Chapter 16
A Vision-Based Quantification Approach for Reinforced Concrete Tunnel Liner Delamination

Qixiang Tang, Shafique Ahmed, Paul Noyce, and Gina Crevello

Abstract Infrastructures such as tunnels and bridges in the United States are facing severe degradation. According to the National Tunnel Inventory, the tunnels' condition needs to be evaluated by a condition state method periodically, which includes detecting and measuring the delamination in the concrete liner due to safety issues. For concrete tunnels in poor conditions, delamination is usually detected using sounding tests (using hammer) and quantified manually (with tape measures and sketch). The quantification process of identified delaminated areas is time-consuming and uneconomical. An alternative approach for quantifying the detected delaminated areas is proposed and validated in this case study. A series of images were extracted from a video recorded from a vehicle traveling through a tunnel. Images were scaled, then converted to binary images, and processed with a pixel-based quantification algorithm. The quantification algorithm can take into consideration the curvature of the surfaces to obtain accurate quantification of surface areas. The delamination dimensions evaluated by the algorithm were verified by the manual quantification method. It is believed that this method could be combined with other structure testing methods for the interdisciplinary perspective of the structural condition.

Keywords Tunnel liner · Nondestructive testing · Concrete delamination · Optical method

16.1 Introduction

As of 2020, there are 526 registered tunnels in the National Tunnel Inventory (NTI) [1] with a total length of 704,092 ft (214.6 km). According to the Specifications for the National Tunnel Inventory [2], these tunnels are required to be inspected using a structural element-based evaluation method routinely. One of the most important structural elements of the tunnel is the liner. The liners are evaluated and quantified into four levels of condition states including the quantification of delaminations of the concrete liner. While various NDT techniques such as impact-echo [3, 4], ultrasonics [5, 6], and radar scanning [7, 8] can be used for identifying delaminated concrete liners, these commonly used quantification methods are time-consuming and costly. Traditional identification/quantification procedures such as on-site measurements involve the use of traffic control and mobile platform over several night shifts, which often cost more than the inspection works itself. To reduce the economic impacts and improve the efficiency, a vision-based delamination quantification method is proposed and utilized during a practical tunnel investigation.

16.2 Background

In this investigation, both the crown and walls of the tunnel liner were previously inspected using hammer sounding test. Specialized hammers and Delam Tools (Sounding Technology, Inc.) were utilized to identify the delamination of the reinforced concrete liners by five trained technicians. Delaminated areas were marked with high-visible spray paints. Without conducting any measurements and estimations on-site, all hammer sounding tests in the 1200-ft tunnel were finished in one night shift (7 h).

Q. Tang (✉) · S. Ahmed · P. Noyce · G. Crevello
Echem Consultants LLC, Poughkeepsie, NY, USA
e-mail: qtang@e2chem.com; qtang@echemconsultants.com; sahmed@echemconsultants.com; pnoyce@echemconsultants.com; gcrevello@echemconsultants.com

D. D. Maio, J. Baqersad (eds.), *Rotating Machinery, Optical Methods & Scanning LDV Methods, Volume 6*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-031-04098-6_16

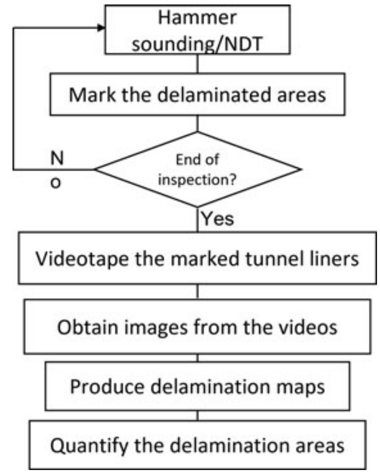

Fig. 16.1 Procedure of producing quantifiable delamination maps of concrete tunnel liner

After completing the hammer sounding test and marking, the entire concrete surface was videotaped using a digital camera mounted in a vehicle traveling through the tunnel. Images were then obtained from the videos based on the traveling speed and the frame rate of the camera. These images were first scaled based on the reference dimensions captured in the images, both in the horizontal and vertical directions. Images were stitched together using the cross-correlation techniques utilizing the overlapped region between adjacent images. These stitched photos were imported into CAD software for global scaling and feature extraction. Delamination maps of the surveyed areas containing the quantitative information (i.e., locations and dimensions of delamination areas) were then produced. The flowchart diagram in Fig. 16.1 shows the procedure of producing delamination maps with the estimation of quantity and location of each delamination.

