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Surface crack detection by flash thermography on concrete surface

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Cracking may impair the durability of concrete by allowing immigration of external aggressive agents; therefore, crack monitoring is always a vital part in building pathology. This study proposes to apply short-duration pulsed thermography – flash thermography (FT) – for surface crack detection. This method allows full-field and non-contact qualitative observation of thermal radiation from an object surface and is highly accepted in the aerospace industry. It is superior to the common practice of surface crack detection – visual inspection. The overall inspection time is reduced and hence maintenance costs lowered. During inspection, the inspected surface is excited with a heat-pulse of short duration (~3 ms). Surface cracking is detected based on the difference in heat emission between cracks and intact region. The results show that FT can detect surface cracks with 0.5 mm to 1 mm crack width successfully but micro-cracks (0.1 mm-0.5 mm) can only be detected by adding water with FT. In addition, this study also compared the performances of traditional Sobel and Canny edge detectors and a proposed shear image subtraction method, for crack detection. The results show that the sheared image subtraction method is significantly more effective than the other two edge detection techniques in identifying cracks.

Keywords: Defects, image processing, infrared, thermography.

1. Introduction

The life of a structure can be extended by early detection of cracks with appropriate repairs. In reality, structural failure is always accompanied by the formation of cracks and early detection of cracks is essential in extending structure life and preventing structural failure(1). Therefore, there is a huge amount of research on monitoring surface crack development in concrete structures, especially in infrastructures such as pavements and bridges. The studies are mainly focused on embedding optical sensors(1), measuring electrical potential by electro-conductive paint(2), or image enhancement techniques for post-processing(3),(4). Surprisingly, until now, the common practice of surface crack detection is still by *visual inspection*(5). This technique is subject to the inspectors' experiences and the fact that it is based on their visual ability makes the detection inefficient and erroneous(3). Surface crack detection by this means is not sufficiently scientific. Therefore, this study proposes to apply short duration (~3ms) pulsed thermography, more specifically named *flash thermography* (FT), for surface crack detection on concrete structures. The technique has been widely used in the aerospace industry(6),(7) in recent years.

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No pre-installation of sensors is required in FT. It is a fast, invasive and full-field detection technique which enables a permanent record. The minimum width at which a crack is considered to be significant depends on the function of the structure members. In general, for interior members a crack width of 0.3 mm is claimed to be significant while for exterior members the figure is 0.15 mm(8). More specifically, according to the technical guideline made by the Buildings Department in Hong Kong, for cracks noted in structural elements such as beams, slabs, columns and walls with crack widths less than 1 mm, no detailed investigation is required and they are classified as severity index 2(5). The follow-up actions and the corresponding severity index on different building defects are listed in Table 1.

Therefore, the range of crack width of interest in this study is from 0.15 mm to 1 mm. A cement panel with major cracks with widths of 0.5-1 mm and micro-cracks having widths of 0.1-0.5 mm are inspected and the results are presented. Moreover, this paper provides a comparison of the effectiveness of two traditional crack detection techniques, Sobel and Canny, and one proposed method, the sheared image subtraction method, and the results are also presented.

Table 1. Severity index and action for building defect

Severity index	Area + affected by crack, spalling or exposed reinforcement	Crack width	Residual deformation	Action to be required
1	No visible defects	Not applicable	No apparent deformation	No action required
2	Less than 10% of the element or 0.3 m^2	Less than 1 mm	Slight deformation	General repair only but no detailed investigation required
3	10% to 30% of the element or 0.3 m^2 to 1 m^2	More than 1 mm at different locations	Not exceeding 1/125 span of the element	Detailed investigation required
4	More than 30% of the element or 1 m^2	More than 1 mm everywhere of the element	Exceeding 1/125 span of the element	Detailed investigation required and to provide immediate protective measures if necessary

Source: Buildings Department (1998)(5)

