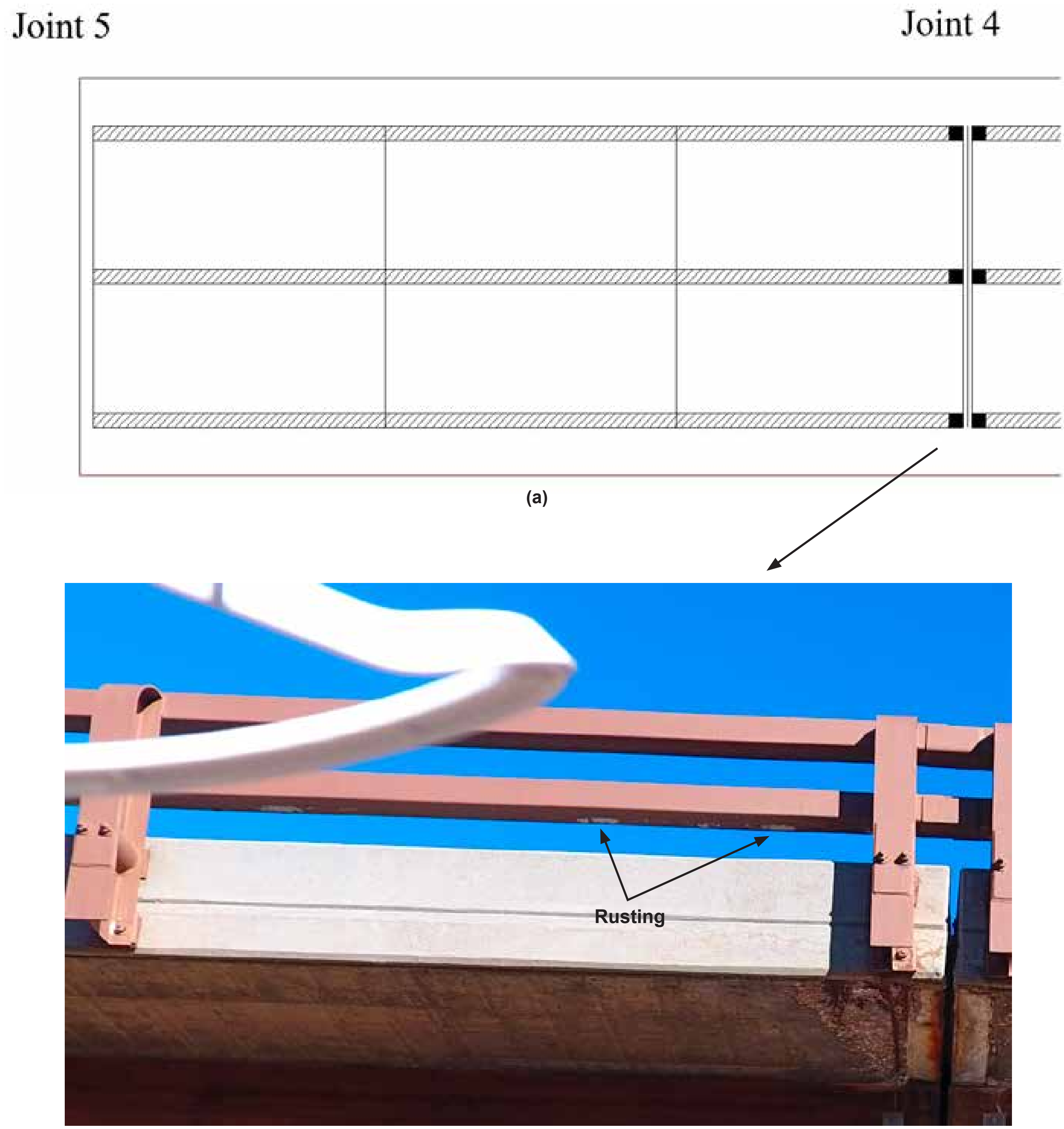


Figure 70. Sample damage on railing: (a) damage location; (b) mild rusting between Joints 4 and 5 near Stringer 1.

Appendix A—Survey to Departments of Transportation

Survey on Evaluation of UAV as bridge inspection tool at Departments of Transportation

As part of U.S. Department of Agriculture Forest Products Laboratory project led by Junwon Seo (PI), James Wacker (Co-PI) and Luis Duque (GRA), this survey is performed to gather information related to the use of Unmanned Aerial Vehicle (UAV) as bridge inspection tools by different Departments of Transportation (DOTs). The goal of this survey is not only to receive input about inspection methods the inspectors in each DOT have used and relevant challenges, but also to gather what type of data they think is necessary if they use drone technology for bridge inspection. The information will be analyzed and serve as the basis to help improve current bridge inspection techniques nationwide. The input provided by your state would be of great importance for the project success.

Q1: Does your state have use or is your state planning to use UAV for bridge inspection?

a) Yes, we have used. The drone we chose was _____________
b) Yes, we are planning to use. The drone we will choose is___________
c) No, we have not used or planning to use
d) If you answered (a) or (b), please list the attachments used if any:
   ____
   ____
   ____
   ____

Q2: If you answered yes to Q1, what techniques or data were or will be used to inspect bridges?

- o Images
- o Video
- o Thermal cameras
- o Displacement sensors
- o Other: _______________

Q3: If you answered yes to Q1, what type of data you think is the most necessary and what challenges you have faced when you use drone technology for bridge inspection?

____
____
____
____
____
____

Q4: What are your main concerns about inspecting bridges using UAV?

____
____
____
____
____
____

Q5: Does your state have either past or ongoing research projects on UAV inspection techniques. If yes, please detail the project (e.g., website, research report, etc.).

Q6: What is the research plan for UAV techniques to inspect bridges in the future?

Q7: Any additional information and comments:

Thank you for completing the survey the information collected will be highly useful for the success of the project. If you have any questions, please contact us using the information below:

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Appendix B—Caltrans Bridge Element Inspection Manual

Element #: 12 —Deck - Reinforced Concrete

Description: All reinforced concrete bridge decks regardless of the wearing surface or protection systems used.

Classification: NBE - National Bridge Element **Units of Measurement**: sq.ft.

Quantity Calculation: Area of the deck from edge to edge, including any median areas and accounting for any flares or ramps present.

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Delamination/Spall/Patched Area
(1080)</td><td>None</td><td>Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. Patched area that is sound.</td><td>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.</td><td rowspan="5">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.</td></tr>
<tr><td>Exposed Rebar
(1090)</td><td>None</td><td>Present without measurable section loss.</td><td>Present with measurable section loss, but does not warrant structural review.</td></tr>
<tr><td>Efflorescence/Rust Staining
(1120)</td><td>None</td><td>Surface white without build-up or leaching without rust staining.</td><td>Heavy build-up with rust staining.</td></tr>
<tr><td>Cracking (RC and Other)
(1130)</td><td>Insignificant cracks or moderate width cracks that have been sealed.</td><td>Unsealed moderate width cracks or unsealed moderate pattern (map) cracking. Cracks from .012 to 0.05 inches wide.</td><td>Wide cracks or heavy pattern (map) cracking. Cracks greater than 0.05 inches wide.</td></tr>
<tr><td>Abrasion/Wear (PSC/RC)
(1190)</td><td>No abrasion or wearing</td><td>Abrasion or wearing has exposed coarse aggregate but the aggregate remains secure in the concrete.</td><td>Coarse aggregate is loose or has popped out of the concrete matrix due to abrasion or wear.</td></tr>
<tr><td>Damage
(7000)</td><td>Not applicable</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary:

The deck evaluation is three dimensional in nature with the defects observed on the top surface, bottom surface, edges or all, and being captured using the defined condition states. Deck top or bottom surfaces that are not visible for inspection shall be assessed based on the available visible surface.

Defects that are visible on the soffit of this element, such as cracking or efflorescence, shall be coded as they are observed regardless of any treatments applied to the top surface of this element, such as methacrylate or polyester concrete overlay.

If both top and bottom surfaces are not visible, the condition shall be assessed based on destructive and nondestructive testing or indicators in the materials covering the surfaces.

A sound patch is constructed of concrete and is functioning similar to the original overlay material. An unsound patch is one constructed of AC or other unsuitable material or a concrete patch that is no longer sound. Patches in concrete consisting of AC or other unsuitable material shall be considered an unsound patch.

The inspector should use judgment when utilizing the condition state defect definitions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structural or non-structural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general reinforced concrete cracks less than 0.012 inches can be considered insignificant and a defect is not warranted. Cracks ranging from .012 to 0.05 inches can be considered moderate, and cracks greater than 0.05 inches can be considered wide.

The condition of the deck area within 1 foot of all joints should be recorded as part of the joint element.

Element #: 111 — Open Girder/Beam - Timber

Description: All timber open girders regardless of protection system.

Classification: NBE - National Bridge Element **Units of Measurement**: ft.

Quantity Calculation: Sum of all the lengths of each girder/beam.

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Connection (1020)</td><td>Connection is in place and functioning as intended.</td><td>Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.</td><td>Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but does not warrant a structural review.</td><td rowspan="6">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.</td></tr>
<tr><td>Decay/Section Loss (1140)</td><td>None</td><td>Affects less than 10% of the member section</td><td>Affects 10% or more of the member but does not warrant structural review.</td></tr>
<tr><td>Check/Shake (1150)</td><td>Surface penetration less than 5% of the member thickness regardless of location.</td><td>Penetrates 5% - 50% of the thickness of the member and not in a tension zone.</td><td>Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural review.</td></tr>
<tr><td>Crack (Timber) (1160)</td><td>None.</td><td>Crack that has been arrested through effective measures.</td><td>Identified crack exists that is not arrested, but does not require structural review</td></tr>
<tr><td>Split/Delamination (Timber) (1170)</td><td>None</td><td>Length less than the member depth or arrested with effective actions taken to mitigate.</td><td>Length equal to or greater than the member depth, but does not require structural review.</td></tr>
<tr><td>Abrasion/Wear (Timber) (1180)</td><td>None or no measurable section loss</td><td>Section loss less than 10% of the member thickness</td><td>Section loss 10% or more of the member thickness but does not warrant structural review.</td></tr>
<tr><td>Damage (7000)</td><td>Not applicable</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary:

Timber girders are longitudinal members that are supported by substructure elements and are significantly greater in depth than other longitudinal members that frame into floor beams. The typical timber girder element would be for glu-lam or built up timber longitudinal members.