In the delamination maps, each delaminated area was automatically assigned with a unique label, and the quantity (e.g., surface area) of each was estimated. It should be mentioned that the crown of the tunnel was an arc surface. The dimensions in the images were distorted from the actual dimensions due to the perspective effect. A factor which varies with the curvature of the crown was incorporated to correct the dimensions in the images of the crown.

16.3 Analysis

Once the images of the tunnel liner were extracted from the video, the results of image stitching were first obtained. For example, Fig. 16.2a shows a 75-ft (22.9-m) section of the tunnel liner stitched from three adjacent images. The stitched image was imported to CAD, and each delamination area was quantified and labeled into a delamination map, as shown in Fig. 16.2b.

In Fig. 16.3a, the delamination (marked in gray) over 1200 ft (365.8 m) of the crown was mapped onto the curved surface. The areas of the delamination were calculated considering the correcting factor of the curvature. Quantitative information of each delamination area such as location and dimensions were estimated using the global coordinates.

With the quantitative information of the delamination, a statistical analysis was able to be performed. For example, Fig. 16.3b shows the delamination distribution along the longitudinal direction, where it can be seen that more delamination areas were observed at the two portal sections and the middle section of the tunnel. This would indicate more durability issues in these sections. In the portal sections, the number of the delamination increased at the location where the waterproof membrane ends, while in the middle section, a vertical ventilation shaft was present. As a result, potentials of water ingress and chloride contamination were higher. This was aligned with other condition assessment results such as half-cell potential tests and chloride tests of concrete samples at these sections. Figure 16.3c shows the delamination distribution along cross-sectional direction where 14 ft was the midpoint of the cross section. More delamination was found in the left side (0–14 ft) in which the ventilation shaft was located. In Fig. 16.3d, the statistical distribution of delamination sizes is shown. It was found that most of the delamination areas were smaller than 10 ft^2 (0.93 m^2). It can also be seen that when the size of the delamination becomes greater, a smaller number of delamination were found. This could indicate that when multiple adjacent small delamination areas grow larger, they might join together and formed a larger delamination. In addition, when delamination areas grow to be greater than 35 ft^2 (3.25 m^2), the delaminated concrete is more likely to spall.

