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Reliability of Crack Detection Methods for Baseline Condition Assessments
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ABSTRACT

Despite billions of dollars of annual exposure from claims and litigation related to construction-induced damage, there are no quantitatively based, agreed upon standards or procedures as to what constitutes due diligence with respect to a pre-construction, condition assessment. Similarly, the relative accuracy, reliability, and costs for various inspection approaches are not well established. This paper compares the relative performance capabilities of crack detection by sidewalk-based, manual inspection with digital photography, terrestrial Light Detection and Ranging (LiDAR), and elevated manual inspections based on 2 brick and 2 concrete buildings (8.2-14.3m high) in Dublin Ireland. Results showed that non-manual methods tended to over-predict crack widths by at least 5 mm and underestimate crack lengths by one-half. Digital photography, however, detected the shortest cracks (as short as 17 mm) and had no significant decline in accuracy beyond 12m high, which he added benefit of generating a permanent, objective record. Terrestrial LiDAR proved neither particularly accurate nor cost-effective. Finally, operator-based, reliability problems emerged with all methods, with discrepancies of at least 11%. Overall, digital photography taken and archived, but not analyzed, was the most cost-effective, accurate, and reliable approach.

KEY WORDS: Bricks, Cracking, Defects, Digital Techniques, Field Investigations, Masonry, Non-destructive Tests, Imaging Techniques, Site Evaluation

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Reliability of Crack Detection for Baseline, Pre-construction Condition Assessments
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INTRODUCTION

Each year construction activities generate billions of dollars of claims and litigation. Projects involving excavations, tunneling, dewatering, and blasting are particularly vulnerable to such financial exposure. Determining the legitimacy of such claims is largely dependent upon the establishment of a high quality, pre-construction, condition assessment. For large-scale projects, such as the installation of a subway, the sheer number of potentially impacted structures poses significant financial and organizational hurdles to efficient and reliable data collection. A recent example is the Dublin Port Tunnel in Ireland, where over 300 structures were damaged – representing 1 in 8 buildings along the tunnel’s route (Cassidy 2006). Given the potential, wide-scale distribution of such damage, the question arises as to what is the most reliable, accurate, and cost effective method for establishing baseline, damage data, when confronted with the need to survey thousands of buildings. In preparation for the upcoming Dublin metro, a study of four buildings in Dublin, Ireland’s city center was conducted to compare various manual, digital, and remote sensing approaches of crack detection, with respect to accuracy, reliability, and cost.

BACKGROUND

Condition assessment is the procedure of documenting the nature and extent of physical degradation of a building and may include an enumeration of any necessary repair work, including associated costs (Brandt and Rasmussen 2002). Condition assessments: (1) identify a building’s current health for the purpose of maintenance planning or risk assessment; (2) help determine the underlying causes of visible damage; and (3) establish a historical record. This last role is done most commonly to assist in determining the validity of third-party damage claims, for buildings possibly impacted by nearby construction activities. Assessments result in the creation of documents critical for evaluating third-party claims and are typically required by contract. However, they are frequently neglected or done without sufficient care to be reliable, because of the resources needed to generate high quality, spatially-referenced records.

Current Approaches to Condition Assessments

There are many well-developed and thoughtful documents on methods related to building inspection and evaluation (e.g. ASTM 2005, ASCE 2000a, ASCE 2000b, Ratay 2005, TMS 2008). These range in detail from a few pages to several hundred and address many critical issues about different technical options, items to inspect, deterioration levels, and causal determination. These documents provide extensive strategies and guidelines, in terms of the selection of investigation techniques to achieve certain outcomes, such as evaluation of a building’s current capacity, identification of safety issues, and determination of active damage mechanisms.

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How documentation (as opposed to investigation) should be done, however, is not addressed in detail in any of those publications. Generally the most that is said is that there are preliminary investigations and in-depth ones, and that the extent of the investigation is a matter to be determined based on the owner's pre-disposition and the reason for the assessment (e.g. upcoming sale of the building, post-disaster safety evaluation). Even Ratay's nearly exhaustive contribution on the subject (Ratay 2005) does not explicitly consider reliability, accuracy, and cost in a quantitative manner. A sampling of the inspection/documentation documents is provided below.

