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SELF-SENSING BUILDING MATERIALS FOR ADVANCED STRUCTURAL HEALTH MONITORING OF MASONRY ARCH BRIDGES: A PROOF-OF-CONCEPT STUDY THROUGH NUMERICAL INVESTIGATIONS

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Abstract. *Masonry arch bridges commonly serve road and rail infrastructure systems. Due to their age of construction, these bridges are often characterized by structural responses influenced by outdated design practices and significant deterioration of building materials. As a result, they require special attention to maintain safe operating conditions within transportation networks. Increasing traffic loads, along with exposure to natural hazards such as earthquakes, ground settlements, and flooding, are key factors contributing to structural failures in masonry arch bridges today. Structural Health Monitoring (SHM) approaches can aid in assessing potential deterioration of the structural integrity of these bridges during operating conditions, allowing for early detection of damage initiation and progression. Maintenance and retrofitting interventions can also be planned based on the insights gained from ongoing SHM activities. Recently, the paradigm of "smart masonry" has been proposed in the literature to advance SHM of masonry structures. It involves using self-sensing building materials to facilitate non-invasive monitoring of structural features for SHM purposes. This paper explores the application of smart masonry to masonry arch bridges through proof-of-concept numerical simulations. In this study, a mechanical model of a masonry arch, discretized using the finite element method, was defined to simulate various loading conditions. Self-sensing building materials are envisioned to be embedded within the arch, with their outputs assessed to detect changes in the structural response. The results from this numerical investigation indicate that implementing smart masonry in masonry arch bridges can significantly improve the monitoring of their structural integrity, paving the way for developing innovative SHM strategies.*

Keywords: Structural health monitoring, Smart masonry, Smart bricks, Strain monitoring, Masonry arch bridges, Numerical simulations.

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1 INTRODUCTION

Masonry arch bridges require special attention to ensure safe operation in transportation networks. This need stems primarily from the fact that these bridges were sometimes built in the absence of Standards or, more often, based on outdated design practices. Additionally, masonry arch bridges commonly exhibit significant degradation of building materials, to the detriment of their structural performance. In this regard, external actions unforeseen in the design stages, such as those induced by increased traffic loads, seismic events, and foundation scour, can lead masonry arch bridges to failure, given their already compromised structural integrity [1, 2]. Structural Health Monitoring (SHM) approaches can help evaluate the possible degradation of the structural integrity of masonry arch bridges under operating conditions. With this information, structural damage and failure mechanisms can be timely detected, as well as maintenance interventions can be planned in a more conscious manner. To date, several SHM strategies have been proposed for monitoring masonry arch bridges [3, 4, 5, 6]. These strategies typically involve the use of contact or non-contact sensors to collect monitoring data. In this paper, the newly introduced paradigm of ”smart masonry” is proposed to develop innovative SHM strategies for monitoring masonry arch bridges, by evaluating features collected from self-sensing building materials embedded within the load-bearing structure. A numerical proof-of-concept study is also reported to explore the feasibility of the proposed approach, starting with a simpler, yet still representative, structural setting, namely, a masonry arch subjected to external forces.

2 SMART MASONRY CONCEPT

Smart masonry is a revolutionary approach for SHM of masonry structures. It is based on the use of innovative self-sensing building materials that enable non-invasive monitoring of structural features, effectively replacing the use of traditional sensing technologies [7, 8]. Specifically, smart masonry combines piezoresistive brick-like sensors for diffuse strain monitoring with electrically conductive mortar layers capable of detecting damage initiation and progression. These multifunctional building materials can be strategically deployed into new structural settings during construction, or implemented into existing load-bearing structures while performing retrofit interventions. In this regard, old bricks can be replaced with self-sensing bricks using expansive mortar to restore the necessary prestress for proper brick function. Similarly, old mortar can be removed and replaced with damage-sensitive mortar layers, possibly evenly spaced from each other to facilitate systematic tracking of crack development. By integrating information from this advanced network of self-sensing building materials, damage mechanisms can be identified effectively and in a timely manner.

