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A Systematic Approach for Large-scale, Rapid, Dilapidation Surveys of Historic, Masonry Buildings

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A SYSTEMATIC APPROACH FOR LARGE-SCALE, RAPID, DILAPIDATION SURVEYS OF HISTORIC MASONRY BUILDINGS

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Dilapidation surveys may require extensive resources to achieve detailed accounts of damage for intervention purposes or may involve only limited resources but be restricted to an extremely rapid assessment (e.g. post-earthquake, life-safety inspection). Neither provides a holistic, cost-effective approach for evaluating the general health of a large number of structures, as is needed for urban planning, historic designation determination, and risk assessment due to adjacent works. To overcome this limitation, index images are introduced for a systematic approach for rapidly conducting large-scale, dilapidation surveys of historic masonry buildings. This method, the University College Dublin Inspection Method (UCDIM), is tested against both a detailed inspection and an alternative rapid approach to determine accuracy and resource intensiveness through its application by three inspectors of various levels of experience to six buildings in the city centre of Dublin, Ireland. The UCDIM provided a damage ranking of $\rho = 0.94$ for all inspectors, regardless of experience, except when painted or rendered façades were included. The UCDIM, when compared to detailed inspection provided a high level of reliability, cost savings of approxi-

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mately 90% and several months of time savings since interior access was not

required.

KEY WORDS: historic; masonry; buildings; dilapidation; survey; condition; assess-ment; urban; planning; risk.

1. INTRODUCTION

Traditionally, a dilapidation survey refers to the evaluation of a building to assess any existing defects. A variety of terms are used (often interchangeably) to describe such inspections including condition assessment, dilapidation survey, and structural survey, as well as others. Problematically, existing methods for assessing building dilapidation vary greatly in purpose and scope, as well as level of detail. Selection of an appropriate system for historic buildings may have national, as well as international implications. For example, European policies such as the Granada Convention for the Protection of the Architectural Heritage of Europe (COE, 1985) outline numerous obligations requiring European states to protect their architectural heritage. Under Article 10 of this Convention, the signed parties must undertake policies which "include the protection of the architectural heritage as an essential town and country planning objective…". In Ireland, the Planning and Development Act 2000 (OAG, 2000) outlines a system for listing structures of special interest, stating that their owners are legally obliged to protect them. Generally, these provisions are interpreted as generating and maintaining heritage inventories, which necessitate large resource commitments. Additionally, the output of a dilapidation survey can form a crucial component in building legislation and, therefore, must provide an accurate and reliable representation of a building at the time of inspection. Furthermore, in the case of adjacent construction works, buildings are often vulnerable to a variety of damage mechanisms. As a re-

sult, a building's condition prior to adjacent construction commonly forms the basis for deciding pre-construction mitigation efforts and post-construction litigation claims. For large subsurface projects, such as tunnelling, hundreds if not thousands of buildings may need inspection. Unfortunately, there has yet to be a widely adopted approach, as will be explained.

2. BACKGROUND

In general, building survey methods vary in purpose, scope, and level of detail. As will be subsequently described, procedures tend to consist either of a highly detailed investigation targeted for individual structures or of a rapid nature suitable for promptly considering the pre- or post-disaster life-safety level for a large number of buildings. Those methods consisting of a detailed exploration generally require a large number of inspection hours to fully document a building's condition. For detailed inspection of residential properties, Bowyer (1971) and Sheeley (1985) recommended a preliminary exploratory inspection to determine the time involvement and extent of specialist services required. For the main inspection, a sequential methodology was advised, whereby the property was divided into sections (e.g. roof, walls, floors, staircases, internal finishes). This type of survey was intended to be undertaken prior to the purchasing of a residential dwelling to inform the potential purchaser of the property's condition and likely repair costs. Also for residential properties, Staveley and Glover (1983) suggested a sequential inspection but following a definitive procedure, e.g. commencing within the roof space and working downwards through the property and leaving external works, installations, and drains until last.

When faced with a large inventory of buildings, including residential and commercial properties, the American Society of Civil Engineers' Guideline for Structural Condition Assessment of Existing Buildings (ASCE, 2000) proposed the use of screening criteria. These included

the building's original construction date, cultural importance, and current occupancy level, and are used to assist in the prioritisation of buildings for preliminary inspection, thereby eliminating unnecessary inspection of certain buildings. The preliminary inspection would consist of an initial analysis of a building's structural adequacy, including a review of available documents, a site inspection, and a decision as to the need for a more detailed analysis. Upon deciding to conduct a detailed assessment, a thorough inspection of the building's structural system, features, and its need for rehabilitation would then be conducted (ASCE, 2000).

For large-scale and multiple, detailed inspections of residential buildings, the Dutch standard NEN 2767 (Straub, 2009) outlined a method to determine a structure's condition according to individual building elements. NEN 2767 is used for maintenance planning and asset management purposes. The method uses a six-point scale, ranging from excellent (1) to very bad (6) to categorise defects. These are subsequently weighted according to their structural importance, intensity and extent, producing an overall condition index for the building. Strictly for commercial office buildings, Brandt and Rasmussen (2002) proposed the Tool for Selecting Office Building Upgrading Solutions (TOBUS), which consisted of a broad checklist of 70 categories, each subdivided into 1-12 object types comprising both structural elements and building services. The method's intent was to assess degradation and aid in the selection of an upgrade solution. TOBUS makes use of index images. These were visual examples which aid in the standardized selection process of one of four degradation codes to each object type, as well four corresponding work codes that indicate the extent of repair required. Index images are commonly employed within Civil Engineering as well as related fields to provide a visual standard for guidance, e.g. Cho et al. (2006), Grünthal et al. (1998).

In contrast to detailed inspections, post-disaster surveying methods typically involve the application of rapid evaluation techniques solely relating to structural integrity. A modified approach to the Applied Technology Council's ATC-20 Forms (ATC, 2005), which are generally used for post-earthquake response, was described by Peraza (2006) for use around the World Trade Center (WTC) site following the September 11th 2001 terrorist attacks. The ATC-20 Evaluation Safety Assessment Forms consider a building according to structural, non-structural, and geotechnical hazards, which are used to assess its condition as a percentage of the overall estimated building damage.

Remote sensing technologies have also been employed to enable rapid, post-disaster assessment. In a novel post-disaster survey method, Corbane et al. (2011) used remote sensing imagery, which provided lateral views of buildings, to assign damage grades based on the European Macroseismic Scale EMS 1998 (Grünthal et al., 1998). According to Corbane et al. (2011), extreme levels of building damage were reliably detected with this approach, but lesser damage levels were not.

Pre-disaster evaluation methods also exist, such as that proposed by the United States' Federal Emergency Management Agency (FEMA, 2002) to determine earthquake risk based on seismicity levels, the building's geometry, soil type, and occupancy levels. From this, a damage score is generated indicating whether or not a detailed evaluation is required. There are also more rapid techniques, such as those described by Martinelli et al. (2008) and Roca et al. (2006) in which typological data such as building location, height, age, and masonry configuration were used to assess seismic vulnerability, as outlined as part of EMS 98 (Grünthal et al., 1998). Since typological information is commonly available from general building censuses, the need for field surveys is minimized, thereby enabling results to be obtained rapidly and at a reduced cost. Simi-

larly, Ho et al. (2011) developed a rapid building assessment method as part of the decision-making process for urban renewal in Hong Kong based on 21 weighted building factors. The method considers the building's existing condition and management criteria to determine the current building dilapidation level, as well as future vulnerability to dilapidation.