The gold standard in general building documentation is arguably that developed by the Historic American Buildings Survey (HABS). Established to document historic buildings in sufficient detail to allow their exact duplication in case of destruction, HABS relies on sketching, manual analysis, and basic surveying techniques (Burns 2004). Spatial referencing of damage is encouraged through measuring and counting repetitive materials, such as bricks and windows (Burns 2004). A more engineering-oriented approach was proposed by ASCE (2000a and 2000b), focusing on structural aspects based on material composition. An incremental, multilevel intervention methodology was advised, due to the high cost of comprehensive assessments. As part of that process, both destructive and non-destructive testing for determining physical conditions and visual examinations were proposed for concrete and masonry structures. Visual examination (with or without optical aids), along with measurement tools and photographic records were suggested for evaluating surface condition deficiencies in joints and determining differential movement. Surveying tools and instruments were recommended to aid in the recording of crack size, alignment, and location, with the caveat that scaffolding may be required for accessing hard to reach areas. Visual examination was found to detect the widest range of physical degradation in both concrete and masonry, even more so than more active forms of non-destructive testing (ASCE, 2000a and 2000b). The Masonry Society's Existing Masonry Committee developed a not dissimilar multi-level intervention document (TMS 2008), but one more driven by identification and causal determination of specific damage mechanisms (e.g. spalling). Driscoll (1995) also proposed assessment and classification of visible damage based on the damage type, damage location, likelihood of progressive deterioration, and identification of possible causes.

An alternative approach based on an element-by-element evaluation was suggested by Brandt and Rasmussen (2002). The approach relies upon systematic registration of an entire building's components (e.g. roof covering, cornice, and parapet) using 70 pre-established objects with an option of a further subdivision into 256 subcategories, to differentiate between major differences in materials or design. The extent of physical degradation of each of the potential 256 objects is then rated at 1 of 4 deterioration levels.

Less comprehensive condition assessments generally focus on crack documentation, in part because cracks are easily identifiable as defects by residents and are, thus, often the subject of damage disputes. These have been used, as well, as indicators of the structure's total health (e.g. Table 1). Burland's work has been used extensively for brick and stone (Burland et al. 1977), while Chung (1994) specifically developed a comparable grading for structural damage identification for reinforced concrete walls (Table 2). Similarly, Suprenant and Basham (1993) suggested concrete crack classification ranging from very fine (crack widths less than 0.1mm) to severe (crack widths greater than 0.4mm). In all condition assessments, the notation of the existence of cracks is an important component, but there is not an industry based standard or established procedure as to what comprises good (or even adequate)

practice in this area, especially with respect to noting the width variation along the cracks and their spatial referencing.

Inspection

Crack identification and documentation often relies upon binoculars used from the sidewalk level supplemented by tele-cameras or other means to facilitate examining hard to view locations (Chung 1994, TMS 2008). Farmer (2004) proposed use of viewings from multiple locations (e.g. street level, roof top, balconies) to be supplemented by a series of closer range examinations done with the aid of a ladder, lift, or scaffolding. Taylor and Gaudette (2004) suggested that these close-up examinations should comprise at least 25% of the surface area of each elevation and should be representative of the entire condition of the façade (based on the visual examination from ground level). Sketches and photographs are regularly recommended to record crack locations, length, width, depth, age, pattern, direction of taper, and level of crack activity (Suprenant and Basham 1993, Driscoll 1995). Unfortunately anything short of affixing a monitoring gauge to each and every crack and simultaneously marking the end of each crack through a physical identifier on the building relies upon documentation methods of unknown reliability levels. Yet physical tracking of each crack relies upon extensive time, funds, and physical access, all of which may be in short supply, when considering the extent of possible damage during a major infrastructure project, where thousands of individual structures may need to be examined along a single tunneling route. As such, the physical, up-close inspection of each crack on every structure may simply not be viable. When that is the case, alternatives are needed in the form of remote inspection, photography, or remote sensing. The following study was designed to provide an assessment of reliability, accuracy and cost of a sampling of such methods.