2.1 Self-sensing bricks

Self-sensing bricks, also known as smart bricks in the scientific literature [9], are produced by doping clay matrices with optimized amounts of electrically conductive filler to induce a piezoresistive response in the resulting composite material. These inclusions can be either metallic or carbon-based. Once equipped with electrodes, smart bricks allow for electrical measurements. Changes in strain are obtained by smart bricks by processing variations in their electrical resistance through the following electromechanical model:

$$\frac{R - R_0}{R_0} = \frac{\Delta R}{R_0} = a' {\epsilon_y}^{-b} - \lambda \epsilon_y + c' \cong a' {\epsilon_y}^{-b} - \lambda \epsilon_y. \quad (1)$$

Here, R is the electrical resistance of the smart brick when mechanically strained, R_0 represents the unstrained electrical resistance of the brick, a' denotes the relative sensing at the contact interfaces between the smart brick's surfaces and its electrodes, ϵ_y signifies the axial strain (positive in compression), b corresponds to an exponential term related to contact resistance, λ is the gauge factor.

2.2 Self-sensing mortar layers

Self-sensing mortar layers are produced by doping cement mortar matrices with electrically conductive fillers, such as graphene, carbon nanotubes, and carbon microfibers [11]. Selected inclusions are optimized in quantity to increase sensitivity to damage, particularly to cracks forming within the electrode pairs embedded in the composite material. Damage detection is performed under the assumption that a crack is a material discontinuity causing a measurable reduction in the mortar's electrical conductivity. The electromechanical response of the self-sensing mortar follows the principle of isotropic piezoresistivity in the elastic regime, which can be expressed as follows:

$$\frac{R - R_0}{R_0} = \lambda \cdot \text{trace}(\boldsymbol{\epsilon}), \tag{2}$$

where R and R_0 represent the strained and unstrained electrical resistance of the mortar between a pair of electrodes, respectively, λ is the gauge factor, and $\boldsymbol{\epsilon}$ signifies the strain tensor. A degradation parameter, D, is then considered to account for abrupt reductions in mortar's electrical conductance, G, when cracks develop within a pair of electrodes:

$$R = \frac{1}{G(\boldsymbol{\epsilon}, D)}. \tag{3}$$

Here, the parameter D can be formulated as in [12] or in a similar manner.

2.3 Potential for SHM of masonry arch bridges

The application of the smart masonry paradigm for SHM of arch bridges has not yet been explored. However, it is expected that the presence of self-sensing bricks within the arch will allow early detection of anomalies in its strain state, thus indicating changes in arch stability due to the onset of structural issues and/or external actions. Similarly, outputs from the self-sensing mortar layers will provide clear indications of crack opening, thus highlighting areas of the arch operating above the materials' ultimate strength.

Figure 1 presents a conceptual exemplification of smart bricks integrated within a masonry arch to monitor changes in its strain state. The trend of the line of thrust is depicted to highlight modifications in the stress state of the arch from the condition where only dead loads are present (see Figure 1(a)), to the perturbed configuration, in which an external force is applied (see Figure 1(b)). A proper positioning of smart bricks within the thickness of the arch can therefore allow the detection of abnormal strain concentrations or relaxations at the level of a single cross section. Consequently, by instrumenting multiple cross sections of the arch with smart bricks, the information provided by the integrated sensor network can highlight potential stability losses, due to the onset of tensile stresses, and thus anticipate the initiation of collapse mechanisms. A numerical proof-of-concept is hereinafter proposed to explore the use of smart bricks for monitoring strain in masonry arch bridges.

