Building envelope inspection management using a hybrid statistical random sampling and Bayesian updating approach

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Abstract

Condition assessment and inspection planning are crucial for preserving existing buildings, especially those with historical values. Building envelopes are especially vulnerable to damage; and their inspection is an important part of the overall building condition assessment. However, often the existence and extent of damage to envelopes may not be visible in a visual inspection. This will lead to uncertainties in condition assessment and building envelope inspection process and management.

In this work, a new hybrid method for building envelope inspection is introduced that employs statistical random sampling and Bayesian updating to provide a better process for planning for the inspection process. The method is specifically for façades made up of masonry stones, bricks or terra-cotta blocks. For these façade elements, common modes of damage include (1) deterioration of their supporting links to the structure; (2) mortar washout; and (3) construction errors or substandard installation practices. Since the type and extent of damage are not often visible using visual inspections, it is necessary to remove blocks for further evaluation of the hidden areas. The process of opening façade for inspection is costly and involves uncertainty; since an inspector is not sure how many openings will need to be selected and at what locations. A statistical sampling method may be used to better manage the façade inspection process by suggesting the number and locations for the openings. In a prior publication, the authors used this method in a limited application for terra-cotta blocks only. In this paper, the method is extended to other types of façades and also in selecting the locations where there is a higher probability of hidden damage.

In this method: (1) a probability distribution for the proportion of damaged blocks is assumed; (2) a limited number of blocks is then randomly selected for removal to determine their damage condition (3) based on the results of this initial investigation, a Bayesian approach is used for updating information on the proportion of damage blocks and modifying the damage probability distribution, (4) a damage index is then introduced with consideration for the probability of proportion of damaged blocks and the probability that damage areas are within specific areas on the façade; and (5) this index is then adjusted based on the spatial probability of damage in different areas on the façade. The index is used as a decision-making tool in planning for façade inspection and condition assessment. The applicability of this approach in building envelope health condition assessment and planning for future inspections is also presented.

Keywords: Inspection Planning, Sampling, Bayesian Updating, Building Envelope

1 Introduction

Structural condition assessment for building envelopes is considered an important part of the structures overall health monitoring. This is especially important for buildings with historical values that require preservations. Depending on their types, building envelopes perform a variety of functions each requiring a different kind of design expertise (see Fig. 1). The types of damage experienced by building envelopes are unique; and as such, the condition assessment of envelopes requires special attention and procedures that are suitable to address their damage potentials. In US, various municipalities have specific rules on how the inspection must be conducted and prescribe a minimum percentage of area coverage that would suffice an adequate level of inspection. As reported in Mohammadi and Modares [1], these requirements are broad; and most often only provide guidance in general with some additional information regarding the level and extent of examination that is needed. Depending on the rules governed by a municipality, the inspection may only be cursory (using afar examination) or rigorous that may involve close examination with or without additional testing by a licensed structural engineer or architect. Since the requirements on inspection are varied across municipalities, there are not very many well-published studies that have covered the subject including the coverage on (1) the long-term effectiveness and shortcomings of the visual inspection on condition assessment; and (2) suggested procedures for optimizing the process especially when the visual inspection must accompany additional tests or localized detailed examination of target

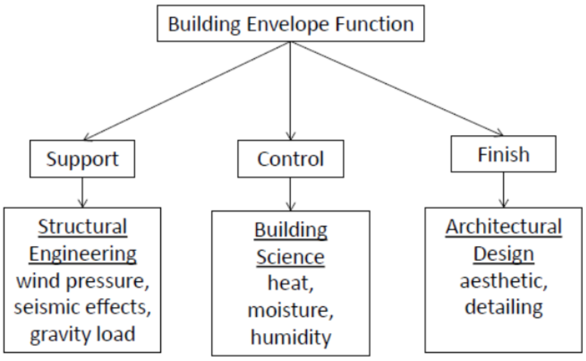

Figure 1: Building envelope functions

areas on a façade. Among limited available literature on the subject, specific details on the evolution of building envelop inspections in the City of Chicago are covered by Kurzydlo and Campisi [2] and Chin and Gerberding [3]. It is noted that Chicago is considered the first municipality in the United States mandating inspection requirements for buildings to safeguard the public from hazard of building envelope damage and deterioration. Thomasen and Searls [4] comment on the final estimation of a façade health condition and indicate a combination of several activities such as observations, test results, and analyses of the system and the materials as the basic components of the process.

