Timber Bridge Inspection Using UAV

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ABSTRACT

Unmanned aerial vehicle (UAV)-enabled bridge inspection has gained more interest over recent years among bridge owners, researchers, and stakeholders due to inefficiency and high cost of conventional access inspection techniques. A large number of deteriorating bridges can be efficiently inspected using UAVs equipped with various sensors. In fact, some departments of transportation (DOTs) (e.g., Minnesota DOT) in cooperation with research institutions have investigated the effectiveness of UAVs as a cost-efficient bridge inspection alternative. Based on the findings from the projects done by the DOTs in their states, this paper is intended to demonstrate the effectiveness of a UAV by inspecting a timber arch bridge in the State of South Dakota (SD). The bridge inspection using UAV was completed based on multiple analyses of high-resolution images and videos recorded from the UAV. Further, the use of a pixel-based damage quantification methodology provided a quantifiable value for the observed damage. The visual results obtained from the UAV-based bridge inspection were compared to those from the past inspection reports from SDDOT. The comparison of results demonstrated the ability of the UAV to identify damage. It is expected that this emerging technology will supplement routine bridge inspections conducted with conventional methods.

INTRODUCTION

For over a decade, the American Society of Civil Engineers (ASCE) has evaluated the structural integrity of the United States' infrastructure. Every four years, the ASCE releases a report card summarizing the results for different infrastructure, including bridges. The last issue revealed that approximately 9.1% of the 614,387 in-service bridges were classified as structurally deficient (ASCE 2016). A significant decrease in deficient bridges from over 12% in 2007 to 9.1% in 2016 demonstrates the commitment of ASCE to repair and enhance their structural integrity. Although some progress has been made over recent years, it was reported that the bridge rehabilitation backlog exceeds $123 billion USD. Additionally, over 44% of the 614,387 in-service bridges are over 40 years old and are approaching the end of their service life. Due to 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 shed light on efficient and effective bridge inspection (Hallermann and Morgenthal 2014).

In recent years, the field of civil engineering has observed a significant increase in the use of drone technology to inspect and monitor infrastructure, especially bridges (Khaloo et al. 2017; Lovelace and Zink 2015; Moller 2008; Otero 2015). The interest of different state Departments of Transportation (DOTs) and other governmental organizations, such as the United States Department of Agriculture – Forest Service (USDA – FS), has provided significant findings on

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the drone technology. For instance, Moller (2008) developed a drone prototype during the early stages of the technology growth for bridge inspection for the Caltrans project. The drone prototype was a twin-motor, single-duct, electric-powered system designed to carry cameras and other sensors to observe damage on bridges.

The Florida DOT (FDOT) in junction with Otero (2015) utilized a multi-rotor drone coupled with high-definition cameras to inspect different types of bridges. During the inspection, stress cracks on the timber stringers were observed with the aid of the high-quality imagery data from the drone. Additionally, a more comprehensive evaluation of the drone capabilities to investigate bridges was conducted by the Minnesota DOT (MnDOT) in partnership with Lovelance and Zink (2015). Four different types of bridges were inspected in the state of Minnesota including a long single span prestressed concrete bridge, an open spandrel concrete arch bridge, a five-span steel underdeck truss bridge, and an arch truss bridge. The research project demonstrated the capability and advantages of the drone to efficiently observe damage the considered bridge types. The USDA – FS and Khaloo et al. (2017) developed an aerial platform based on the DJI S800 airframe with Gyrostabilized Sony Nex7 and GoPro cameras to inspect the Placer River Trail Bridge in the Alaskan Kenai Peninsula. It was found that the drone was able to gather sufficient data to recreate the bridge in 3D virtual space to observe damage on the structure.

The main objective of this study was to identify the capabilities of drones as supplemental tools for the inspection of bridges. The efficiency of the structural damage identification was studied by executing drone-enabled inspection of an identified bridge in South Dakota (SD). The inspection of the bridge considered state and federal regulations (e.g., SDDOT and Federal Aviation Administration (FAA)). This study is subdivided into six different section, including this section. The second section details the selected drone and bridge to perform this study. The third section shows the bridge inspection approach, including a damage quantification method used to evaluate the damage on the bridge. The fourth section presents the results gathered from the damage identification and its comparison with historical inspection reports from SDDOT. The final section presents conclusions derived from this inspection work.