One of the difficulties of using the above methods is that they were generally devised for an extremely large range of building types. In contrast, the Critical Element Factor (CEF) System was specifically devised for historic buildings to offer a rapid assessment of the condition and use of a building by individually assessing its roof, walls, windows and doors, ancillary items, associated boundary items, and overall state (Table 1) (The Handley Partnership, North Yorkshire, UK). These are considered along with the building's occupancy density. The CEF System is a registered trademark and was developed by The Handley Partnership, a surveying and structural engineering practice, specializing in the assessment of large groups of historic buildings as well as other structures. This method is intended to be conducted by a single inspector across an entire building stock, thereby enabling targeted resource planning by governmental authorities; however this is not always feasible due to time and budget constraints. In a similarly rapid and quantitative approach, Burland et al. (1977) proposed detailing damage classification according to visible cracking, thereby allowing for an objective and consistent building assessment to be made, although on an extremely limited set of damage indicators (Table 2). Despite this limitation, Burland's approach has been widely adopted in the engineering community for subsurface construction risk assessment [(Aye et al., 2006), (Laefer, 2001), (Torp-Petersen and Black, 2001)].

Table 1. CEF System (The Handley Partnership, North Yorkshire, UK)

Historic buildings commonly require non-contact documentation procedures. This can be achieved through the employment of digital photography, photogrammetry or terrestrial laser scanning (TLS). In each case the general geometry of the building can be effectively documented. Whilst photogrammetry has been a popular choice for general documentation (Yilmaz et al., 2007), increasingly there is also its application for the detection and monitoring of structural damage, such as was used at the C14th Basílica da Ascención in Northern Spain for crack measurement (Armesto et al., 2008).

Laser scanning is being fairly regularly used for obtaining cultural heritage building data, e.g. Andrés et al. (2012), Grussenmeyer and Guillemin (2011). Yastikli (2007) contended that laser scanning is more applicable for complex structures than photogrammetric techniques which use digital image rectification since it is suitable for planar surfaces. A study by Laefer et al. (2010) which compares TLS, digital photography and direct visual inspection, demonstrated that both TLS and photography are good sources of a permanent record. However, TLS data proved difficult in determining crack location and size, due to the pixelated nature of the datasets. Although these methods offer viable solutions for the inspection of historic structures, highly experienced inspectors are required, thus limiting their application amongst multiple inspectors. Furthermore, the high costs associated with remote sensing technologies further limit their usage.

In the cases of both underground infrastructure works and national inventories, what is particularly sought is a strategic approach for consistently and reliably comparing the status of large groups of buildings. To this end Laefer et al. (2008) proposed the use of four scales (Tables 3-6) to be used in conjunction with Burland et al.'s (1977) system (Table 2) to rapidly assess a building's condition. The results are then weighted according to Table 7, and finally normalized

by the summation of weighting fractions (i.e. 13) to better identify structural versus non-structural concerns using the original categories of negligible (0) to very severe (5).

Table 2. Cracking (after Burland et al., 1977)

Table 3. Protruding or loose brickwork (after Laefer et al., 2008)

Table 4. Replaced or repaired brickwork (after Laefer et al., 2008)

Table 5. Exposure-based damage (after Laefer et al., 2008)

Table 6. Plant growth (after Laefer et al., 2008)

Table 7. Weighting system (after Laefer et al., 2008)

Ideally there would be a method that could be applied rapidly and consistently with relatively limited resources by multiple inspectors. The best case would be that the method could be used to ascertain the state of an area and the individual buildings within it for historic registration, general condition monitoring, and base-line documentation in the case of adjacent works. However, to date there has been no consensus for a method for rapidly evaluating large groups of historic buildings for either large-scale, risk-assessment near infrastructure projects or for long-term documentation, as in the case of national inventories.

3. SCOPE AND METHODOLOGY

To help overcome the problems of limited available expert knowledge and time resources, and to enable the repeatable and consistent surveying of large groups of historic structures, a rapid assessment method is proposed - the University College Dublin Inspection Method (UCDIM). The UCDIM employs five tables relating to the degradation of a building's façade, as

proposed by Laefer et al. (2008) (Tables 2-7), to be used alongside accompanying index images, which offer a visual standard against which to judge varying degrees of degradation. These index images (Figures 1-3) were taken prior to the study. They provide a means for visual comparison when inspecting a building's façade and aid in the damage classification, allowing testing of the UCDIM, as will be explained.

The aim of the study was to improve user understanding and repeatability both between multiple building investigations and across investigators. The intention is that a single digital photograph of the front façade of each building is taken using a camera capable of producing photographic quality of at least 300dpi to which the UCDIM is then applied. Where a single photograph is not possible due to street width restrictions, multiple photographs should be taken and subsequently merged using an editing tool in a graphics software programme. Ideally, all images for the study area would be taken under similar lighting and weather conditions, as common for the locale. The UCDIM, therefore, relies upon digital photography to ascertain the assigning of a damage level. The UCDIM is presently limited to masonry buildings since these are often most vulnerable to excavation-induced damage and are of the most relevance in the case of historical documentation and designation.

To determine the UCDIM's cost efficiency, repeatability amongst inspectors, and time resource intensiveness, it was tested against both a lengthy detailed inspection and an alternative rapid method, the CEF System (Table 1). The detailed inspection consisted of a comprehensive investigation of all parts of each building (e.g. internal and external walls, floors, ceilings, windows, doorways), documenting all identified defects. This involved a thorough visual inspection of both the exterior and interior of each building, beginning at the top storey of the building and working downwards, with each detected defect being photographed and noted. The CEF System

(The Handley Partnership, North Yorkshire, UK), as described previously, consisted of a rapid condition assessment of building components and subsequent weighting according to the building's occupancy. Damage classifications for both the rapid methods were determined numerically. For the UCDIM, the higher the numerical value, the worse the state of degradation of the building. However, for the CEF System, the opposite case exists, whereby a lower numerical value implies a worse state of building damage. Damage ratings for the detailed inspection were determined qualitatively, whereby buildings were ranked according to the nature and extent of defects present, requiring an engineer's judgement.

To benchmark these inspection methods, three inspectors of various experience levels surveyed six buildings in the city centre of Dublin, Ireland. As illustrated in Table 8, one inspector had extensive experience, having surveyed nearly 500 buildings. The other two inspectors had highly limited experience, one having surveyed less than 20 buildings and one with no formal previous experience.

Firstly, the rapid CEF System was conducted by each inspector individually. Next the detailed inspection was conducted by the three inspectors working together as a team; because of the commercial nature of the properties, the inspection period was not open-ended. Since this method acted as a benchmark for the other two methods, the inspection of the building by the team of inspectors was felt to be justified. In the detailed inspection, the three inspectors simultaneously examined all building components, both structural and decorative, commencing within the uppermost storey and working downwards through the building, followed by an examination of the building's exterior. Each identified defect was discussed amongst the team of inspectors before reaching a general consensus about the extent and nature of this defect, which was subsequently photographed by one inspector and recorded on paper by another. Defects which were

noted included the following: interior cracking of plasterwork and walls; interior chipping of plasterwork; interior sagging of floor joists; exterior flaking and weathering of masonry; and exterior cracking through coursing and mortar joints.