Element #: 117 — Stringer - Timber

Description: Timber members that support the deck in a stringer floor beam system regardless of protective system.

Classification: NBE - National Bridge Element **Units of Measurement**: ft.

Quantity Calculation: Sum of all of the lengths of each stringer.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	GOOD	FAIR	POOR	SEVERE
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but does not warrant a structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Decay/Section Loss (1140)	None	Affects less than 10% of the member section	Affects 10% or more of the member but does not warrant structural review.	
Check/Shake (1150)	Surface penetration less than 5% of the member thickness regardless of location.	Penetrates 5% - 50% of the thickness of the member and not in a tension zone.	Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural review.	
Crack (Timber) (1160)	None.	Crack that has been arrested through effective measures.	Identified crack exists that is not arrested, but does not require structural review	
Split/Delamination (Timber) (1170)	None	Length less than the member depth or arrested with effective actions taken to mitigate.	Length equal to or greater than the member depth, but does not require structural review.	
Abrasion/Wear (Timber) (1180)	None or no measurable section loss	Section loss less than 10% of the member thickness	Section loss 10% or more of the member thickness but does not warrant structural review.	
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

Element Commentary:

Timber stringers are longitudinal members that are typically sawn lumber supported by other superstructure members.

Element #: 146 — Arch - Timber

Description: Only timber arches regardless of protective system.

Classification: NBE - National Bridge Element **Units of Measurement**: ft.

Quantity Calculation: Sum of all of the lengths of each arch panel measured longitudinally along the travel way.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	**GOOD**	**FAIR**	**POOR**	**SEVERE**
Connection (1020)	Connection is in place and functioning as intended.	Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.	Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but does not warrant a structural review.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Decay/Section Loss (1140)	None	Affects less than 10% of the member section	Affects 10% or more of the member but does not warrant structural review.	
Check/Shake (1150)	Surface penetration less than 5% of the member thickness regardless of location.	Penetrates 5% - 50% of the thickness of the member and not in a tension zone.	Penetrates more than 50% of the thickness of the member or more than 5% of the member thickness in a tension zone. Does not warrant structural review.	
Crack (Timber) (1160)	None.	Crack that has been arrested through effective measures.	Identified crack exists that is not arrested, but does not require structural review	
Split/Delamination (Timber) (1170)	None	Length less than the member depth or arrested with effective actions taken to mitigate.	Length equal to or greater than the member depth, but does not require structural review.	
Abrasion/Wear (Timber) (1180)	None or no measurable section loss	Section loss less than 10% of the member thickness	Section loss 10% or more of the member thickness but does not warrant structural review.	
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

Element Commentary:

Observed distress in arch diagonal and vertical members (including spandrel columns) shall be reported as the projected length along the arch. The portion of the arch below the spring line is considered substructure.

For filled arches**,** the arch quantity shall be measured from spring line to spring line; the length below the spring lines is considered substructure and shall be reported under the appropriate substructure element.

Monolithic wing walls on arches, up to the first construction joint (cold joint, felt paper, water stop or other break), shall be considered in the quantity and assessment of the substructure element below the spring line.

Element #: 205 — Column - Reinforced Concrete

Description: All reinforced concrete columns regardless of protective system.

Classification: NBE - National Bridge Element **Units of Measurement**: Each

Quantity Calculation: Sum of the number of columns.

Condition State Definitions

	Condition States			
	1	**2**	**3**	**4**
Defects	**GOOD**	**FAIR**	**POOR**	**SEVERE**
Delamination/Spall/Patched Area (1080)	None	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.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None	Present without measurable section loss.	Present with measurable section loss, but does not warrant structural review.	
Efflorescence/Rust Staining (1120)	None	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate width cracks that have been sealed.	Unsealed moderate width cracks or unsealed moderate pattern (map) cracking. Cracks from .012 to 0.05 inches wide.	Wide cracks or heavy pattern (map) cracking. Cracks greater than 0.05 inches wide.	
Abrasion/Wear (PSC/RC) (1190)	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.	
Settlement (4000)	None	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits, but is less than the critical limits determined by scour evaluation and does not warrant structural review.	

Defects	Condition States			
	1	2	3	4
	GOOD	FAIR	POOR	SEVERE
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

Element Commentary:

The inspector should use judgment when utilizing the condition state defect definitions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structural or non-structural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general reinforced concrete cracks less than 0.012 inches can be considered insignificant and a defect is not warranted. Cracks ranging from .012 to 0.05 inches can be considered moderate, and cracks greater than 0.05 inches can be considered wide.

Reinforced concrete columns constructed using the stay in place steel shell forms should use this element rather than Element #202, Steel Column if the column is fully reinforced and not reliant on the steel shell for capacity. When the steel shell is intact the RC column will be coded in CS 1.

Columns are defined as any substructure element between the ground, pile cap or obvious construction break distinguishing it from a pile, and the superstructure.

In cases of single element substructure supports, columns shall be coded if the width of the single element is less than ten feet. If the width of the element is greater than ten feet, it shall be coded as a pier wall element (Elements #210-213).

For single element substructure supports with variable widths, such as flared columns, the minimum width of the element shall be used to determine if it is a column element or pier wall element.

Scour is defined as erosion or removal of streambed or bank material around substructure or foundation elements due to river or stream flow. Scour defect elements shall only be applied to river or stream flow scour, not to erosion caused by roadway runoff.

Distress to an element resulting from erosion other than scour shall be captured with the appropriate defect element that reflects the distress, such as cracking, settlement, etc.

Element #: 215 — Abutment - Reinforced Concrete

Description: Reinforced concrete abutments. This includes the material retaining the embankment and monolithic wingwalls and abutment extensions. For all reinforced concrete abutments regardless of protective systems.

Classification: NBE - National Bridge Element **Units of Measurement**: ft.

Quantity Calculation: Sum of the width of the abutment with monolithic wingwalls and abutment extensions measured along the skew angle.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	GOOD	FAIR	POOR	SEVERE
Delamination/Spall/Patched Area (1080)	None	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.	The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.
Exposed Rebar (1090)	None	Present without measurable section loss.	Present with measurable section loss, but does not warrant structural review.	
Efflorescence/Rust Staining (1120)	None	Surface white without build-up or leaching without rust staining.	Heavy build-up with rust staining.	
Cracking (RC and Other) (1130)	Insignificant cracks or moderate width cracks that have been sealed.	Unsealed moderate width cracks or unsealed moderate pattern (map) cracking. Cracks from .012 to 0.05 inches wide.	Wide cracks or heavy pattern (map) cracking. Cracks greater than 0.05 inches wide.	
Abrasion/Wear (PSC/RC) (1190)	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.	
Settlement (4000)	None	Exists within tolerable limits or arrested with no observed structural distress.	Exceeds tolerable limits but does not warrant structural review.	
Scour (6000)	None	Exists within tolerable limits or has been arrested with effective countermeasures.	Exceeds tolerable limits, but is less than the critical limits determined by scour evaluation and does not warrant structural review.	

Defects	Condition States 1 GOOD	2 FAIR	3 POOR	4 SEVERE
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.

Element Commentary:

Monolithic wingwalls, up to the first construction joint (cold joint, felt paper, water stop or other break), shall be considered in the quantity and assessment of the abutment element. Wingwalls that are not monolithic with the abutment shall not be included in the quantity or assessment of the abutment element.

The inspector should use judgment when utilizing the condition state defect definitions, especially for concrete cracking. The crack defect description definitions describe generalized distress, but the inspector should consider width, spacing, location, orientation, and structural or non-structural nature of the cracking. The inspector should consider exposure and environment when evaluating crack width. In general, reinforced concrete cracks less than 0.012 inches can be considered insignificant and a defect is not warranted. Cracks ranging from .012 to 0.05 inches can be considered moderate, and cracks greater than 0.05 inches can be considered wide.

When abutment backwall deterioration affects both the abutment and joint, it is appropriate to capture the deterioration under both elements.

Abutments constructed of piles/columns and lagging should be coded using both an appropriate material abutment element for the lagging and appropriate material column/piles/cap elements.

Scour is defined as erosion or removal of streambed or bank material around substructure or foundation elements due to river or stream flow. Scour defect elements shall only be applied to river or stream flow scour, not to erosion caused by roadway runoff.

Distress to an element resulting from erosion other than scour shall be captured with the appropriate defect element that reflects the distress, such as cracking, settlement, etc.

Element #: 330 — Bridge Railing - Metal

Description: All types and shapes of metal bridge railing. Steel, aluminum, metal beam, rolled shapes, etc. will all be considered part of this element. Included in this element are the posts of metal, timber or concrete, blocking, and curb.

Classification: NBE - National Bridge Element **Units of Measurement**: ft.

Quantity Calculation: Number of rows of bridge rail times the length of the bridge. The element quantity includes only the rail on the bridge. Exclude pedestrian fencing or chain link fencing.

Condition State Definitions

<table>
<tr><th rowspan="3">Defects</th><th colspan="4">Condition States</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th>GOOD</th><th>FAIR</th><th>POOR</th><th>SEVERE</th></tr>
<tr><td>Corrosion
(1000)</td><td>None</td><td>Freckled Rust. Corrosion of the steel has initiated.</td><td>Section loss is evident or pack rust is present but does not warrant structural review.</td><td rowspan="4">The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the defects impact strength or serviceability of the element or bridge.</td></tr>
<tr><td>Cracking
(1010)</td><td>None</td><td>Crack that has self arrested or has been arrested with effective arrest holes, doubling plates, or similar.</td><td>Identified crack exists that is not arrested but does not warrant structural review</td></tr>
<tr><td>Connection
(1020)</td><td>Connection is in place and functioning as intended.</td><td>Loose fasteners or pack rust without distortion is present but the connection is in place and functioning as intended.</td><td>Missing bolts, rivets, broken welds, fasteners or pack rust with distortion but does not warrant a structural review.</td></tr>
<tr><td>Distortion
(1900)</td><td>None</td><td>Distortion not requiring mitigation or mitigated distortion.</td><td>Distortion that requires mitigation that has not been addressed but does not warrant structural review.</td></tr>
<tr><td>Damage
(7000)</td><td>Not applicable</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 2 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 3 under the appropriate material defect entry.</td><td>The element has impact damage. The specific damage caused by the impact has been captured in condition state 4 under the appropriate material defect entry.</td></tr>
</table>

Element Commentary:

The number of rows of rail on a bridge is commonly two, one on each side of the traveled way. In some cases there may be more than two rows when the bridge has a center median or protected pedestrian/bicycle lanes. Refer to the other bridge rail material elements (concrete, timber, masonry, other) for specific defects for assessing the condition of posts, blocking and curbs that may be constructed of materials other than metal.

