6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Image-based Bolt-loosening Detection Technique of Bolt Joint in Steel Bridges

J.H. Park[1], T.H. Kim[2], J.T. Kim[3]

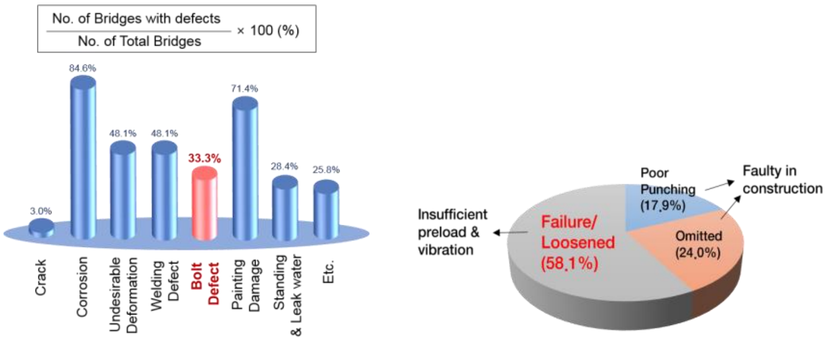
1 *BK21+ Research Professor, Dept. of Ocean Engineering, Pukyong National University, Busan, Republic of Korea. E-mail: cross96@gmail.com*
2 *Graduate Student, Dept. of Ocean Engineering, Pukyong National University, Busan, Republic of Korea E-mail: whrxkaos@naver.com*
3 *Professor, Dept. of Ocean Engineering, Pukyong National University, Busan, Republic of Korea E-mail: idis@pknu.ac.kr*

ABSTRACT
This paper presents a novel bolt-loosening detection technique using image information of bolted joints in steel bridges. Firstly, existing bolt-loosening detection techniques are reviewed and their benefits and limitations are analyzed. Secondly, a bolt-loosening detection algorithm using image processing techniques is newly proposed for bolted joints in steel bridges. It consists of 3 steps: (1) taking a picture for a bolt joint, (2) segmenting the image to identify a splice plate and each nut, and (3) identifying rotation angle of each nut and detecting bolt-loosening. As a key technique, the Hough transform is used to identify rotation angles of nuts, and then bolt-loosening is detected by comparing the angles before and after bolt-loosening. Finally, the applicability of the proposed technique is evaluated by experimental tests with bolt-loosening scenarios. A bolted joint model which consists of a splice plate and 8 sets of bolts and nuts with 2×4 array is used for the tests.

KEYWORDS: *image processing, bolt-loosening, bolted joint, steel bridge, bridge inspection*

1. INTRODUCTION

Bolts are important elements to connect members of steel structures. In most steel bridges, the members are connected to each other by friction bolt joints. Insufficient preload by bolt-loosening leads to bolt joint failure and reducing load carrying capacity of bridges. In accordance with a report for structural defects in steel bridges operated by Korea Expressway Corporation [1], bolt defects occurred in 33.3% of the bridges and a main cause of the defects was investigated as bolt-loosening by insufficient preload or vibration as shown in Fig. 1.1. Because bolt failures might cause tragic structural failure, bolt-loosening detection is important to maintain the structural performance of steel bridges.



(a) Defect types and occurrence rate (b) causes of bolt defect

Figure 1.1 Structural defects occurred in steel bridges operating by Korea Expressway Corporation

To date, many techniques to detect bolt-loosening in steel bridges have been developed, and they can be classified into two groups as: (1) in-situ inspection techniques including visual inspection, hammer impact method and torque wrench technique [2] and (2) sensor-based monitoring techniques including methods using acoustoelastic wave, guided wave, electro-mechanical impedance, a wireless sensor to detect change in rotational angle of nut and electric potential drop [3-5]. The in-situ inspection techniques are very simple but they could not early detect bolt-loosening or have large error in measurement [3]. The sensor-based monitoring techniques are promising bolt-loosening monitoring methods but they need high-cost monitoring systems and fixed sensors.