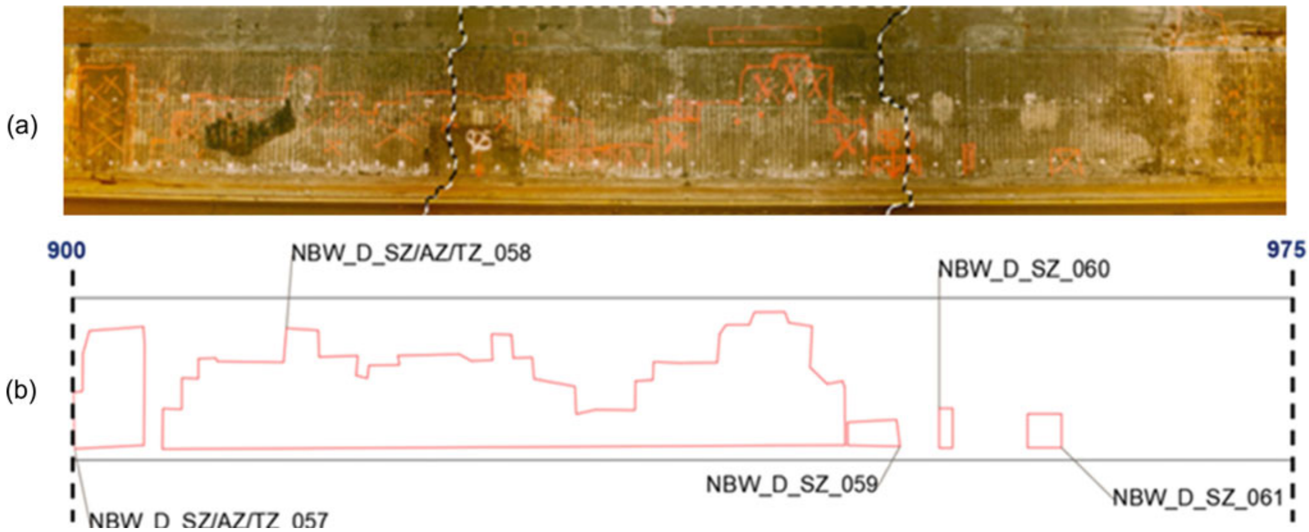

Fig. 16.2 (**a**) Stitched images of a portion of tunnel liner (dash lines represent boundaries between two images) and (**b**) extracted delamination map with unique label for each identified delaminated area