DRONE AND BRIDGE SELECTION

Prior to conducting the bridge inspection, a suitable drone and bridge structure were first selected. A drone platform capable of safely flying near a target structure with high-resolution cameras was needed, while the bridge having accessibility limitations was required to check the effectiveness of the drone inspection. The following subsections detail the drone and bridge selection.

Drone Selection

A variety of considerations were analyzed prior to selecting a drone. Specifically, the study done by Otero (2015) recommended that various drone specifications, including user-controls/interface, maneuverability, software capability, adaptability, size, and payload, be considered when selecting a drone for the bridge inspection. It can be noted that the conclusion of the Otero's study considered the DJI Phantom 2 (the latest DJI Phantom series drone on 2015) as a suitable drone. Based upon the recommendation from the study, the DJI Phantom 4, which is the latest version of DJI drones, was considered an appropriate drone for this study. The drone contains obstacle avoidance technology and capability to fly without Global Positioning System (GPS) signal for the underside of deck observation, enabling it to conduct the bridge inspection safely. The drone (see Fig. 1) was also satisfactory with additional criteria, including fly time,

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camera resolution under low illumination, and remote range along with costs.

Fig. 1. DJI Phantom 4 approaching the selected bridge - Courtesy of Junwon Seo.

Bridge Selection

To efficiently conduct the bridge inspection, the Keystone Wye timber arch bridge (built in 1966) located near the city of Keystone, SD (see Fig. 2) was selected. The bridge has three 20 m glulam, single-hinged arches and three glued-laminated timber stringers across bents. In detail, the superstructure consists of three glulam stringers spaced at 3.12 m o.c. supporting a concrete deck width (out-out) of 7.92 m. The bridge is 88.4 m long with steel guardrails along the edge of the superstructure.

BRIDGE INSPECTION PROCEDURE

The inspection of the bridge was conducted based on an established inspection procedure. The procedure was developed based on the knowledge gained from the brief literature review, in addition to safety guidelines from both the SDDOT and FAA. To ensure all the information was efficiently gathered, several considerations prior and during the inspection were recognized. Details on the bridge inspection procedure including the damage quantitation method are presented below.

Prior to Inspection

Three main steps can be followed to identify damage on the target bridge: (1) bridge documents review, (2) visual observation of bridge surroundings, and (3) drone pre-flight check.

The first step allows the drone operator, or Pilot-in-Command (PIC), to identify critical bridge areas. Documentation such as bridge construction plans and related inspection reports should be studied prior to arriving at the bridge site. These plans allow the PIC to plan the flight and identify inaccessible areas across the bridge system. On the other hand, the historical inspection reports provide critical information regarding past and current bridge damage, helping better understand the damage spectrum in terms of time for the bridge. This information will aid in determining critical sections that should be focused by the drone inspection.

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The second step focuses on the observation of the bridge surroundings to identify potential risks to the drone flight. During this step, safe take-off and landing locations must be identified for the satisfactory operation of the drone. A more detailed flight plan should be also developed to avoid any objects near the bridge (e.g., adjacent trees). It should be noted that regulations either from the DOT or FAA should be accounted for. These regulations include but are not limited to FAA flying permits, FAA airspace class restriction (e.g., flying within 5 miles of an airport), DOT flying regulations, and DOT safety measures. Especially, traffic control warning signs should be displayed to protect the inspectors, while operating the drone within the right of way of the highway.

The last step prior to the inspection is to conduct a drone pre-flight check. Both the drone manufacturers and the FAA recommend a thorough inspection of all the components to ensure high performance during the flight. This checklist includes, but is not limited to: propellers and rotors inspection, full charging of all instruments (e.g., a remote controller, storage batteries, and a monitor), remote controller adjustments, gimbal inspection, and firmware updates. Finally, a compass calibration should be conducted as to avoid GPS signal loss during the flight and possible flyaway.

Fig. 2. Overview of the selected Keystone Wye Timber Arch Bridge captured using the drone – Courtesy of Luis Duque.

During Inspection

After all the preparation steps are followed, the inspection of the bridge can be completed. It is recommended that the PIC considers weather conditions and other limitations (e.g., the drone manufacturer' limitations) during the operation of the drone. For example, it is advised to avoid flying the drone during high wind speed days (15 mph or more) to limit drone instability and difficulties while flying near the bridge. For the data acquisition, it is recommended to obtain overview images, and then proceed to gather more detail sections to efficiently identify all damage on the bridge. The PIC should double check with DOT and FAA regulations, such as the restriction of flying over traffic. It is noteworthy that the PIC is continuously assisted by an observer to avoid distractions and possible accidents.