Element #: 516 — Steel Protective Coating - Galvanization

Description: The element is for steel elements that have a protective galvanized coating system.

Classification: ADE – Agency Defined Element **Units of Measurement**: sq.ft. (surface)

Quantity Calculation: Should include the entire protected surface of the steel element.

Condition State Definitions

	Condition States			
	1	2	3	4
Defects	GOOD	FAIR	POOR	SEVERE
Peeling/Bubbling/Cracking (Steel Protective Coatings) (3420)	None	Finish coats only.	Finish and primer coats	Exposure of bare metal
Oxide Film Degradation Color/ Texture Adherence (Steel Protective Coatings) (3430)	Tightly adhered, capable of withstanding hammer-ing or vigorous wire brushing.	Granular texture.	Small flakes, less than 1/2 in. diameter.	Large flakes, 1/2 in. diameter or greater or laminar sheets or nodules.
Effectiveness (Steel Protec-tive Coatings) (3440)	Fully effective	Substantially effective	Limited effectiveness	Failed, no protection of the underyling metal
Damage (7000)	Not applicable	The element has impact damage. The specific damage caused by the impact has been cap-tured in condition state 2 under the appropriate material defect entry.	The element has impact damage. The specific damage caused by the impact has been cap-tured in condition state 3 under the appropriate material defect entry.	The element has impact damage. The specific dam-age caused by the impact has been captured in condi-tion state 4 under the appropriate material defect entry.

Element Commentary:

This element shall describe all galvanized coating systems.

This protective coating shall only be captured when the primary structural members are protected with galvanization.

Elements NOT requiring this coating system to be reported: Bearings (311,313,314,315, 316), Restrainer Cables (180-182), Gusset Plates (162), Pin and Hanger Assemblies (161), Secondary Cables (148-149), Bridge Railing (330-334).

Calculating Coating Areas:
Girders, stringers and floor beams with top flange embedded = 3x flange width + 2x girder depth
Girders, stringers and floor beams with top flange not embedded = 4x flange width + 2x girder depth
Trusses = 1.3x projected area of truss
Box girders, – use flat plate areas for decks, girders, and soffits; count both faces; exclude diaphragms, and secondary members.

Appendix C—Federal Aviation Administration Part 107 Rule Summary

FAA News

Federal Aviation Administration, Washington, DC 20591

June 21, 2016

SUMMARY OF SMALL UNMANNED AIRCRAFT RULE (PART 107)

Operational Limitations	• Unmanned aircraft must weigh less than 55 lbs. (25 kg). • Visual line-of-sight (VLOS) only; the unmanned aircraft must remain within VLOS of the remote pilot in command and the person manipulating the flight controls of the small UAS. Alternatively, the unmanned aircraft must remain within VLOS of the visual observer. • At all times the small unmanned aircraft must remain close enough to the remote pilot in command and the person manipulating the flight controls of the small UAS for those people to be capable of seeing the aircraft with vision unaided by any device other than corrective lenses. • Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle. • Daylight-only operations, or civil twilight (30 minutes before official sunrise to 30 minutes after official sunset, local time) with appropriate anti-collision lighting. • Must yield right of way to other aircraft. • May use visual observer (VO) but not required. • First-person view camera cannot satisfy “see-and-avoid” requirement but can be used as long as requirement is satisfied in other ways. • Maximum groundspeed of 100 mph (87 knots). • Maximum altitude of 400 feet above ground level (AGL) or, if higher than 400 feet AGL, remain within 400 feet of a structure. • Minimum weather visibility of 3 miles from control station. • Operations in Class B, C, D and E airspace are allowed with the required ATC permission. • Operations in Class G airspace are allowed without ATC permission. • No person may act as a remote pilot in command or VO for more than one unmanned aircraft operation at one time. • No operations from a moving aircraft. • No operations from a moving vehicle unless the operation is over a sparsely populated area. • No careless or reckless operations. • No carriage of hazardous materials.

	• Requires preflight inspection by the remote pilot in command. • A person may not operate a small unmanned aircraft if he or she knows or has reason to know of any physical or mental condition that would interfere with the safe operation of a small UAS. • Foreign-registered small unmanned aircraft are allowed to operate under part 107 if they satisfy the requirements of part 375. • External load operations are allowed if the object being carried by the unmanned aircraft is securely attached and does not adversely affect the flight characteristics or controllability of the aircraft. • Transportation of property for compensation or hire allowed provided that- o The aircraft, including its attached systems, payload and cargo weigh less than 55 pounds total; o The flight is conducted within visual line of sight and not from a moving vehicle or aircraft; and o The flight occurs wholly within the bounds of a State and does not involve transport between (1) Hawaii and another place in Hawaii through airspace outside Hawaii; (2) the District of Columbia and another place in the District of Columbia; or (3) a territory or possession of the United States and another place in the same territory or possession. • Most of the restrictions discussed above are waivable if the applicant demonstrates that his or her operation can safely be conducted under the terms of a certificate of waiver.
Remote Pilot in Command Certification and Responsibilities	• Establishes a remote pilot in command position. • A person operating a small UAS must either hold a remote pilot airman certificate with a small UAS rating or be under the direct supervision of a person who does hold a remote pilot certificate (remote pilot in command). • To qualify for a remote pilot certificate, a person must: o Demonstrate aeronautical knowledge by either: ▪ Passing an initial aeronautical knowledge test at an FAA-approved knowledge testing center; or ▪ Hold a part 61 pilot certificate other than student pilot, complete a flight review within the previous 24 months, and complete a small UAS online training course provided by the FAA. o Be vetted by the Transportation Security Administration. o Be at least 16 years old. • Part 61 pilot certificate holders may obtain a temporary remote pilot certificate immediately upon submission of their application for a permanent certificate. Other applicants will obtain a temporary remote pilot certificate upon successful completion of TSA security vetting. The FAA anticipates that it will be able to issue a temporary remote pilot certificate within 10 business days after receiving a completed remote pilot certificate application. • Until international standards are developed, foreign-

	certificated UAS pilots will be required to obtain an FAA-issued remote pilot certificate with a small UAS rating. A remote pilot in command must: • Make available to the FAA, upon request, the small UAS for inspection or testing, and any associated documents/records required to be kept under the rule. • Report to the FAA within 10 days of any operation that results in at least serious injury, loss of consciousness, or property damage of at least $500. • Conduct a preflight inspection, to include specific aircraft and control station systems checks, to ensure the small UAS is in a condition for safe operation. • Ensure that the small unmanned aircraft complies with the existing registration requirements specified in § 91.203(a)(2). A remote pilot in command may deviate from the requirements of this rule in response to an in-flight emergency.
Aircraft Requirements	• FAA airworthiness certification is not required. However, the remote pilot in command must conduct a preflight check of the small UAS to ensure that it is in a condition for safe operation.
Model Aircraft	• Part 107 does not apply to model aircraft that satisfy all of the criteria specified in section 336 of Public Law 112-95. • The rule codifies the FAA’s enforcement authority in part 101 by prohibiting model aircraft operators from endangering the safety of the NAS.

Appendix D—Da-Jiang Innovations (DJI) Phantom 4 Specifications

AIRCRAFT

Weight (Battery & Propellers Included)	1380 g
Diagonal Size (Propellers Excluded)	350 mm
Max Ascent Speed	S-mode: 6 m/s
Max Descent Speed	S-mode: 4 m/s
Max Speed	S-mode: 20 m/s
Max Tilt Angle	S-mode: 42° A-mode: 35° P-mode: 15°
Max Angular Speed	S-mode: 200°/s A-mode: 150°/s
Max Service Ceiling Above Sea Level	19685 feet (6000 m)
Max Wind Speed Resistance	10 m/s
Max Flight Time	Approx. 28 minutes
Operating Temperature Range	32° to 104°F (0° to 40°C)
Satellite Positioning Systems	GPS/GLONASS
Hover Accuracy Range	Vertical: ±0.1 m (with Vision Positioning) ±0.5 m (with GPS Positioning) Horizontal: ±0.3 m (with Vision Positioning) ±1.5 m (with GPS Positioning)

VISION SYSTEM

Vision System	Forward Vision System Downward Vision System
Velocity Range	≤10 m/s (2 m above ground)
Altitude Range	0 - 33 feet (0 - 10 m)
Operating Range	0 - 33 feet (0 - 10 m)
Obstacle Sensory Range	2 - 49 feet (0.7 - 15 m)
FOV	Forward: 60°(Horizontal), ±27°(Vertical) Downward: 70°(Front and Rear), 50°(Left and Right)
Measuring Frequency	Forward: 10 Hz Downward: 20 Hz
Operating Environment	Surface with clear pattern and adequate lighting (lux>15)

REMOTE CONTROLLER

Operating Frequency	2.400 - 2.483 GHz
Max Transmission Distance	FCC Compliant: 3.1 mi (5 km) CE Compliant: 2.2 mi (3.5 km) (Unobstructed, free of interference)
Operating Temperature Range	32° to 104°F (0° to 40°C)
Battery	6000 mAh LiPo 2S
Transmitter Power (EIRP)	FCC: 23 dBm CE: 17 dBm
Operating Current/Voltage	1.2 A@7.4 V
Video Output Port	USB
Mobile Device Holder	Tablets and smart phones

INTELLIGENT FLIGHT BATTERY

Capacity	5350 mAh
Voltage	15.2 V
Battery Type	LiPo 4S
Energy	81.3 Wh
Net Weight	462 g
Charging Temperature Range	41° to 104°F (5° to 40°C)
Max Charging Power	100 W

