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Crack detection limits in unit based masonry with terrestrial laser scanning

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ABSTRACT

This paper presents the fundamental mathematics to determine the minimum crack width detectable with a terrestrial laser scanner in unit-based masonry. Orthogonal offset, interval scan angle, crack orientation, and crack depth are the main parameters. The theoretical work is benchmarked against laboratory tests using 4 samples with predesigned crack widths of 1–7 mm scanned at orthogonal distances of 5.0–12.5 m and at angles of 0°–30°. Results showed that absolute errors of crack width were mostly less than 1.37 mm when the orthogonal distance varied 5.0–7.5 m but significantly increased for greater distances. The orthogonal distance had a disproportionately negative effect compared to the scan angle.

1. Introduction

Surface crack identification and maximum crack width determination have long played important roles for condition and risk assessment of buildings (e.g. [1,2]). To this end, several instruments have been developed to either detect visible cracks or measure crack characteristics (e.g. length and width). Mechanical probes and electronic sensors are generally used [3–5]. However, while such instruments offer high precision for crack measurement, most have significant limitations: (1) predefined permanent positions on the structure; (2) prefixed, uniaxial measurement; (3) limited measurement range; (4) physical access requirements, and/or (5) considerable cost. To overcome these shortcomings, there has been a great interest in non-contact, image-based methods including photogrammetry and terrestrial laser scanning (TLS) to measure structural deformations [6–8], detect surface decay [9], and estimate mass loss [6,10]. In such cases, as well as in crack detection, most published research only presents empirical limits. The following study provides a mathematical basis for using TLS to detect cracking in unit-block masonry (i.e. stone, brick, or concrete masonry units).

2. Related work

Photogrammetry and laser scanning are often adopted to overcome the five limitations listed above. Since a fairly systematic overview of the wider range of techniques applicable to cultural heritage and civil infrastructure was recently published elsewhere (e.g. [11]), this background section is restricted to image- and laser scanning-based methods for structural deformation, mass and volume loss, and defect detection.

In image-based methods, digital images provide geometric and radiometric content to measure the crack width and boundaries. Image-based crack detection has some definitive advantages as it (1) generates a permanent record, (2) is repeatable, (3) circumvents direct contact, and (4) enables crack-by-crack analysis. The last is an advantage over many other approaches such as acoustic emissions where only the severity and density of cracking can easily be ascertained [12]. Barazzetti and Scaioni [13] employed the RGB intensity component to extract the sides of a crack in a wide variety of construction materials (e.g. concrete, brick, and asphalt) and then computed the crack width at a given cross-section. When compared to results from mechanical probes and

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electronic sensors, the proposed procedure reported crack measurement errors in the range of ±5 μm to ±19 μm. In contrast, Hampel and Maas [14] applied a cascade image analysis approach to estimate crack width in textile-reinforced concrete in tension testing. In this approach, edge detection techniques were applied to dense displacement vector fields generated by image matching techniques obtained from consecutive images. That study reported that hairline cracks 1/20 of a pixel wide could be detected at a precision of 1/50 of a pixel, but that errors of crack position were 5.8 pixel in each coordinate direction. Additionally, Niemeier et al. [15] implemented the polyline-fly-fisher algorithm proposed by Dare et al. [16] to estimate outliers and to determine the mean crack width from images taken by a digital retinal scanner camera. The approach required users to choose start and end points of the crack. Six field tests showed a relative error in measuring crack width of approximately 15%, while the largest absolute error was 0.05 mm for a 3 mm wide crack.

To monitor crack changes in concrete surfaces, Sohn et al. [17] modified a Hough transform based algorithm (as previously proposed by Habid and Kelley [18]) to estimate 2D transformation parameters for registering sequential images, while the crack itself was extracted using image-processing techniques (e.g. enhancement, noise removal, histogram thresholding, thinning). Object coordinates in subsequent images were analyzed to determine any changes. The error in calculating the object coordinates of the crack was ±0.3 mm. While image-based methods can provide good accuracy, they require supplementary information that is not always readily available, such as camera lens, focal length, or the exact distance from the camera to the target surface. As an alternative, interest in terrestrial laser scanning has rapidly increased.