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Damage Quantification Method

A suite of images collected after the inspection can be used to identify and quantify the damage on the bridge components through an image analysis. This analysis using commercially available image analysis software is utilized to measure the damage on the bridge structure. For example, the ImageJ program is able to use a pixel-based algorithm to take length and area measurements directly from an image. Precisely, a scale (i.e., 100 pixels equal to 5 cm) is assigned based on a known distance from the image (i.e., stringer depth), and measurements can be obtained via the available image analysis tool. Further capabilities such as edge detection may be used to efficiently identify cracks. The edge detection function available in ImageJ applies a Sobel-filter to identify sudden changes in color gradient (edges) typically seen in crack boundaries.

APPLICATION

Once all the critical considerations were identified and the bridge inspection procedure was established, the inspection of the Keystone Wye Bridge was conducted. The following subsections detail the results following the bridge inspection procedure.

Prior to Inspection

The review of the bridge plans and inspection reports provided by SDDOT was conducted. The general dimensions of the bridge and special characteristics such as the bents location and arch were identified. A schematic of the plan and elevation view is presented in Figs. 3a and 3b. The inspection reports were reviewed to obtain critical information on the past and current damage state of the bridge. It was determined that the north abutment had a significant transverse crack and the deck joints presented noticeable concrete spalling with exposed reinforcement bars. Based on the information, the drone-enabled bridge inspection focused on the deck and abutments with critical damage.

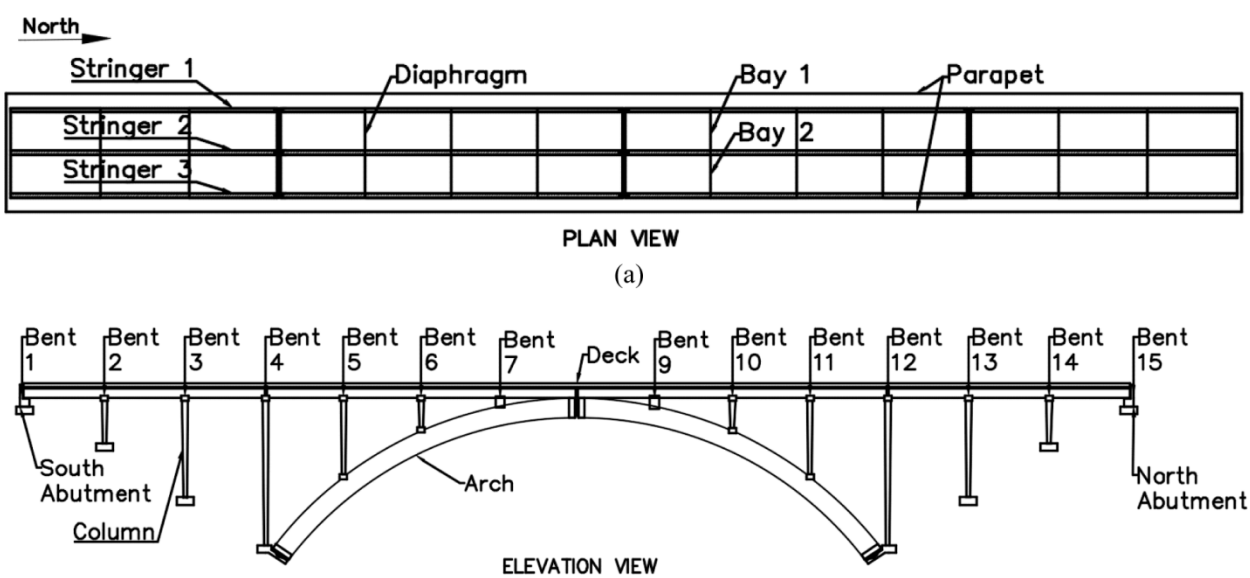

Fig. 3. Bridge overview and components: (a) plan view and (b) elevation view.

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During the visual observation of the surroundings, there were no major critical zones. The bridge is not located in a high-risk zone as there are no major structures surrounding it or large trees over or adjacent to the structure. Prior to the inspection, the SDDOT and FAA regulations were checked and considered. The SDDOT stated that the operation over the deck or roadway was prohibited. Also, traffic control signs were displayed at 228.6 m from the bridge location per SDDOT requirement. Although no additional specific regulations were mentioned, the general FAA regulations to operate a drone still applied. The detailed regulations can be found elsewhere in FAA (2016).

