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Image analysis method for crack distribution and width estimation for reinforced concrete structures

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ABSTRACT

Crack observation is important for evaluating the structural performance and safety of reinforced concrete (RC) structures. Most of the existing image-based crack detection methods are based on edge detection algorithms, which detect cracks that are wide enough to present dark areas in the obtained images. Cracks initiate as thin cracks, generally having width less than the width of a pixel in images; such cracks are generally undetectable by edge detection-based methods.

An image analysis method is proposed to observe the development and distribution of thin cracks on RC surfaces; it also allows estimation of crack widths. Image matching based on optical flow and subpixel is employed to analyze slight concrete surface displacements. Camera calibration is included to eliminate perspective effects and lens distortion. Geometric transformation is adopted so that cameras do not need to be perpendicular to the observed surface or specified positions. Formulas are proposed to estimate the width of shear crack opening. The proposed method was then applied to a cyclic test of an RC structure. The crack widths and their development analyzed by the image analysis were verified with human inspection in the test. In addition, concrete surface cracks that appeared at a very early stage of the test could be observed by the proposed method before they could be detected by the naked eye. The results thus demonstrate that the proposed image analysis method offers an efficient way applicable not only for structural tests but also for crack-based structural-health-monitoring applications.

1. Introduction

Crack observation is an important aspect of most reinforced concrete (RC) structural experiments and structural safety evaluation. The crack patterns, angles, and distribution density may reveal the failure modes, damage levels, and stiffness degradation for concrete models [1,2]. The effect of cracks on structural strength or water permeability has been discussed in many studies [3,4]. The reasonable limits of crack widths and repair methods have been recommended by standard codes or regulations [5,6]. In addition, for the containment vessel of a nuclear reactor, cracks indicate the risk of radiation leak [7]; therefore, regulations have been established [8]. While many numerical models of concrete materials adopt the concept of smeared cracks to estimate crack-induced strength degradation (e.g., [9]), some methods involve simulation of concrete cracks and numerical analysis of crack widths for better prediction of crack-induced structural behaviors [10,11].

Since the advancement of digital image technology, image analysis methods have been utilized for crack detection as they provide more advantages and feasibility for structural health monitoring (SHM) applications. Image analysis offers a cost-effective, alternative solution to concrete crack observation and has potential in SHM applications. Using image analysis, we can not only record the overall visual appearance of an RC surface but also analyze vibrations [12], deformation [13,14], and terrain models [15] as well as assess construction quality such as welding quality [16] or loosened bolts [17]. Structural deformations, mode shapes, natural frequencies, and motion magnification can also be estimated using image analysis [18]. Image analysis has been also employed to detect cracks. Yu et al. [19] analyzed infrared images to detect tunnel lining surface cracks. Hutchinson and Chen [20] conducted image analysis to evaluate concrete damage of bridges induced by cracks and spalling. Zakeri et al. [21] developed an approach to interpret and classify pavement cracks. Chen et al. [22] recognized cracks through analyzing hundreds of photos in a bridge management database. Li et al. [23] recognized bridge cracks through

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image edge detection and noise reduction. Dinh et al. [24] proposed a method to extract concrete cracks based on the image gray-scale histogram. Machine-learning-based computer vision has been applied and trained to detect concrete cracks under various environmental conditions, e.g., Prasanna et al. [25] and Cha et al. [26]; it is capable of detecting a wide variety of concrete surface defects as well as reducing the effects of uncontrollable ambient lights, provided that sufficient training data are available. Most of the existing crack detection methods are based on edge detection, which extracts the dark shadow lines or crack regions.

However, these methods are suitable for observing only wide cracks that present dark lines in the images, but not for thin cracks that do not present dark lines in the images or in cases where the camera is located too far from a specimen for the dark lines to appear.

Crack width is not easy to measure on the basis of the number of dark pixels or the pixel intensity if the crack is thinner than about one pixel in an image. Cracks appear dark because they do not reflect light. In an image, the boundary of a crack is at a gray level between dark (corresponding to the crack) and light (corresponding to the intact concrete surface), indicating that only a part of the gray pixel corresponds to the crack. If a crack is thinner than one pixel, it only appears as a gray line in an image. The pixel intensity does not represent the area occupied by the crack because it depends on not only the crack width but also the light in the environment, exposure time and aperture of the camera, and many other factors.

A preliminary test [27] showed that cracks that are thinner than about one-third of a pixel in an image cannot be recognized. This preliminary image test (Fig. 1) showed that a 0.15 mm dark line printed on a crack width ruler cannot be recognized clearly even in images captured using a high-resolution digital camera (e.g., 22 MP) at a close object distance (< 2 m). The equivalent pixel size is about 0.45 mm per pixel, i.e., the crack width corresponding to a 0.33-pixel crack is about 0.15 mm. In this paper, a thin crack is defined as a crack whose width is as small as 0.1 mm and is invisible in photos taken in this study. In possible future SHM applications, 0.1-mm cracks are still invisible in photos, even if a 100-mega-pixel camera is used to monitor a 6-meter-wide area.