Meanwhile, image processing techniques have been widely adopted to recognize medical image, object, pattern, character and so on. Many researchers have tried to apply the techniques to inspection and monitoring of civil structures. The image processing techniques in civil structures were used to identify crack on concrete [6-7] and pavement surface [8], to detect damage on surface of stay-cable [9], to diagnose steel bridge coating [10], and to measure displacement of bridge [11-12]. The main benefits of the image-based techniques in civil structures are as follows: (1) providing intuitive and scientific information for bridge maintenance, and (2) utilizing low-cost equipment such as cameras which are non-contact sensors.

In this study, a novel bolt-loosening detection technique using image information of bolted joints in steel bridges is developed. To achieve the research objective, the following approaches are implemented. Firstly, existing bolt-loosening detection techniques are reviewed and their benefits and limitations are analyzed. Secondly, a bolt-loosening detection algorithm using image processing techniques is newly proposed for bolted joints in steel bridges. It consists of 3 steps: (1) taking a picture for a bolt joint, (2) segmenting the image to identify a splice plate and each nut, and (3) identifying rotation angle of each nut and detecting bolt-loosening. As a key technique, the Hough transform is used to identify rotation angles of nuts. Finally, the applicability of the proposed technique is evaluated by experimental tests with bolt-loosening scenarios. A bolted joint model which consists of a splice plate and 8 sets of bolts and nuts with 2×4 array is used for the tests.

2. BRIEF REVIEW OF EXISTING BOLT-LOOSENING DETECTION TECHNIQUES

2.1. In-situ Inspection Techniques

The in-situ inspection techniques detect bolt-loosening by the visual inspection or using mechanical devices such as hammer and torque wrench [2]. They are the most widely used techniques for the bolt joint inspection of steel bridges in real applications.

Visual inspection is the simplest method and provides intuitive information for the bolt-loosening detection, however it cannot detect bolt-loosening until a bolt is completely loosened as shown in Fig. 2.1. The loosened bolt does not contribute any more to friction resistance of a joint in a steel bridge.

Bolt joints in steel bridges must be examined every 2 or 3 years by using the impact hammer technique according to a law for structural safety in Korea [2]. To implement the technique, an inspector touches his finger around a bolt and then hits the bolt head by a hammer. If he feels abnormal vibration from his finger, he decides bolt-loosening. It is relatively simple but its accuracy depends on the inspector's experience and sense.

Current practice relies on the torque wrench technique as the best way to detect bolt-loosening and measure axial preload of bolt. However, several researchers demonstrated the torque wrench method has large intrinsic errors in bolt tension measurement by up to 50% due to the friction between the bolt threads and the nut [3, 13]. Also, the method needs cost- and time-consuming processes in large structures with thousands bolts, especially steel bridges, because bolt-loosening is examined one by one.

Figure 2.1 Examples of completely loosened bolts

2.2. Sensor-based Monitoring Techniques

The sensor-based monitoring techniques detect bolt-loosening by analyzing responses from sensors which are attached around bolts and they can apply for real-time monitoring. They can be classified into 5 methods: acoustoelastic effect based method, guided wave based method, impedance-based method, magnet field-based method, and electric potential drop method.

The acoustoelastic effect-based method is similar to the impact hammer technique but provides scientific bolt-loosening detection results by measuring ultrasonic wave and vibration from a sensors attached on a bolt head. For the method, many researchers proposed time-of-flight methods, velocity ratio methods and mechanical resonance frequency shift methods, and the methods are ideal ways for the bolt-loosening monitoring. However the stress-induced velocity changes are quite small; thus the time-of-flight variation and frequency shift are very small. Furthermore, there are many factors, which should be analyzed to increase the accuracy, such as the material-microstructure effects, environmental noise, temperature, and the thickness of bonding layer [3].