The final step prior to proceeding with the bridge inspection was to conduct the drone pre-flight check. The inspection of all drone components including rotors, propellers, batteries, iPad, remote controller, gimbal, and software updates was conducted to ensure efficient performance of the aerial platform. During this check, all the components were found to be in excellent condition and no signs of defects were found. In addition, the compass was calibrated successfully to ensure full GPS signal during the operation of the drone. To complete the compass calibration, the drone is rotated counterclockwise with the camera facing down. Then, the same movement is repeated with the camera facing forward.

(a) (b) (c)

Fig. 4. Sample images for the drone-enabled bridge inspection: (a) close view of the arch; (b) identified damage on deck joint; and (c) operation of the drone near the bridge – Courtesy of Junwon Seo.

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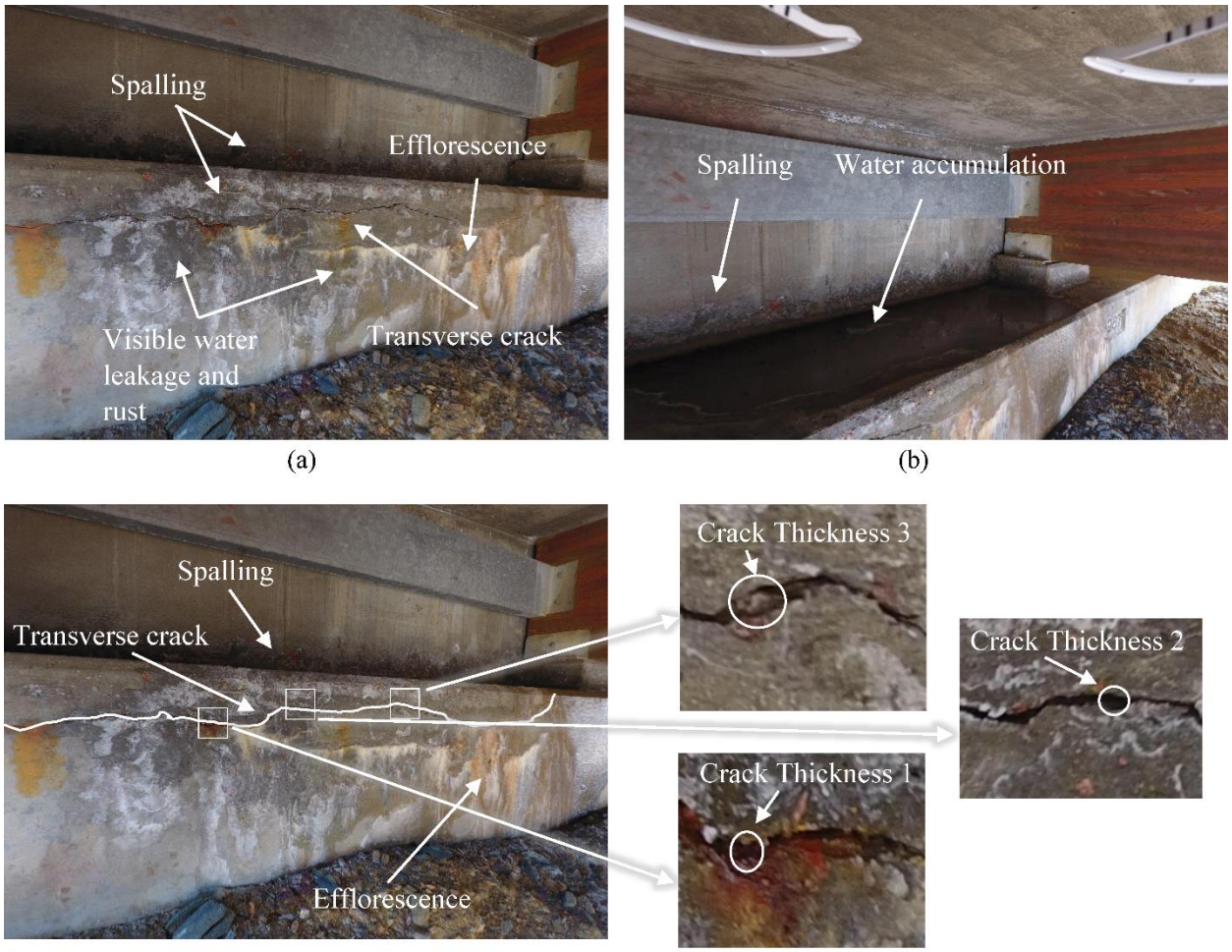

Fig. 5. Sample abutment damage detected using the drone on North Abutment: (a) transverse concrete crack, visible water leakage, efflorescence, and spalling; (b) water accumulation over crack; and (c) quantified damage on North Abutment on Bay 1 – Courtesy of Luis Duque.