Following this, the front façade of each building was photographed as per the requirements for the UCDIM. This photograph was subsequently examined individually by each inspector who then applied the UCDIM. For each method, the resource requirements, time allotments, and data obtained were recorded.

Table 8. Inspector experience

Figure 1. Protruding or loose brickwork index images (to be used in conjunction with Table 3)

Figure 2. Replaced or repaired brickwork index images (to be used in conjunction with Table 4)

Figure 3. Damage due to exposure index images (to be used in conjunction with Table 5)

The overall study focused on the Grafton Street region in Dublin's city centre, for which an underground railway system has been granted planning permission by Dublin City Council (An Bord Pleanála, 2010). The majority of the region forms an Architectural Conservation Area with a high number of Georgian buildings constructed of unreinforced masonry (Casey, 2006). A letter requesting permission to gain access to the buildings in this region was hand delivered to 207 individual addresses. Due to the high number of building tenancies in this region, it was difficult in many instances to gain contact with the property owner to seek permission, as many of the tenants claimed to have little or no contact with their landlords, often refusing to accept the letter. Furthermore, a large proportion of the premises consisted of multiple tenants occupying a single building, which further complicated inspection co-ordination. Ultimately, responses were

obtained from only 5% of this dataset, resulting in access to only 6 buildings (Figure 4). Details of these six buildings are provided in Table 9.

Figure 4. Selected buildings

Table 9. Building details

4. RESULTS

4.1 General Findings

Two distinct building types were identified as part of this study. The first, herein called Type 1, consisted of a highly maintained ground floor retail unit. This unit contained large amounts of shelving and display units. As a result, the majority of the interior walls were concealed, thereby making defects difficult to detect. The remaining storeys were generally used for storage and employee facilities and, thus, remained out of view of the public. The state of dilapidation for these storeys was significantly worse than that of the ground storey; numerous defects were visible, and in many instances these areas appeared poorly maintained compared to publicly visible areas.

Buildings A, B, C and E are examples of Type 1. In Building E (Figure 5), structural and non-structural damage was evident in the upper stories; with cracking of up to 10mm in width propagating through brick and mortar (Figure 5b), as well as separation of walls at junction points (see Figure 5d). Non-structural damage was also present in many rooms in the form of cracked plaster on walls, corners, and coving (Figure 5c-d). However, the ground floor consisted of no defects whatsoever (Figure 5a), thus highlighting the potential disparity in damage across storeys within a single building.

Figure 5. Type 1 (Building E) – interior views

Buildings D and F provided examples of Type 2, where the building consists of highly maintained commercial units on all floor levels, with public access at the ground level and private offices in the upper storeys. Visible defects were mainly aesthetic in nature and limited to cracked plasterwork. Figure 6 illustrates the state of Building F's interior.

Figure 6. Type 2 (Building F) – interior views

4.2 Survey Methods

The results of the CEF System are illustrated in Figure 7, in which a lower rating indicates increasing damage severity. Therefore according to the CEF System, Building D is in the best condition and Building E the worst. Damage ratings across the three inspectors were in good agreement, with a maximum coefficient of variance of 0.21 occurring in Building A and most variance in single digits. Notably, in two-thirds of the cases, greater experience correlated with improved agreement between inspectors.

Figure 7. Survey results for the CEF System

Figure 8 illustrates the damage ratings for each of the three inspectors for use of the UCDIM. Increasing damage classification is represented by the higher the numerical score. Therefore, in

agreement with the results of the CEF System, Building E is shown as the most damaged and Building D as the least.

Figure 8. Survey results for the UCDIM

The outcome of the detailed inspection consisted of a list of defects present with accompanying photographs. Since the results were qualitative in nature, buildings were ranked according to the nature and extent of defects present, beginning with the least damaged building. Table 10 summarizes the main findings and provides a classification order based on these findings (1 = least damaged; 6 = most damaged). The results of each method were considered with respect to (1) reliability across inspectors; (2) consistency of damage classification; (3) time expended; and (4) overall efficiency.

Table 10. Findings of the detailed inspection

4.2.1 Reliability across inspectors

The reliability of the CEF System, based on the coefficient of variance across inspectors, was generally higher than the UCDIM (Figure 7). This demonstrates a level of consistency in the application of the method irrespective of the inspector's level of experience. The higher discrepancies for Building A appear to be due to the fact that the CEF System does not account for cases where certain building elements were not included in the damage assessment. For example, in Building A Inspectors I and III did not rate ancillary items (e.g. shop fronts, architectural details). As scoring is cumulative and non-weighted, the overall score assigned by Inspector II was

significantly higher. Figure 8 shows a higher level of variance for the application of the UCDIM. None of the coefficients of variance were single digit, and the maximum was 0.56 for Building C, which consisted of a painted façade. This highlighted the difficulties of applying this method to painted structures. A similar scenario for structures c0onsisting of rendered façades is likely. Nonetheless, all three inspectors identified Building E as the most dilapidated, with a coefficient of variance of 0.1 across the assigned damage ratings.

Table 11 illustrates the ranking of damage classification by each of the inspectors according to the CEF System and the UCDIM. Spearman's Rank-Order Correlation Coefficient (ρ) was calculated for each when compared with the results of the detailed inspection. The value of ρ can vary between -1 and 1, where a value closer to 1 or -1 indicates a match between the order of the two sets of data, while a value of 0 represents no correlation between the two datasets. A plus sign indicates identical rankings, and a minus sign demonstrates reverse rankings (Walpole et al., 2002). The results of the CEF System indicate that the experience of the inspector contributes to a more accurate result since both Inspectors I and II have a higher value of ρ than Inspector III. The results of the UCDIM demonstrate that if the dataset did not include a building with a painted façade (Building C), a reasonably accurate evaluation would have been achieved across all inspectors, irrespective of previous experience.

Although the CEF System provided a relatively good damage classification of the 6 buildings, with a value of ρ ranging from 0.5 for an inspector with no experience to 0.7 for both an inspector of limited experience and one with extensive experience, several issues were noted upon use. The CEF System did not account for varying levels of dilapidation within a building across storey levels, as was common for Building Type 1. This may lead to inaccuracies in the results. Furthermore, as described earlier, the number of items that were assessed were not

weighted (Table 1), which may further lead to inaccuracies. However, it should be noted that a detailed version of the CEF System employs a weighting system (The Handley Partnership, North Yorkshire, UK). However, due to lack of details of this further developed version, its application remained beyond the scope of study. The UCDIM appears to provide a more precise evaluation irrespective of inspector experience, with the possible limitation of its use for buildings consisting of painted and/or rendered façades where damage is harder to discern, particularly when applying Tables 2,4 and 5. This was an issue previously identified in a study of crack detection methods including close-up digital images where cracking in rendered façades were much more difficult to accurately detect than exposed brick ones (Laefer et al., 2010).

Table 11. Spearman's Rank-Order Correlation Coefficient

4.2.2 Consistency of damage ranking

Figure 9 illustrates the damage ranking for the three methods according to Inspector I. All three methods assign Building D as the least dilapidated state and Building E as the most. However, differences are evident for the rankings in between. The detailed inspection considers Building C to be ranked fifth, i.e. second highest level of damage. However, the CEF System ranks this building fourth while the UCDIM places it third. The CEF System ranks Building A fifth, while the UCDIM ranks it fourth, and the detailed inspection ranks it third. Furthermore, the CEF System considers Building F as the second least damaged building, while the UCDIM lists it the second most damaged. Even though the UCDIM considers only the exterior façade, the findings reveal that for the majority of instances, this can provide a good estimation of the overall state of dilapidation for buildings in this region.