GIMBAL

Stabilization	3-axis (pitch, roll, yaw)
Controllable Range	Pitch: -90° to +30°
Max Controllable Angular Speed	Pitch: 90°/s
Angular Control Accuracy	±0.02°

CAMERA

Sensor	1/2.3” CMOS Effective pixels:12.4 M
Lens	FOV 94° 20 mm (35 mm format equivalent) f/2.8 focus at ∞
ISO Range	100-3200 (video) 100-1600 (photo)
Electronic Shutter Speed	8 - 1/8000 s
Image Size	4000×3000

Still Photography Modes	Single shot Burst shooting: 3/5/7 frames Auto Exposure Bracketing (AEB): 3/5 bracketed frames at 0.7 EV Bias Timelapse HDR
Video Recording Modes	UHD: 4096×2160 (4K) 24 / 25p 3840×2160 (4K) 24 / 25 / 30p 2704×1520 (2.7K) 24 / 25 / 30p FHD: 1920×1080 24 / 25 / 30 / 48 / 50 / 60 / 120p HD: 1280×720 24 / 25 / 30 / 48 / 50 / 60p
Max Video Bitrate	60 Mbps
Supported File Systems	FAT32 (≤32 GB); exFAT (>32 GB)
Photo	JPEG, DNG (RAW)
Video	MP4, MOV (MPEG-4 AVC/H.264)
Supported SD Cards	Micro SD Max capacity: 64 GB Class 10 or UHS-1 rating required
Operating Temperature Range	32° to 104°F (0° to 40°C)

CHARGER

Voltage	17.4 V
Rated Power	100 W

APP / LIVE VIEW

Mobile App	DJI GO
Live View Working Frequency	2.4 GHz ISM
Live View Quality	720P @ 30fps
Latency	220ms (depending on conditions and mobile device)
Required Operating Systems	iOS 8.0 or later Android 4.1.2 or later
Recommended Devices	ios: iPhone 5s, iPhone 6, iPhone 6 Plus, iPhone 6s, iPhone 6s Plus, iPod touch 6, iPad Pro, iPad Air, iPad Air Wi-Fi + Cellular, iPad mini 2, iPad mini 2 Wi-Fi + Cellular, iPad Air 2, iPad Air 2 Wi-Fi + Cellular, iPad mini 3, iPad mini 3 Wi-Fi + Cellular, iPad mini 4, and iPad mini 4 Wi-Fi + Cellular. This app is optimized for iPhone 5s, iPhone 6, iPhone 6 Plus, iPhone 6s and iPhone 6s Plus. Android: Samsung tabs 705c, Samsung S6, Samsung S5, Samsung NOTE4, Samsung NOTE3, Google Nexus 9, Google Nexus 7 II, Ascend Mate7, Huawei Mate 8, Nubia Z7 mini, SONY Xperia Z3, MI 3, MI PAD

*Support for additional Android devices available as testing and development continues.

Appendix E—South Dakota Department of Transportation Inspection Report for Timber Girder Bridge

Structure Number: 52-308-411 Date: 05/10/2016 Page 1 of 11

BRIDGE INSPECTION REPORT

Structure Number 52-308-411 **Maint Proj No.** 016A-W -491

Feature Carried US 16AW **MRM** 59.46 **County** Pennington

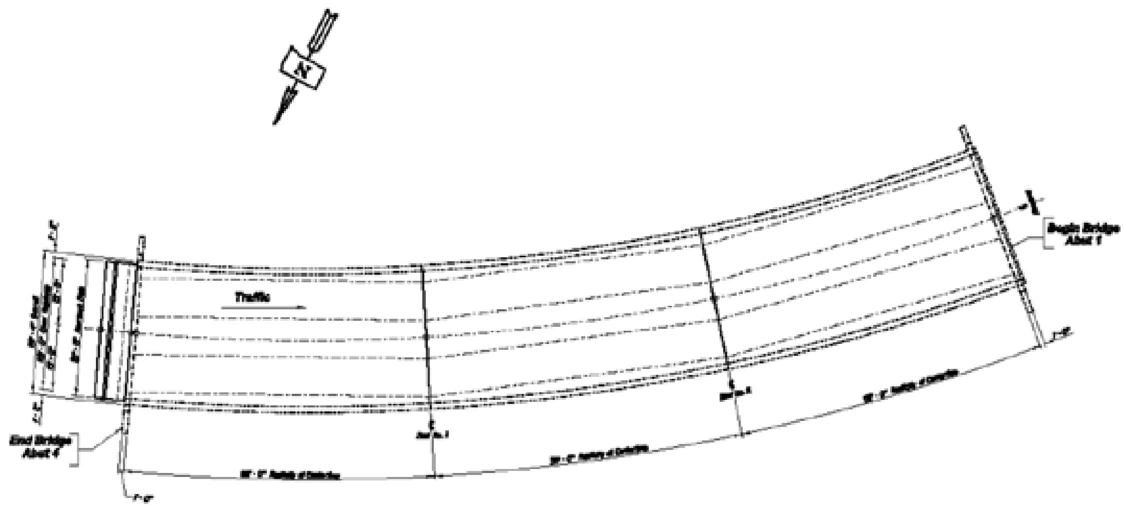
Feature Crossed US 16E

Location Keystone Interchange

Bridge Description 170'- 0" Three span timber girder bridge

26'-0" roadway X901 Built 1968

Orientation sketch



Date Inspected	Inspector(s)	Crew Leader's Signature	Temperature
05/22/2012	Sauter, Neiderworder	Signed by R. Sauter	86° F
05/21/2014	Kamarainen		58° F
05/10/2016	Kamarainen		57° F
			° F
			° F

REGION REPAIR RECOMMENDATIONS/CONTRACT REPAIRS

2013 Project NH0016(81)50, PCN 0362: Mill and overlay up to Abut 4 sleeper slab and shortening of w-beam guardrail on the Abut 4 end.

APPROACH: ITEMS 65.00 - 65.09

(1) Alignment Structure is on 15º horizontal curve and -0.513% vertical grade. Approximately 6' at begin bridge is on the end of a 200' vertical curve. Traffic is one-way and is from Abutment 4 end to Abutment 1 end. Sight distance is limited.

(2) Condition
Previous inspection(s):
5/22/2012: Four foot strip of asphalt between approach PCC pavement and Abut 1 end of bridge. Asphalt has some raveling edges, 1" to 2" gaps to the approach pavement and to the end of the bridge, and the asphalt is higher than both the bridge and the approach pavement. Approach slab (approx. 4' length) and sleeper slab at Abut 4 end of bridge. The approach slab has 4 longitudinal cracks and the sleeper slab has several longitudinal cracks. The approach pavement off the sleeper slab has longitudinal cracks.
5/21/2014: No change except:
Abut 4: Mill and overlay performed in 2013 up to sleeper slab has corrected any deficiencies in the Abut 4 approach pavement.
5/10/2016:
Abut 4: Sleeper slab lug has 6 longitudinal HL cracks and the approach slab has fine random cracks in the right ½.

(3) Joints
Previous inspection(s):
5/22/2012: Strip seal joint between approach slab and sleeper slab at Abut 4 end of bridge. Strip seal filled with dirt, but gland appears intact.
5/21/2014: No change except:
Abut 1 RT asphalt approach/approach PCC joint has RT corner damage 4"x8".
5/10/2016:
No change.

(4) Guard Rails Weathering steel W beam left and right at the Abut 4 "on" end and at Abut 1 left "off" end. W beam is attached to end blocks on the bridge and rub rail is provided at the Abut 4 end only. The Abut 4 approach rail terminals are ET2000. The Abut 4 left rail is on the outside of the horizontal curve and has a trailing end shoe terminal. Rail on the one-way roadway beneath the structure is weathering steel W beam on both sides with ET2000 terminals on the "on" end and trailing end shoes on the off end.
Previous inspection(s):
5/22/2012: Rail is in good condition.
5/21/2014: No change except:
Abut 1 RT has previous w-beam connection still in place at the bridge end block.
5/10/2016:
No change.

(5) Embankment
Previous inspection(s):
5/22/2012: Erosion at Abut 4 right.
5/21/2014: No change except:
Erosion at Abut 4 was corrected on the shoulder of pavement, but washout further down the slope still remains.
5/10/2016:

No change.

(6) Drainage
Previous inspection(s):
5/22/2012: Curb and gutter on right side at both ends of bridge. Drop inlet off end of bridge at Abut 1 right is open.
5/21/2014: No change.
5/10/2016:
No change.

(7) Signing
Previous inspection(s):
5/22/2012: 35 mph speed limit. Object markers at Abut 4 “on” end only. Abut 4 left object marker is loose.
5/21/2014: No change.
5/10/2016:
No change.

DECK: ITEMS 58.00 - 58.17

(1) Deck Condition

(1A) Deck Cracking
Previous inspection(s):
5/22/2012: Transverse cracks in deck where ECS has worn off.
5/21/2014: No change.
5/10/2016: No change.

(1B) Deck Scaling
Previous inspection(s):
5/22/2012: None.
5/21/2014: No change.
5/10/2016: No change.

(1C) Deck Spalling
Previous inspection(s):
5/22/2012: Several spalls in span 1 and adjacent to Abut 4 in span 3were repaired in 2011.
Repairs are in good condition. Several rust stains through the epoxy chip seal from rebar with lack of clear cover.
5/21/2014: No change except:
There are a few small spalls/popouts where the ECS has failed and aggregate in the concrete is exposed in span 3. The adjacent areas also appear to be delaminated.
5/10/2016:
A number of deck spalls and delaminations were repaired in April 2015.

(1D) Deck Delaminations
Previous inspection(s):
5/22/2012: Deck delam check May 2011 = 256 sf, 5.8%.
5/21/2014: No change except:
Areas adjacent to spalls/popouts are delaminated. August 2013 delam check = 240 sf / 5.4%
5/10/2016:
A number of deck spalls and delaminations were repaired in April 2015.
April 2015 delam check = 195 SF, 4.05%
A few small shallow spalls are visible including (3) approx. 4”x4” spalls in span 1 and (2) approx. 4”x4” spalls in span 3.

(2) Overlay
(2A) Type of Overlay Epoxy chip seal in 2004.