STUDY

In anticipation of Dublin Ireland's first subway project, four city center structures were selected (fig. 1) that were reflective of the general building stock (Casey 2004). Two buildings were brick and two were concrete. One of each was two-story and the other four-story. Building selection was influenced also by occupancy, accessibility, sidewalk width, and the quantity of foot traffic, as well as owner permission.

Scope and Methodology

The goal was to locate all visible cracks and document their widths, lengths, and locations. The four buildings were examined by applying different assessment techniques and, in some cases, also by using multiple inspectors. Condition assessment was done manually (first by the naked eye and then with binoculars), through digital photography, and with a terrestrial Light Detection and Ranging (LiDAR) unit (fig. 2); erection of scaffolding was not possible for any of the structures due to logistics and finances.

LiDAR is a fairly recent development in three-dimensional (3D) laser scanning that generates surfaces from point clouds surveyed by laser technology, by measuring the properties of scattered light to find the range and other information of a distant object. Point clouds resulting from laser scanning contain shape and intensity information (Lersch et al. 2004). The range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. The resolution at which the point clouds are produced during LiDAR scanning is operator selected. Resolution of a

LiDAR scan refers to the distance data points are from each other on a recorded surface, when producing a point cloud of that surface. A 10mm x 10mm resolution scan detects and records points at distances of 10mm from one another, based on the equipment being located 100m from the target. Higher resolution scans gather more data and are, therefore, more accurate but more time intensive (fig. 3). A 5mm x 5mm (at 100m) resolution was selected as the most time effective for the defects captured; this was based on a series of test cases, not herein included. The equipment was located at a distance of 20-35m resulting in actual data sampling ranging from 1 x 1 mm to around 1.75 x 1.75 mm. Although LiDAR has been used extensively for nearly a decade to document entire structures and more recently for detailed oriented work, such as tracking artificial weathering of historic masonry (Birginie and Rivas 2005), little has been published to assess its viability for crack detection (Laefer et al. 2009).

To verify the data, up close inspections were conducted for two of the buildings: using a 3m high ladder for the two-story structure (Building 1) and employing a 14m high boom lift for the four-story structure (Building 2). In the second case, both observers individually inspected the building via the boom lift. The examination process was iterative. It began with the technique that was the simplest and, thus, believed to be least reliable and progressing towards greater levels of complexity (and potentially greater reliability and accuracy). Each assessment was separated by several weeks to try to avoid an a priori knowledge bias of the data sets. The up close inspections via ladder or boom lift were done last. For each approach, the identified damage (cracks and flaws) was recorded onto a photograph of the building covered by acetate. These background drawings improved the spatial accuracy of crack documentation and promoted swift data collection.

Vernier calipers were used for all up close inspections. Crack widths were measured in three different locations along the crack length (i.e. beginning, middle, and end of the crack) to account for any variability in crack width along its length. Crack conditions (e.g. whether the mortar was missing) were noted. Using a tape measure and a laser distance-measuring tool, the dimensions of the building and major features (e.g. windows) were established and recorded on the background drawing. After viewing the structure with the naked eye to identify visible cracks or flaws, a set of high power binoculars (Zeiss, 10 x 40) were used to re-observe the building, and any further cracks visible were recorded on the background drawing. The photographic and LiDAR equipment were similarly stationed to maximize unobstructed views. Photographic output and LiDAR scans were evaluated via computer. Photoshop (v. 7.0) was used to examine the photographs, and a post-processing program called RealWorks (Trimble 2007) was used to register point clouds scanned from different locations, to remove extraneous points from the final point cloud, and to generate triangular meshes for surface generation from the raw data. The time spent on all inspection and analysis was recorded for each approach.