Figure 9. Damage ranking according to Inspector I

4.2.3 Time

Figure 10 illustrates the average time across the three inspectors to conduct each of the methods. The UCDIM was the most rapid with time per building varying from approximately 4 to 6 minutes for assessment, with a further 2 minutes for photographing and processing the image. While the CEF System required only roughly twice the assessment time (averaging between 7 and 12 minutes per building), the method necessitates interior building access, thereby requiring significantly more resources to organise access. Assuming time requirements for entry of approximately 30 minutes for delivery of a letter of request to the premises and a further 15-20 minutes for scheduling the inspection, an estimate of 56.5 minutes can be attributed to the CEF System. While this is significantly more than the UCDIM, the time required for the detailed inspection was even greater. For the inspection alone, it was roughly three times longer than the CEF System (approximately six times longer than the UCDIM). Furthermore, the detailed inspection also necessitates interior building access. Consequently, the overall time was approximately 80 minutes per building.

Figure 10. Average time required for methods

4.2.4. Overall efficiency

The overall efficiency for each of the survey methods according to the three inspectors was calculated according to Equation 1 and is presented in Table 12. The time was calculated as

an average across the six examined buildings and is presented as a fraction of the time taken for the detailed inspection. Since access was obtained for just 5% of the buildings in the selected study area, methods for which access was required were weighted 20 times those for which no access was required. Therefore, a value of 0.02 was applied where access to the building was necessary. A value of one represents the maximum possible efficiency.

Efficiency = (1 - T) x (ARC) x (ρ)   (1)

where T = time, ARC = Access Requirement Constant, ρ = Spearman's Rank-Order Correlation Coefficient

Table 12. Efficiency

Since both rapid survey methods (CEF System and UCDIM) were benchmarked against a detailed inspection, an efficiency value of zero was evaluated for the detailed method. Significant differences can be seen between the efficiencies calculated for the two rapid methods. The UCDIM was on average approximately 70 times more efficient across inspectors than the CEF System.

5. DISCUSSION

The condition of a masonry building's façade was previously shown by Peraza (2006) as being potentially indicative of the condition of the entire building. If adequately demonstrated to be the case, this provides a means for substantial cost and time savings when conducting large-scale dilapidation surveys of historic masonry buildings. The UCDIM has been shown to accu-

rately provide a damage classification for the six buildings examined according to their exterior façade, thus offering a highly economic means for assessing large groups of historic buildings in this region, with the exception of those that are painted or rendered. In such instances, an alternativee specified means of assessment is required. Furthermore, extensively renovated buildings may also be a concern when using the UCDIM, as no explicit consideration is made of any interior features. Since heritage laws often ensure the protection of the original façade of a building, the exterior of such a building may not always be representative of the overall state of the building. Likewise, the opposite may also exist where only the original interior is maintained.

An ancillary benefit of the UCDIM is that it creates a permanent historic record. This plays an important role in establishing a reliable means for condition assessment of a building since this record may be revisited, thereby providing the opportunity for assessment by multiple inspectors and at regular time intervals in the future. In the case of litigation, photographic documentation offers solid evidence, upon which disputes may be resolved. Furthermore, Laefer et al.'s (2010) recent study using two inspectors and four historic façades to compare crack detection from terrestrial laser scanning, ground level binocular based inspection, and digital photography versus elevated manual inspections showed vast discrepancies between techniques and inspectors, demonstrating digital photography to be the most accurate and reliable approach.

In order to illustrate the potential cost savings of the UCDIM, a sample calculation is presented for the planned Metro North, an underground railway system approved for this area. According to the Environmental Impact Statement (EIS) produced by the Railway Procurement Agency (RPA, 2008), the state agency responsible for the provision of the project, approximately 500 buildings lie within the potential zone of influence along the initial portion of the route. Assuming a yearly wage of €20k and a 39 hour working week, a sample cost analysis is presented

in Table 13. The UCDIM is shown to cost approximately 12.4% of that required for the CEF System and just 8.7% of the cost required for the detailed inspection. Furthermore, substantial time savings are also noted for the UCDIM, which may be conducted for a dataset of this size in less than two weeks, while both the CEF System and the detailed inspection require several months for completion. In the case of risk assessment due to adjacent works, there exists a requirement for condition assessments to be conducted in a short time frame so as to minimize disparities between buildings based on temporal or environmental conditions.

Table 13. Sample cost analysis

6. CONCLUSIONS AND FUTURE WORK

This study examined six historic buildings in an architectural conservation area of Dublin's city centre according to three surveying methods: a rapid method known as the UCDIM for which index images have been provided herein, another rapid method known as the CEF System, and a full detailed inspection. Three inspectors of varying experience applied the two rapid methods to the six individual buildings. Results were compared to each other and were benchmarked against the detailed inspection which was conducted by the team of three inspectors collectively for each building. The UCDIM results appear to be most accurate, except in the case of painted façades. Furthermore, the UCDIM was roughly 70 times more efficient than the CEF System and significantly more efficient than the detailed inspection. This can be attributed mainly to the fact that interior building access is not required for the UCDIM. Gaining access to buildings has been shown to be extremely difficult for this region due to the high prevalence of rented properties and lack of communication between tenants and landlords. Furthermore, in the

case of high security buildings such as jewellery shops and banks, interior access is especially problematic. Overall, the UCDIM appears to be most advantageous when rapidly assessing large numbers of structures, as is needed for urban planning, historic designation, and risk assessment for upcoming infrastructure projects.

The three methods applied in this study focused solely on the physical attributes of a building. However, in the case of national inventories for historic designation or urban planning, all buildings are not viewed equally in terms of cultural importance and community valuation. Existing damage in a building highly regarded by its community is generally perceived more seriously than damage incurred in a building of little or no cultural worth. In the past, this idea has not commonly been incorporated into risk analyses or national inventories. The incorporation of a system that accounts for varying levels of architectural significance reflecting the cultural value regarded by the community for a building would provide more accurate risk analyses applicable for historical designation, as well as planning efforts in the case of adjacent construction works. Such efforts are currently being undertaken by the authors.

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Figure 1. Protruding or loose brickwork index images (to be used in conjunction with Table 3)

Figure 2. Replaced or repaired brickwork index images (to be used in conjunction with Table 4)

Figure 3. Damage due to exposure index images (to be used in conjunction with Table 5)

Figure 4. Selected buildings

Figure 5. Type 1 (Building E) - interior views

Figure 6. Type 2 (Building F) - interior views

Figure 7. Survey results for the CEF System

Figure 8. Survey results for the UCDIM

Figure 9. Damage ranking according to Inspector I

Figure 10. Average time required for each method

Table 1. CEF System (The Handley Partnership, North Yorkshire, UK)

Table 2. Cracking (after Burland et al., 1977)

Table 3. Protruding or loose brickwork (after Laefer et al., 2008)

Table 4. Replaced or repaired brickwork (after Laefer et al., 2008)

Table 5. Exposure-based damage (after Laefer et al., 2008)

Table 6. Plant growth (after Laefer et al., 2008)

Table 7. Weighting system (after Laefer et al., 2008)