During Inspection

The drone-enabled bridge inspection was conducted without inconveniences over two days. The drone successfully operated near structural components during the first day of inspection to capture small details such as cracks on the structure. The weather conditions were appropriate and allowed for an efficient inspection of the structural components. During the second day of inspection, high wind speeds impeded the normal conduction of the bridge inspection. Due to the inability to maintain a stable flight and approach the structure safely, while capturing images, a video-based data gathering approach was studied. The video-based approach allowed the PIC to fly without any distractions caused by the picture taking process. Sample images for the inspection of the Keystone Wye Bridge are presented in Figs. 4a and 4b. Fig. 4a shows a close view of the glued-laminated arch and Fig. 4b presents damage on one of the joints of the concrete deck. Also, the operation of the drone near the bridge can be seen in Fig. 4c.

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Table 1. Damage Quantification for North Abutment

Identified damage	Pixel-Based Measurements and Observation
Transverse crack length	354 cm
Crack thickness 1	1.42 cm
Crack thickness 2	2.08 cm
Crack thickness 3	1.75 cm
Spalling	Spalling along bay width
Efflorescence	White surface with accumulation and rust stains

RESULTS OF THE BRIDGE INSPECTION

This section provides a more detailed presentation of the identified damage and its quantification and a visual comparison to images provided by SDDOT. The subsection presents identified damage on the bridge abutments and stringers and their quantifications. Then, the results are compared to the damage identified on the inspection report provided from the SDDOT. A complete documentation of the identified damage can be seen in Seo et al. (2017).

Abutments

The abutments presented some critical damage, such as cracks. For instance, a significant transverse crack was observed on the north abutment as seen in Fig. 5a. Some water leakage along the surface of the abutment was observed as seen in Fig. 5b. Further, the quantification of the damage on the north abutment (see Fig. 5c) was completed using the pixel-based methodology described previously and listed in Table 1.

The damage identified using the drone on the abutments was also reported by the SDDOT. Some damage in enclosed sections of the abutments were not completely observed due to wind gusts affecting the stability of the drone during the second day of inspection. For example, some cracks on Bay 2 at the South Abutment and near Stringer 3 at the North Abutment were not fully observed. Some critical damage such as the transverse concrete crack on the North Abutment on Bay 1 was captured. Images for the abutment were not available in the SDDOT to be compared.

Stringers

The stringers were found to be in good condition. Some minor deterioration at supporting areas, especially near deck joints were visible due to water leakage. One visible shear crack on Stringer 1 at Joint 4 was found as seen in Fig. 6a. Fig. 6b shows stains on Stringer 1 between Joints 3 and 4. The damage on Stringer 1 at Joint 4 was also quantified using the pixel-based measurement approach as seen in Fig. 6c. The quantifiable damage is presented in Table 2.

The results gained from the drone were related to the inspection reports provided by the SDDOT. Some horizontal cracks on Stringer 1 and 3 reported by the SDDOT were not fully observed due to high wind conditions during the second day of inspection. Fig. 6d shows an image provided by SDDOT with some sharp cracking at the support of Stringer 1 at Joint 4 and can be compared to Fig. 6a.