Equipment

An eight mega pixel Canon digital camera was tripod-mounted for digital image collection. All documentation occurred under similar weather conditions (dry, slightly overcast skies). Close-up, overlapping photographs of the facade were taken, in addition to a full image of the building for spatial referencing. The terrestrial LiDAR unit was a Trimble GS200 3D Scanner, which can be used at a range as far away as 350 meters, has a horizontal field of view of 360°, and a 60° vertical field of view (Trimble 2007). The Trimble GS200 is capable of producing point samples spaced at 3 millimetres at a distance of 100 meters.

Data Interpretation

Although a bit has been written about how to take good photographs of buildings in terms of lighting and distortion (e.g. Burns 2004, Peterman 2004), interpretation of those images has not been addressed. One persistent challenge is that damage tends to be localized. Thus, a close-up photograph is usually required. However, the scale required to detect damage often excludes sufficient external markers (e.g. edge of building, cornice, or other façade elements) to identify definitively the image's exact location (e.g. fig. 4). Additionally, as the image is expanded, pixilation occurs further obfuscating feature identification (fig. 4b). Similar challenges exist with terrestrial LiDAR, but interpretation is additionally exacerbated by the fact that the LiDAR image is a point cloud, thus the image is not continuous, which makes determination of discontinuities and their boundaries difficult. Using the scanner's proprietary software (RealWorks 5.0) and segmenting the image into smaller areas and then rotating the image, greatly facilitated crack detection (fig. 4d).

RESULTS

Findings were considered with respect to the ability to detect cracks (1) consistently, (2) at the smallest scale (width and length), (3) without degradation with building height, (4) reliably across inspectors, and (5) in the most economical manner. As the large brick structure (Building 2) underwent inspection by boom lift by both inspectors and full manual, digital, and LiDAR analysis by both inspectors as well, it is used herein to illustrate the trends found across the four inspected buildings. For Building 2, there were a total of 95 cracks thought to be found by the two inspectors using the 4 inspection methods (fig. 5).

Consistent Crack detection

Figure 6 compares the findings of the two observers, with respect to total time per square meter of area examined to the total length of cracks detected for each method. For both observers, manual analysis was the fastest (less than 0.03 hr/m^2 per crack), however the accuracy of this method was low, with each observer detecting only 13% of the 95 cracks detected in total. Additionally, the total detected crack length differed between observers by 5 fold.

Digital analysis was the most accurate of the methods, detecting up to 46% of all detected cracks, but it required between 0.04 and 0.05 hr/m^2 per crack (fig. 6). The boom lift appeared to be the most efficient; detecting 31% of the total number of cracks at a rate of approximately 0.032 hr/m^2 – more than double the manual method, for a relatively small supplemental time commitment; in nearly all cases, the expenditure of additional time resulted in the identification of additional cracks, irrespective of method (fig. 6). Additionally, the cumulative crack length of all cracks detected by the boom lift was significantly longer than that of any other method. Figure 6 suggests that the manual and LiDAR methods have a significantly poorer ability to accurately detect crack lengths. Although the civil engineering community has generally discussed cracks with respect to maximum width, length can be an important indication of a crack's progression. Figures 7 and 8 show the lack of consistency between the techniques, with many of the cracks only being detected by one of the methods.

As seen in figure 7, the LiDAR tended to overestimate crack width by more than 7 mm [as verified where comparison with vernier calipers were possible (cracks 1-17)]. This bias would exacerbate the reported severity of nearly all the cracks according to Tables 1 and 2, thereby giving the impression that damage was more severe than it actually was. On average, all techniques underestimated crack length

by 50% compared to that which was measured from the boom lift (fig. 8). Given reports that cracks in reinforced concrete regularly vary 40% along their length (Suprenant and Basham, 1993), the inability to discern the ends of a crack is not surprising, but in terms of establishing a true base-line against which to compare third-party claims, determination of the true length of the cracks can be considered fairly critical.

Although the manual assessment made from the ground level, a few meters from the building, detected the fewest cracks overall, the dimensions of those crack widths and lengths were very similar to that found in the up-close assessment, suggesting that they were the most accurate recordings obtainable without benefit of a boom lift.

