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Visual recognition and assessment of concrete crack properties

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Abstract

Post-earthquake structural safety is evaluated manually by certified construction inspectors and structural engineers. They inspect visible damage (e.g. cracks) on critical structural elements (e.g. concrete columns). This process is time-consuming and costly. In order to automate this type of visual inspection, several damage detection methods have been developed. However, most of them can only detect the presence of damage. The next step, retrieving damage properties and further using these properties to assess the impact of the damage on the structural elements has not yet been adequately investigated. This paper presents a novel method of retrieving crack properties. Under this method, the crack map on a structural element surface is first produced using state-of-the-art crack detection techniques. Then, the topological skeletons of cracks are created through binary image thinning, and the distance field of crack pixels in the map is produced using a distance transform. According to skeleton configurations and the distance values of the crack pixels, crack properties (width, length, orientation and location) are calculated. These properties are related to the properties of the structural element to produce relative measurements for the estimate of concrete column damage states. The method is implemented in a C++ based prototype and tested on a set of real crack images.

Keywords: crack detection, property retrieval, post-earthquake reconnaissance, image processing

1 Introduction

After an earthquake occurs, entry into damaged buildings as soon as possible is necessary for a variety of reasons, including emergency search and rescue, building stabilization and repair, and salvage and retrieval of possessions (ATC-35, 1999). There are always extensive risks associated with entering damaged buildings after an earthquake, and often, further structural collapse produces additional victims. Currently, the safety of entering damaged buildings is evaluated manually by structural specialists (e.g. structural engineers and/or certified inspectors). They follow the guidelines provided by the Federal Emergency Management Agency (FEMA) and the Applied Technology Council (ATC), and assess the impact of visual damage (e.g. cracks) on critical structural components to make sure that the damaged building remains stable and maintains a specific level of structural integrity.

Although civil engineers are supposed to be appropriate candidates to evaluate the safety of highly engineered environments (Prieto, 2002), several limitations were found in the current evaluation process. First, it is time-consuming. In the October 15, 2006 Hawaii Earthquake and the December 22, 2003 San Simeon Earthquake, the whole building safety evaluation processes took several weeks due to the large number of buildings requested to be assessed (Chock, 2007; Johnson, 2004). Also, the subjective inspection nature may lead to erroneous judgements (Kamat and El-Tawil, 2007).

The aforementioned limitations can be overcome if the current manual evaluation practices are fully automated. This requires the damage lying on structural member surfaces not only to be detected but also to be assessed based on their properties. So far, many machine vision based methods have been created to locate the damage on structural member surfaces, and their effectiveness has been validated in inspecting structures such as bridges, pipes and tunnels. As a contrast, little work was found regarding how to automatically retrieve useful damage properties from detection results and further apply these properties to estimate the damage state of structural members.

This paper presents a novel method of retrieving crack properties. First, a percolation-based crack detection method is used to produce a crack map on a concrete structural element surface. Then, the topological skeletons of cracks and the distance field of crack pixels in the map are produced through binary image thinning and a distance transform, This information can be used to calculate crack properties (width, length, orientation and location). Further, these properties are related to the dimension and orientation of the structural element to produce relative measurements for the estimation of structural element damage states. The method is implemented in a C++ based prototype and tested on a set of real crack images.

2 Background

2.1 Current practices of post-earthquake damage assessment

The safety evaluation of buildings in the event of an earthquake is based on the procedures outlined in ATC-20 documents. These documents outline three procedural levels: rapid evaluation, detailed evaluation, and engineering evaluation. Rapid evaluation is typically based on an exterior inspection of a structure only; detailed evaluation is a thorough visual inspection of a structure inside and outside; and in an engineering evaluation, engineers/inspectors investigate the safety of a damaged structure from construction drawings and new structural calculations (NASA, 2009). The purpose of the rapid evaluation is to quickly identify apparently "Unsafe" or "Safe" buildings after an earthquake. A building is regarded as unsafe if it partially collapses or its stories lean severely (ATC-20, 1989). The buildings that cannot be determined as "Safe" or "Unsafe" are further assessed in the detailed and engineering evaluations, where the severity and extent of damage to the structural and non-structural elements throughout a building is observed, measured and recorded. For example, in a reinforced concrete building, extent and severity of damage to the load-bearing elements is quantified primarily by the width and orientation of the cracks that lie on these elements (ATC-20, 1989). Compared with the rapid evaluation, the detailed and engineering evaluations will most often provide more accurate assessment information of a structure, but both procedures expense great resources and time, as the evaluations tend to take up to two hours and one week, respectively (NASA, 2009).

