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Image-based retrieval of concrete crack properties for bridge inspection

R.S. Adhikari *, O. Moselhi [1], A. Bagchi [2]

Department of Building, Civil, and Environment Engineering, Concordia University, Montreal H3G 1M8, Canada

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ABSTRACT

Cracking can invite sudden failures of concrete structures. The objective of this research is to develop an integrated model based on digital image processing in developing the numerical representation of defects. The integration model consists of crack quantification, change detection, neural networks, and 3D visualization models to visualize the defects in such a way that it mimics the on-site visual inspections. The crack quantification model evaluates crack lengths based on the perimeter of the skeleton of a crack which considers the tortuosity of the crack. The change detection model is based on the Fourier Transform of digital images eliminating the need for image registration as required in the traditional. Also, the integrated model as proposed here for crack length and change detection is supported by neural networks to predict crack depth and 3D visualization of crack patterns considering crack density as a key attribute.

1. Introduction

The problems of cracking in reinforcement concrete structures are natural and can invite spectacular failure of entire structures [1]. There always exist constraints in reinforced concrete structures and hence cracking is unavoidable regardless of the types of structures. Cracks not only provide access to harmful and corrosive chemicals inside concrete, but also allow water and de-icing salts to penetrate through bridge decks which can damage superstructures and bridge esthetics [2]. In spite of significant research in addressing the problems of cracking in bridges, it still remains a challenging problem whether it is old and newly constructed bridges [3]. Therefore, a rigorous study towards the evaluation of the extent and severity of cracks is necessary for condition assessment of bridges, and to maintain database for bridge inspections for long-term analysis [3].

Currently, the method of data collection for bridge inspections is by performing site visits [4,5]. The collected information during field visits is the fundamental input data for automated Bridge Management Systems (BMSs), such as PONTIS [10]. In Canada, there is a need for a unified BMS to maintain Canadian bridges. Canadian bridges need to be inspected frequently to ensure that the functionality of structural members meets the safety requirements because more than 40% of all bridges are older than 50 years [6]. In practice, the existing condition of bridges is documented through routine bridge inspections performed in every two years. The major tasks outlined in bridge inspection manuals during routine bridge inspection are two folds [7,8]. The primary purpose of the routine bridge inspection is to inspect the physical condition of bridge structures in terms of the extent and severity of defects (quantification model) and the secondary purpose is to verify and update information about structures reported in last inspections (change detection model). Traditionally, the routine bridge inspection is carried out through visual inspection and several limitations of visual inspection have been identified by previous researchers [4,5,10,36]. For example, it provides only qualitative information of defects as well as the inspection process is laborious, time-consuming and influenced by subjective behavior of individual inspectors. The aim of this research is to enhance the two fundamental tasks of routine bridge inspection considering crack as a major concrete defect for condition assessment of concrete bridges. The authors propose an integrated model which develops numerical representation of concrete defects based on digital image processing to achieve the objective of this research. The proposed integration model consists of crack quantification, change detection, neural networks, and 3D visualization models to represent concrete defects with few numbers and to visualize the defects in such a way that it mimics the on-site visual inspection.

Many attempts have been made earlier to enhance traditional approaches of condition assessment of concrete bridges. Abudayyeh et al. [66] proposed a framework for automated bridge imaging system based on digital image processing and integrated with Bridge Management Systems (BMSs) PONTIS. Their models were capable of storing different surface defects. However, the condition rating of bridge elements was assigned manually displaying the collected images on computer monitors. To automate this process, an automated prediction of condition rating model is required. However, the pre-requisite to such automated models is the digital representation of defects i.e. the defects or

* Corresponding author. Tel.: +1 514 848 2424x7144; fax: +1 514 848 7965.
E-mail addresses: r_adhika@encs.concordia.ca, ram_adhikari91@yahoo.com (R.S. Adhikari), moselhi@encs.concordia.ca (O. Moselhi), abagchi@bcee.concordia.ca (A. Bagchi).
[1] Tel.: +1 514 848 2424x3190.
[2] Tel.: +1 514 848 2424x3213.

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change detection that needs to be defined numerically to automate the process. Such numerical models can be trained for automated prediction of condition state rating as proposed by Adhikari et al. [67]. Hence, this paper focuses on the development of an integration model which can be integrated with an automated system to overcome the limitation of traditional approach of condition assessments of bridges.