The guided wave-based method uses that bolt preload changes the dynamic characteristics of the splice plate, and it affects the ultrasonic wave, which is generated by the piezoelectric transducer, passing through the splice plate. By monitoring and analyzing the received ultrasonic signal, the bolt-loosening can be detected [3]. Because this method can investigate all bolts on a splice plate, it has a great potential for bolt-loosening detection monitoring. However, it is difficult to pin-point loosened bolts and it is also affected by environmental noise and temperature.

The impedance-based method has high sensitivity to the local structural damage and a large-frequency bandwidth. It is specially fitted for monitoring bolted joints which are dominated by local dynamics of high-frequency characteristics. The impedance method has a good potential for in situ monitoring of bolted connections [3, 14]. However, it has small range, which can monitor, per one sensor and so needs a lot of sensors and impedance analyzers to cover all bolts in the steel bridges. Also, the method is affected by temperature and environmental noise [15].

The magnet field-based method is based on a simple phenomenon which the bolt-loosening is caused by rotating a nut and the rotation changes magnetic field around the nut. It consists of a nut cap with magnets and a reed switch. If a nut is rotated in the nut cap, magnet field is changed and then the reed switch is turned on and bolt-loosening is detected [4]. This method is very simple but it can apply only one bolt similar to the acoustoelastic effect-based method.

The electric potential drop method uses relationship between electrical resistance and change in thickness of a steel spice plate. If a bolt is loosened, cross-section area of the splice plate is increased and then the electric resistance is decreased. When constant current flows through the splice plate, the voltage is decreased by bolt-loosening and then bolt loosening can be detected [5]. Also, this method can approximately estimate bolt preload from finite element analysis. For field applications, however, paint coating to prevent corrosion must be removed and environmental conditions such as temperature should be considered.

The above five methods are promising methods to detect bolt loosening with high accuracy. For real application, however, the real-time monitoring using fixed sensors is inefficient because it is rare that bolts in steel bridges are rapidly loosened. Furthermore the methods require many high-cost sensors and instruments to monitor all bolts in a steel bridge.

3. IMAGE-BASED BOLT-LOOSENING DETECTION TECHNIQUE

In this study, a bolt-loosening detection technique by image processing is newly proposed to overcome the disadvantages of the existing techniques. Compared with the existing techniques, this technique is economical and quickly detect bolt loosening for tens bolts because it requires only images of bolted joints pictured by a digital camera. The proposed technique consists of 3 steps: taking picture for a bolt-joint, segmenting the image for each nut, and detecting bolt-loosening by identifying rotation angle of each nut, as shown in Fig. 3.1.

In the first step, a digital image for a bolt joint in a steel bridge is acquired from a digital camera. A bolt joint of a steel bridge consists of a pair of splice plates, bolts, nuts and washers. The digital image must be shot on an area including the nuts and the corresponding splice plate, because the bolt-loosening can be detected by identifying rotation of the nuts from the proposed technique. The image can be acquired by various cameras using CCD (charge-coupled device) such as digital cameras, video cameras and cameras embedded in smart phones.