2.2 Automated crack detection

Existing crack detection methods are generally classified into two categories. The first category recognizes only whether or not an image contains a crack (crack presence). For example, Abdel-Qader et al. (2006) proposed a principal component analysis (PCA) based algorithm for recognizing crack presence in a bridge surface image. In their algorithm, an image was first segmented into sixteen square blocks. Each block was filtered by linear feature detectors (horizontal, vertical and oblique) and then projected onto dominant eigenvectors which were pre-generated from a training data set. The projection result was further compared with the projection results of training data to identify whether or not the blocks contain a crack. This way, cracks in an image can be recognized sequentially on the basis of these blocks. Similarly, Liu et al. (2002) developed a crack classification system, where a support vector machine (SVM) was used to differentiate regions in an image as "crack," "non-crack" and "intermediate" regions.

In addition to recognizing the presence of cracks, those methods which fall in the second category also locate crack points in an image (i.e. produce a crack map). The methods utilize cracks' special visual characterstics in images and adopt various image processing techniques, such as wavelet transforms, thresholding, and edge detection, to extract crack points from the image background. Cheng et al. (2003) detected cracks in an image by simply thresholding the concrete surface image. The threshold value was determined based on the image's mean and standard deviation values. Abdel-Qader et al. (2003) compared the effectiveness of four edge detecton techniques (the Canny edge detector, Sobel edge detector, Fourier transform and fast Haar transform) with respect to the detection of cracks on concrete bridges and found that the fast Haar transform was more reliable than the other three. These methods belong to global-processing techniques that do not consider crack connectivity. As a result, their detection accuracy is affected by image noise (Yamaguchi and Hashimoto, 2009). To address this problem, Yamaguchi and Hashimoto (2009) proposed a type of scalable local percolation-based image processing method that considers crack connectivity among neighboring image pixels. Also, Sinha and Fieguth (2006) introduced two crack detectors that consider relative statistical properties of adjacent image regions. These two detectors are applied in four directions (0°, 45°, 90°, 135°) to identify crack pieces in buried concrete pipes, and then a linking and cleaning algorithm is used to connect crack pieces. Iyer and Sinha (2006) designed morphology-based filters with linear structuring elements to detect cracks.

A crack map is a binary image where each isolated crack point is shaded white, and non-crack points are shaded black. Directly from the map, the specific properties (length, orientation, maximum width, and average width) of each crack are all unknown. Little work has focused on automatically retrieving this information. To the authors' knowledge, Yu et al. (2007) calculated the length, thickness and orientation of concrete cracks through a graph search; however, their method required the start and end points of the crack to be manually provided first. Chae and Abraham (2001) relied on an artificial neural network to retrieve crack properties, but it is unclear how to form the network's input data sets and how effective the network is.