(2B) Overlay Thickness 0.12”

(2C) Overlay Condition
Previous inspection(s):
5/22/2012: ECS is thin and scraped in several spots.
5/21/2014: No change except:
There are a few small spalls/popouts where the ECS has failed and aggregate in the concrete is exposed in span 3.
5/10/2016:

ECS has failed where spalling/patching is present.

(3) Joints
Previous inspection(s):
5/22/2012: Compression seals at Bents 2 & 3. Dirt on seals, but glands appear intact from the top. Joints on underside have evidence of past leakage with rust staining.
5/21/2014: No change except:
Seals at bents are full of dirt. Seals are turned up at the curbs which causes water to pool at the curb on the right side of the bridge. Leakage through the joint where water pools is apparent from below.
- Bent 3 compression seal adhesion to armor angle is beginning to fail.
5/10/2016:
No change.

(4) Drains NA

(5) Curbs and Median
Previous inspection(s):
5/22/2012: Curbs have vertical cracks in the face and transverse cracks on top. Curbs have some exposed rebar. Abut 1 left & right and Abut 4 right curb at end block is cracking.
5/21/2014: No change.
5/10/2016:
No change.

(6) Sidewalks NA

(7) Railing or Barrier
Previous inspection(s):
5/22/2012: Steel 2 tube, modified to be continuous, RT-2 railing with face not set flush with the face of the curb. Abut 1 right end block end has diagonal cracks and is spalling. Abut 4 right end block back has diagonal cracks.
5/21/2014: No change except:
Abut 1 LT & RT end blocks (exterior) have map cracking and discoloration at bottom. RT side also has rust staining.
Abut 4 RT end block (exterior) has map cracking, scaling, delam, and spalling.
5/10/2016:
No change.

(7A) Railing Paint
Previous inspection(s):
5/22/2012: Rail has mild rust throughout. Abut 1 RT rail at end block has moderate rust. Rail posts have moderate rust.
5/21/2014: No change except:
Rail posts have some heavy rust. Paint is peeling in locations throughout, especially on the RT railing.
5/10/2016:
No change.

(8) Lighting NA

(9) Utilities NA

JOINT OPENINGS

Date	Temp °F	Joint Location/Type								
		Bent 2 Compression Seal			Bent 3 Compression Seal			Abutment 4 Approach Strip Seal		
		Joint Opening – Measured								
		Left	Center	Right	Left	Center	Right	Left	Center	Right
5/2012	86°	1-1/8”	7/8”	1-3/16”	1-1/8”	1-1/4”	1-1/4”	2”	2”	2”
5/2014	58°	1”	7/8”	1”	1-1/4”	1”	1”	1-1/2”	1-1/2”	1-3/8”
5/2016	-	-	-	-	-	-	-	-	-	-

SUPERSTRUCTURE: ITEMS 59.00 - 59.20

(1) Underside of Deck

Previous inspection(s):

5/22/2012: Span 1 Bay 2 has 7' length by bay width of scaling, delamination & efflorescence at mid-span. Span 1 Bay 3 and the right cantilever also have scaling, discoloration and efflorescence. The left cantilever at Bent 2 has discoloration. The right cantilever at Bent 2 has cracking, delamination, discoloration and efflorescence. The deck adjacent to the Bent 2 joint in Bays 2 & 3 has cracking and minor scaling. The deck adjacent to the Bent 3 joint has scaling, cracking & delamination in Bays 2 & 3; the left cantilever has cracking and discoloration; the right cantilever has scaling, cracking, delamination, discoloration & efflorescence. The edge of deck has vertical & horizontal cracking, discoloration and efflorescence. The end of deck at Abut 4 right is spalling and has exposed rebar. Edge & underside of deck at Abut 1 right and Abut 4 right at end block & back of curb is cracking and has discoloration & efflorescence.

5/21/2014: No change.

5/10/2016:

Significant delaminations on underside of deck correspond with patching on top side of deck. The right cantilever at Bents 2 and 3 have deteriorated to the point where rebar is exposed.

Span 2, Bay 2 has a 1'x 2' area of spalling with exposed rebar.

(2) Bearing Devices

Previous inspection(s):

5/22/2012: Bearing devices at Bents 2 & 3 beam to column connections consist of galvanized steel brackets with horizontal plates for beam bearing, vertical side plates & stiffening plates. Bearing devices at Abutments 1 & 4 consist of galvanized steel shoes with masonry plates and vertical side plates. All bearing devices include ½" neoprene bearing pads between the timber girders and the steel bearing surfaces. Bearing devices are attached with through bolts and shear plates for beam to bracket, beam to shoe and bracket to column connections. Neoprene bearing pads are working out of bearings: 2" to 2 ½" at Bent 2 Span 2, 1" to 2" at Bent 3 Span 2, to 1" at Bent 3 Span 3. There is a gap between the neoprene bearing pad and the steel bracket at Girder 3 Span 1 Bent 2. Devices are unsealed to timber girders. Moisture and debris are trapped in devices between the ends of both interior and exterior girders at the bents, causing deterioration of the girder ends. The bracket below the neoprene pad at Girder 3 Span 1 Bent 2 is rusty.

5/21/2014: No change except:

Water is pooled in between ends of girders at Bent 2 - G3 & G4. Ends of girders are wet without pooling water at Bent 3 - G2, G3, & G4. In these areas that are damp, bolt washers on the connection plates have heavy rust with minor section loss.

5/10/2016: No change.

(3) Girders or Beams

Previous inspection(s):

5/22/2012: Girders are glue laminated timber—4 lines of simple spans. Girders are generally good, but have a few horizontal cracks. Some of the cracks were sealed with the 2009 staining project. The bottoms of the girders at the supports have discoloration and decay due to the trapped moisture and debris at the bearings. Girder 1 in Span 2 has the bottom edge (2" x 2" x 10' over driving lane) cracking off. See Item 13 below also.

5/21/2014: No change except:

G3 LT at 10' from Bent 3 has a surface scratch. Decay continues at girder ends where water is leaking through joints and becoming trapped on top of columns.

5/10/2016: No change.

(3A) Stiffeners NA

(3B) Welds
Previous inspection(s):
5/22/2012: Brackets and diaphragms have welds—good.
5/21/2014: No change.
5/10/2016: No change.

(3C) Splices NA

(4) Diaphragms
Previous inspection(s):
5/22/2012: Diaphragms at bent supports and one-third points of spans are galvanized steel tube cross frames. Diaphragms at abutments are galvanized steel channels. Good condition.
5/21/2014: No change except:
Diaphragms have slight discoloration where water has been present.
5/10/2016: No change.

(5) Trusses NA

(7) Rivets or Bolts
Previous inspection(s):
5/22/2012: Through bolts with shear plates at bearing devices and diaphragms. Bolts good except there are a few rusty washers on bolts at the brackets.
5/21/2014: No change except:
In areas that have been wet, bolt washers on the connection plates have heavy rust with minor section loss.
5/10/2016: No change.

(8) Welds See 3B.

(9) Paint
Previous inspection(s):
5/22/2012: Structure was cleaned and stained in 2009. There is some deterioration of the stain throughout. Stain is deteriorating at ends of girders as noted in Item 3.
5/21/2014: No change.
5/10/2016: No change.

(10) Drainage System NA

(11) Utilities NA

(12) Reaction Under Load None noted.

(13) Collision Damage
Previous inspection(s):
5/22/2012: Span 2 Girders 3 & 4 have previous traffic impact damage that was repaired. Span 2 Girder 1 has a minor spot of impact damage over the driving lane.
5/21/2014: No change.
5/10/2016: No change.

SUBSTRUCTURE: ITEMS 60.00 - 60.05

(1) Abutments

(1A) Wingwalls
Previous inspection(s):
5/22/2012: Abut 4 left WW back is spalled off and has exposed rebar.
5/21/2014: No change except:
Abut 1 RT WW outside of G4 has efflorescence, scaling, and spalling. Abut 1 LT expansion material is wet and there is a small spall at bottom of deck corner.
5/10/2016: No change.

(1B) Backwalls
Previous inspection(s):
5/22/2012:
Abut 1 BW:
- Bays 1 & 2 have scaling and spalling at top.

Abut 4 BW:
- Top of BW is spalling at G1 and under left & right deck cantilevers.
- BW has significant scaling in Bay 2 and Bay 3.

5/21/2014: No change except:
Abut 4:
- Delaminated areas left of center in Bay 2, behind G3, and in Bay 3.

5/10/2016: No change.

(1C) Footings
Previous inspection(s):
*5/22/2012:*Abutment sills are good.
5/21/2014: No change.
5/10/2016: No change.

(2) Piers or Bents

(2A) Caps No caps. Girders are supported directly by columns through steel brackets.

(2B) Columns
Previous inspection(s):
5/22/2012: Glue laminated timber columns. Columns have some checking with some of the cracks sealed. Timber columns are supported by steel brackets on concrete pedestals. Include the concrete pedestals in the Pontis elements as concrete columns—one at each timber column. Concrete column pedestals:
Bent 2 has horizontal crack along Bay 3 wall on Span 2 side and crack along top of left side of Column 3 pedestal.
Bent 3 right end of pedestal has a spall with exposed rebar and there are vertical cracks at top of left side of Column 3 and left side of Column 4.
5/21/2014: No change except:
Bent 2:
- Horizontal crack noted previously along Bay 3 wall on Span 2 side actually appears to be in Bay 2.
- C4 pedestal LT has horizontal crack.
- Longitudinal crack on top of wall in Bay 2.

5/10/2016: No change.

(2C) Footings Pile footings not visible.

(3) Grout Pads
Previous inspection(s):
5/22/2012: Abut 1 grout pads: vertical cracks on right side of G1 and left side of G3.
5/21/2014: No change except:
Abut 4: G1 ground pad has a crack on the RT corner.
5/10/2016: No change.

(4) Anchor Bolts
Previous inspection(s):
5/22/2012: Swedge bolts at column brackets to concrete pedestals (not visible) and abutment bearings--good.
5/21/2014: No change.
5/10/2016: No change.

(5) Piles 12BP53 steel piles at abutments and bents.

(6) Bracing
Previous inspection(s):
5/22/2012: Glue laminated timber bracing for bents. Good condition.
5/21/2014: No change.
5/10/2016: No change.

(7) Paint
Previous inspection(s):
5/22/2012: Structure was cleaned and stained in 2009. There is some deterioration of the stain throughout.
5/21/2014: No change.
5/10/2016: No change.