2. Principles and crack detection techniques

2.1 Principles of surface crack detection by flash thermography

Inspected surfaces are excited by a flash-light and there are instantaneous reflections of visible light and IR radiation that can be recorded by an infrared camera. After the flash has been exerted on the inspected area, with high capturing frequency, immediate reflection of IR radiation can be recorded and hence surface cracks can be indicated. This is due to the fact that, because of the steeper slope of crack walls, incident light (from the flash lamp) bounces against the walls several times. Each bounce heats up the crack walls slightly. The net effect of the multiple reflections, or bounces, causes the crack to act as a cavity with warmed walls, which is basically similar to a small black body. The incident radiation is reflected, absorbed and/or transmitted from the surface in a predictable manner that depends on factors including the surface roughness, colour, optical reflectivity and IR emissivity. Figure 1 illustrates the process.

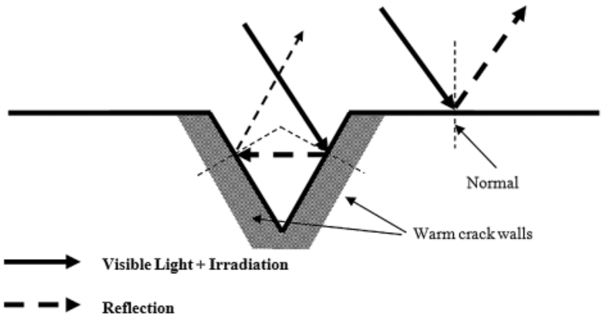

Figure 1. Reflectivity of radiation on cracked surface

2.2 Traditional and the proposed crack detectors for surface crack detection

There are two commonly used edge detectors, Sobel and Canny which are available in the commercial analysis package Matlab®. These are applied for outlying the surface cracks on the captured thermal images in this study. The Sobel edge detector is a convolution filter[9] and is well-known for its simplicity and speed compared to Canny's algorithm[3]. It is based on spatial gradient algorithm. However, it is very susceptible to image noise. Therefore, the other edge detector, Canny, is applied for crack detection on the thermal image[9]. The Canny method is also a convolution filter and is slightly more powerful than Sobel[10]. The image is first smoothed by convolving with a Gaussian mask, therefore most of the noise is eliminated and hence the image is better than with Sobel. Then, edges are detected by detecting the maxima of the gradient modulus taken in the direction of gradient.

As mentioned in the introduction, this study proposes a traditional method, sheared image subtraction method, which has been widely used in shearography for defect detection[11]. The image is subtracted by its shifted image in x- and y-directions. Shear image subtraction is dealing with the temperature difference relative to the nearby intact region. Therefore, the contrast of cracks with broken temperature field distribution is significantly increased. The basic algorithm of this method is presented in the schematic diagram Figure 2.

A sharper edge is obtained by calculating the intensity gradient of the adjacent pixels. The new edge intensity is expressed by the following equation:

$$L(x,\ y) = [P(x_0, y_0) - P(x_{0+1}, y_{0+1})] \qquad (1)$$

where L(x,y) is the light intensity in x, y coordinate obtained by subtracting the diagonal pixels (sheared image) and the results are presented.

3. Experimental set-up

The experiments were carried out by applying flash thermography on a cement panel with artificially made surface cracks. Surface cracks ranging from 0.1 mm to 1 mm width were made for inspections. The cement panel was made with cement paste and surface cracks were produced by attaching tiles at the back of the cement panel without absorbing water. Therefore, the water from the cement paste diffused quickly to the dry tile underneath, and hence natural shrinkage cracks were produced on the cement panel. The cement panel was then sprayed with black emulsion paint which has an emissivity close to 1. It allows better measurement by reducing the differences on thermal absorption due to emissivity difference.