Minimum detectable size (width and length)

Minimum detectable crack size is arguably the most important parameter, as a previously undetected crack may be the subject of future litigation. This study found that crack width was largely a function of method, although cracks in brick buildings were much more easily discerned than those in concrete ones. This was particularly true in the case of Building 3, where the terra cotta colored concrete further exacerbated the difficulty of finding the cracks in the concrete. With the exception of the manual inspection of the concrete, the digital method was largely superior in detecting the cracks, although identification from the digital images was extremely tedious and time consuming. Figure 9 shows the large number of cracks that could not be discerned through non-digital methods, as well as only the loosest of correlations between crack width and length.

Capacity degradation with height

Examination of figure 10 shows that manual analysis was most accurate for the bottom 2 meters, with Observer 1 detecting 40% of all cracks cumulatively detected by the 4 methods applied to that area. However, at heights above this level, accuracy greatly decreased. LiDAR performed the worst below the 2m level due to obstacles; repositioning the unit is time consuming as it requires the registration of the various images. Compared with the other 3 methods of analysis, LiDAR performed reasonably well in the range of 6-12m but detected no cracks above 12m. The boom lift provided the most consistent performance by detecting a large percentage of cracks in each area of the building, up to a height of 10m, but was also hampered below 2m, because of access. The chief advantage of the boom lift is that, generally, it allows detailed examination to take place by positioning the lift such that the observer is at eye level with the crack. In the case of this study, at heights above 10m, the restricted reach of the 14m boom lift prevented fully detailed examinations from occurring. Digital analysis performed the most consistently over the height of the façade for each of the four buildings in the study, and as building height increased, digital analysis was clearly the most effective method of crack detection.

Reliability across inspectors

Shown most clearly in figure 11, but also seen in figures 6 and 10, there is a significant amount of discrepancy that can emerge between inspectors. In certain regions of Building 2, differences as much as 11% for the manual, 14% for the upclose, 14% for the LiDAR, and 35% for the digital emerged. The issue of observer bias is a documented problem. Consequently, those methods that generate a permanent record (i.e. digital and LiDAR) offer the advantage of generating the opportunity for additional assessment by others and reassessment at a later date.

Relative costs

While accuracy and reliability are important, cost often drives decision-making. For inspection, costs consist of both capital investment and hourly labor expenditures. Manual assessments incur no significant capital cost, since standard tools are required (i.e. measuring tape, binoculars, clip board). Digital analysis requires minimal capital cost: a high-resolution camera (€800) and associated software (€1000). Conversely, capital cost of a terrestrial LiDAR machine is significant (around €100,000, plus approximately €5000 for the associated software). Costs incurred for use of the boom lift was €500 plus 21% value added tax (VAT) for a total of €605. Capital costs were calculated based on the maximum time spent by a particular technique during the course of field work and analysis. In the case of digital and LiDAR assessment, the maximum total time spent on site for any of the 4 buildings was approximately 8 hours. Assuming that on average 3 condition assessments could be carried out per week and that the technology has a life span of 3 years, in the region of 468 condition assessments could be completed over the course of this time resulting in a cost per assessment (including set up and break down time) of €224.36 for the LiDAR versus €3.85 for the digital camera.

Variable costs are calculated based on the number of hours per examination.

$$\text{Variable Cost} = \text{Cost/hour} * \text{No. of hours (field work + data analysis)} \quad \text{eqn 1}$$

For both manual and digital assessments, labor costs were taken as €15/hour, based on the typical starting salary of a junior engineer (typically employed in such a case). A LiDAR technician is paid approximately €20/hour. Figure 12 outlines the cost efficiency of the 4 techniques over the course of each of the 4 buildings examined. The figure relates efficiency (eqn 2) for each building. Accuracy expresses the number of cracks detected by the particular method of analysis as a percentage of the collective number of cracks detected, divided by the total cost per assessment (Capital plus Variable) for all techniques.