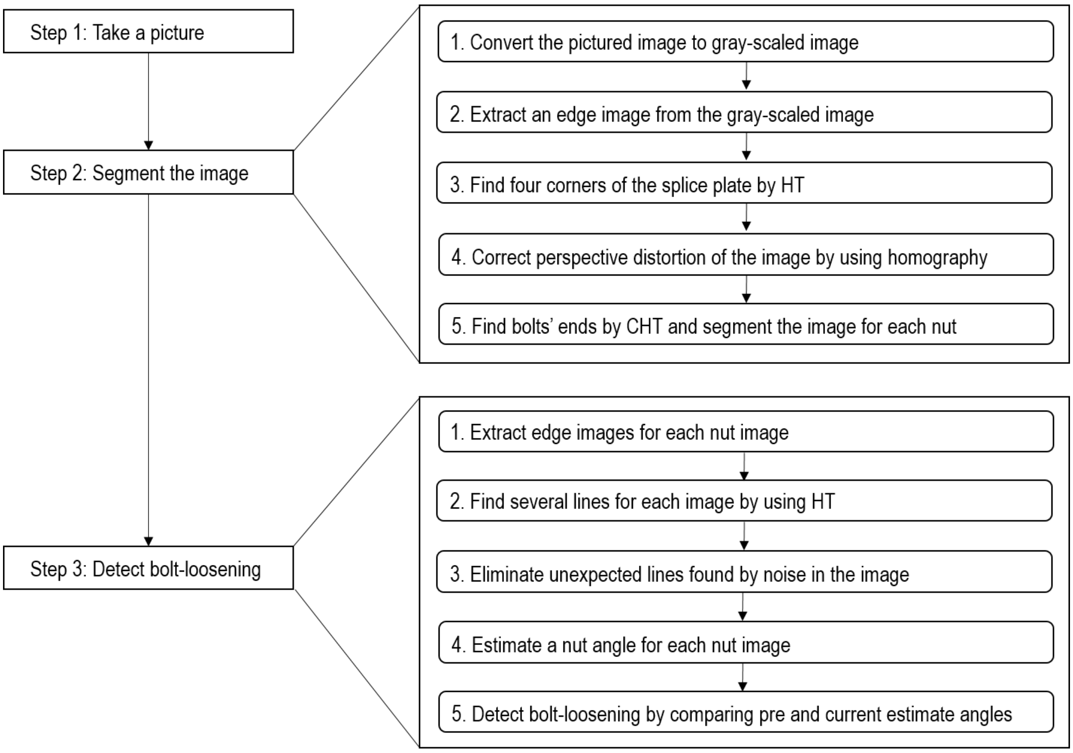


Figure 3.1 Process of the proposed image-based bolt-loosening detection technique

In the second step, the image is segmented and labeled for each nut. This step is processed by the following 5 procedures. Firstly, the pictured image is converted to a gray-scaled image. Secondly an edge image is extracted from the gray-scaled image by using an edge detector. As the edge detector, Canny detector [16] is selected in this study. Thirdly, four side lines of the splice plate are detected by using Hough transform (HT) [17], and then four corners' coordinates of the splice plate are detected from cross points of the side lines. Fourthly, perspective distortion on the image caused by picturing angle of the camera is corrected by projective transformation (so-called homography) [18]. The projective transformation uses the detected coordinates and size of the splice plate which is known from design documents or direct measurements. Finally, the bolts' ends, which form circular shapes, are detected by circular Hough transform (CHT) [17] and then the image is segmented to N images for the nuts where N is the number of nuts. For the segmentation, the bolts' center coordinates and radiuses, which identified by CHT, and distances from the centers to corners of nuts R are used. The size of each segmenting image is determined by

$$L = n \times 2 \times r_c \tag{1}$$

where L is the size of a segmented image, r_c is the radius of a bolt's end, and n is a ratio between r_c and R. In general, n is about 1.5 ~ 1.6. Considering the estimation error of r_c, however, n should be selected to larger value than 2. Fig. 3.2 shows an example of the segmented image by using n=2.5. Finally, the segmented nut images are labeled by sorting the center coordinates of the bolts' ends.

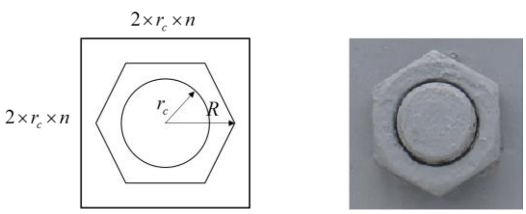


Figure 3.2 An example of segmented image for a nut

In the third step, bolt-loosening is detected for each nut image. This step is also processed by the following 5 procedures. Firstly, edge images are extracted for the segmented nut images by Canny edge detector. Secondly, k