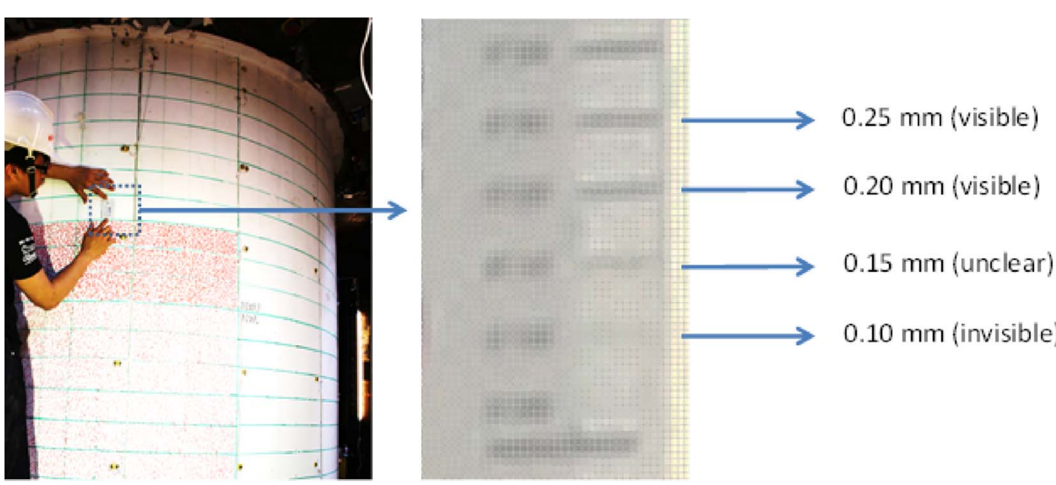
In addition to being used in structural safety evaluation, image analysis of crack development can be applied in structural laboratories. In a concrete structure test, the development of surface cracks is typically observed and recorded by pausing the test and the inspectors manually sketching lines on the crack surfaces, which is time consuming, labor intensive, and risky at a certain level. While the hydraulic actuators that apply force on the specimen appear fixed and stable, they in fact move back-and-forth within a small displacement range and are controlled hydraulically at a high frequency, rather than being physically fixed. A long experiment pause could result in stress relaxation in the specimen, leading to inconsistent or inaccurate experimental results [28].

This study proposes an image analysis method that can estimate shear crack opening fields on an RC surface. This method is based on the surface displacement field measurement that was previously developed and has been applied to many experiments [29]. Surface displacement field measurements are applied to observe horizontal flexural cracks. In this paper, we present the geometric transformation between the observed surface and the cameras and the analysis of the crack widths according to the displacements measured using image analysis. In addition, we compare manual estimation and image analysis of cracks.

2. Analysis procedures and formulas

The image analysis method that was employed and modified in this work has been implemented in a program named ImPro Stereo [30,31]. This method generally consists of four major steps: stereo calibration of two cameras, three-dimensional (3D) control point positioning, metric image rectification, and surface displacement and deformation analysis. Stereo calibration is carried out to estimate the intrinsic and extrinsic parameters of cameras, including coordinate system transformation relationships between cameras, focal lens, and distortion coefficients. Thus, the calibration provides sufficient parameters to carry out coordinate transformation between image coordinates and a 3D coordinate system. Stereo calibration is performed using a self-calibration method implemented by Bouguet [32] and OpenCV [33,34], which only requires a planar board such as a chessboard rather than a 3D calibration apparatus. Therefore, the ease of calibration is increased, thereby improving the wide applications of image analysis in engineering. Note that since the parameters obtained by the stereo calibration are critically important in the follow-up calculation, this method requires the focal lengths and positions of both cameras to be fixed during the measurement.

3D control point positioning is used to determine four control points of a part of a cylindrical surface (named the region of interest, ROI) by using image tracking with sub-pixel accuracy and stereo triangulation techniques, as shown in Fig. 2(a). A cylindrical coordinate is then defined by determining the cylindrical surface parameters, including the central axis, the reference origin, and the radius of the cylinder, as shown in Fig. 2(b). Then, the ROI can be mathematically described on the basis of the cylindrical coordinate. The mathematical procedure for determining the parameters of a cylindrical surface is outlined in



(a) A photo of the crack ruler image test (b) Zoomed image of crack width ruler lines

Fig. 1. Minimally recognizable cracks in images taken in the test [27].