$$\text{Efficiency} = (\text{Cracks detected} / \text{Total cracks present}) / [(\text{Capital costs pro-rated} + \text{variable cost}) * \text{hours required for inspection and analysis}] \quad \text{eqn 2}$$

Figure 12 clearly shows that over the course of all 4 buildings, manual assessment was most cost-effective, detecting the highest percentage of total cracks per euro. However, in the case of Buildings 1 and 4, digital assessment performance was relatively similar and offered the additional benefit of generating a permanent record. LiDAR, however, had low efficiency, mostly due to the high capital cost of €224 per examination. Similarly, the accuracy of the boom lift analysis on Building 2 was offset by the high rental cost of equipment (€605/day including operator but not inspector). Considering that time on site using the boom lift was approximately 2.5 hours but rental was required for the whole day, carrying out a number of boom lift examinations over the course of a day would reduce the total cost per building nearing the cost of the digital approach. The most accurate results are likely to have been obtained by erecting scaffolding on the façade of the building, as access would have been complete. However, cost of rental, erection and removal was quoted as €3,025 including VAT. Dividing this by the total 95 cracks detected and even assuming a 100% accuracy would have still resulted in an efficiency ratio less than the digital camera and without the benefit of a permanent, objective record, unless gauges were attached to the building at each crack.

CONCLUSIONS

The aim of the project was to evaluate a number of techniques used when carrying out crack detection for the purpose of condition assessments of structures, and to compare them to a relatively new remote sensing technique (LiDAR), to establish which method was the most beneficial with respect to reliability, accuracy, and cost. Because of the high percentage of cracks that were discerned using only one method, without going to the expense and disruption of setting up a scaffold, the authors recommend the use of a boom lift supplemented by a series of digital photographs for which analysis should only be performed in the case of third-party dispute. LiDAR may hold promise in the future as the cost continues to decrease and the speed of both scanning and processing increases, but currently use of a high megapixel camera represents a higher degree of reliability, accuracy, and objectivity at a fraction of the cost. Given the limited number of structures examined, full extrapolation may require further verification.

SUMMARY

Reliability, accuracy, and cost effectiveness are necessary requirements for effective and legally defensible condition assessments. Yet, to date quantifiable exploration of these issues has been lacking. This paper presents the results of an investigation of four buildings (2 brick and 2 concrete) in Dublin Ireland via manual, digital, and remote sensing means. The terrestrial LiDAR was especially disappointing, particularly with respect to the cost. The results cast grave doubts on the defensibility of any of these methods because of issues of observer bias and height based degradation, as well as technology driven specifics, with discrepancies of at least 11% emerging between operators for all methods. Non-manual methods tended to over-predict crack widths by at least 5 mm and underestimate crack lengths by half. The shortest detectable crack was 17 mm, and this could only be achieved via digital photography, which has the added benefits of no significant decline in accuracy for heights up to at least 14m and the generation of a permanent, objective record. Overall, digital photography taken and archived, but not analyzed, was the most cost-effective, accurate, and reliable method.

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Table 1. Crack Width versus Damage Level (adapted from Burland et al. 1977)

Approximate Crack Width (mm)	Damage Level	Sample Symptoms
Up to 0.1	Negligible	Hairline cracks
0.1 to 1	Very Slight	Cracks usually visible only on interiors or up close external inspection
1 to 5	Slight	Cracks visible in external brickwork on close inspection, and doors and windows may stick
5 to 15	Moderate	Doors and windows stick, and service pipes may fracture
15 to 25	Severe	Floors sloping and service pipes disrupted
Usually 25+	Very Severe	Walls lean badly, and windows broken with distortion

Table 2. Concrete Crack Classification (adapted from Chung 1994)

Grade	Intensity	Visual Damage
1	Light	Fine cracks (<1mm)
2	Moderate	Medium cracks (1-2mm)
3	Severe	Wide cracks (>2mm) at different locations
4	Very Severe	Wide cracks everywhere, doors and windows distorted, and utility pipes and glass broken