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BUILDING ENVELOPE INSPECTION MANAGEMENT USING A HYBRID STATISTICAL RANDOM SAMPLING AND BAYESIAN UPDATING APPROACH

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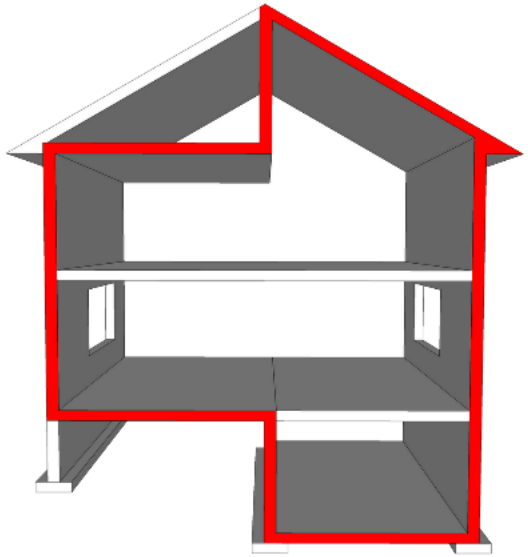
BUILDING ENVELOPE

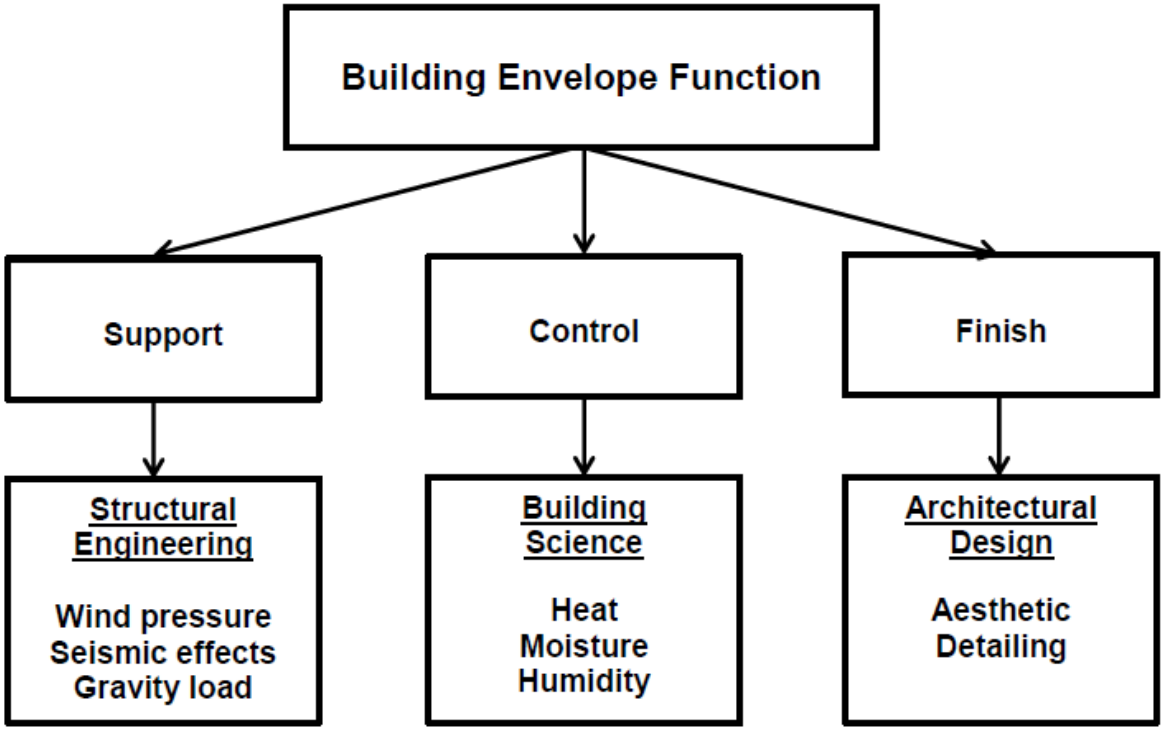
- The building envelope is all of the components of the building outer shell.
- They are designed to isolate indoor environment from outdoor moisture and temperature and facilitate building climate control.



(Photo courtesy of solidsteelbuildings.com)

BUILDING ENVELOPE (Cont.)

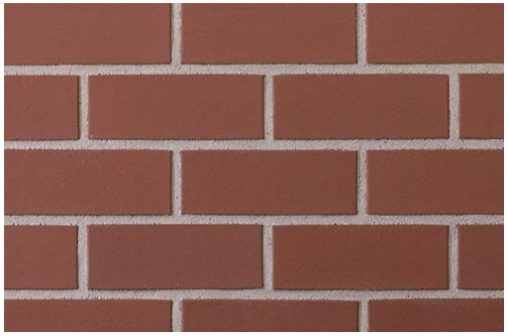
- Building envelopes perform a variety of functions each requiring a different kind of expertise.