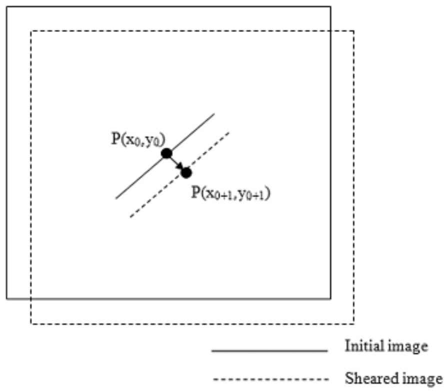

Figure 2. Schematic diagram on sheared image subtraction method

It is difficult to observe surface cracks by the unaided eye, as shown in Figure 3(a), and it is even more difficult to observe after black paint is sprayed on the cement panel, as shown in Figure 3(b). The black painted panel surface is used to simulate the concrete slabs in tunnels where upper slabs are usually painted in black.

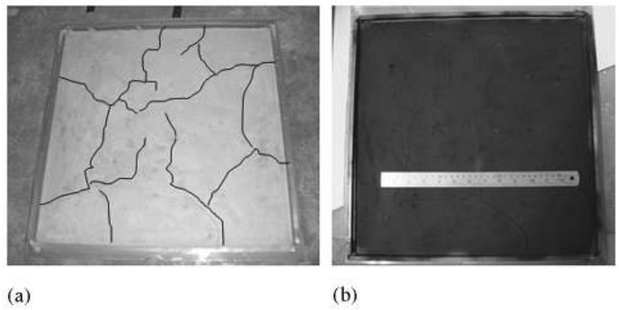

Figure 3. (a) Cement panel with surface cracks. (b) Cement panel painted in black

In the experiment, the panel was stimulated by a flash pulse produced by two 4.8 kJ powered xenon flash lamps with full width at half maximum (FWHM) duration of 3 ms. Surface thermograms after pulse are captured by the infrared camera SC3000 with a 320×240 pixel quantum-well infrared photon detector (QWIP) focal plane array. It has a sensitivity of 0.02ºC and maximum frame rate of 50 Hz. The distance between the infrared camera and cement panel is 90 cm at which distance surface cracks cannot be observed by the unaided eye. The flash lamps are set at the location where the whole cement panel can be covered by the flash lamp, and 60 cm is selected as the excitation distance. Figure 4(a) shows the photo and Figure 4(b) illustrates the schematic diagram of the experimental set-up of flash thermography for surface crack detection on the cement panel. The distance between flash lamps and IR camera is 60 cm and 90 cm respectively.

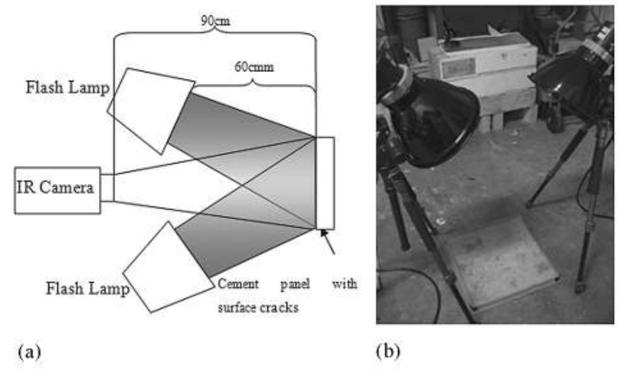

Figure 4. (a) Schematic diagram of surface crack detection by flash thermography and (b) photos of the set-up

4. Experimental results

Surface cracks having crack widths between 0.5 mm to 1 mm are classified as major surface cracks, while cracks with widths of 0.1 mm to 0.5 mm are called micro-cracks. The results show that major cracks can be seen by flash stimulation while micro-cracks can only be seen after adding water.

4.1 Major surface crack detection (0.5 mm-0.1 mm width)

The results in Figure 5 show that major surface cracks (0.5 mm-0.1 mm width) can be observed successfully by applying flash, yet the system fails to detect micro-cracks (0.1 mm to <0.5 mm). Figure 5(a) is a photo of the cement panel taken by digital camera and (b) is the second thermal image captured after pulse, which is after 0.04 s since the capturing frequency is 50 Hz.