potential lines are detected by HT for each, where k is an integer number. It is noted that the detected lines in an nut image may include lines corresponding to 6 sides of the nut as well as unexpected lines by noise in the nut image. Thirdly, the unexpected lines such as lines passing through the bolt are eliminated and the strongest p lines are selected. The larger p is selected, the higher accuracy might be. Then, rotation angles $\theta_i^{'}$ from the p lines are estimated by

$$\theta_i^{'} = 90 + \theta_i \tag{2}$$

where θ_i is an angle of the i^{th} line's perpendicular detected by HT as shown in Fig. 3.3. Meanwhile the rotation angle of the nut can be only measured from 0 to 60 degrees because it forms the shape of a regular hexagon. It means that the angle is recognized as same one when a nut is rotated to every 60 degrees. Furthermore, an extracted line by HT could be any one among 6 sides of the nut, and the rotation angles of the other side except one side of the nut are out of 0 ~ 60 degrees. Therefore the angle is recalculated to remain between 0 and 60 as

$$\theta_i^{n} = rem[(90 + \theta_i)/60] \tag{3}$$

where θ_i^n is the nut angle for the i^{th} detected line in the n^{th} nut image and $rem[\bullet]$ is an operator to calculate the remainder after division. Then, the nut angle is determined by averaging the nut angles for the selected p lines. Finally, bolt-loosening is detected by comparing the before and the current estimated angles for each nut.

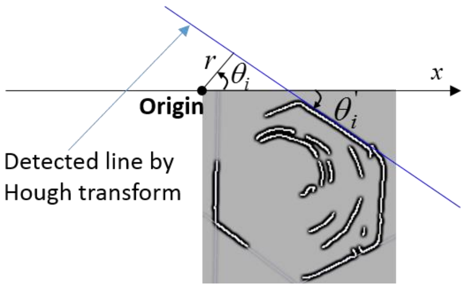
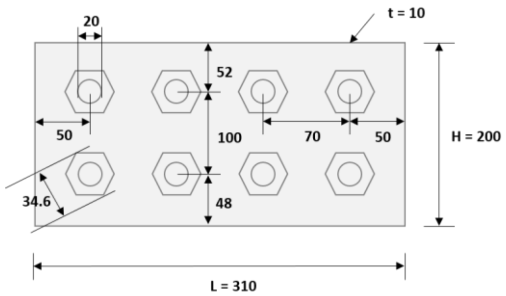


Figure 3.3 Identified line from HT and rotation angle of nut

4. EXPERIMENTAL VERIFICATION

4.1. Sensor-based Monitoring Techniques

In order to evaluate the applicability of the proposed technique, experimental tests were performed for a bolt joint model. The bolt joint model was consisted of a splice plate, and eight bolts and nuts. The splice plate was made by steel with length (L) of 310 mm, height (H) of 200 mm and thickness (t) of 10 mm as shown in Fig. 4.1(a). The eight standard bolts and nuts, M20, were used. The bolts and nuts were arrayed by 2 × 4, and the distances between the centers of bolts are 70 mm in the horizontal direction and 100 mm in the vertical direction. Also, the bolt joint model is coated by gray anticorrosive paint to simulate real steel structures.



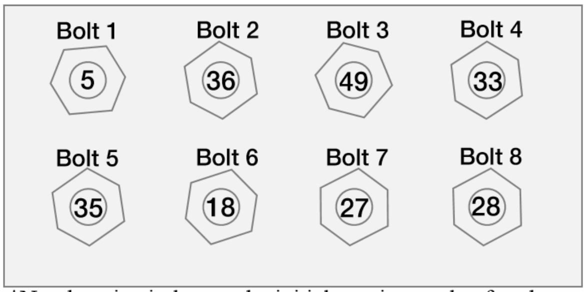
(a) Main dimensions of bolt joint model

(b) experimental setup

Figure 4.1 Main dimensions of bolt joint model and experimental setup

A digital camera (D7000 model by Nikon Co.) was used to take pictures of the splice plate. The camera was fixed by a tripod and approximately set to that the center of the camera screen is placed at the center of the splice plate as shown in Fig. 4.1(b). The pictures were shot by using the maximum resolution (3253×4928 pixels) of the camera. At taking the pictures, the camera was set to turn on the camera flash to remove shadows of the nuts by fluorescent lamps.