Several Non-Destructive Testing (NDT) techniques such as corrosion detection, alkali–silica reactions, and sulfate attacks exist to identify the existence and extent of deterioration in concrete structures in order to understand the behavior of concrete structures [9]. However, the detection of the extent and severity of a defect inside a concrete component is laborious, time-consuming, and often unreliable. But, the concrete structures show the combined effects of internal and external defects in the form of surface cracks which can be tracked with digital images. Also, bridges operate usually under fatigue loads and the components of bridges show initial fatigue reactions in the form of cracks on surfaces. For this reason, this work adopts concrete cracks as the major defect parameter for condition assessment of concrete elements. For the analysis of cracks, crack quantification and identification of crack patterns are necessary to reveal the condition of bridges. In recent years, many algorithms for automated crack detection have been studied in literatures [36,39,40,51]. However, the existing methods have several limitations which add difficulty in automating the entire process. A recent work on crack length quantification as reported in [36] uses an object-oriented bounding box which also ignores the crack tortuosity in calculating the length of a crack. From a practical point of view, cracked length needs to be divided into several small segments and average width of each segment requires to be analyzed separately. The proposed crack quantification model evaluates the length of a crack from the crack skeleton perimeter which considers the tortuosity, segmentation and branching of the crack. The existing approach for crack segmentation requires searching of crack pixel connectivity, which needs input of at least one point to start searching of connected points and matching with orientation angle to decide whether the pixel in question belongs to same group or not [36]. If there exists multiple of crack skeletons (unconnected crack regions) in a same image frame, the existing approach of segmentation becomes time-consuming. This method could be improved by automatic detection of the branch points and segments. Additionally, the numbers of branch points in themselves could serve as a good indicator of condition rating of concrete elements. The increasing numbers of branch points could be an indicator of decreasing integrity of structural elements. The proposed method addresses some of these issues as well.

Another contribution of the current paper comes from a proposed change detection model which provides a numerical representation of crack images making it easy for comparison of temporal defects. The change detection model proposed in this work is based on spectral analysis of images obtained through Fast Fourier Transform of digital images. The traditional approach of change detection is based on image subtraction and image rationing which requires image registration process [60]. The image registration is cumbersome process and often it is difficult to achieve the desired accuracy [63–65]. The proposed approach for change detection does not require image registration process and has added advantage of capturing the surface information contained in the image texture.

Identification and detection of individual cracks are not sufficient in understanding the structural behavior. The engineer needs to know how the crack patterns change with time and where they lie on structural members. For this purpose, this work develops 3D visualization model of crack patterns measured through crack density defined as total length of cracks divided by total surface area. Maksymowicz et al. [71] developed 3D visualization models of defects based on digital image processing. However, their models were supported by manual operations using advanced graphical editor software to model defects from photos. The proposed integrated model is supported by 3D visualization of crack density by projecting digital images and neural network models to predict crack depth necessary for condition assessment of concrete components. With the successful application of the proposed approach, the two tasks of routine bridge inspection can be greatly enhanced by incorporating them in an automated Bridge Management System.

2. Background

2.1. Cracking patterns in bridge decks

The characteristics of critical cracks need to be understood in reinforced concrete structures because the misunderstanding of the nature of cracks and their crack patterns can result in a sudden failure of structures. The common forms of crack patterns experienced in reinforced concrete structures are longitudinal, transverse, and diagonal cracks; crack map; and random cracks [11]. Transverse cracks are generally formed perpendicular to the longitudinal axis of a bridge deck under the transverse reinforced steel. Transverse cracks are typically full depth across sections and crack spacings are 3–10 ft as observed along the length of a bridge deck [12]. Field survey requires identifying the location and orientation of such cracks. Similarly, the cracks running parallel to the longitudinal axis are called longitudinal cracks which appear just above the longitudinal reinforced steels. These cracks follow the paths of reinforcing steel in structural elements [13]. Crack patterns also differ from one bridge type to another. Skewed bridge decks are more prone to diagonal cracks as compared to straight aligned bridges [14]. Another way of visualizing a crack pattern is Map Cracking. Improper curing and restraining volumetric change of concrete are the primary causes of Map Cracking [11]. Many attentions have given in design of concrete structures. However, a proper modeling and visualization of the crack patterns are lacking which can aid in the decision making process effectively.

2.2. Deck performance against cracks

Transverse cracks accelerate the process of corrosion by allowing moisture, oxygen, and chloride ions into concrete spaces [15]. For reinforced concrete beams and decks, crack widths of less than 0.3 mm (0.01 in.) have little effect on overall corrosion of reinforcing steel [16,17]. As the width of cracks is more than 0.3 mm, the chances of corrosion in reinforcing steel increase and it leads to spalling of concrete. The recommended clear cover is necessary to protect reinforcing steel. In many cases, concrete spalling is the consequence of inadequate cover of reinforcing steel [18]. Since cracks are progressive in nature, timely inspection and evaluation of critical crack length, width, and density are necessary to prevent failure of structures. Bridge inspection manuals and guidelines have different way of handling cracks in concrete structures. For example, PONTIS [10] uses a smart flag element 358 for condition assessment of surface cracks in bridge decks. This element addresses the extent of cracking in four condition states on the basis of crack width and crack [20]. After the recognition of element condition states, the proper action plan is necessary to repair the cracks. Any concrete cracks wider than 0.9 mm (0.035″) require to be maintained by contractors according to Colorado Department of Transportation in USA (0.035″) [19].

2.3. Current practices of crack survey

The crack survey described here is based on the protocol developed at the University of Kansas as a part of Pooled Fund TPF — 5(051) Construction of Crack-Free Concrete Bridge Decks [3,21]. The cracks considered in this protocol are greater than 0.2 mm because this size of cracks is visible with the naked eyes while bending at the waist. The initial preparation of deck surfaces is required before carrying out crack survey. The bridge decks might require cleaning with clear water so that