Construction and Building Materials 162 (2018) 345–358

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A method of detecting the cracks of concrete undergo high-temperature

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HIGHLIGHTS

- Local binarization and extraction were used to detect the cracks.
- The binarization of a local area is based on the intensity of the local area.
- The method performs well in detecting the cracks in the cross-sections.
- No additional process was needed before the images were taken.
- Geometric attributes are acquired during the detection process.

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 1 December 2017
Accepted 1 December 2017

Keywords:
Crack detection
Local binarization
High-temperature-damaged concrete
Cross-section

ABSTRACT

Cracking of concrete is one of the critical parameters for the structural safety evaluation of building components after high-temperature exposure. In this paper, a method was developed to detect the cracks of concrete after exposure to high temperature. The gray-scale images of the cross-sections of concrete were binarized with a local-binarization algorithm, and then the isolate cracks were extracted to analyze the geometric attributes, including length, average width, and area. The factor of circle of each isolate crack was used to filter the noise and fake cracks. The proposed method was applied to the real images of both cross-sections and surfaces of high-temperature-damaged concrete to test the effectiveness. Moreover, based on the detection results, the effects of four parameters, i.e. local window size (S_w), step size (S_{step}), local threshold ratio (R_t) and upper limit of factor of circle ($F_{c,lmt}$), in the proposed method were discussed to decide the optimal option. The results indicate that with the optimal parameters ($S_w = 10$ pixels, $S_{step} = 0.5$, $R_t = 0.85$ for cross-sections and 0.95 for surface, $F_{c,lmt} = 0.3$), the proposed method can detect the cracks on both the surface and cross-section of concrete effectively. Some unclear cracks which were not detected with the optimal parameters can be detected out by combining the results from different groups of parameters.

1. Introduction

It is well known that the high-temperature exposure of concrete results in the deterioration of properties, including both strength and durability. And it is convinced that the thermal-induced cracks, both on the surface and inside the concrete are mainly responsible for the deterioration [1–3]. Therefore, the analysis of thermal-induced cracks, including the length, width or density, has become an important part of the studies about fire-damaged concrete [2,4–10]. With the images of the concrete, either surface or cross-sections, the cracks can be detected. The conventional method is manual sketching, but it is time-costing and operator-dependent [11]. So it is meaningful if the thermal-induced cracks can be detected automatically with the aid of the computer.

Some wavelet-based methods such as fast Haar transform, fast Fourier transform, Sobel filter, Canny filter have been applied on the detection of surface cracks. Abdel-Qader et al. [12] found that among those four transform methods, fast Haar transform gave the best performance in detecting the cracks in the concrete bridge. A percolation method based on brightness and shape was introduced by Yamaguchi and Hashimoto [13,14] to detect the surface crack on concrete, and this method was improved to reduce the time consumption while preserving the detecting accuracy [15]. Some other methods based on genetic programming [16], neural networks [17–19] and minimal path [20,21] are also reported to detect the surface cracks of concrete.

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https://doi.org/10.1016/j.conbuildmat.2017.12.010
0950-0618/

The cracks can be detected because the intensity of cracks is lower than the neighbor background. Therefore, another practical method is to distinguish cracks from the background by the intensity directly [22], this process is called thresholding, binarization or segmentation. Otsu [23] proposed a method to select the threshold from the gray-level histograms, and this method performed excellently on the scanning electric microscopic (SEM) images [24]. However, the complexity of the textural and noisy background of the macroscopic images makes the results of direct thresholding not satisfying.

To promote the performance of direct thresholding, an impregnation process was applied by Ammouche et al. [25,26] before the images were taken. The impregnation of red dye into the concrete slices, followed by the polishing process to remove the excess dye, was conducted before the observation with SEM. After this process, the cracks were colored red while the background remained the original color and as a result, the contrast in the red channel between the cracks and the background was enlarged. A similar method was reported by Soroushian et al. [27], but Wood's metal was used as the impregnation material for the SEM and ink-epoxy for the fluorescent microscope.

On the other hand, the thresholding results can also be enhanced during the detection process. Ito et al. [11] proposed a two-step-thresholding method to detect the cracks on the surface of concrete blocks. A further thresholding process was conducted in the region around each crack pixel detected during the primary thresholding process to maximize the interclass distance and consequently, the discontinued cracks are linked. Aiming at lower the noise of the background, Lee et al. [28] used a morphology technique including subtraction and openness operations before the thresholding process to normalize the background, and a double extraction process was adopted to enhance the detection accuracy. With an optimized local binary pattern method, Hu and Zhao [29] classified the local neighbor pixels into rough and smooth area, and apply the thresholding operation only on the rough areas to reduce the effect of the noise from the background.