The initial condition of the bolt joint model is shown in Fig. 4.2. In Fig. 4.2, numbers in circles indicate the initial rotation angles of the nuts measured by a digital goniometer. Several bolt-loosening scenarios were selected as shown in Table 4.1. Firstly, Bolt 1 is loosened to 5, 15 and 45 degrees step by step. Then Bolt 7 is loosened to 12, 23 and 57 degrees step by step. Therefore total 7 cases including the intact case were used to simulate bolt-loosening. For each cases, 10 pictures were shot to evaluate the measurement error of the proposed technique.



*Numbers in circles are the initial rotation angle of each nut

Figure 4.2 Rotational angles of the eight nuts at initial condition

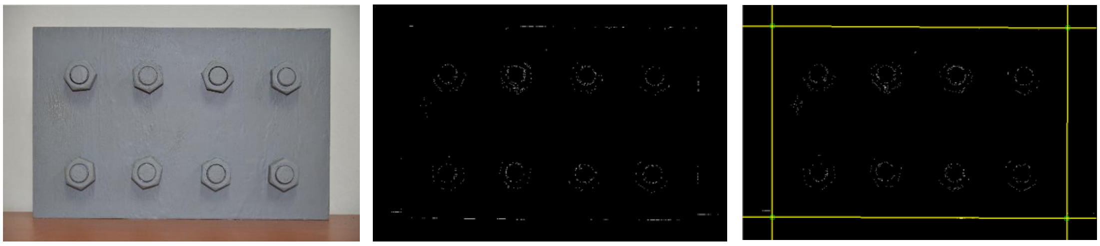
Table 4.1 Bolt-loosening scenario

Case	Loosened Bolt	$\Delta\theta$	No. of Pictures
Intact	-	-	10
Damage 1	Bolt 1	5	10
Damage 2	Bolt 1	15	10
Damage 3	Bolt 1	45	10
Damage 4	Bolt 7	12	10
Damage 5	Bolt 7	23	10
Damage 6	Bolt 7	57	10

4.2. Bolt-loosening Detection Results

Fig. 4.3 shows edge detection and line detection results by the Canny edge detector and HT as described in Step 1 of Chapter 3. For the edge detection, the two thresholds are set to 0.03 and 0.3, respectively, and the four lines in Fig. 4.3(c) were manually selected by checking each line. The four circles with green color in the Fig. 4.3(c) are identified corners. As shown in Fig. 4.3(c), the image of the splice plate is distorted a little because the picture was shot in front of the plate as possible.

Fig. 4.4(a) shows a corrected image for perspective distortion by using the identified corners and the known size. As shown in Fig. 4.4(a), the distorted image was projected to a rectangular shape corresponding to the size of the splice plate. Fig. 4.4(b) shows circles, which indicate bolt ends, found by using CHT, and the eight bolt ends were exactly identified. Fig. 4.4(c) shows images segmented by using Eq. (1) with n=2.



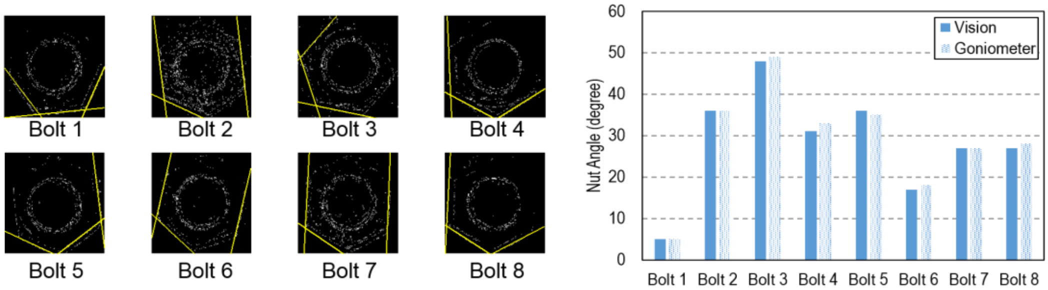
(a) Original image (b) edge image (c) identified lines of plate