In case of façades made up of masonry stone, bricks and terra-cotta blocks, in addition to visual inspections, depending on the overall health condition of the system, the detailed investigation will require removing blocks and examining hidden areas. This is because there are damage scenarios that are hidden and not easily visible during visual inspections. Buildings with historical values in most part possess envelopes made up of those façade elements. As such, some may involve hidden damage areas that are simply because of old construction practices. However, the process of opening a façade for inspection is costly and involves uncertainty. This is because there are many causes for damage; and damage occurs at random at different locations on the façade. An inspector does not often have the exact knowledge of how many openings will need to be selected, and at what locations, to have a reasonable coverage of damage areas and to make certain a good idea on the extent of damage to the façade has been obtained. Terra-cotta blocks are especially critical in façade condition assessment. This is because: (1) they have architectural values used in façades mainly in early twentieth century; and (2) they are not being widely used in today's practice, and thus any repairs must utilize old terra-cottas already in place or custom-made new ones through a few manufacturers that are still in operation. Mohammadi and Modares [1] provide an overview of terra-cotta façade elements and their compositions and installation practice.

An efficient inspection process requires an adequate number of openings that can be made to provide a reasonable estimate of the overall condition of the façade with minimum cost. Specific to terra-cotta blocks and the mode of failure associated with corrosion in metal anchors that are used to attach blocks to the structural system, Mohammadi and Modares [1] demonstrated that a random sampling method along with a Bayesian updating approach may be employed for decision making in regard to the selection of openings for inspections. The specific parameter used for updating is the proportion of damaged blocks within a façade. The process arrives at probability levels for this parameter, which is then updated as new inspection results are obtained. They also introduced a damage index based on these probability levels, which can be used as a decision-making tool in determining the state of the health of the façade and planning for further evaluation of the condition of blocks.

Using the model introduced by Mohammadi and Modares [1] as a basis, this paper extends the model to (1) other types of façades such as masonry stone and bricks, (2) applications where specific areas within the façade will need to be prioritized for inspection because of a higher probability of hidden damage; and (3) modify the damage index and adjust it for areas with higher probability of hidden damage within a façade.

2 Overview

Along with development of the general method of building envelope inspection, this paper provides an overview of façade hidden damage types and their causes, the application of the aforementioned statistical sampling methods and model formulations, and illustrative examples to demonstrate the applicability of the model.

3 Decision Making and Planning for Inspection

In current practice, when detailed investigation of the condition of façade blocks is required, the location and number of openings on the façade is decided by the engineer or architect of the record primarily based on (1) his/her experience; (2) urgency for inspection and target timetable; and (3) budget. There are no specific rules on what percentage of façade blocks must be removed to have a sufficient sample size and to establish confidence on the overall condition of the façade. Unless there are some indications for damage-prone blocks, the location of the openings is selected at random, because of the uncertainty involved in the damage locations. There is even more uncertainty in regard to how many openings must be selected. In the simplest form, the planning includes using a prescribed percentage value for the number of openings. However, it is not uncommon to notice that none of the openings selected indicate any damage. And in this situation, it is not clear on how to proceed with the final conclusion on the condition of the façade. Is it fair to indicate that the entire façade has no damage? Obviously one cannot state this with much confidence, especially if the façade is part of an aging structure using older construction methods and materials. At the same time, one cannot conclude that there is still damage within the system, since the samples collected do not support this notion. These uncertainties may end up with erroneous decision-making, which will result in the loss of effort and resources.

4 Previous Work

To better manage the process of selecting the number of openings, Mohammadi and Modares [1] suggest using a statistical sampling method and the Bayesian updating approach. This model is exclusively used for damage due to corrosion of metal anchors in terra-cotta blocks. They use the proportion of the number of damaged blocks (p) as a random variable, which also represents the parameter in the binomial distribution model (Khisty, Mohammadi and Amedkudzi [5]). This can be used to estimate the probability of damage among blocks. In principle, the main trust of the method is to use the outcome of the investigation on a limited number of blocks as the "prior probability" values in the Bayesian process to update the results and arrive at "posterior probability" values for the variable p. The initial probability values for p can be obtained based on experts opinion," is outlined below.