BUILDING FAÇADE ENVELOPES

- Building façade envelopes can be made up of masonry stone, bricks and terra-cotta blocks

Masonry Stone



Brick

Terra-Cotta

(Photo courtesy of pxhere.com, beldenbrick.com, and connectingthewindycity.com)

CONDITION ASSESSMENT OF BUILDING ENVELOPES

- Condition assessment and inspection planning are crucial for preserving existing buildings
- This is especially true with buildings with historical values.
- Building envelopes are especially vulnerable to damage because of the outdoor exposure.
- Their inspection is an important part of the overall building condition assessment.

FAÇADE VISUAL INSPECTION

- Condition assessment of building envelopes is primarily performed through visual inspection.
- 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.
- These uncertainties must be addressed with further detailed investigations.

COMMON FAÇADE BLOCK DAMAGE
Undetected by Visual Inspections

Type of Block	Typical Damage Scenario
Masonry stone (e.g. limestone)	Crack in block Deteriorated mortar Damaged anchor Deterioration of block at anchor Damaged lintel
Brick	Deteriorated mortar Damaged shelf angle or lintel Brick damaged
Terra-cotta	Damaged metal anchor Crack in block

FAÇADE DETAILED INVESTIGATION – UNCERTAINTIES

- Detailed investigation of building envelopes require removing blocks and examining hidden areas.
- As damage occurs at random at different locations on the façade, this process is costly and involves uncertainty.
- Because of these uncertainties, a prescribed minimum percentage of area coverage that would suffice an adequate level of inspection is ambiguous.
- As a result, the number and location of openings needed for a reasonable coverage of damage areas and the extent of damage are unknown.

RESEARCH OBJECTIVE

To develop a more efficient and cost-effective methodology for building envelope inspection planning, through decision making on the number of openings, using a hybrid random sampling and Bayesian updating approach.

RESEARCH PROCEDURE

To use the outcome of investigation on a limited number of blocks in a Bayesian process for obtaining the estimation of location and extent of damaged blocks on the façade.

METHODOLOGY

I. Assign initial probability distribution for proportion of number of damaged blocks using expert opinion (prior probabilities)

II. Select a limited number of openings at random for inspection (likelihood)

III. Use the Bayesian method and obtain the updated probability for the proportion of number of damaged blocks (posterior probabilities)

IV. Estimate the number of damaged blocks using the statistics obtained and updated for proportion of damage blocks

V. Adjust the number of damaged blocks based on spatial distribution of areas that are more prone to damage

GENERAL FORMULATION – BAYESIAN UPDATING

$$P''(p = p_i) = \frac{P(\varepsilon \mid p = p_i)P'(p = p_i)}{\sum_{i}^{n} P(\varepsilon \mid p = p_i)P'(p = p_i)}$$

$\boldsymbol{p}$**:** proportion of damaged blocks as a random variable with binomial probability mass function

$\boldsymbol{(p=p_i)}$**:** event that the proportion of damaged blocks is a value equal to p_i

$\boldsymbol{\varepsilon}$**:** new information on the number of damaged blocks discovered in detailed investigations using openings in the façade are made

GENERAL FORMULATION – BAYESIAN UPDATING (Cont.)

$P(\varepsilon \mid p=p_i)$**:** likelihood function defined using the binomial distribution as:

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

q**:** number of damaged blocks
k**:** total number of openings

$P'(p=p_i)$**:** existing initial information on the proportion of damaged blocks (prior probabilities)

$P''(p=p_i)$**:** updated information on proportion of damaged blocks (posterior probabilities)

DAMAGE INDEX

- A damage index is defined as the estimate of the mean for the proportion of damaged blocks, based on the posterior probabilities:

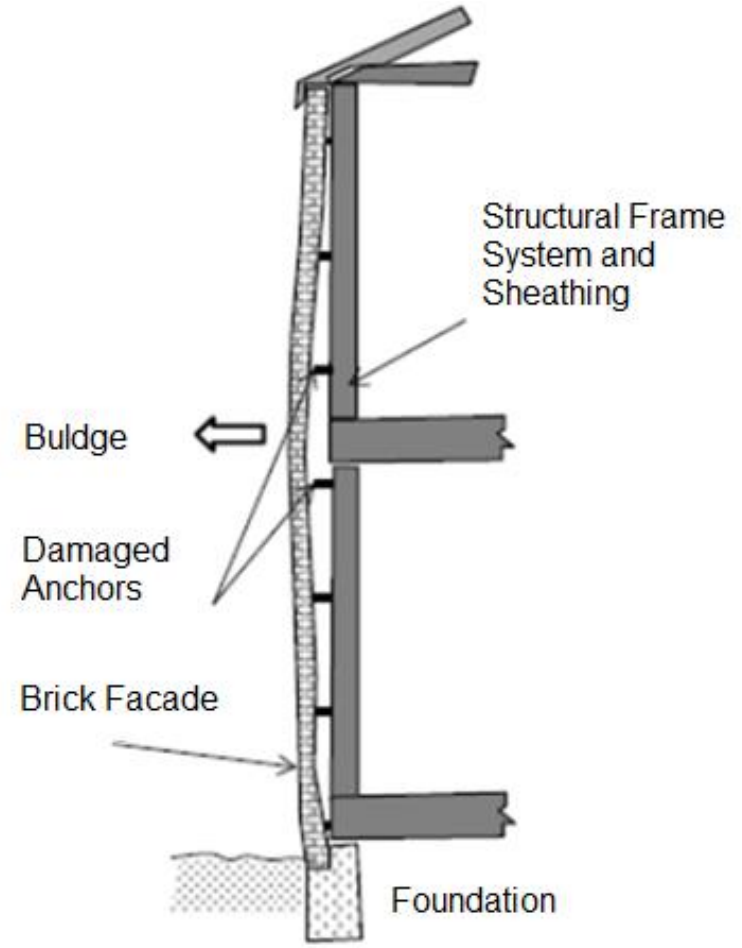
$$\hat{p}'' = \sum_{i=1}^{n} p_i \; P''(p = p_i)$$