Figure 4.3 Identified splice plate by HT

(a) Corrected image for distortion (b) circles identified by CHT (c) segmented images

Figure 4.4 Segmented images for each nut

Fig. 4.5(a) shows identified side lines of the all nuts by HT. For each nut, the first 3 strongest lines were selected to estimate the rotation angle by averaging the angles of lines. Fig. 4.5(b) shows rotation angles of the nuts identified by HT in the initial condition. Also, the angles were compared with ones measured by the goniometer. As shown in Fig. 4.5(b), the estimated angles by the proposed method are good matched to ones by the goniometer with the error of ±2 degrees. Fig. 4.6 shows the changes in the rotation angles of the nuts estimated by the proposed technique. As shown in Fig. 4.6, the loosened Bolt 1 and Bolt 7 were exactly detected and the rotation angles of all nuts estimated within error of ±2 degrees. Also, angles for other bolts were exactly estimated within the error of ±2 degrees.



(a) Identified side lines of the nuts by HT (b) Identified Initial rotation angle

Figure 4.5 Rotation angles of nuts estimated for the initial condition

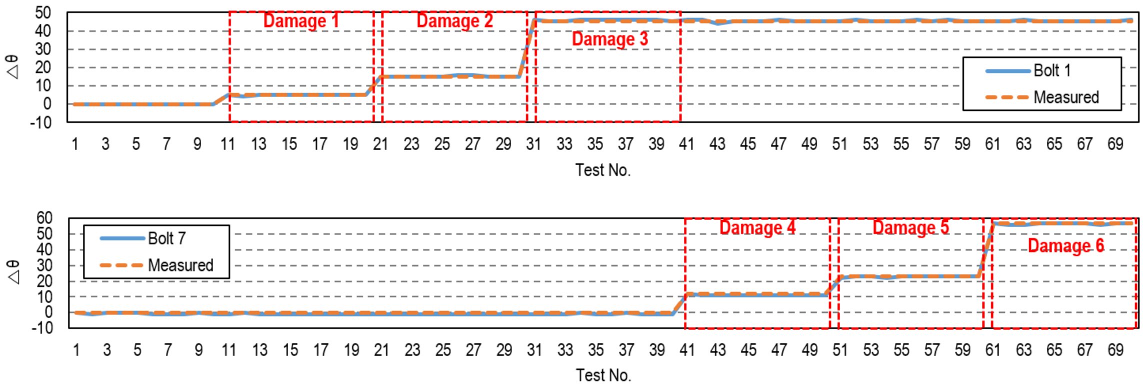


Figure 4.6 Bolt-loosening detection results

5. CONCLUSION

In this study, a novel bolt-loosening detection technique using image information of bolted joints in steel bridges was developed. To achieve the research objective, the following approaches were implemented. Firstly, existing bolt-loosening detection techniques were reviewed and their benefits and limitations are analyzed. Secondly, a bolt-loosening detection algorithm using image processing techniques was newly proposed for bolted joints in steel bridges. It consists of 3 steps: (1) taking a picture for a bolt joint, (2) segmenting the image to identify a splice plate and each nut, and (3) identifying rotation angle of each nut and detecting bolt-loosening. As a key technique, the Hough transform was used to identify rotation angles of nuts. Finally, the applicability of the proposed technique was evaluated by experimental tests with bolt-loosening scenarios. From the results, the nut angles estimated by the proposed technique were good matched to ones by the goniometer with the error of ±2 degrees. Furthermore, the proposed technique found the change in the nut angles and detected bolt-loosening exactly within the error of ±2 degrees.