(8A) Movement-Plumbness Appears plumb.

(8B) Movement-Settlement No apparent settlement.

(8C) Movement-Horizontal No apparent horizontal movement.

52-308-411

Year	Item No.	Item Description	Total Quantity	Units	Condition State Quantity			
					CS 1 Good	CS 2 Fair	CS 3 Poor	CS 4 Severe
2016								
	321	RC Approach Slab	158	SF	148	10	0	0
	1130	Cracking	38		28	10		
	820	Epoxy Resteel	316	SF	316	0	0	0
	300	Strip Seal Expansion Joint	28	LF	28	0	0	0
	2350	Debris Impaction	28		28			
	12	RC Deck	4,816	SF	4,654	156	6	0
	1080	Delam/Spall	98			98		
	1090	Exposed Rebar	2			2		
	1120	Efflorescence	8			8		
	1130	Cracking	240		240			
	1190	Abrasion/Scaling	54			48	6	
	1080	Spall/Delam	99			99		
	1090	Exposed Rebar	6			6		
	1120	Efflorescence	2,160			57		
	1130	Cracking	2,160		246			
	812	Epoxy Chip Seal	4,420	SF	3,923	0	221	276
	3230	Effectiveness	497				221	276
	330	Metal Bridge Railing	340	LF	85	255	0	0
	1000	Corrosion	255			255		
	816	Lead Based Paint	1,615	SF	1,453	0	0	162
	3420	Peeling	162					162
	331	RC Bridge Railing (Curb)	340	LF	202	138	0	0
	1090	Exposed Rebar	2			2		
	1130	Cracking	136			136		
	302	Compression Joint Seal	57	LF	47	10	0	0
	2310	Leakage	10			10		
	2350	Debris Impaction	47		47			
	2350	Debris Impaction	57		57			
	311	Moveable Bearing	8	EA	4	4	0	0
	1000	Corrosion	4			4		
	818	Galvanized Coating	130	SF	122	0	0	8
	3440	Effectiveness	8					8
	313	Fixed Bearing	8	EA	8	0	0	0
	818	Galvanized Coating	28	SF	28	0	0	0
	111	Open Girder, Timber	672	LF	651	21	0	0
	1140	Decay/Section Loss	4			4		
	1160	Crack	17			17		
	7000	Damage	4			4		
	215	Abutment, RC	77	LF	38	34	5	0
	1080	Spall/Delam	9			4	5	
	1090	Exposed Rebar	4			4		
	1190	Abrasion/Scaling	26			26		
	1080	Spall/Delam	5			5		
	1120	Discoloration	1			1		
	1190	Abrasion/Scaling	32			32		
	205	Columns, RC	8	EA	7	1	0	0
	1090	Exposed Rebar	1			1		
	1130	Cracking	3		3			
	1080	Spall	1			1		
	1130	Cracking	4		4			
	206	Columns, Timber	8	LF	5	3	0	0
	1150	Check/Shake	5		5			
	1160	Cracking	3			3		

(Shaded) Not wholly included due to coincidental defects

52-308-411	Element Ratings	5/10/16 SPK			1 of 4
		CS1	CS2	CS3	CS4
321 RC Approach Slab 158 SF					
1130 Cracking					
6 long. HL cracks @ 2' ea (Sleeper) = 12 SF		12SF			
4 long. HL cracks @ 4' ea (App Slb) = 16 SF		16SF			
Fine random crks in RT ½ = 10 SF			10 SF		
		28 SF	10 SF		
820 Epoxy Resteel					
Not visible.					
300 Strip Seal Exp Joint 28 LF		28LF			
2350 Debris Impaction					
28 LF					
12 RC Deck 4,816 SF					
1080 Spall/Delam					
Repaired Delams:					
Sp1 = 28SF Sp2 = 1SF Sp3 = 21SF			50SF		
Spalls (Small)					
Span1 = 3SF Sp3 = 2SF			5SF		
• Underside:					
Delaminations					
Sp1: Bay 2: 6'x4' = 24 SF			24 SF		
Bay 3: 2.5'x6' = 15 SF			15SF		
Sp2:					
Bay 2: spall w/exp rebar = (2SF) 1 (1'x2')			(2 SF) 1 SF		
Bay 3: 3SF delam			3SF		
Abut 4 RT w/ exp rebar = (1 SF) 0			(1SF) 0		
			98 SF (99)		
1090 Exposed Rebar					
From above = Sp1 RT cant = (1SF) 0			(1SF) 0		
Sp2 RT cant = (3 SF) 0			(3SF) 0		
Bay 2 = 1 SF					
Abut 4 RT = 1 SF			2SF		
			2SF (6)		

52-308-411 | Element Ratings | 5/10/16 SPK | 2 OF 4

	CS1	CS2	CS3	CS4
12 RC Deck, continued 4,816 SF				
1120 Efflorescence				
All delam w/ disc as well = (49 SF) 0 underside		(49 SF) 0		
+ LT cant @ Bent 2 = 2 SF		2 SF		
LT cant @ Bent 3 w/ crks & discolor. = 2 SF		2 SF		
LT & RT edge of deck near Abut's 1 RT & 4 RT × 2 SF ea = 4 SF		4 SF		
		8 SF (57)		
1130 Cracking				
LT cant @ Bent 3 = (2 SF) 0	(2) 0			
Abut 1 RT & Ab 4 RT = (4 SF) 0	(4) 0			
+ 5% underside = 240 SF	240 SF			
	240 SF (246)			
1190 Abrasion/Scaling				
@ Bents on both sides of joint in Bays 2 & 3 1′ × 2 × 12′ × 2 = 48 SF		48 SF		
Cantilevers w/ exp. rebar Bent 2 RT = 2 SF, 3 RT = 4 SF			6 SF	
		48 SF	6 SF	
812 Epoxy Chip Seal 4,420 SF				
3230 Effectiveness				
NO effectiveness in repairs & spalls = 55 SF				55 SF
+ 5% more (4420) = 221 SF			221 SF	221 SF
+ 5% limited effect (4420) = 221 SF				
			221 SF	276 SF
330 Metal Bridge Rail 340 LF				
1000 Corrosion				
75% Rusted (340) = 255 LF		255 LF		
816 Lead Based Paint 1,615 SF				
3420 Peeling				
10% (1,615) = 162 SF				162 SF
331 RC Bridge Rail (curb) 340 LF				
1090 Exposed Rebar				
LT Curb Top: 2 LF		2 LF		
1130 Cracking				
every 2.5 feet 340/2.5 = 136		136 LF		

52-308-411	Element Ratings	5/10/16 SDK			3 OF 4
		CS1	CS2	CS3	CS4
302 Compression Joint Seal 57 LF					
2310 Leakage					
10 LF along RT @ Bent 2 & 3			10 LF		
2350 Debris Impaction					
(57LF) 47LF		(57LF) 47LF			
111 Open Girder, Timber 672 LF					
1140 Decay					
1' on either side of bents 2 & 3, 63 & 64					
1'×2×2 = 4 LF			4LF		
1160 Cracking					
2.5%(672) = 17 LF			17LF		
7000 Damage					
Sp 2: G1 = 2LF			4LF		
G3/G4 = 2LF					
313 Fixed Bearings 8ea					
Abut 1 & 4 OK					
818 Galvanized 28 SF					
OK					
311 Moveable Bearings 8 ea					
1000 Corrosion					
Bent 2 & 3 63 & 64 = 4ea			4ea		
818 Galvanized 130 SF					
3440 Effectiveness					
Not effective where corrosion exists					8SF
2 SF per bearing ×4 = 8SF					
205 RC Columns 8ea					
1080 Spall					
Bent 3 RT end, C4 = (1ea) 0			(1ea) 0		
1090 Exposed Rebar					
Bent 3 RT end, C4 = 1ea			1ea		
1130 Cracking					
Bent 2: C3 LT = 1ea C4 LT = 1ea		2ea			
Bent 3: C3 LT & C4 LT = (2ea) 1ea		(2ea) 1			
		3ea (4)			

52-308-411	Element Ratings		5/10/16	SPK	4 OF 4

206 Column, Timber — 8ea

1150 checks
5 ea — 5 ea

1160 cracks
3 ea — 3 ea

215 RC Abutment — 77 LF

1080 Spall
Abut 4 LT WW spalled w/ exp rebar (1LF) 0 — (1LF) 0
Abut 1 BW:
Bay 2 = 2LF ③ — 1LF — 5LF
Bay 3 = 3LF ③
RT Cantilever = 1LF ②

Abut 4 BW:
Top of BW spalling @ G1 & LT cant. = 1LF — 1LF
RT deck cantilever = 1LF — 1LF
Bay 2 @ G3 & in Bay 3 delam 1LF — 1LF

Totals: 4LF (5) — 5LF

1090 Exposed Rebar
Abut 4 LT WW spall w/ exp rebar = 1LF
Abut 4 adj to G4 3LF — 4 LF

1120 Discoloration
Abut 1 RT WW: Eff/Scaling (1LF) 0 — (1LF) 0

1190 Abrasion/Scaling
Abut 1 RT WW outside G4 = 1 LF — (16LF)
Bay 1 & 2 (16LF) 11 LF — 11 LF
Abut 4 Bay 2 & 3 (16LF) 15 LF — (16LF) 15LF

Total: 26LF (32)