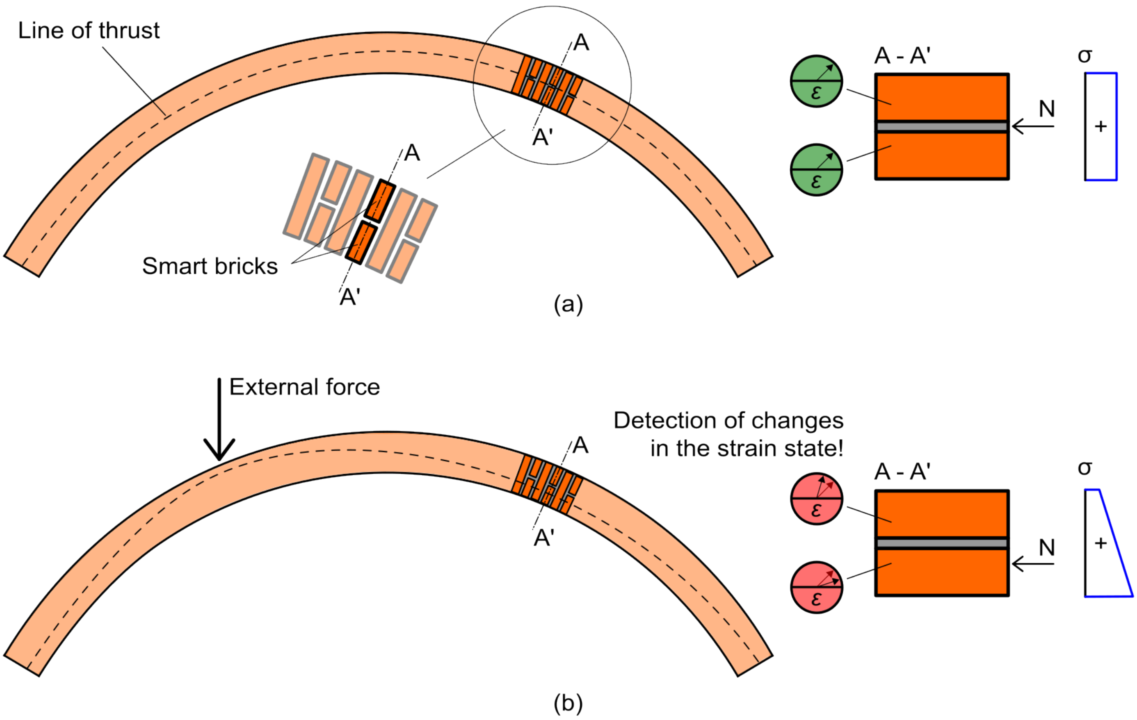

Figure 1: Conceptual illustration of smart bricks in a masonry arch for strain monitoring. The thrust line highlights stress changes from dead loads: (a) Arch under dead loads; (b) Arch subjected to an external force.

3 NUMERICAL PROOF OF CONCEPT

Figure 2 shows the mechanical model used to begin exploring the use of smart bricks for strain monitoring when incorporated into masonry arch bridges. The simulated structural element, representing a round arch, had a span of 300 cm, a rise of 150 cm, and a thickness of 25 cm. It consisted of clay bricks measuring 25×5.5×12 cm^3, arranged with cement mortar layers up to 1 cm thick, forming a two-headed masonry system. Smart bricks were envisioned to be embedded within the load-bearing structure, as highlighted in Figure 2 (red rectangles), allowing strain monitoring across four different cross-sections of the arch. The mechanical model was discretized using the Finite Element (FE) method, employing a simplified micro-modeling approach to represent bricks and mortar layers separately [10]. The mechanical properties of the adopted building materials are listed in Table 1. The FE model's geometry was discretized using a mesh of 137,541 linear hexahedral elements of type C3D8R and 152,800 nodes.

Two loading conditions were simulated. First, a dead load analysis was performed, and the axial strain ϵ_y was retrieved from each smart brick according to a local coordinate system defined in Figure 2. Subsequently, an external force of 100 N was applied to the arch with a certain eccentricity relative to the crown. Strains from smart bricks were extracted as before and benchmarked against the reference measurements (dead loads). A steel plate was modeled to allow the external axial force to be applied, with a tie constraint connecting the steel plate mesh to the arch mesh.