Table 8. Inspector experience

Table 9. Building details

a) **Risk category 0** b) **Risk category 1** c) **Risk category 2**

d) **Risk category 3** e) **Risk category 4** f) **Risk category 5**
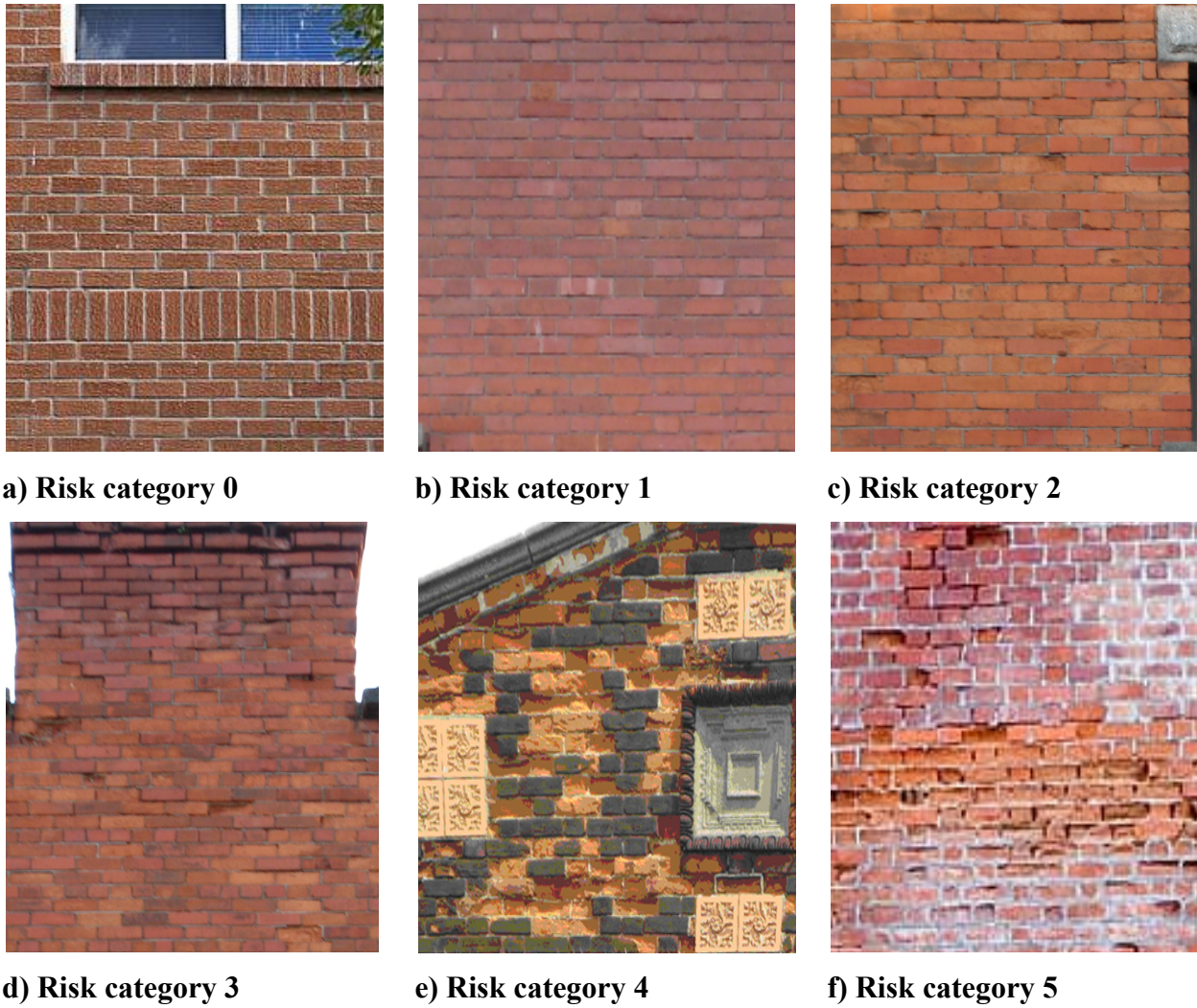
Figure 1. Protruding or loose brickwork index images (to be used in conjunction with Table 3)

a) Risk category 0   b) Risk category 1   c) Risk category 2

d) Risk category 3   e) Risk category 4   f) Risk category 5

Figure 2. Replaced or repaired brickwork index images (to be used in conjunction with Table 4)

a) Risk category 0 **b) Risk category 1** **c) Risk category 2**
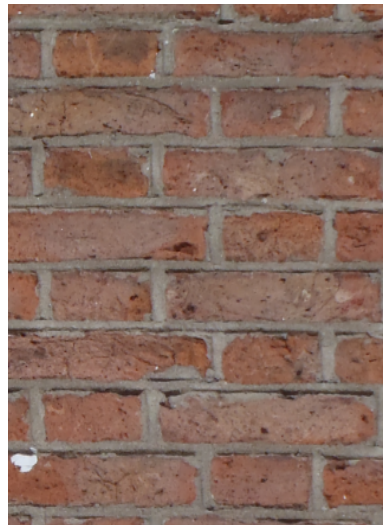
d) Risk category 3   **e) Risk category 4**   **f) Risk category 5**

Figure 3. Damage due to exposure index images (to be used in conjunction with Table 5)
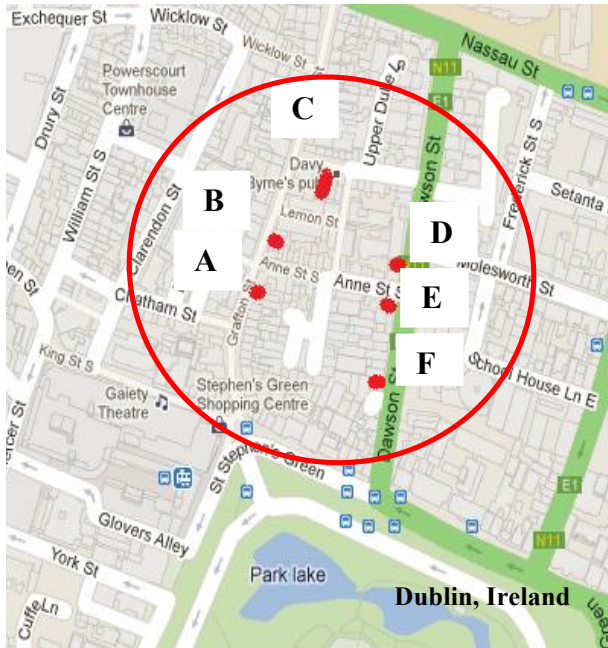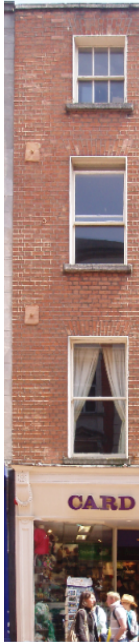
A) 31 Grafton Street   Building Locations   B) 35 Grafton Street

C) 21 Duke Street   D) 47 Dawson Street   E) 44 Dawson Street   F) 34 Dawson Street