- This damage index, based on presumed values, can be used for decision making on the health condition of the façade.

- For planning purposes, the needed number of openings is determined based on the expected number of damaged blocks which is the multiplication of total number of blocks and damage index.

SPATIAL DISTRIBUTION – DAMAGE PROBABILITY

- Specific areas on the façade may be believed to be more prone to damage.
- A spatial distribution for the number of damaged blocks can be established.
- This focuses more attention to damage-prone areas.
- In this figure, a bulge is appeared.
- This indicates a damage-prone area on a brick façade.



SPATIAL DISTRIBUTION – FORMULATION

Consider *(m+1)* areas A_0, A_1, A_2, …, A_m are identified in which the probability of damaged blocks in the area A_0 is the highest among all areas.

The proportion of damaged blocks in the area A_0 is:

$$\hat{p}_0 = \frac{\hat{p}''.A}{A_0 + \sum_{i=1}^{m} \alpha_i A_i}$$

$\boldsymbol{\alpha_i}$**:** ratio of probability of damaged block in the area A_i to that in area A_0

Estimated mean value for the proportion of damage block in area A_i:

$$\hat{p}_i = \alpha_i.\hat{p}_0 \qquad (i=1,\ldots,m)$$

NUMERICAL EXAMPLE

- A brick façade inspection with 3600 blocks
- 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* (p_i = 0., 0.1, 0.2, 0.3, … 1.0):

$$P'(p = p_i)=1/11=0.091$$

(i =0, 1, 2, 3 …, 10)

SOLUTION

No Updating

- Estimated mean value for the proportion of damage blocks: $\hat{p}'$= 0.5
- Estimated number of required openings for only for A_0: 0.5x3,600=1,800
  (Indicates that 1800 openings will be needed for further investigations)

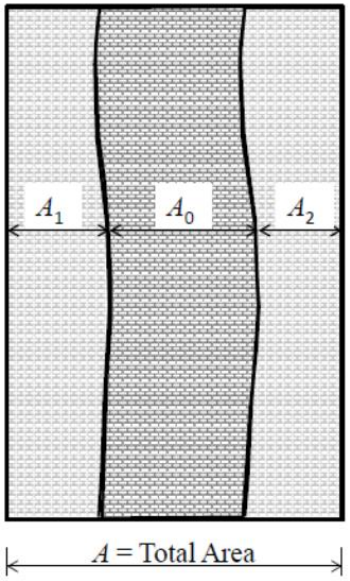
Upon updating

After the first round on inspections (with q=0 damaged blocks in a total of k=10):

- Estimated mean value for damages blocks is reduced $\hat{p}''$= 0.045
- Estimated number of required openings = 0.045x3,600 = 162
  (Substantially less than the case without the updating)

SOLUTION – SPATIAL DISTRIBUTION

Special conditions on about 50% of the façade are observed in the middle portion that indicate a higher probability of damaged block (A_0=0.5 A, and A_1= A_2= 0.25A).



The decision is that this area has 5 times more possibility of damaged blocks. (Mean values less than 0.05 do not trigger any opening)

SOLUTION – SPATIAL DISTRIBUTION (Cont.)

- Mean value for the proportion of damage blocks in area A_0: $\hat{p}_0$ = 0.075
- Estimated number of required openings for only for A_0: 0.075x1,800=135
- With the rest of openings (162-135=27) considered for the other two areas

Observations

- By using the adjusted value for the proportion of damaged blocks for area A_0, the area that needs more attention is specifically targeted.
- This leads to distributing the effort and resources more efficiently.

CONCLUSIONS

- The Bayesian updating can be used for planning and management of building envelope inspection can including facades made up of terra-cotta, masonry stone and bricks.
- 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.
- 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.

QUESTIONS