1. Start with an initial probability distribution for the parameter p (prior probability).
2. Select a limited number of openings at random for inspection.
3. Use the Bayesian method and obtain posterior probabilities for p.

The authors further introduce the idea of using a "damage index" as a means to utilize the results of the analysis for decision-making and planning for the follow-up steps in the process.

General formulation of Bayesian updating applied to façade inspection

The formulation of the Bayesian approach in information updating is governed by the following equation (see for example Ang and Tang [6]).

$$P''(p = p_i) = \frac{P(\varepsilon \mid p = p_i)P'(p = p_i)}{\sum_i^n P(\varepsilon \mid p = p_i)P'(p = p_i)} \tag{1}$$

where:
$(p = p_i)$ is the event that the proportion of damaged blocks is a value equal to p_i .
P' = existing information on the proportion of damaged blocks (prior probability). The parameter P' represents the probability that the proportion of damaged blocks is equal to p_i (i.e., the probability that $p = p_i$) based on the available information.
ε = new information on the number of damaged blocks discovered when detailed investigations using openings in the façade are made.
P'' = updated information on the proportion of damaged blocks (posterior probability). It is noted that P'' represents the probability that the proportion of damaged blocks is equal to p_i (i.e., the probability that $p = p_i$) based on new information just acquired. The prior probability values (P') can be prescribed using the inspector's notion and past experience. In case no prior information on P' is known, an arbitrary distribution model may be used. This work suggests using a uniform or triangular distribution. The new data (ε) is described by the number of damaged blocks identified during detailed investigations.

The conditional probability $P(\varepsilon \mid p = p_i)$ describes the outcome to be ε, if the proportion of damaged metal anchors is p_i . With a binomial distribution function, the term $P(\varepsilon \mid p = p_i)$ can be written as:

$$P(\varepsilon \mid p = p_i) = \frac{k!}{q!\,(k-q)!}(p_i)^q(1-p_i)^{k-q} \tag{2}$$

in which q is the number of damaged blocks in a total of k openings.

It is noted that using the updated probabilities described by Eqs. (1) and (2), the estimate of the mean for the proportion of damaged blocks ($\hat{p}''$), based on the posterior probabilities, can be obtained as:

$$\hat{p}'' = \sum_{i=1}^{n} p_i P''(p = p_i) \tag{3}$$

this value is used as a damage index for decision making on the health condition of the façade as described below:

1. For cases where $\hat{p}'' < 0.05$, the façade is considered to be in good condition. This means that on the average, less than 5% of blocks are damaged.

2. For cases where $0.05 < \hat{p}'' < 0.20$, it is recommended that detailed investigations by implementing more openings be considered; and based on the outcome, $\hat{p}''$ be recomputed for decision making.

3. Finally in cases where $\hat{p}'' > 0.20$, still additional openings are recommended. However, it is indicated that if the new outcome still indicates a large value for the damage index ($\hat{p}''$), major repair may be necessary.

It is further noted that $\hat{p}''$ can also be used to determine how many openings are needed for planning purposes, since the expected number of damaged blocks is equal to the total number of blocks on the façade multiplied by $\hat{p}''$.

5 Methodology

In this paper, the model developed by Mohammadi and Modares [1] is further expanded and applied to other types of façades made up of masonry stone and bricks. Although the mathematics of the updating model is still the same as that used for terra-cotta blocks, there are some differences that need to be considered in the final outcome of the model and the decision making process. These differences primarily stem from the type of damage that would lead to additional information in regard to the location and areas where conceivably there is a higher probability that damaged blocks are found. And as such, the estimate obtained for the proportion of damaged blocks will not be the same on the entire façade and will be subject to a spatial probability distribution. It is emphasized the model introduced by the authors in their prior publication assumes the distribution and estimates for p do no vary from one area on the façade to another.