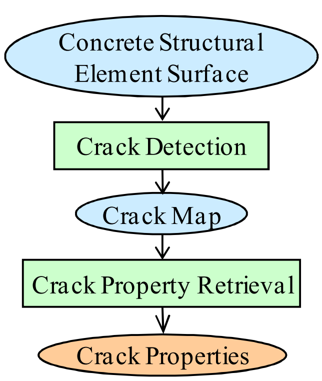


Figure 1. Method overview

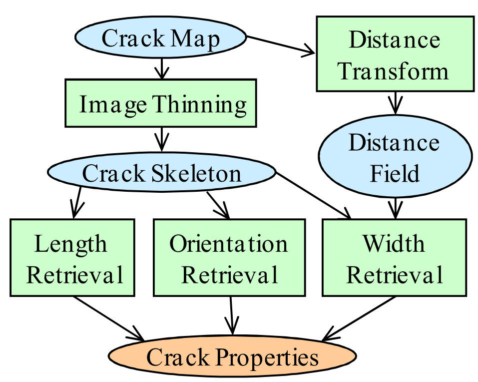


Figure 2. Crack property retrieval overview

3 Method overview

In order to automate the current manual practices in evaluating the damage severity and extent to structural and non-structural elements, a novel method of retrieving the properties of the cracks inflicted on structural elements is proposed. The method is divided into two chief stages (Figure 1): 1) crack detection and 2) crack property retrieval, which includes length retrieval, orientation retrieval, and width retrieval using image thinning and distance transform techniques (Figure 2). Details are explained in the following sub-sections.

3.1 Crack Detection

As previously mentioned, there are currently many developed crack detection methods. The percolation-based method developed by Yamaguchi and Hashimoto is selected due to its high detection accuracy and efficient computation time for a large-size concrete surface image (Yamaguchi and Hashimoto, 2009). A slight modification is made for the sake of further reducing the computation time. Instead of initiating a percolation process at each image pixel, the percolation is performed only at the pixels that have high gradient magnitude. This is because the crack boundaries in an image are always characterized by large first derivatives which result in high magnitude along a particular direction (Sun et al., 2007). Although not all true crack boundary points can be found and some false crack boundary points are introduced, the side-effects of both are remediated through the percolation.

The idea of detecting crack pixels using percolation is from the natural phenomenon of liquid permeation at a crack on a concrete surface. Imagine water is poured at crack boundaries and it always makes its way to fill the cracks. If it is poured on a concrete surface, it will be spread evenly as a circle. In order to simulate this phenomenon, the method regards image intensities as depth values in 3D, and the percolation is performed based on the different intensities of crack and non-crack pixels. First, the image pixels selected to initiate the percolation process form a region, D_p, and the image pixels neighbouring to D_p form another region, D_c. The image pixels in D_c are checked, and those that have less image intensities than any image pixel in D_p are identified and percolated into D_p. As D_p grows, new image pixels neighbouring to D_p are found and included in D_c. This process continues until all image pixels in D_c have higher intensities than any image pixel in the region D_p. Then, the circularity (F_c) of D_p is measured using Equation 1 (Yamaguchi and Hashimoto, 2009). If F_c approaches zero, the shape of D_p is linear, and the image pixels in D_p are marked as crack pixels.

$$F_c = \frac{4 * C_{count}}{\pi * C_{\max}^2} \tag{1}$$

where C_{count} is the number of the pixels in D_p and C_{max} is the maximum length of D_p.

3.2 Crack property retrieval

The crack properties useful for evaluating the safety of structural elements include length, orientation, maximum width and average width. In order to attain these properties, a binary image thinning algorithm (Cychosz, 1994) is applied in the crack map to retrieve cracks' topological skeletons. Also, a Euclidean distance transform (Fabbri et al., 2008) is used to calculate the distance field, which supplies each crack pixel in the map with the nearest distance to its boundaries. A crack skeleton together with the distance values from the points to the crack boundaries can serve as a representation of a crack since they contain all the information necessary to reconstruct the crack.

The properties of a crack are retrieved based on its skeletons and the distance field. The crack length is equivalent to the crack skeleton length, which is approximated by the height of an object-oriented bounding box that circumscribes crack skeleton points. The crack orientation is the crack skeleton orientation, which is indicated by the direction of the object-oriented bounding box. The average of the distance values of all skeleton points is calculated, and the doubled result denotes the average crack width. Similarly, the double of the largest distance value that exists at skeleton points represents the crack's maximum width.