As shown in Figure 5(b), major cracks with crack width 0.5 mm-1 mm can be clearly seen while is it difficult to be observed in the digital photo, Figure 5(a). However, there is uneven heat distribution which affects the surface crack observation. This uneven heat distribution may be due to the positioning of flash lamps or uneven surface of the cement panel. Therefore, several crack detection techniques are proposed in this study to outline the surface cracks automatically without the influence of uneven heat distribution. Performances of applying the three crack detection techniques on Figure 5(b) are compared and presented in Figure 6. This presents the optimum results obtained by adjusting suitable threshold for edge detections. Edge detecting results obtained by Sobel, Canny and sheared image subtraction are shown in Figures 6(a), (b) and (c) respectively.

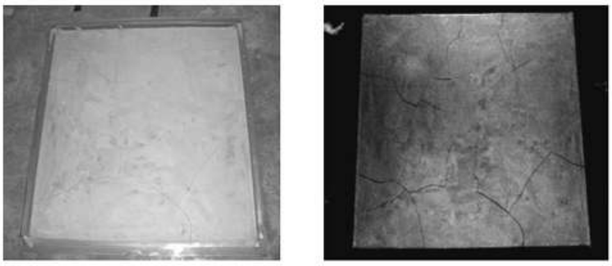
(a) (b)

Figure 5. (a) Photos of surface cracks; (b) thermal image at 0.04 s after pulse

From the results in Figures 6(a) and (b), it is clear that both Sobel and Canny edge detectors are not capable of detecting surface cracks by searching the maximum intensity gradient from a noisy thermal image, while the sheared image subtraction method gives the best result in terms of eliminating image noise and detecting spatial gradient successfully, as shown in Figure 6(c).

4.2 Micro-surface crack detection (0.01 mm-<0.5 mm width)

As stated previously, micro-cracks cannot be observed with only pulse excitation. A very simple but effective active thermography is introduced for micro-crack detection, *ie* using water as stimulus. The temperature difference between micro-cracks and intact region is induced by water and the thermal image is recorded by infrared camera. Water can seep through the micro-cracks because water molecules are very small. Water is cooler than the other intact region and hence micro-cracks can easily be shown on the thermal image. A very satisfactory result for micro-crack detection is obtained by this method, as shown in Figure 7.

However, several water ponds and vague micro-cracks are observed in Figure 7. In order to have a clearer image for micro-cracks, another stimulus, *ie* pulse, is applied and the thermal image is immediately captured by infrared camera. Therefore, the micro-cracks are detected by FT with water added on the inspected surface. The instant separation between water along the cracks and

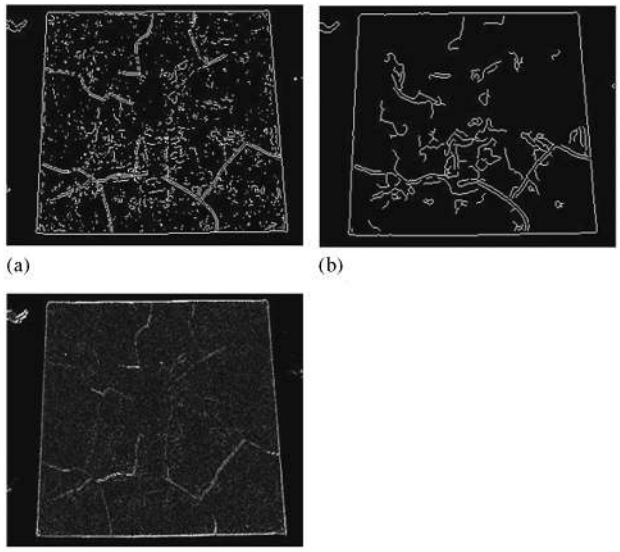
(a) (b) (c)

Figure 6. Edge detection of Figure 5(b) by (a) Sobel edge detector with threshold of 10; (b) Canny edge detector with threshold of 0.15 and (c) sheared image subtraction method

intact region is due to the difference in heat capacity of water. A sharper image of micro-cracks is shown in Figure 8.

Again, crack detectors Sobel, Canny and the sheared image subtraction method are applied and the results shown in Figure 8 for automatic surface micro-crack detection.