4 RESULTS

Figure 3 shows the distribution of the maximum principal strain within the FE model, obtained from simulations of the two loading conditions. Figure 3(a) displays uniform and low strain values, as the masonry arch is primarily compressed under dead loads. In contrast, the

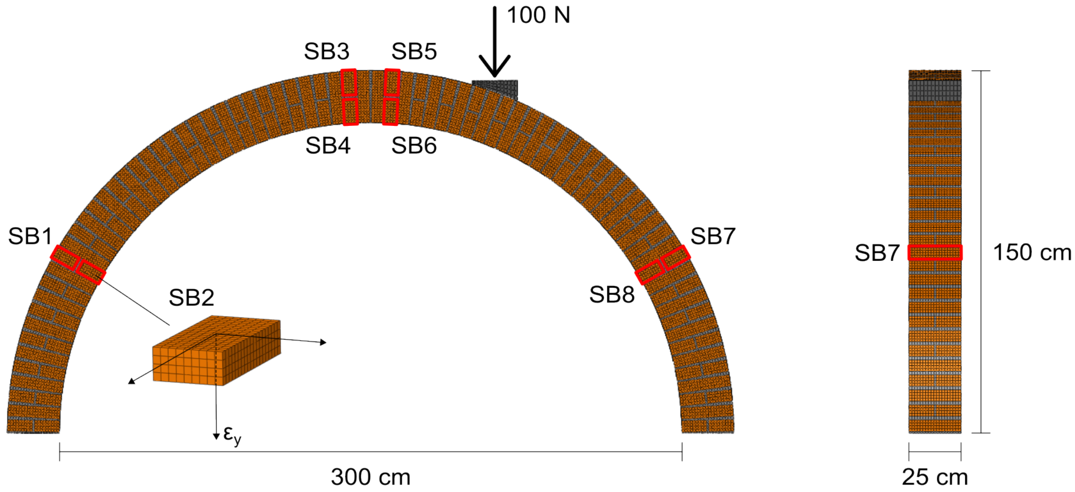

Figure 2: Mechanical model of the masonry arch with annotated the positioning of smart bricks (red rectangles). A local coordinate system has been defined for each sensor, as exemplified for smart brick SB2, where ϵ_y is the axial strain, which is positive in compression.

Table 1: Mechanical properties adopted to characterize the mechanical response of the building materials simulated in the FE model.

Clay bricks		
ρ = 16.2 Kg/m^3	E = 10500 MPa	ν = 0.13
Cement mortar		
ρ = 17.5 Kg/m^3	E = 2100 MPa	ν = 0.15

strain distribution in Figure 3(b) reveals localized regions of the arch with higher tensile strain concentrations, which may indicate areas where failure mechanisms could occur as the magnitude of the applied external force increases. Strain measurements retrieved from smart bricks, which are envisioned to be embedded within the FE model, are shown in Figure 4. Changes in strain relative to the reference condition (i.e., the arch under dead loads) can be observed in every sensor of the network. While most of the bricks experienced increases in their compressive strain, smart bricks SB1, SB6, and SB7 are found to be strained in tension upon the application of the external force. The sensor network, therefore, enables the detection of abnormal tensile strain concentrations within the thickness of the masonry arch. Changes in the thrust line path can be anticipated from the results from the embedded sensor network, thus helping in the timely detection of potential loss of arch stability.

5 CONCLUSIONS

The paper has explored the potential application of the smart masonry paradigm, specifically smart bricks, for SHM of masonry arch bridges. A conceptual approach for using smart bricks to monitor strain in such structural settings has been proposed and corroborated through a proof-of-concept numerical investigation. To simplify the problem, a mechanical FE model of a masonry arch was defined, with a network of smart bricks embedded within it as part of the load-bearing structure for strain monitoring. The self-sensing bricks revealed changes in their strain state following the application of an external force to the masonry arch, highlighting a condition that could evolve into a potential loss of stability. Overall, the obtained results suggest that the application of smart bricks for strain monitoring in masonry arch bridges is promising, paving the way for the development of innovative SHM strategies based on the smart masonry.