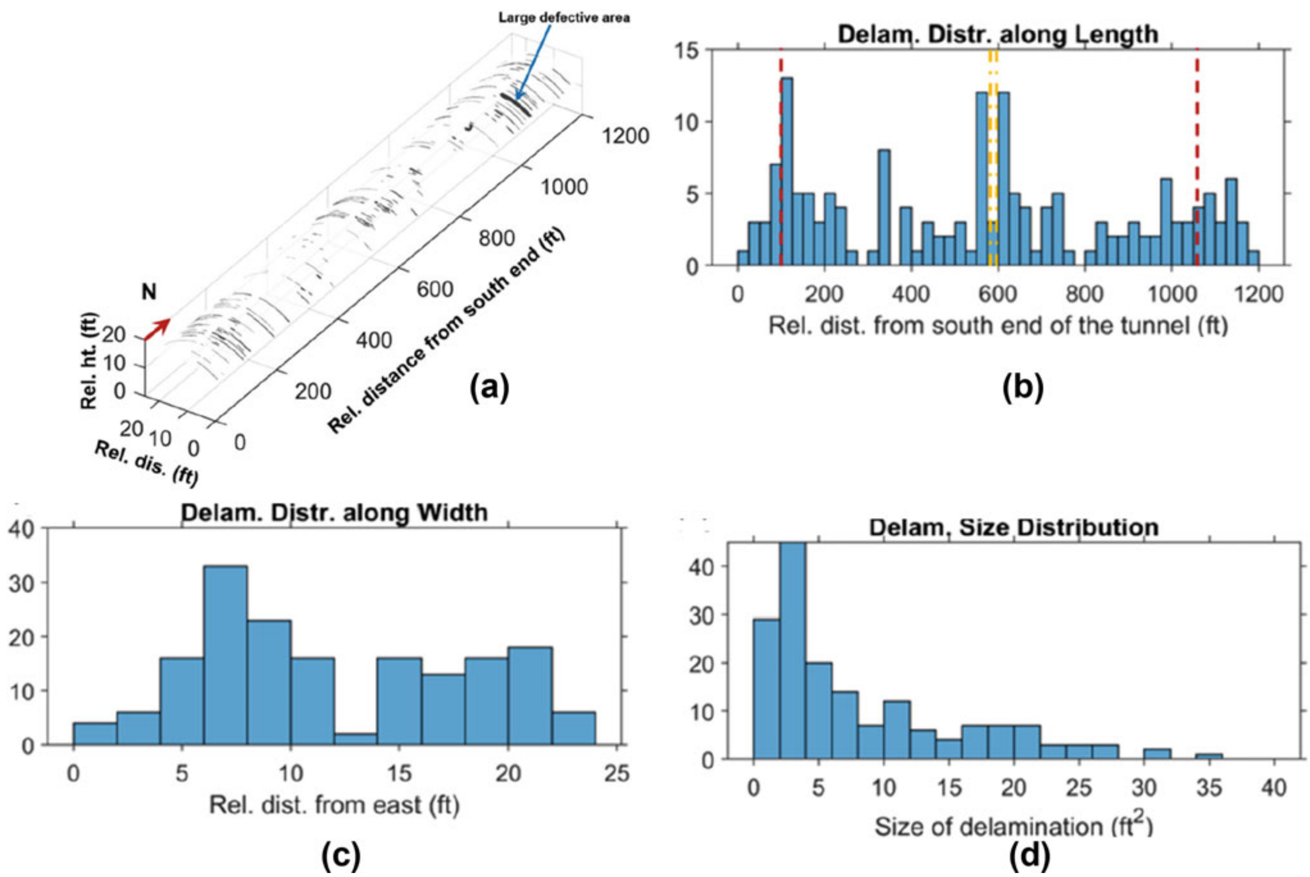

Fig. 16.3 (**a**) Delamination map of crown surface; (**b**) distribution of delamination along longitudinal direction; (**c**) distribution of delamination along cross-sectional direction; and (**d**) statistic distribution of delamination size

Comparing to the traditional on-site measurement method, the proposed method could be providing historical quantitative data from periodical inspections. It is believed that by combining with other NDT techniques, the historical quantitative data can be used for predictive condition assessment of the tunnel and served as a guideline for the following inspection. For example, more delaminations were identified at the portals and middle sections suggesting more aggressive corrosion environment in these sections. It is anticipated that the delamination/corrosion activity would be more severe overtime. Thus, when planning for the future inspection, these sections should be paid more attentions. Moreover, the estimated time for quantifying all the delamination areas using traditional on-site measurement methods was 1.5–2 night shifts (10–14 h), while only a few minutes of videotaping was spent on-site using the proposed quantification method. Thus, the efficiency in both time and financial manners is greatly improved.

16.4 Conclusion

A rapid quantification method for concrete liner delamination was proposed. Such method significantly reduces the on-site workhours by replacing the time-consuming on-site measurement process with short time of videotaping in the vehicle and off-site post-processing. It is believed that the post-processing techniques can be further advanced in the future to improve the efficiency and accuracy. With routine inspections of the tunnel liners, statistical analysis of historical quantitative data can be utilized to evaluate the development of delamination areas. By combing with other NDT techniques, this historical data can be used for optimizing condition assessment and inspection/maintenance programs and served as a database for structural health monitoring.

References

1. U.S. Department of Transportation Federal Highway Administration, "National Tunnel Inventory [database]," 2020 Retrieved from https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm
2. U.S. Department of Transportation Federal Highway Administration, "Specifications for the National Tunnel Inventory," Federal Highway Administration. FHWA-HIF-15-006, 2015
3. Cheng, C., Sansalone, M.: The impact-echo response of concrete plates containing delaminations: numerical, experimental and field studies. Mater. Struct. **26**, 274–285 (1993)
4. Zhu, J., Popovics, J.S.: Imaging concrete structures using air-coupled impact-echo. J. Eng. Mech. **133**(6), 628–640 (2007)
5. Pristov, E., Dalton, W., Likins, G.: Measurement of concrete thickness and detection of defects using ultrasound methods. In: Proceedings of the fifth highway geophysics–NDE conference: Charlotte, NC (pp. 295–301) Dec 2008
6. Shokouhi, P., Wöstmann, J., Schneider, G., Milmann, B., Taffe, A., Wiggenhauser, H.: Nondestructive detection of delamination in concrete slabs: multiple-method investigation. Transp. Res. Rec. **2251**(1), 103–113 (2011)
7. Yu, T., Twumasi, J.O., Le, V., Tang, Q., D'Amico, N.: Surface and subsurface remote sensing of concrete structures using synthetic aperture radar imaging. J. Struct. Eng. **143**(10), 04017143 (2017)
8. Barnes, C.L., Trottier, J.F., Forgeron, D.: Improved concrete bridge deck evaluation using GPR by accounting for signal depth–amplitude effects. NDT & E Int. **41**(6), 427–433 (2008)