52-308-411	Quantities	5/10/16 SPK	1 OF 2

$\boxed{\text{12 RC Deck}}$

1'+56'+56'+56'+1' = 170' × 28'4" = 4,816 SF

$\boxed{\text{812 Epoxy Chip Seal}}$

170' × 26' = 4,420 SF

$\boxed{\text{321 RC Approach Slab}}$

27' × (4'1" + 1'9") = 158 SF

$\boxed{\text{330 Metal Bridge Rail}}$

170 LF × 2 = 340 LF

$\boxed{\text{820 Epoxy Resteel}}$

Top & Bottom

158 × 2 = 316 SF

$\boxed{\text{816 Lead Based Paint}}$

Type RT-2 steel Rail @ 4.75 SF/LF

× 340 = 1,615 SF

$\boxed{\text{331 RC Bridge Rail (Curb)}}$

170 LF × 2 = 340 LF

$\boxed{\text{300 Strip Seal Expansion Jt}}$

28 LF @ Abut 4

$\boxed{\text{302 Compression Joint Seal}}$

28'4" × 2 = 57 LF

$\boxed{\text{111 Open Girder, Timber}}$

56' × 3 × 4 = 672 LF

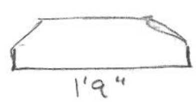
$\boxed{\text{313 Fixed Bearings}}$

Abut 1 & 4 = 8 ea

$\boxed{\text{818 Galvanized}}$

3.5 SF/ea × 8

= 28 SF



7" × 2 = 2.0 SF

21" × 21" Plate

21"–11" × 21" = 1.5 SF

311 Moveable (See page 2)

52-308-411 | Quantities | 5/10/16 SPK | 2 of 2

205 Columns, RC

4 per Bent × 2 = <u>8 ea</u>

206 Columns, Timber

4 per Bent × 2 = <u>8 ea</u>

215 Abutment, RC

38'6" ea × 2 = <u>77 LF</u>

311 Moveable Bearings

Bent 2,3

4 ea × 2 = <u>8 ea</u>

818 Galvanized

Bents 2/3

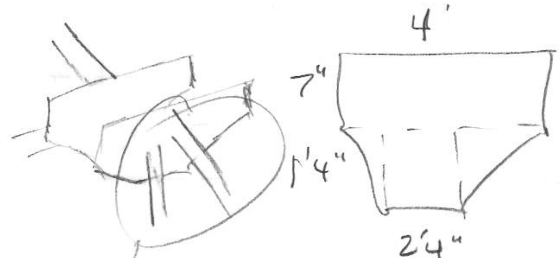
Int @ 17.31 SF/ea

× 4 = 69 SF

Ext @ 15.20 SF/ea

× 4 = 61 SF

Total = <u>130 SF</u>



$(4' \times 7" \times 2) = 4.67$ SF

$\left(\frac{2'4" + 4'}{2}\right)(1'4") = 4.21$ SF

× 2

= 8.42 SF

Sides = <u>13.09</u>

2.11 per set of legs

Int = 13.09 + 2.11 × 2 = 17.31 SF

Ext = 13.09 + 2.11 = 15.20 SF

Appendix F—South Dakota Department of Transportation Inspection Report for Keystone Wye Timber Arch Bridge

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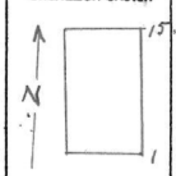
Page 1

Bridge Inspection Report

Structure Number 52-308-412 Maint. Proj. No. 016A-491
Feature Carried US 16A MRM 59.44 County Pennington
Feature Crossed US 16A
Location Keystone Interchange
Bridge Description 14 Span 290' 0" Timber arch bridge 26' Roadway
Built 1968 X904

Orientation Sketch



Date Inspected	Inspectors	Crew Leaders Signature	Temperature
5 / 11 / 2010		[signature]	35 Deg F
5 / 22 / 2012	Neiderworder, Sauter	[signature], PE	86 Deg F
5 / 21 / 2014	KAMARAINEN	[signature], PE	44 Deg F
5 / 10 / 2016	KAMARAINEN	[signature], PE	45 Deg F
/ /			Deg F

Region Repair Recommendations / Contract Repairs

Approach - Items 65.00 - 65.09

1. Alignment
2. Condition
3. Joints
4. Guard Rails
5. Embankment
6. Drainage
7. Signing
8.
9.
10.

(1) Tangent On end. Horizontal curve Off end.
(2) PCC good. Good ride.
(3) 4' asphalt strip at both ends. Asphalt raveling
(4) W-beam all four corners. Abut 1 SRT/HBA 6 post system. Abut 15 has flared ends. All good.
(5) No erosion (6) C&G Abut 1 Lt only. Good. Drop inlet open.
(7) Object markers Lt & Rt Abut 1. Good.

5-22-12

No change except:
(3) Asphalt strips are raveling and cracking. Gaps between end of bridge and asphalt are up to 3" wide at both abutments. Gaps between asphalt and approach pavement are up to 4" wide at abut 1 and up to 5" wide at abut 15. Asphalt is higher than bridge ends and approach pavement.
(4) Abut 15 has trailing end terminals on both sides. Both sides of Abut 1 end have rub rail. Weathering steel.

5-21-14

No change except:
(2) Abut 1 PCC approach paving has minor edge spalling along center joint causing sealant to fail.
Abut 15 Asphalt/Approach joint is unsealed with loss of material up to 3" deep.
(7) MRM is in place at Abut 15 RT with minor damage to the upper RT corner.

5-10-2016

No change except:
(5) There has been washout of gravel shoulder material at the left edge of concrete pavement at Abut 15, which has exposed the entire edge of slab some areas.

Comments

DOT-861 (Rev. 03/91) Page 2

Structure Number 52 - 368 - 412 Date 05 / 11 / 2010

Deck - Items 58.00 - 58.17

1. Deck Condition
   - -A. Cracking
   - -B. Scaling
   - -C. Spalling
   - -D. Delaminations
2. Overlay
   - -A. Type of Overlay
   - -B. Overlay Thickness
   - -C. Condition
3. Joints
   - -A. Joint Openings
4. Drains N
5. Curbs and Median
6. Sidewalks N
7. Railing or Barrier
   - -A. Railing Paint
8. Lighting N
9. Utilities N
10. ______
11. ______
12. ______
13. ______

(1.A,B,C) None visible (1.D) Checked 8-09, 208 SF detected, 2.8%.
(2.A) ECS (2.C) A few thin spots.
(3) Compression Seals. Glands appear intact. No leakage.
(5) A few vertical HL cracks.
(7) No distortion.
(7.A) Approx. 50% scraped with light to moderate rust.

5-22-12

No change except:

(1C) Span 10 has a spall on left side between 3rd and 4th rail posts back of Bent 12. The underside of the deck has deterioration and efflorescence below this spot. Span 2 has a small popout at approximately 1/3 span. Both ends of deck have edge spalls, cracking and some rust.
(1D) Deck delam check May 2011 = 375 sf, 5%.
(2C) Epoxy chip seal is thin with many scraped spots. Chipseal has transverse cracks with adjacent delamination areas.
(3) Compression seals appear intact on top. However, the seals appear, from below, to leak with bearings and ends of girders (both interior and exterior) being wet or show signs of being wet. Bent 4 joint is higher than surrounding deck. Bent 12 off side joint armor angle is higher than on side and has snow plow damage. Dirt on seals.
(5) Vertical and transverse cracks throughout. Ends of curbs are cracked and discolored.
(7) Abut 1 left end block is cracking and has rust. Abut 15 lt and rt end blocks have spalls on top corner at end. Bottom bolts (two) of right rail attachment at Bent 8 are sheared off.
(7A) Right rail top tube is scraped and rusty most of the length. Significant rust on rail face at Abut 15 right end block. Some heavy rust—particularly on rail posts.

5-21-14

No change except:

(1C) A number of spalls throughout. 6"x6" spall w/ surrounding delam 15' from Abut 1 (RT). 6"x6" spall w/ surrounding delam 22' from Abut 1 (LT). 8"x8" spall in the left wheel path at the midpoint of the south main span with rebar showing. 8"x4" spall with surrounding delam in the right wheel path near the midpoint of the north main span, just south of the limits of previous repair.
(1D) Deck delam check July 2013 = 419 SF, 5.6%
(2C) Rust staining throughout showing through ECS.
(3) Bent 4 & 12 joints are currently leaking as seen from underneath.

5-10-2016

No change except:

(1C) The worst spalls & delams were repaired in April 2016 but a few minor spalls & delams remain. Most numerous minor spalls & rust stains remain in spans 9, 10, 11.
(1D) (1) 6"x6" delam remains in South approach section. Another area of spall & delam remains in the north arch section.
• April 2014 delam check = 350 SF, 4.26%
(3) Leakage at joints continues. Armor angle is not completely sound along the left edge of the bridge for approx. 10' at Bent 4, 6' at Bent 8, & 4' at Bent 12.
(5) Water holds on deck along the left curb in a number of areas.

Joint Openings

Joint Location	Exp/Cont Length		Date / Temperature 5-10 / 35°	5-12 / 86°	5-14 / 44°	5-16 / 68°	/
			Joint Opening - Measured/ Corrected to 45 Deg F				
Bent 4		Rt	1 1/4" /	1 1/4" /	1 1/4" /	1 1/4" /	/
		℄	1 1/4" /	1" /	1 1/4" /	1" /	/
		Lt	1 1/8" /	1" /	1" /	1" /	/
Bent 8		Rt	1 1/8" /	1 1/8" /	1" /	1" /	/
		℄	1 1/8" /	1 1/8" /	1 1/8" /	1" /	/
		Lt	1 1/4" /	1 1/8" /	1 1/8" /	1 1/8" /	/
Bent 12		Rt	1 1/2" /	1 3/8" /	1 3/8" /	1 1/4" /	/
		℄	1 7/8" /	1 5/8" /	1 3/4" /	1 1/2" /	/
		Lt	1 1/4" /	1 1/8" /	7/8" /	1" /	/
		Rt	/	/	/	/	/
		℄	/	/	/	/	/
		Lt	/	/	/	/	/
		Rt	/	/	/	/	/
		℄	/	/	/	/	/
		Lt	/	/	/	/	/

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Page 3

Structure Number 52 - 308 - 412 Date 05 / 11 / 2010

Superstructure - Items 59.00 - 59.20

1. Underside of Deck
2. Bearing Devices
3. Girders or Beams
   - -A. Stiffeners N
   - -B. Welds N
   - -C. Splices N
4. Diaphragms
5. Trusses N
   - -A. Main Members N
   - -B. Portals N
   - -C. Bracing N
   - -D. Gusset Plates N
7. Rivets or Bolts
8. Welds N
9. Paint
10. Drainage System N
11. Utilities N
12. Reaction Under Load
13. Collision Damage
14. Arch ribs & bracing
15.
16.