Figure 4. Selected buildings

a) Ground floor – retail unit
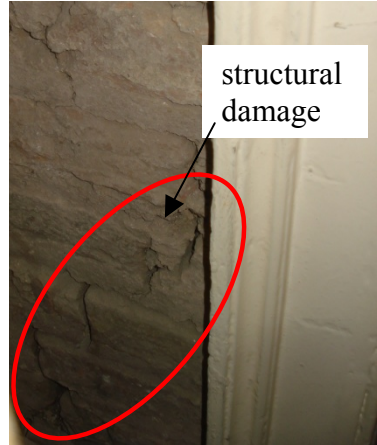
b) First floor – stockroom
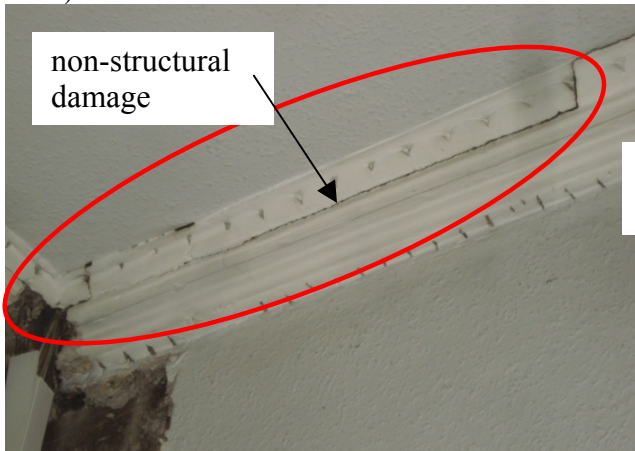
c) Second floor – stock room
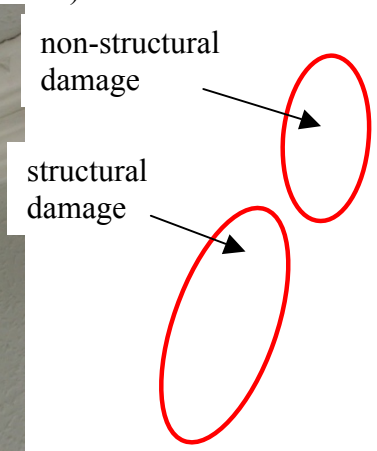
d) Second floor – stockroom

Figure 5. Type 1 (Building E) - interior views

a) Ground floor – retail unit
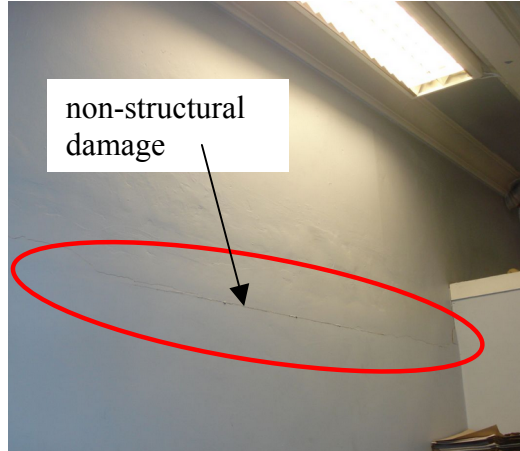
b) First floor – office
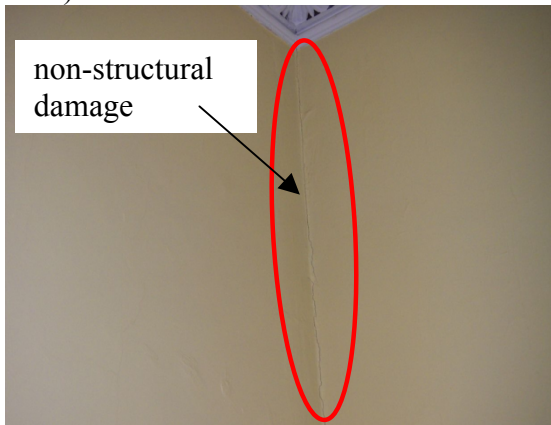
c) Second floor – office
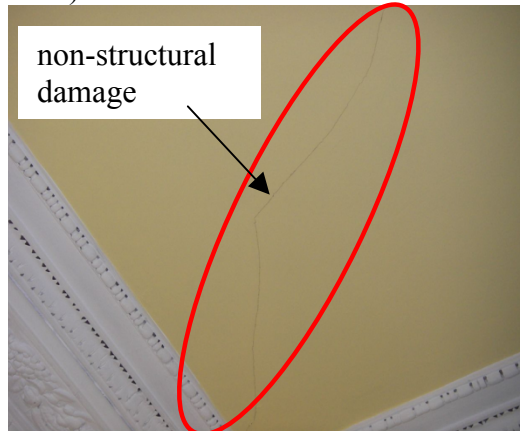
d) Second floor – office

Figure 6. Type 2 (Building F) - interior views
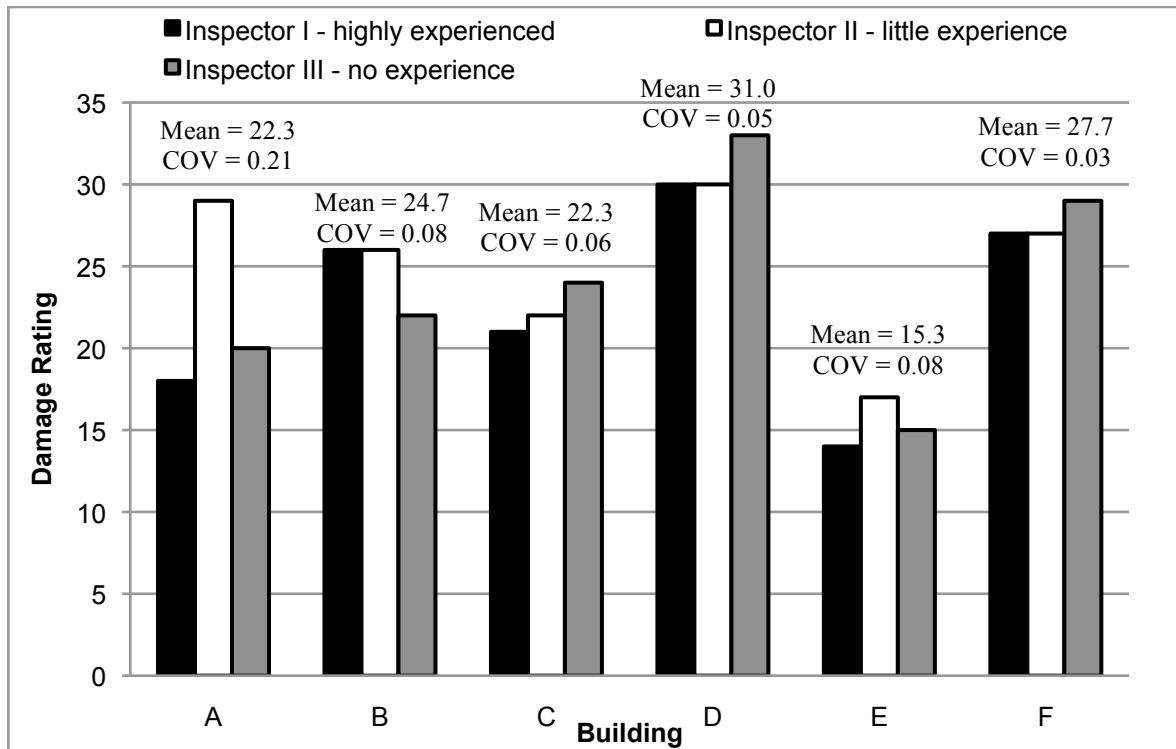
Figure 7. Survey results for the CEF System
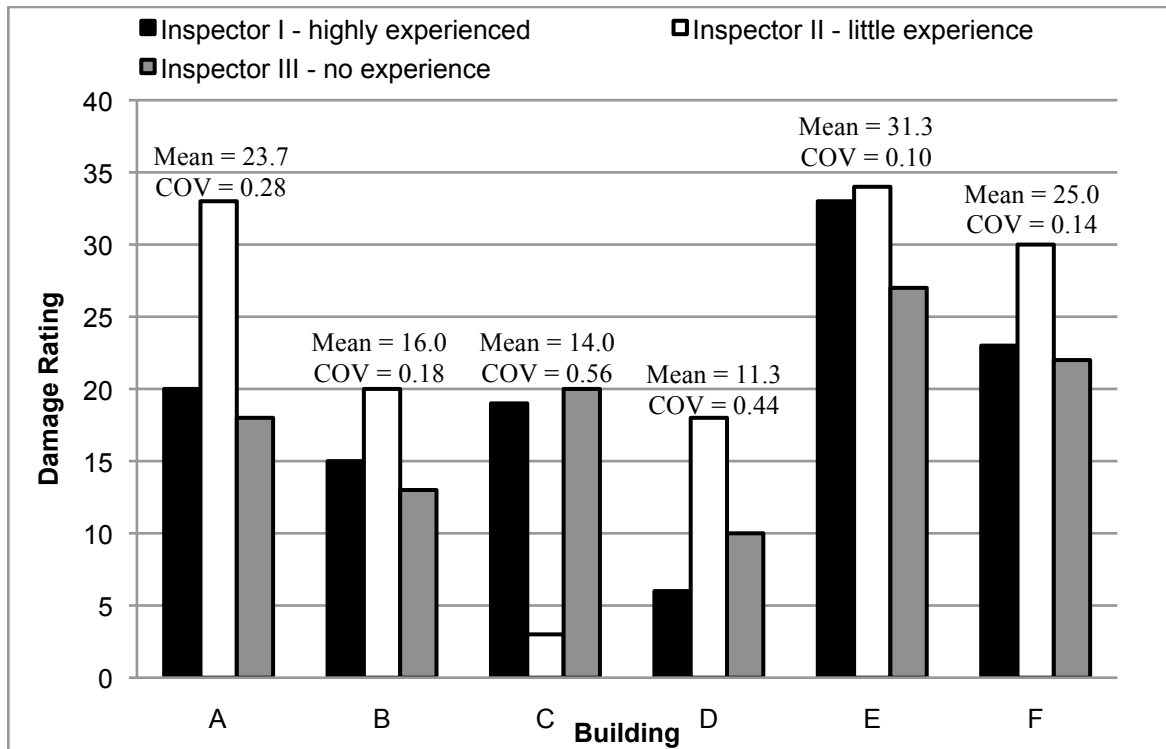
Figure 8. Survey results for the UCDIM

