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Thin crack observation in a reinforced concrete bridge pier test using image processing and analysis

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ABSTRACT

In reinforced concrete (RC) structural experiments, the development of concrete surface cracks is an important factor of concern to experts. One conventional crack observation method is to suspend a test at a few selected testing steps and send inspectors to mark pen strokes on visible cracks, but this method is dangerous and labor intensive. Many image analysis methods have been proposed to detect and measure the dark shadow lines of cracks, reducing the need for manual pen marking. However, these methods are not applicable for thin cracks, which do not present clear dark lines in images.

This paper presents an image analysis method to capture thin cracks and minimize the requirement for pen marking in reinforced concrete structural tests. The paper presents the mathematical models, procedures, and limitations of our image analysis method, as well as the analysis flowchart, the adopted image processing and analysis methods, and the software implementation. Finally, the results of applying the proposed method in full-scale reinforced concrete bridge experiments are presented to demonstrate its performance. Results demonstrate that this method can capture concrete surface cracks even before dark crack lines visible to the naked eye appear.

1. Background

Crack observations play an important role in reinforced concrete (RC) structural tests. The directions, patterns, and density of crack distributions reveal different failure modes, the degradation of stiffness and strength of structures, and many other kinds of significant information to researchers (e.g., Figs. 1a and 1b) for failure mode studies [1] and numerical model development [2–3]. Conventionally, cracks are observed by suspending a test to allow inspectors to approach the concrete surfaces and manually sketch lines on the cracks (Fig. 2). However, this method can be more dangerous than it would seem. The specimen structures are damaged and partially unstable. During test suspension for crack observations, specimens are normally under tensioned, compressed, bent, or distorted conditions with tons of internal forces keeping cracks open. Normally hydraulic actuators that applying forces on specimens are still running control loops, slightly vibrating, and adjusting tons of applied forces on the specimens even if they seem to be paused. Helmets are insufficient to completely ensure human safety if any parts of the specimens, experimental devices, or connecting components unexpectedly become unstable.

As digital imaging technology rapidly improves and hardware costs drop, image analysis offers an alternative and cost-effective way for structural experimental measurements. Displacements, strain fields, cracks, or even dynamic motions can be captured and measured by using image analysis. Many crack detection methods have been proposed in the literature. Most of them are based on edge detection methods that detect and measure large cracks, whose presence appears as dark shadow lines in images [4]. Recent studies include improvement on crack depth prediction [5], change in detection without image registration [5], crack pattern recognition based on artificial neural networks [6], applications to micro-cracks of rocks [7], and efficient sub-pixel width measurement [8]. However, the development of concrete cracks of interest start from thin cracks that are not thick enough to clearly evidence a distinct dark line in images taken by remote cameras. Image resolution of cameras that are typically used in structural tests is on the order of about 1 mm per pixel or coarser: dark shadow lines that are thinner do not appear in the images.

To address this deficiency, this paper presents an image analysis method that is suitable for thin crack observations. In this method, cracks that are thinner than dark lines can appear in the images.

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Fig. 1a. A horizontal crack indicating flexural failure.

This method assumes that the materials at different sides of a crack have movement along different directions. A movement analysis method developed in the computer vision field was employed to analyze such small movements. The formula and the procedure are briefly introduced, followed by applications of this method to selected full-scale RC structural experiments. Dark line detection or edge detection-based approaches are not considered in this paper. However, this study does not reduce the values of the existing dark-line detection and edge-based methods. In practical applications, the proposed method and these past methods can be employed concurrently or combined for a more thorough method.

2. Procedures and analysis formulas

The proposed image-based crack observation method includes two procedure types: (1) experimental procedures, and (2) image analysis procedures. The aims of the experimental procedures are to acquire clear photos that contain sufficient and accurate information for the image analysis procedures. On the other hand, the aims of image analysis procedures are for the transformation and analysis of the photos into crack observation information and for visualization.

The experimental procedures include the following steps: (1) surface processing, (2) setting up of two cameras, (3) taking calibration photos, and (4) taking experimental photos. Surface processing consists of painting or marking sufficient features or textures so that the observed region of interest (ROI) contains sufficient image features for movement trace detection. The speckle spray method, which applies random speckles and texture patterns over a surface, has been widely used in past image measurements in structural experiments (*e.g.* Carroll et al. [9] and Yang et al. [10]). However, speckle painting may increase the difficulty of crack observation by the naked eye. It is necessary to obtain agreement with other members of the testing team before applying speckle painting.

When setting up the cameras, it must be ensured that the cameras are firmly fixed to take calibration photos and experimental photos. The cameras should be adjusted so that the ranges of camera views (or field of views, FOVs) sufficiently contain the region of interest of the specimen. The ROI of the specimen ought to be kept within the central region of the camera view (see Fig. 3), leaving the boundary part unused. This is suggested because there may not only be displacements larger than what we expect at the boundary, but also because the boundary normally contains more violent (high-order nonlinear) distortion effects that are more difficult to mitigate during calibration. In addition, the focal lengths and focal distances of the cameras should not be allowed to automatically adjust, and must instead be manually fixed. It is also suggested that the apertures, exposure time, and environmental lighting conditions be kept constant as much as possible for a consistent exposure condition for all photos taken in an experiment.

A few pairs of photos of a calibrated object are taken to provide information to estimate the parameters of each camera (i.e., intrinsic parameters) and the transformation between the coordinate systems of the two cameras (i.e., extrinsic parameters) [11]. A chessboard-like pattern is one of the widely used models for camera calibration. Both cameras need to take photos at the same time for each pair of photos to ensure that objects in left photo are at the same 3D positions of those in the right photo. Some experts have suggested taking ten or more pairs of calibration photos of a 7-by-8 or larger chessboard [11]. The calibration object should be positioned at different positions to cover the entire ROI.

Experimental photos are taken as a series of photos of the ROI of the specimen during the entire experiment. It is very important to keep the cameras firmly and constantly fixed without movement. Even a very slight touch may induce camera movement and affect the accuracy of the results. The camera shutters should be controlled by remote controllers to minimize any external inference. The remote controllers can be operated by a person manually, a timer (that triggers the shutters in an equal interval of time), or an electronic device that connects the shutters with an experimental data logging system (so that the photos can be easily synchronized with other experimental data).

The image analysis procedures of the proposed method includes the following major steps: (1) stereo calibration, (2) control points positioning, (3) surface formula estimation, (4) metric rectification, (5) deformation analysis, and (6) visualization. The procedures were implemented into a tool named ImPro Stereo [12]. Most of the computer implementation of ImPro Stereo was written in MATLAB codes and mixing language for external calls to a

Fig. 1b. A 45-degree crack indicating shear failure.

Fig. 2. Manual pen marking on cracks.