AKCNOWLEDGEMENT

This research was supported by a grant (code 12 Technology Innovation E09) from Construction Technology Innovation Program funded by Ministry of Land, Transportation and Maritime Affairs (MLTM) of Korean government. The graduate student and BK21plus professor involved in the research were also partially supported by the Brain Korea 21 Plus program of Korean Government.

REFERENCES

1. Korea Expressway Corporation (2013). Improvement of bridge inspection system by the damage analysis, Korea Expressway Corporation, Korea.
2. Korea Infrastructure Safety & Technology Corporation (2008). Guideline for bridge inspection, Korea Infrastructure Safety & Technology Corporation, Korea.
3. Wang, T., Song, G., Liu, S., Li, Y. and Xiao, H. (2013). Review of Bolted Connection Monitoring, *International Journal of Distributed Sensor Networks*, **2013:Article ID 871213**, 1-8.
4. You, Y.J., Park, K.T., Lee, W.S., and Han, S.H. (2010). Development of information detection unit on the loosening of bolted joints using USN technology, *Korea Society of Civil Engineers (KSCE) Conference & Expo 2010*, Incheon, Korea
5. Hyun, S.H. (2013). The study on inspection for relaxation of bolted joins by electric potential drop method, Chung-Ang University, Seoul, Korea.
6. Abdel-Qader, I., Abudayyeh, O., and Kelly, M.E. (2003). Analysis of edge-detection techniques for crack identification in bridges, *Journal of Computing in Civil Engineering ASCE*, **17:4**, 255-263.
7. Yamaguchi, T., and Hashimoto, S. (2010). Fast crack detection method for large-size concrete surface images using percolation-based image processing, *Machine Vision and Applications*, **21:5**, 797-809.
8. Subirats, P., Dumoulin, J., Legeay, V., and Barba, D. (2006). Automation of pavement surface crack detection using the continuous wavelet transform, *IEEE International Conference on Image Processing*, Atlanta, USA.
9. Ho, H.N., Kim, K.D., Park, Y.S., and Lee, J.J. (2013). An efficient image-based damage detection for cable surface in cable-stayed bridges, *NDT&E International*, **58**, 18-23.
10. Korea Expressway Corporation (2006). Performance optimization of steel bridge coating diagnosing system for field application, Korea Expressway Corporation, Korea.
11. Ho, H.N., Lee, J.H., Park, Y.S., and Lee, J.J. (2012). A synchronized multipoint vision-based system for displacement measurement of civil infra structures, *The Scientific World Journal*, **2012:Article ID 519146**, 1-9.
12. Fukuda, Y., Feng, M.Q., Narita, Y., Kaneko, S., and Tanaka, T. (2013). Vision-based displacement sensor for monitoring dynamic response using robust object search algorithm, *IEEE Sensor Journal*, **13:12**, 4725-4732.
13. Kim, N., and Hong, M. (2009). Measurement of axial stress using mode-converted ultrasound, *NDT and E International*, **42:3**, 164-169.
14. Kim, J.T., Park, J.H., Hong, D.S., and Ho, D.D. (2011). Hybrid acceleration-impedance sensor nodes on Imote2-platform for damage monitoring in steel girder connections, *Smart Structures and Systems*, **7:5**, 393-416.
15. Hong, D.S., Nguyen, K.D., Lee, I.C., and Kim, J.T. (2012). Temperature-compensated damage monitoring by using wireless acceleration-impedance sensor nodes in steel girder connection, *International Journal of Distributed Sensor Networks*, **2012:Article ID 167120**, 1-12.
16. Canny, J. (1986). A computational approach to edge detection, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **8:6**, 679-698.
17. Duda, R. O., and Hart, P.E. (1971). Use of the Hough transformation to detect lines and curves in pictures, *Communications of the ACM*, **15:1**, 11-15.
18. Hartley, R., and Zisserman, A. (2000). Multiple view geometry in computer vision, Cambridge University Press, United Kingdom.