	Detailed Inspection					
	D	B	A	F	C	E
CEF System						
	D	F	B	C	A	E
UCDIM						
	D	B	C	A	F	E
Damage Ranking	1 (Least damaged)	2	3	4	5	6 (Most damaged)

Figure 9. Damage ranking according to Inspector I
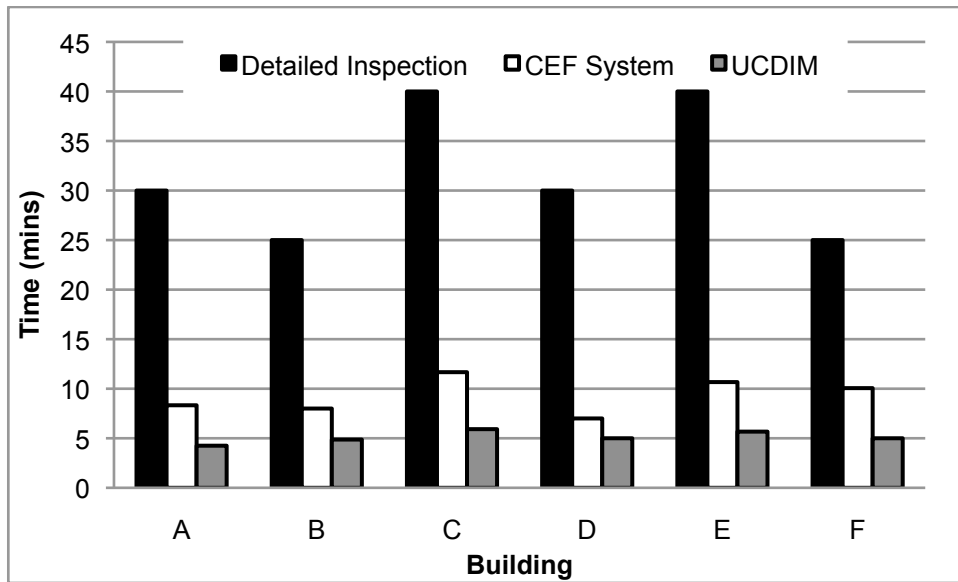
Figure 10. Average time required for each method

Table 1. CEF System (after The Handley Partnership, North Yorkshire, UK)

Condition	(1) Very Bad			(2) Poor			(3) Fair			(4) Good		
Occupancy	V	PO	FO	V	PO	FO	V	PO	FO	V	PO	FO
Risk Score	1	2	3	3	3	4	4	4	5	5	6	6

V = Vacant; PO = Partial Occupancy; FO = Full Occupancy

Table 2. Cracking (after Burland et al., 1977)

Risk Category	Degree of Damage	Approximate Crack Width (mm)
0	Negligible	Hairline cracks
1	Very Slight	0.1-1
2	Slight	1-5
3	Moderate	5-15 or a number of cracks greater than 3
4	Severe	15-25 but also depends on number of cracks
5	Very Severe	Greater than 25 but depends on number of cracks

Table 3. Protruding or loose brickwork (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	All bricks in the same plane
1	Very slight	A few bricks (1-3) are noticeably out of plane / Mortar appears to be loose/weak/missing around 1-3 bricks
2	Slight	Overall, more than 5 bricks appear to be slightly out of plane/ Gaps in mortar are more noticeable/ Just perceptible difference in line of brick
3	Moderate	Overall up to 10% of bricks are noticeably out of plane Noticeable slope in masonry Windows, lintels, doorframes etc. are noticeably tilted
4	Severe	Overall, up to 15% of bricks are missing entirely Noticeably outward bulge in the wall Window lintels and doorframes are at an angle greater than 15 degrees
5	Very severe	More than 15% of bricks are missing entirely Sections of the wall are on the verge of collapse Repair work would require majority of wall to be rebuilt

Table 4. Replaced or repaired brickwork (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	Brickwork was replaced as a result of filling a doorway or window.
2	Slight	Replacement occurred in rarely occurring small clusters (i.e. 2-6) of bricks
3	Moderate	Replacement occurred in larger clusters (greater than 6)
4	Severe	More than 10% of the wall is comprised of replaced brickwork
5	Very severe	More than 25% of the wall is comprised of replaced brickwork

Table 5. Exposure-based damage (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	Isolated, rarely occurring chipping (i.e. 1-3 bricks)/ Lower perceptible damage of overall wall.
2	Slight	Perceptible overall damage (weathering) of bricks in wall.
3	Moderate	Numerous examples of significant damage i.e. greater than 5%
4	Severe	Noticeable damage to greater than 15% of bricks in wall
5	Very severe	Greater than 25% of bricks are subjected to heavy chipping / spalling. Bricks are heavily eroded due to exposure