Masonry stone – For masonry stone blocks, the damage scenarios are very similar to the ones mentioned for terra-cotta blocks. The most critical mode of damage is the corrosion of the metal anchors and deterioration of the spot where the anchor is attached to the stone. The latter causes a loose connection, which is often not visible in a visual inspection unless the damage is widespread on the façade. The method presented for planning and inspection process and the determination of the proportion of damaged blocks are expected to be very similar to the case of terra-cotta blocks.

Bricks – Specific to brick masonry, because of its composition, the way blocks are laid and the type of anchors they used, there may be changes in the appearance or deformations that may indicate a higher probability of damage in some areas on the façade. For example, a persistent prevalence of moisture may appear as efflorescence deposits on brick. Ineffective anchors (because of deterioration and damage) may result in a portion of façade bulging out (see Fig. 2). Although a bulge may not necessarily be resulted from damaged anchors, it can still be considered a “hot spot” on the façade that needs more attention. This indicates that perhaps bricks in the bulged area have a higher probability of anchor damage compared with those located elsewhere on the wall.

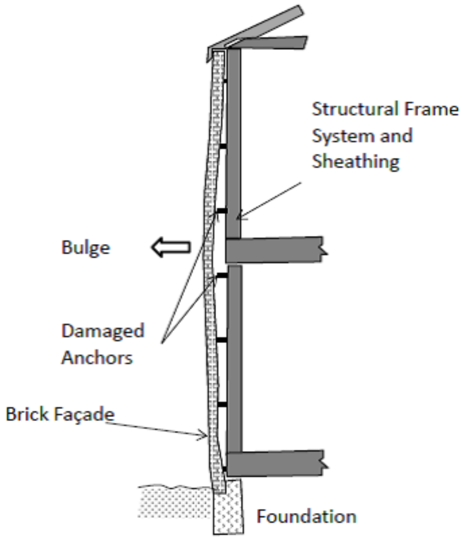

Figure 2: Damaged metal anchor causing brick wall to bulge out

6 Significance of Spatial Distribution of Probability of Damage on the Façade

As indicated earlier, specific to brick façades, there may be changes in the appearance of the blocks that may indicate certain areas have a higher probability of damaged bricks than other areas. In a preliminary investigation, the inspection report may note these areas and provide a spatial distribution as a judgmental call on the relative values of the probability of damage. For example, the appearance of a bulge (as shown in Fig. 2) may indicate that the bulge area has a higher probability of possessing damaged blocks. Of course establishing a relative probability for damage for the bulge area depends on the inspector's notion and intuitive judgment. For example, as shown in Fig. 3 a middle area on the façade (marked as A_0) has certain signs of damage; and as such in the opinion of the inspector there is a higher probability that the area contains more damaged blocks.

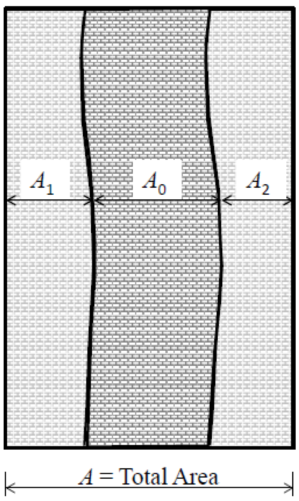

Figure 3: An example of spatial distribution of damage areas on a façade (the darker area represents a higher probability for damaged blocks)

The inspector may provide his/her own notion (or seek expert opinion) on a relative value for the probability of damaged blocks in areas A_1 and A_2 compared to that in area A_0. Denoting the mean values for the proportion of damaged blocks as $\hat{p}_0$, $\hat{p}_1$ and $\hat{p}_2$, respectively, for the three areas A_0, A_1 and A_2, we can write the following equations.

$$A_0 \cdot \hat{p}_0 + A_1 \cdot \hat{p}_1 + A_2 \cdot \hat{p}_2 = A \cdot \hat{p}'' \tag{4}$$

$$\hat{p}_1 = a_1 \cdot \hat{p}_0 \tag{5}$$

$$\hat{p}_2 = a_2 \cdot \hat{p}_0 \tag{6}$$

In which $\hat{p}''$ is the mean value for the proportion of damaged blocks obtained for the entire façade (the value from Eq (3)) and a_1 and a_2 are smaller than 1 and represent, respectively, the relative probability of damaged blocks in the areas A_1 and A_2 compared to that in area A_0. Solving Eqs. (4)-(6), the value for the mean value for the proportion of damaged blocks ($\hat{p}_0$) in area A_0 is now adjusted and is estimated as:

$$\hat{p}_0 = \frac{\hat{p}'' \cdot A}{A_0 + a_1 A_1 + a_2 A_2} \tag{7}$$

In deriving Eq. (7), only three areas are considered with one having a higher probability for damaged blocks compared with the other two. In a more general form, assume some $(m+1)$ areas $A_0, A_1, A_2, \ldots, A_m$ are identified in which the probability of damaged blocks in the area A_0 is the highest among all areas. Furthermore, it is determined that the ratio of the probability of damaged blocks in an areas such as A_i (where $i = 1, 2, \ldots, m$) to that in area A_0 is a_i. Then the proportion of damaged blocks in in the area A_0 can be written in terms of $\hat{p}''$ in the following form:

$$\hat{p}_0 = \frac{\hat{p}'' \cdot A}{A_0 + \sum_{i=1}^{m} a_i A_i} \tag{8}$$

and

$$\hat{p}_i = a_i \cdot \hat{p}_0 \quad (\text{for } i = 1, 2, \ldots, m) \tag{9}$$

It is further noted that in incorporating the spatial probability distribution for the probability of damage, the areas A_i (in the special case of Fig. 3 $i = 0, 1$ and 2) were treated as deterministic values. In a more advanced formulation, these can be treated each as a random variable such that the significance of uncertainties in them can be considered in the formulation.

7 Numerical Illustrations

In a façade inspection, and as initial step, a uniform probability function (prior probabilities) for the proportion of damaged blocks (p) on the façade is used. With 11 possible values for p (i.e., $p_i = 0., 0.1, 0.2, 0.3, \ldots, 1.0$):

$$P'(p = p_i) = \frac{1}{11} = 0.091 \tag{10}$$

for $(i = 0, 1, 2, 3, \ldots, 10)$

The inspector decides to use 10 openings at random distributed over the entire façade (which has a total area $= A$) and removes blocks for investigating whether there are any hidden damage. During these inspections, q blocks (out of a total of 10) indicate they had hidden damage. If $q = 0$ (i.e., no damaged blocks were found), using Eqs. (1) and (2), the values for the posterior probabilities, $P''(p = p_i)$, are computed as summarized in Table 1. Furthermore, using Eq. (3), these values result in a posterior mean value for the proportion of damaged blocks (i.e., $\hat{p}''$) $= 0.045$.

Now assume the inspector observes special conditions on about 50% of the façade, in the middle portion, that indicate there may be a higher probability of damaged blocks. Based on previous experience, the inspector decides that this area has 5 times more possibility to possess damaged blocks. Referring to Fig. 3 thus:

$$A_0 = 0.5A, \text{ and } A_1 = A_2 = 0.25A$$

Table 1: Posterior probabilities when new outcome reveals there are no damaged blocks in 10 openings

p_i	$P''(p = p_i)$
0	0.670
0.1	0.234
0.2	0.072
0.3	0.019
0.4	0.002
0.5	0.001
≥ 0.60	0

Futhermore,

$$a_1 = a_2 = 0.20$$

Using Eq. (7),

$$\hat{p}_0 = 1.67\hat{p}'' = 1.67 \times 0.045 = 0.075$$

and

$$\hat{p}_1 = \hat{p}_2 = 0.33\hat{p}'' = 0.33 \times 0.045 = 0.015.$$

These values indicate that even with opening resulting in no damaged blocks, the middle area has an estimated value for the proportion of damaged blocks that is more than 0.05 and thus needs to be investigated further with more openings.

To further explore other possibilities for the number of damaged blocks in a first batch of 10 openings, Table 2 is developed which shows $\hat{p}''$, $\hat{p}_0$, $\hat{p}_1$ and $\hat{p}_2$ for cases of $q = 0, 1, 2, 3, 4$ and 5. This means upon conducting 10 openings, $1, 2, \ldots$ damaged blocks are found. As noticed from results in Table 2, if one or more damaged blocks in 10 openings are found, the estimated proportion of damaged blocks in the middle area $\hat{p}_0 > 0.2$, which indicates decision in favor of repair.