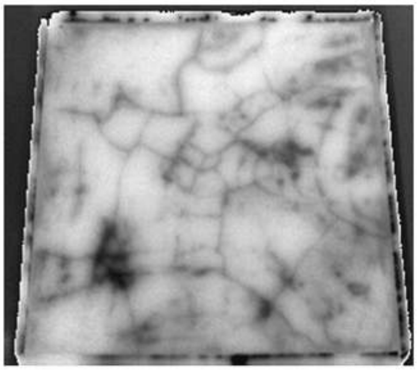

Figure 7. Thermal image captured after water spray

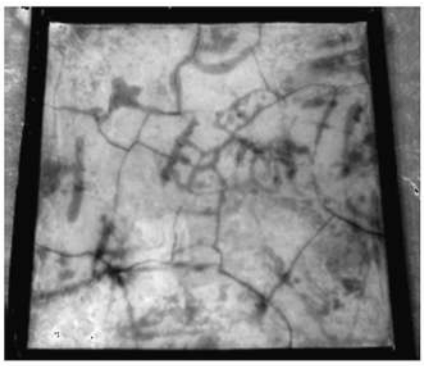

Figure 8. Thermal image with water spray followed by pulse

The results in Figure 9 are similar to the major surface crack detection in which sheared image subtraction method gives the best result compared to the other two edge detectors. However, it is not as clear as the pulsed image as shown in Figure 8. In conclusion, the sheared image subtraction method is not suitable to be applied for micro-cracks detection where the image contains much noise but it is superior to the other two common crack detection techniques.

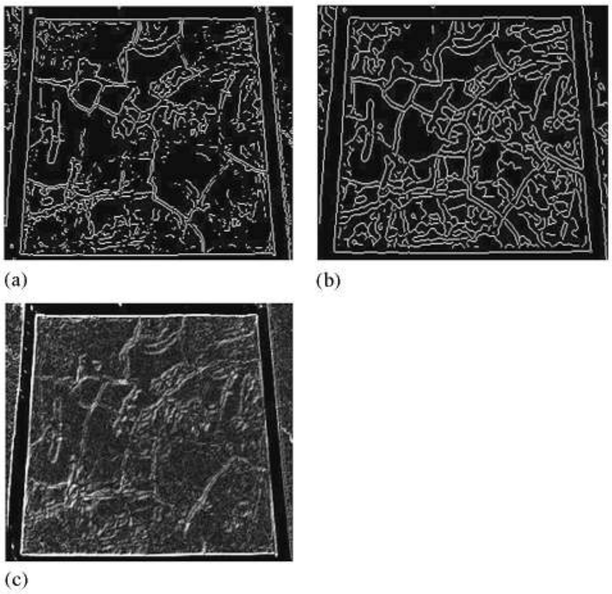

Figure 9. Edge detection of Figure 8 by (a) Sobel edge detector with threshold of 10; (b) Canny edge detector with threshold of 0.1 and (c) sheared image subtraction method

5. Conclusion

According to the above results, surface cracks ranging from 0.5 mm to 1 mm width can easily be obtained by flash thermography with flash excitation only. The method is useful for building appraisal since the maximum crack width in which detailed investigation is not required is 1 mm. However, the thinner cracks, *ie* micro-cracks with widths smaller than 0.5 mm, can only be observed by active thermography with water as the stimulus instead of pulse. Water molecules fill up the micro-cracks and due to their difference in heat capacity, different reflected radiation is measured by the infrared camera and shown on the thermal images. However, water cools down the temperature of the whole cement panel and an unclear thermal image recorded. The solution is to add external heat energy on the inspected surface in order to increase the temperature difference so that clearer identification of micro-cracks can be observed. Therefore, FT is still being applied when pre-stimulated by water and a satisfactory result is obtained and presented.

This study also compares the effectiveness of different commonly used image processing techniques for crack detection. It shows that the sheared image subtraction method is more effective than Sobel and Canny edge detectors on eliminating image noise and enhancing spatial gradient. It sharpens the contrast of surface cracks while retaining most of the object features in the thermal image.

6. References

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