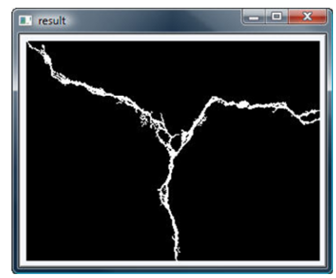
All values are measured at the image pixel level and are of little value to estimate actual structural element damage states until they are spatially correlated with the dimension and orientation of the structural elements. For example, a diagonal crack with maximum width of 10mm indicates a different type of damage on a column with a width of 1m versus that with a width of 0.5m. Spatially correlating cracks to structural elements produces relative measurements. Although specificity as to the type of relative measurements necessary for structural element damage state estimation is still under investigation, the following measurements can be calculated for concrete columns: 1) the angle of crack direction in relevance to the column's vertical edges, 2) the projection of the crack length on the column width, and 3) the largest crack width in relevance to the column width.

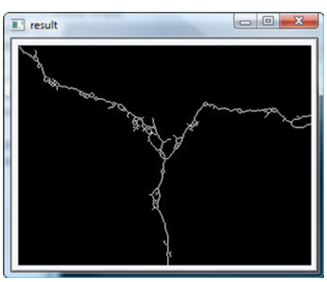
4 Implementation and preliminary results

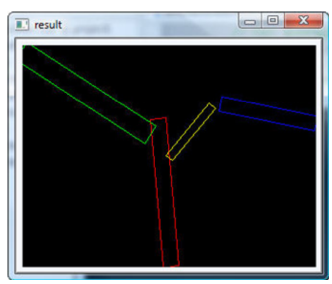
The methodology presented in this paper is implemented into a C++ based prototype. The prototype was written in Microsoft Visual Studio C++ 2005. Intel® Open Source Computer Vision Library was used as the prototype's main image processing toolbox. Figure 3 illustrates the intermediate and final results of the method in crack detection and property retrieval. In order to measure the performance of the proposed method, the crack properties calculated by the method are compared with those retrieved from manual surveys in an image, and the relative errors are measured (Table 1).


(a) Original image


(b) Edge pixels


(c) Crack map


(d) Crack skeleton


(e) Bounding box

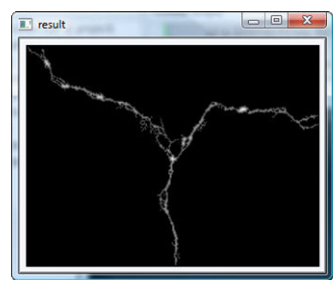

(f) Distance field

Figure 3: Immediate and final results of the method; the crack is divided into four segments based on the orientation information (S1-red, S2-green, S3-blue and S4-yellow).

Table 1. Comparison of the crack properties retrieved by the method and from manual surveys.

Methods	Crack Properties									
	Length (pixels)				Orientation (angle to x-axis)				Width (pixels)	
Proposed method	S1	S2	S3	S4	S1	S2	S3	S4	Avg.	Max
	161	168	106	74	95°	147°	168°	50°	3.0	8.0
Manual survey	135	166	109	65	97°	146°	167°	57°	4.1*	9.0

*Calculated from 30 sample sections in the image

5 Conclusions

When an earthquake occurs, entry into damaged buildings as soon as possible is often necessary for a variety of reasons. However, current manual post-earthquake building safety evaluation practices are time-consuming, and the subjective results easily lead to erroneous judgements. Therefore, the concept of automating the current manual practices is proposed to overcome these limitations.

Although many methods have been created in detecting the damage that lies on structural elements, little work was found in automatically retrieving damage properties from detection results.

This paper presents the authors' recent work in automatically detecting cracks on a concrete structural element and retrieving their properties. First, a well-developed percolation-based crack detection method is used in producing a crack map. Then, a binary image thinning algorithm and a distance transform are applied in the crack map to get crack topological skeletons and the distance values of skeleton points to crack boundaries. Based on this information, crack properties (width, orientation and length) are calculated, and these properties can be further related to the properties of structural elements to produce relative measurements. Real concrete surface crack images were used to validate the work presented in the paper. The crack properties that are retrieved by the method are compared with the crack properties that are retrieved manually. The results indicate that most crack properties can be retrieved at an acceptable level. Future work will focus on identifying how to use the retrieved relative crack properties to estimate structural element damage states.