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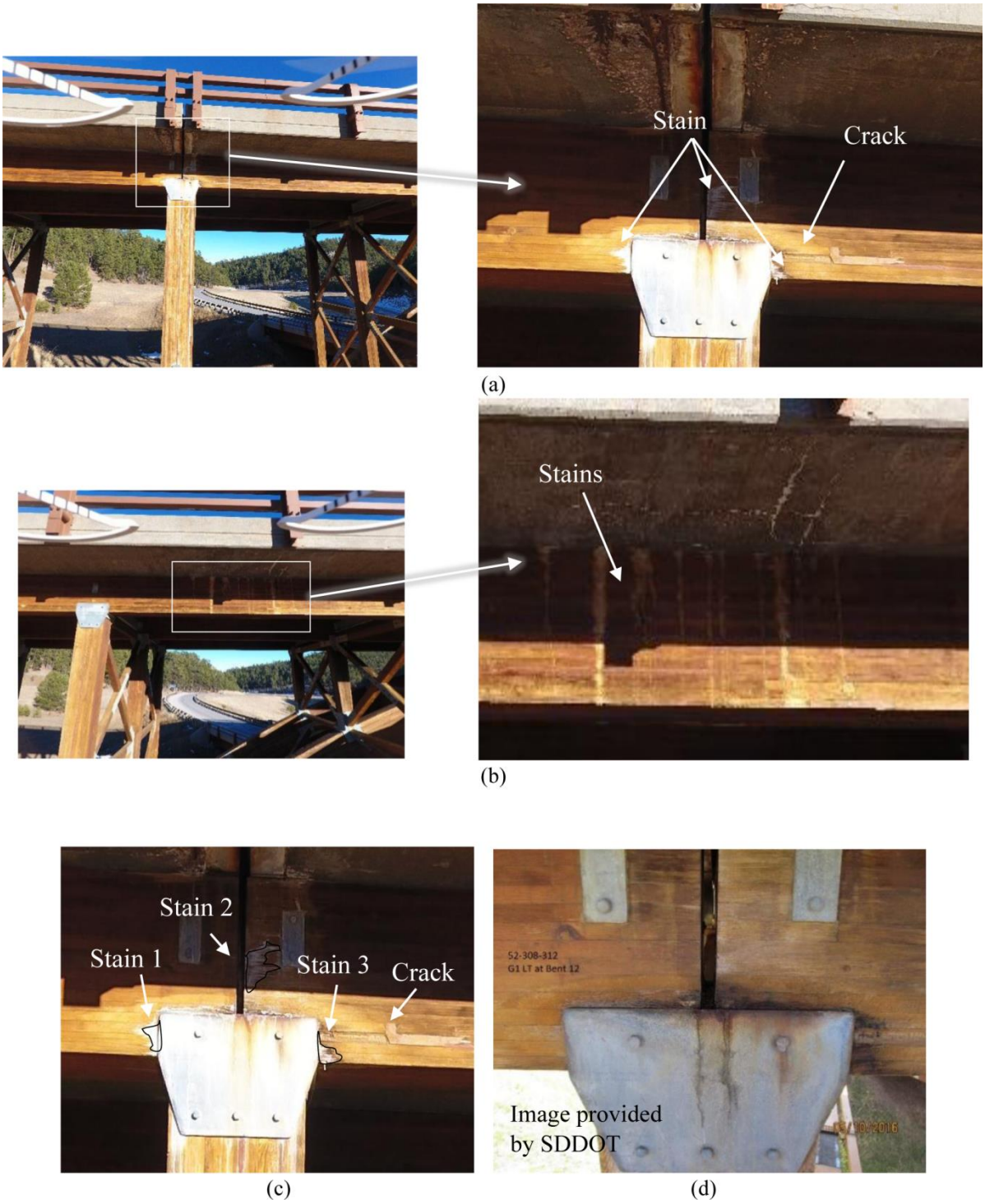

Fig. 6. Sample stringer damage detected using drone:
(a) damage at Joint 4; (b) damage on Stringer 1 between Joints 3 and 4; (c) quantified damage on Stringer 1 at Joint 4; and (d) image provided by SDDOT for comparison. – Courtesy of Junwon Seo.

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Table 2. Damage Quantification for Stringer 1 at Joint 4

Identified damage	Pixel-Based Measurement
Crack (timber split)	31.2 cm
Stain area 1	98.7 cm^2
Stain area 2	210.3 cm^2
Stain area 3	64.5 cm^2

CONCLUSIONS

Based on the findings obtained during this study, the following conclusions can be drawn from the drone-enabled bridge inspection of the selected bridge in SD.

1. It was determined that weather conditions must be considered as wind can adversely affect the operation of the drone, especially near the bridge.
2. The abutments and stringers were successfully inspected using the drone, demonstrating the ability to observe different types of damage, such as crack and stain. With the aid of ImageJ on the suite of images from the drone, the damage was quantified.
3. The comparison of results between the drone-based and conventional inspections demonstrated the ability of the drone to identify damage.

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