Most of the crack-detecting methods mentioned above only involve in the crack detection on the concrete surface. Some reports are about the detection of cracks on the cross-section of the concrete, but the detection was conducted on the SEM images [24–27]. The crack detection on the cross-sections of concrete in macroscale images is rarely reported. However, our former study indicated that the analysis of the cracks on the cross-section is also a method to evaluate the residual properties of the concrete after the high-temperature exposure [30]. In Ref. [30] the cracks were detected manually, which is very low efficient and subjective. We have been considering to detect these cross-section-cracks automatically with the macroscale images. But the noise induced by the aggregates in the background makes the practice very challenging. Therefore, in this paper, we proposed a local-binarization method to detect the cracks on the cross-sections of the concrete after high-temperature exposure with the noisy background due to the existence of the aggregates. The outcome of this paper is it provides a method to detect the cracks, both on the cross-sections and surfaces of the high-temperature-damaged concrete automatically. Furthermore, it would be effective and interesting to apply the method proposed in this paper to analyze the change of parameters of the thermal-induced cracks in concrete exposed to different temperatures in the future studies.

2. Methodology

2.1. Framework of the proposed method

There are two major steps to acquire the information of the cracks from the source grayscale images of the concrete, i.e. binarization and extraction, as shown in Fig. 1. During the first step, the source image in RGB mode was transcoded to grayscale with the MATLAB built-in function named *rgb2gray*. The intensity of each pixel in grayscale is calculated according to:

$$I_{x,y} = 0.2989 \times R_{x,y} + 0.5870 \times G_{x,y} + 0.1140 \times B_{x,y} \quad (1)$$

where $I_{x,y}$ is the intensity of pixel (x, y) and $R_{x,y}$, $G_{x,y}$, $B_{x,y}$ are the brightness of the pixel (x, y) in channel red, green and blue, respectively.

Then the grayscale image was binarized with a local-binarization algorithm. Some pixels were binarized as cracks while others as background. But not all the pixels binarized as cracks are real cracks. Some pixels are background but binarized as crack. Therefore, during the second step, every single isolate crack was detected and extracted with an extraction algorithm for analyzing its geometrical attributes, including length, area, width and aspect ratio. Real cracks are generally long and narrow, and the length in one dimension is much larger than the other dimension. So it is possible to filter the fake cracks by analyzing their aspect ratio. After filtering, the isolate real cracks are assembled together to acquire the complete crack image. Each step of the proposed method is detailed in the following section, and the flow chart of the programs is shown in the appendix.

2.2. Binarization

In MATLAB, the grayscale image in the size of $m \times n$ is recorded as a matrix with m rows and n columns, in which the intensity of each pixel is recorded as an integer from 0 for the darkest to 255 for the brightest. With a giving threshold, the binarization process converts the value of each pixel to 0 or 1 according to:

$$B_{x,y} = \begin{cases} 0, & I_{x,y} < T \\ 1, & I_{x,y} \geqslant T \end{cases} \quad (2)$$

where $B_{x,y}$ is the binarized value of a certain pixel, $I_{x,y}$ is the intensity of the pixel in the grayscale image, and T is the giving threshold.

The cracks are usually darker than the background, so it is possible to distinguish the cracks and background with a proper threshold, as shown in Fig. 2a. But the binary result of the concrete cross-section image is not as good as that of the concrete surface image. The existence of the aggregate in the cross-section makes the background much more complex, as shown in Fig. 2c. So it is impossible to clearly distinguish the cracks and background with an overall threshold. A lower overall threshold leads to the obliteration of some small cracks while a higher one remains too much noise, as shown in Fig. 3b and c.

To solve this problem, a local-binarizing method was proposed, with which the binarization of a local region is based on the local threshold rather than an overall threshold of the entire image. For an image in the size of $m \times n$, a window in the size of $w \times w$ ($w < m$ and $w < n$) is extracted as a local region for binarization. In the following text, figures and tables, the parameter window size is referred as S_w. The pixels in this window with the intensity higher than the local threshold are set to 0 while others are set to 1. The local threshold is determined as:

$$T_L = R_t \times I_{LA} \quad (3)$$

where T_L is the local threshold. R_t is the local threshold ratio which represents the ratio of the local threshold to the average intensity of the local window. The value of R_t is smaller than 1 since the brightness of the crack is usually lower than the average brightness. I_{LA} is the average brightness of the local window.

During the binarization process, the local window moves along the rows and columns in a step size s. The step size should be no larger than S_w to ensure each pixel to be binarized at least once.