References

ABDEL-QADER, I., ABUDAYYEH, O. and KELLY, M., 2003. Analysis of edge-detection techniques for crack identification in bridges. *Journal of Computing in Civil Engineering,* 17(4), 255-263.

ABDEL-QADER, I., PASHAIE-RAD, S. and YEHIA, S., 2006. PCA-based algorithm for unsupervised bridge crack detection. *Advancement in Engineering Software,* 37(12), 771-778.

APPLIED TECHNOLOGY COUNCIL (ATC), 1999. *Earthquake aftershocks - entering damaged buildings, ATC-35 TechBrief 2,* Available online: https://www.atcouncil.org/atc-pdf/atc35tb2.pdf, Last accessed: June 2008.

APPLIED TECHNOLOGY COUNCIL (ATC), 1989. ATC-20 procedures for post earthquake safety evaluations of buildings. In: *ATC-20 Report.* Redwood City, CA.

CHAE, M. and ABRAHAM, D., 2001. Neuro-fuzzy approaches for sanitary sewer pipeline condition assessment. *Journal of Computing in Civil Engineering,* 15(1), 4-14.

CHENG, H., SHI, X. and GLAZIER, C., 2003. Real-time image thresholding based on sample space reduction and interpolation approach. *Journal of Computing in Civil Engineering*. 17(4), 264-272.

CHOCK, G., 2007. *ATC-20 post-earthquake building safety evaluations performed after the October 15, 2006 Hawai'i Earthquakes Summary and Recommendations for Improvements (updated)*, Available online: http://www.scd.state.hi.us/HazMitPlan/chapter_6_appM.pdf, Last accessed: July 2009.

CYCHOSZ, J., 1994. *Efficient Binary Image Thinning using Neighborhood Maps*. Academic Press Graphics Gems Series-Graphics Gem IV, ISBN 0-12-336155-9, pp. 465-473.

FABBRI, R., COSTA, L., TORELLI, J. and BRUNO, O., 2008. 2D euclidean distance transform algorithms: a comparative survey. *ACM Computing Surveys,* 40(1), 2:1-2:44.

IYER, S. AND SINHA, S.K., 2006. Segmentation of pipe images for crack detection in buried sewers. *Computer-Aided Civil and Infrastructure Engineering,* 21(6), 395-410.

JOHNSON, K., 2004. *San Simeon Earthquake, City of Paso Robles Emergency Response Report*, Available online: http://www.prcity.com/government/pdf/EQResponseRpt.pdf, Last accessed: March 2009.

KAMAT, V. AND EL-TAWIL, S., 2007. Evaluation of augmented reality for rapid assessment of earthquake-induced building damage. *Journal of Computing in Civil Engineering,* 21(4), 247-258.

LIU, Z., SHAREL, A., OHASHI, T., and TOSHIAKI, E., 2002. Tunnel crack detection and classification system based on image processing. *SPIE Machine Vision Applications in Industrial Inspection X*, 4664, 145-152.

NASA, 2009. *Disaster Assistance and Rescue Team—Structural Assessment Team*, Available online: http://dart.arc.nasa.gov/SAT/SAT.html, Last accessed: December 2009.

PRIETO, R., 2002. The Three R's: Lessons Learned from September 11, 2001. *Royal Academy of Engineering,* London.

SINHA, S.K. AND FIEGUTH, P., 2006. Automated detection of cracks in buried concrete pipe images. *Automation In Construction,* 15(1), 58-72.

SUN, G., LIU, Q., JI, C. and LI, X., 2007. A novel approach for edge detection based on the theory of universal gravity. *Pattern Recognition,* 40(10), 2766-2775.

YAMAGUCHI, T. AND HASHIMOTO, S., 2009. Fast crack detection method for large-size concrete surface images using percolation-based image processing. *Machine Vision and Applications* (in press).

YU, S.N., JANG, J.H. and HAN, C.S., 2007. Auto inspection system using a mobile robot for detecting concrete cracks in a tunnel. *Automation in Construction,* 16(3), 255-261.