Table 2: Estimated proportion of damaged blocks in different areas of façade of Fig. 3

q	$\hat{p}''$ (for entire façade)	$\hat{p}_0$ (for area A_0)	$\hat{p}_1$ (for area A_1)	$\hat{p}_2$ (for area A_2)
0	0.045	0.075	0.015	0.015
1	0.182	0.300	0.060	0.060
2	0.251	0.419	0.082	0.082
3	0.333	0.556	0.110	0.110
4	0.417	0.696	0.138	0.138
5	0.500	0.835	0.167	0.167

To further demonstrate the significance of updated results, consider using the case of $q = 0$ again. Assume there are some $3,600$ blocks on the façade, of which about 1,800 are in the middle area A_0 and 900 each at areas A_1 and A_2 (see Fig. 3). If no updating is used, and with the prior probability values suggested by Eq. (10), the estimated mean value for the proportion of damaged blocks ($\hat{p}'$) is 0.5. Using this value, the estimated number of damaged blocks is $0.5 \times 3,600 = 1,800$, which indicates that an approximately the same number of openings would be needed for further investigations. Obviously, this requires a substantial effort involving considerable costs and resources. Upon updating, after the first round of inspections (with $q = 0$ damaged blocks in a total of 10), the estimated mean for damaged block is reduced to $\hat{p}'' = 0.045$. This in turn reduces the number of required openings to $0.045 \times 3,600 = 162$, which is substantially less than the case without the updating. If there is no notion on target areas for higher probability of damage, these 162 openings will need to be selected randomly on the entire façade. However, if there is a notion that the area A_0 has about 5 times higher probability of possessing damaged blocks, compared with those in areas A_1 and A_2, the mean value for the proportion of damaged blocks in area A_0 is adjusted to 0.075 (see Table 2). This requires some $0.075 \times 1,800 = 135$ openings only for area A_0 with the rest of openings $(162 - 135 = 27)$ considered for the other two areas. By using the adjusted value for the proportion of damaged blocks for area A_0, the specific area is targeted that needs more attention by distributing the effort and resources more efficiently.

8 Conclusions

The following presents the main conclusions of the studies presented in this paper.

1. The Bayesian updating introduced in a prior publication by the authors for planning and management of terra-cotta façade inspection can also be extended to façades made up of masonry stone and bricks.

2. Specific to the brick façade application, certain condition of bricks may indicate a higher probability for damage. This notion can be considered for developing a spatial distribution for damage in different areas on the façade.

3. The information on spatial distribution for the probability of damage can be used in adjusting the estimate for the proportion of damaged blocks. The results may be helpful in planning a more refined schedule for further inspections and determination of areas that need to receive more attention when detailed investigations through openings on the façade will be necessary.

References

[1] J. Mohammadi and M. Modares, Application of statistical random sampling and bayesian updating in planning for terra-cotta façade inspection, *Journal of Architectural Engineering* **23**, 04016020 (2017).

[2] A. Kurzydlo and J. S. Campisi, Practical considerations for complying with the city of chicago maintenance of exterior walls and enclosures ordinance, *Practice Periodical on Structural Design and Construction* **14**, 146 (2009).

[3] I. R. Chin and H. Gerberding, Evolution of the development of the chicago facade inspection ordinance, *Building Facade Maintenance, Repair, and Inspection* 9–29 (2004).

[4] S. E. Thomasen and C. L. Searls, *Assessment of building facades in masonry and stone* (ASTM International, West Conshohocken, PA, 1990), 108–116.

[5] C. J. Khisty, J. Mohammadi, and A. Amedkudzi, *Systems engineering with economics, probability, and statistics* (J. Ross Publishing, 2012).

[6] A. H. S. Ang and W. H. Tang, *Probability concepts in engineering planning and design* (Wiley, New York, NY, 2007).

[7] J. L. Erdly and T. A. Schwartz, *Building facade maintenance, repair, and inspection:*, vol. 1444 (ASTM International, 2004).

[8] M. Mehta, W. Scarborough, and D. Armpriest, *Building construction: principles, materials, and systems* (Pearson Prentice Hall, New York, NY, 2008).