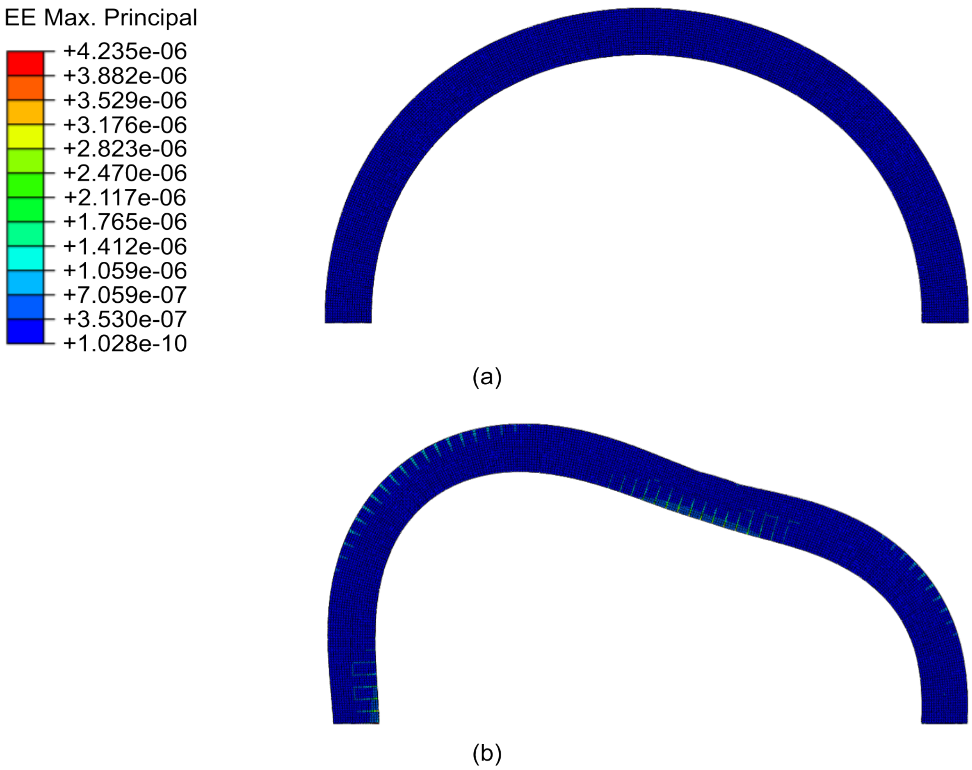

Figure 3: Maximum principal strain from numerical simulations: (a) Arch under dead loads; (b) Arch subjected to an external force.

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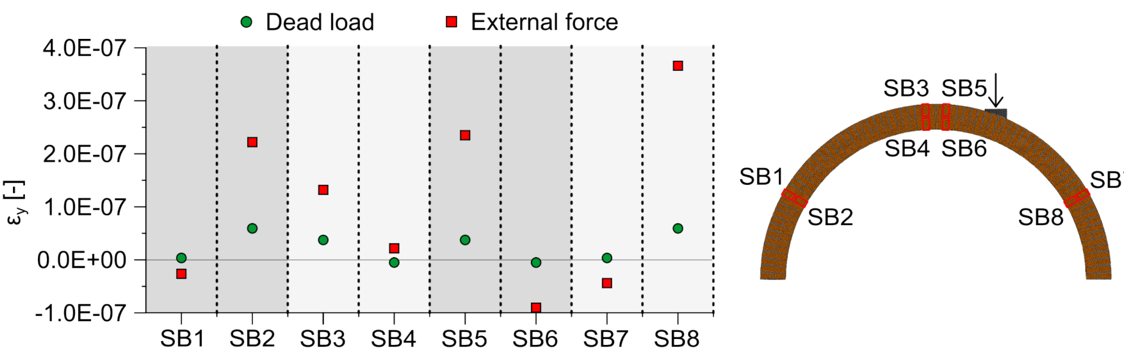

Figure 4: Strain measurements retrieved from smart bricks, which are envisioned to be embedded within the numerical model, for the simulated loading conditions (positive strain in compression).

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