Table 6. Plant growth (after Laefer et al., 2008)

Risk Category	Degree of Damage	Description of Existing Damage
0	Negligible	None
1	Very slight	One or two examples of weeds growing in typical places (i.e. top of chimney, ledge etc)
2	Slight	Weeds are more numerous, as well as being more overgrown
3	Moderate	Whole wall ensconced with vegetation
4	Severe	Minor bush/tree growing out of masonry
5	Very severe	Major (fully grown) tree growing out of masonry

Table 7. Weighting system (after Laefer et al., 2008)

Scale Used	Modifier / Weight Used
Cracking (Table 1)	4
Protruding or loose brickwork (Table 2)	3
Replaced or repaired brickwork (Table 3)	3
Exposure-based damage (Table 4)	2
Plant growth (Table 5)	1

Table 8. Inspector experience

Inspector	Experience Level	Number of Buildings Previously Examined
I	Extensive	≈ 500
II	Minimal	< 20
III	None	0

Table 9. Building details

Building	Address	Number of Stories	Approx. Dimensions (m)			Year of Construction	Building Usage
			Length	Width	Height		
A	31 Grafton Street	4+basement	15	4	14	Unknown	Retail/ Commercial
B	35 Grafton Street	4+basement	9	4	13	Unknown	Retail/ Commercial
C	21 Duke Street	2+basement	14	5	12	1939	Pub
D	47 Dawson Street	4+basement	10	5	16	1825	Commercial
E	44 Dawson Street	4+basement	15	8	14	1820	Retail/ Commercial
F	34 Dawson Street	2+basement	20	5	14	1870	Commercial

Table 10. Findings of the detailed inspection
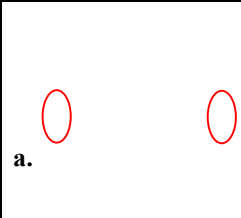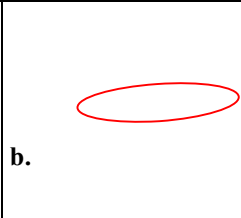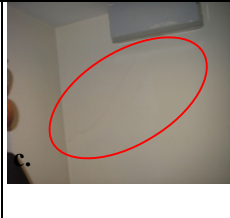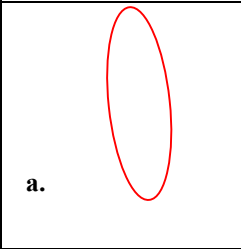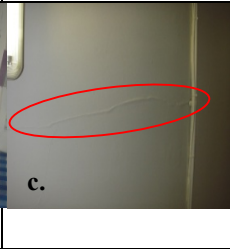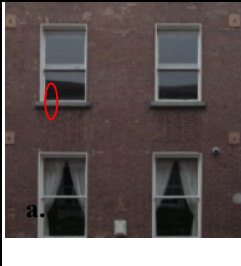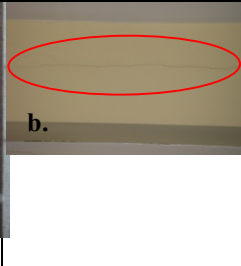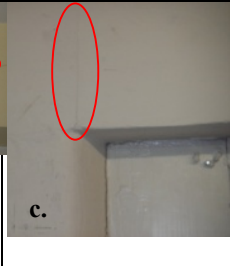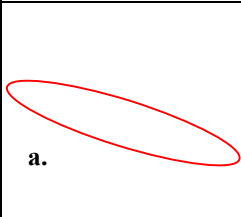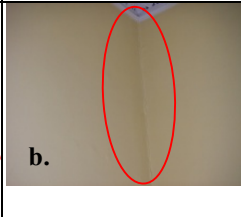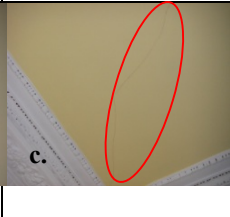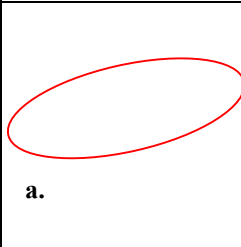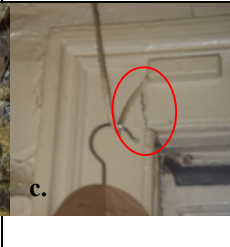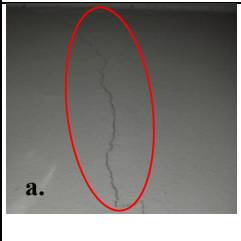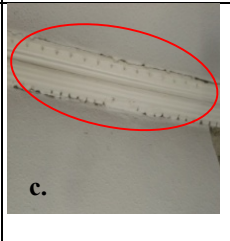
Relative Damage Rating	Main Defects Noted			
1 (Least Damaged) Building D	a.	b.	c.	a. Cracking through window sill of external façade. b. Hairline cracking in façade. c. Cracking through plasterwork of walls at ground floor level.
2 Building B	a.	b.	c.	a. Cracking ~1mm through plasterwork of ceiling at basement level. b. Missing window sills on interior at first floor level. c. <1mm cracking through plasterwork of walls and ceiling at third floor level.
3 Building A	a.	b.	c.	a. Vertical crack in window sill of external façade. b. ≈1mm cracking through plasterwork along walls of second floor level. c. Cracking above upper corners of window and door openings at third floor level.
4 Building F	a.	b.	c.	a. <1mm cracking through plasterwork of walls at ground floor level. b. <1mm cracking through plasterwork of walls at 1st floor level. c. <1mm cracking through plasterwork of ceiling at 1st floor level.
5 Building C	a.	b.	c.	a. Cracking >2mm adjacent to window openings and in chimney.*(Structural damage)* b. Reinforcement visible at underside of ground floor slab.*(Structural damage)* c. Cracking >2mm in ceiling and in corners of window frame.
6 (Most Damaged) Building E	a.	b.	c.	a. Cracking >4mm surrounding openings.*(Structural damage)* b. Cracking of façade.*(Structural damage)* c. Cracking of coving on interior.

Table 11. Spearman's Rank-Order Correlation Coefficient

Detailed Inspection	Building	CEF System Inspector			UCDIM Inspector		
		I	II	III	I	II	III
1	D	1	1	1	1	1	1
2	B	3	3	4	3	6	3
3	A	5	5	5	2	3	2
4	F	2	2	2	4	2	4
5	C	4	4	3	5	4	5
6	E	6	6	6	6	5	6
ρ		0.7143	0.7143	0.5429	0.9429	0.3714	0.9429

Table 12. Efficiency

Method	Inspector	Time (T)	1 - T	Access Requirement Constant (ARC) Yes = 0.02, No = 1	ρ	Efficiency
Detailed Inspection	N/A	1	0	0.02	1	0
UCDIM	I	0.216	0.784	1	0.9429	0.739
	II	0.213	0.787		0.3714	0.292
	III	0.227	0.773		0.9429	0.729
CEF System	I	0.369	0.631	0.02	0.7143	0.009
	II	0.326	0.674		0.7132	0.010
	III	0.353	0.647		0.5429	0.007

Table 13. Sample cost analysis

Method	Time per building (mins)	No. of buildings	Total time (hrs)	Wage per hour (€/h)	Cost (€)
Detailed Inspection	80.0	500	666.67	10.68	7120.04
CEF System	56.5		470.83		5028.46
UCDIM	7.0		58.30		622.64