(1) A few transverse HL cracks. Some light eff on overhang.
(2) Good (3) Good (4) Good
(7) All in place & Secure.
(9) Stain is all good. (Re-stained with 2009 contract RSauter)
(12) None noted (13) None
(1) (Rust stains, exposed rebar, scaling adjacent to deck joints - R. Sauter 9-17-09)
5-22-12
No change except:
(1) Deck has longitudinal, transverse and random cracks. Bay 1 in Span 5 has a transverse crack with efflorescence. Span 10 adjacent to G1 has 6¼'x4' area with leakage, scaling, cracking and efflorescence (there is a spall on top of the deck above this area). The deck at the Bent 4 deck joint has a spall at G1 and minor scaling (joint has evidence of past leakage with armor angle staining). Deck in Bays 1 and 2 at Bent 12 has scaling and spalling next to the joint. There is concrete between the shims and deck joint armor angles at several locations.
Deck cantilevers: scaling at Abut 1 left; Bent 4 right has minor scaling and cracking; Bent 4 left has some concrete deterioration; Span 5 right has transverse crack with efflorescence; Span 5 left has 2 transverse cracks with effl; Span 6 left has transverse crack with effl; right at Bent 8 is cracked, scaling and delaminating; right has 2 transverse cracks with effl in span 9 and 3 in Span 10; Span 10 left (adj to area at G1 noted above) has leakage, scaling, cracking, efflorescence, rust staining and delamination; right at B12 has scaling and cracking; left at B12 has scaling, delamination and spalling with exposed rebar. Edge of deck has cracking and discoloration adjacent to deck joints. Edge of deck and back of curb at Abut 15 left has cracking, efflorescence and rust stains.
(2) Fixed bearing quantities are revised to include fixed shoes at begin and end bridge abutments, hinged bearings at arch rib abutments, steel brackets for girder to bent column (including spandrel bent) connections, steel brackets on top of arch crown hinges, steel brackets between bottoms of spandrel columns and tops of arch ribs. Bearings are generally good except at the tops of shared Bents 4 & 12. At these locations, ends of adjacent continuous span girders are supported with a gap between the ends of the girders. These bearings are also located below deck joint compression seals that have leaked in the past or are leaking. Precipitation and debris can also be blown into gaps between the ends of the girders at these locations. The debris and moisture is trapped in the bearings between the steel bracket side plates and the ends of the girders. The trapped moisture and debris is causing deterioration of the girders. Bearing brackets at shared Bent 12: G1 has debris and approximately 3½" of water ponded in it, G2 & G3 are filled with debris and have evidence of past leakage. The steel bearing brackets at the supports of the exterior continuous girders are good except the bracket side plates are not sealed to the sides of the girders. The steel bracket at the bottom of spandrel bent column is unsealed at Bent 5 column 1. The hinged bearings at the arch rib abutments are good.
(3) Girders are glue laminated timber (3 lines — 3 span continuous for approach spans and two sets of 4 span continuous for the main span). Girders are generally good, but have some horizontal cracking. (OVER)

Comments

5-22-12 (continued)

(3 continued) Some of the cracks were sealed with the 2009 staining project. Girder 1 in spans 2 & 3 has horizontal cracking at approximately mid-depth on both sides for almost the full length of the spans. Span 3 otherwise has some horizontal cracking. Span 5 G1 and Span 13 G3 have horizontal cracking. Outside face of Span 10 G1 has partially sealed horizontal crack at approximately 1/4 depth from bottom. Span 10 G1 both sides have deterioration of stain due to leakage through deck cracks. Ends of girders at steel bearing brackets have deterioration including discoloration and decay due to water and debris in bearings at Bents 4 and 12.

(4) Girder diaphragms are steel channels at interior and end supports in good condition.

(7) Bolts at brackets for girders to columns & columns to arch ribs, arch hinges, diaphragms, arch rib bracing, bent bracing. Good condition.

(9) Structure was cleaned and stained in 2009. Some deterioration of stain notably on tops and sides of arch ribs and on tops of bracing. Deterioration on the ends of girders under deck joints. Deterioration of stain at girder bearings at Bents 4 and 12 girder bearing brackets. Deterioration on girders due to leakage through cracks in deck. (Three segments of Bent 13 column bracing appear to have not been stained in 2009 project - Move to substructure sheet. RS)

(12) Some creaking of connections due to loads.

(13) None

(14) Three lines of glue laminated timber arches in main span. Arches are three hinged. Arches are braced with glue laminated strut frames and longitudinal bracing. Hinges are good. Arches and bracing are good except some stain deterioration noted in (9).

5-21-14

No change except:

(1) Bent 4 deck joint is currently leaking. Abut 15 RT has a horz. crack on the edge of deck. Bent 12 deck joint is currently leaking.

(3) The bottom of girders in a number of spans have minor splits.

5-10-2016

No change except:

(1) Areas of delamination & spalling at bents with leaking joints continue to deteriorate near left cantilever.

(3) G1 at Bent 4 has roadway salt deposits on tops of girders at joint & between the ends of girders at top of column. Water damage continues to deteriorate timber at locations below deck leakage.

(9) Stain protection continues to lessen, especially in the areas noted previously that are exposed to weathering & leakage. In many areas, the stain no longer appears effective.

(1) Span 2 in Bay 2 has (2) 2'x2' areas of water leakage indicated by discoloration on the underside. These areas are in the middle of the bay and appear to correspond with repaired areas on the top of deck. There are additional areas similar to this over G1 & in LT cantilever of Spans 1 & 2.

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Substructure - Items 60.00 - 60.05

1. Abutments
   - A. Wingwalls
   - B. Backwalls
   - C. Footings
2. Piers or Bents
   - A. Caps
   - B. Columns
   - C. Footings
3. Grout Pads
4. Anchor Bolts
5. Piles
6. Bracing
7. Paint
8. Movement
   - A. Plumbness
   - B. Settlement
   - C. Horizontal
9.
10.
11.

(1.A) 1 horizontal HL crack on Abut 15 Rt. Balance good.
(1.B) Abut 15 has 2 vertical HL cracks with light eff.
Abut 1 has 1 vertical HL crack with light eff.
(1.C) Abut 15 has several vertical HL cracks & 1 horizontal HL to 1/16" crack 4' long in Bay 1 with moderate eff.
(2.A) Good (2.B) Good (2.C) Good
(3) Good (4) In place & Secure (5) Steel piling
(6) Good (7) Stain is all good
(8.A) Good (8.B,C) None

5-22-12

No change except:

(1) Revised quantities to include begin and end bridge abutments in the approach spans and abutments for the main span arch which are included as shared Abutments/Bents 4 and 12.
(1A) Abut 1 left has diagonal cracks at deck/ww joint. Abut 1 right has horizontal crack at bottom of deck. Abut 15 right has horizontal crack with discoloration at top of sill and one near bottom of slab.
(1B) Abut 1 has vertical crack with efflorescence in Bay 3. Abut 15 Bay 1 has 2 cracks; Bay 2 has 2 vertical with efflorescence (one into top of sill then into face of sill), several other vertical cracks, 2 vertical cracks that go into top of sill.
(1C) Abut 1 sill Bay 3 has 2 vertical cracks on face of sill and then into top. Abut 15 sill has several vertical cracks without efflorescence on face, vertical crack in sill to right of G3 riser, Bay 1 face of sill has 1 > 1/16" horizonal crack without efflorescence and several horizontal cracks with significant efflorescence. Abutment/Bent 4 skewback (inclined support that receives the thrust from the arch) at Arch 2 has 1 diagonal crack at bottom corner of grout pad. Abutment/Bent 12 skewback: Bay 1 has 2 vertical cracks, several small delaminated areas, 1½'x2' rust spot next to Arch 1; area outside Arch 1 has small delaminations; Bay 2 has 1 vertical crack, 3 small delaminations, horizontal cracks next to top and bottom of Arch 2 grout pad.
(2A) No caps. Girders are supported directly by columns or the arch crown hinge devices through steel brackets.
(2B) Glue laminated timber columns in approach span bents and spandrel bents on the arch ribs. Steel brackets at spandrel Bents 7 and 9 are included as steel columns. Concrete pedestals at approach span bents and shared abutments/bents are included as concrete columns. Timber columns have some checking with some of cracks sealed. The base of Bent 3 column 1 is not sealed to steel bracket. Steel columns at Bents 7 and 9 good. Concrete pedestals: Bent 4 column 1 has 3 cracks in top; Bent 4 column 3 has 2 cracks in top; Bent 12 column 1 has cracking, discoloration, efflorescence and spalling. Bent 14 column 1 has 2 cracks in top corner & 2 in grout pad; Bent 14 column 2 has 1 crack in grout pad; Bent 14 column 3 has 1 crack in top corner and 1 in grout pad; Bent 3 column 2 has a vertical crack.
(2C) Not visible.
(3) Grout pads good or with minor cracks as note above.
(4) Good.
(5) 12 BP 53 steel piles at all substructure units.
(6) Glue laminated timber bacing for approach span bents and main span spandrel bents. Good.

(OVER)

Comments

5-22-12 continued

(7) Glue laminated timber stained in 2009 project. Stain has some deterioration, particularly on tops of brace members. Three segments of Bent 13 column bracing appear to have not been stained in 2009 project.

(8A) Appears plumb.

(8B&C) No apparent movement.

5-21-14

No change except:

(1B) Abut 1: vertical crack with efflorescence appears to be in bay 2 not bay 3.
Abut 1 LT has efflorescence under cantilever.
Abut 15: Horz crack with discoloration extends to G3 from RT WW.
Bay 2 has 3 vertical cracks with efflorescence.
Bay 1 top fillet has efflorescence.

(1C) Abut 1 sill has 2 vertical cracks in Bay 2 not Bay 3.
Abut 15 sill has rust stain under G2. Bay 1 face has delam along horizontal crack noted previously.
Abut/Bent 12 has minor map cracking in bay 1.

(2B) Bent 2: C1 & C3 concrete pedestals have 1 vertical crack each.
Bent 12: C1 pedestal has continued to deteriorate with large area of delaminations.
Bent 14: 2 cracks in column 1 are on the top edge, not corner.
Bent 13: C1 has 1 vert. crack that continues from pedestal into grout pad.
C2 has 1 vert. crack that continues from pedestal into grout pad.
C3 has 1 vert. crack in the grout pad.

5-10-2016

No change except:

(2B) Bent 4, C1 pedestal now has fine map cracking with discoloration on LT face.

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