However, to date, most research using laser scanners in structural assessment has focused on measuring structural deformation, estimating material loss, or finding surface defects. For structural deformation, Gordon et al. [8] compared vertical displacements from the LMS-Z210 and Cyrax 2500 TLS units against photogrammetry. The root mean square (RMS) of the differences was in the range of ±2.4 mm to ±9.5 mm for the LMS-Z210 and as little as ±0.29 mm for the Cyrax 2500 TLS. To detect bowing of marble cladding, Al-Neshawy et al. [19] used the FARO LS 880HE80 scanner to achieve a sampling step of approximately 1 mm at a distance of 4.36 m, in which the semantic distance error was ±3 mm. The TLS based results showed the magnitudes to differ 1–2 mm for convex bowing and 6–7 mm for concave ones when compared to manual measurements, in which the bowing magnitude was expressed as a term of the measured value of bowing over the distance between the supports of the 950 mm long marble panel. Olsen et al. [6] detected structural damage of reinforced concrete beam-columns using TLS. Volumetric calculations were performed using the crossing section method. In that, the specimen was divided into multiple sections, and then the volume was calculated based on the area of a polygon by fitting data points on a section and the thickness between two consecutive sections. Volume loss was recognized by comparing the determined volumetric surface to that of the original structure.

Concrete surface mass loss was automatically recognized in TLS data based on the analysis of curvature distributions in equally sized sub-areas divided within a scanning region [10]. The principal curvatures were computed by using methods of differential geometry. Damage was detected when the Gaussian curvature distribution changed dramatically in a sub-area. The method failed, when data noise exceeded 0.8–1.0 cm, or if a crack had a width significantly lower than the linear dimension of the sub-area. For detecting changes in excavation volume, Girardeau-Montaut et al. [20] looked at two approaches using octree-based comparisons. In one, a pair of sub-sets of points was contained in two homologous cells of the source, and target clouds were compared based on the average distance from a best plane fitting. In the other, the Hausdorff distance was used to identify changes over time. The latter was reported as more precise but slower; however quantification of the results was not given.

Armesto-González et al. [9] used an automated classification algorithm to analyze 2D intensity images generated from 3D point clouds for detection of moisture based damage in historic stone buildings. This work used various TLS units (e.g. FARO Photon, TRIMBLE GX200, and RIEGL-Z390i) to collect data. Damaged ashlars with differing moisture contents were reported. In concrete, Liu et al. [21] proposed distance and gradient based criteria for detecting defective areas of the extended pile cap of a concrete bridge. For this work, the reference plane was defined, and a selected area for analysis was divided into smaller grids, in which a data point was arranged with column and row numbers. Then, gradient and distance information in the reference plane were calculated. The grid area was considered to contain a defect, if the gradient and distance were larger than predefined thresholds; no guidance was provided for threshold selection. In an alternative approach, to identify cracks in asphalt paving, Tsai and Li [22] used a dynamic-optimization-based crack segmentation method followed by a linear-buffered Hausdorff scoring method for quantitative crack segmentation.

So while TLS has been used successfully for measuring structural deformation and monitoring surface deterioration, crack identification and documentation still remains a challenge because of an absence of a rigorous, mathematically based methodology from which inspection programs can be devised. The first step to

Table 1
Summary of technical specifications of commercial scanning system.

Brand	ThirdTech [25]	FARO [26]	Trimble [27]	Optech incorporated [28]	Leica geosystems [29]	RIEGL laser [30]
System	DeltaSphere-3000IR	Focus 3D	FX	ILRIS-HD	Leica ScanStation C10	RIEGL VZ-6000
Metrology method	Phase	Phase	Phase	Pulse	Pulse	Pulse
Min./max. range (m)	0.3/16	0.6/120	2/350	3.0/1200	0.1/300	5/6000
Point accuracy* (1 sigma)	5 mm	2 mm @ 10 m and 25 m	0.4 mm @ 11 m; 0.8 mm @ 21m; 2 mm @ 50 m	3–4 mm @ 100 m	6 mm @ 1–50 m	15 mm @ 150 m
Beam diameter	7 mm @ 9 m	3 mm	2.3 mm @ 5 m; 16 mm @ 46 m	19 mm @ 100 m	4.5 mm @ from 0 to 50 m (FWHH-based)	15 mm @ exit; 60 mm @ 500 m
Scan angle step size H/V (°)	0.015/0.015	0.009/0.009	0.01/0.005	0.000745	Minimum point spacing < 1 mm	0.002–3/0.002–0.280
Scan angle accuracy H/V (°) (1 sigma)	0.015/0.015	0.015	0.008	0.046	0.003	0.0005
Field of view H/V (°)	360/290	360/305	360/270	40/40	360/270	360/60

* Positional measurement.