FEM analysis of functional cavities to improve the thermo-mechanical properties of hollow bricks made up of 3D printable cement mortar

Matteo Sambucci & Marco Valente

Department of Chemical and Materials Engineering, Sapienza University of Rome, Via Eudossiana, 18, 00184, Rome, Italy

matteo.sambucci@uniroma1.it – marco.valente@uniroma1.it

1. Introduction and Scope

Currently, the main challenges in the building industry are characterized by the maximal tendency to the design and production materials and components aimed at enhancing the **energy efficiency** and **safety** of structures. In this framework, **hollow bricks** have found widespread use in the construction sector due to their enhanced lightweight, durability and thermo-acoustic insulation properties. As confirmed by some analytical studies, the mechanical and thermal performance of the brick (in terms of stiffness-weight ratio and thermal insulation) can be modulated by optimizing the geometry of the internal cavity system [1]. However, researches on functional configuration of the bricks are very limited due to the restricted architectural freedom offered by traditional manufacturing techniques. The development of **3D Printing methodologies for cementitious materials (3DCP)** implies considerable advantages in terms of design flexibility and product quality, allowing to prototype building elements with highly complex configurations. Furthermore, to investigate the behaviour of hollow bricks and perform topological optimization studies, **Finite Element Method (FEM) analysis** represent advanced and useful tools for predicting the response of a model to various type of stresses (mechanical, thermal, acoustic, electromagnetic) and verifying any vulnerabilities before manufacturing. In this work, innovative inner architectures based on **hexagonal** and **fractal cavities** are proposed to design novel hollow blocks made up of **3D printable cementitious mortar**. **Numerical mechanical** and **thermal analysis** by FEM were performed to evaluate the effect of optimized cavity shape on the brick's properties and compare them with common designs.

2. Background

Hexagon-based cavities

High bending stiffness, damping properties, and strength at the given minimum weight make **hexagonal hollow structures** attractive for use in several engineering applications where weight saving and vibration control are crucial. Cavity geometry is a key parameter regarding the mechanical response of the component to static or dynamic mechanical loads. Hexagonal holes significantly reduce the **stress concentration** in the material compared to conventional geometries (such as square-based cavities), improving the component's strain capacity [2,3]. Besides, hexagonal perforated patterns are highly efficient in terms of **acoustic attenuation**. They confer remarkable structural tortuosity to the element, which reduces the sound wave intensity through reflection phenomena against the cavity's external walls [4].

Hexagonal hollow structure

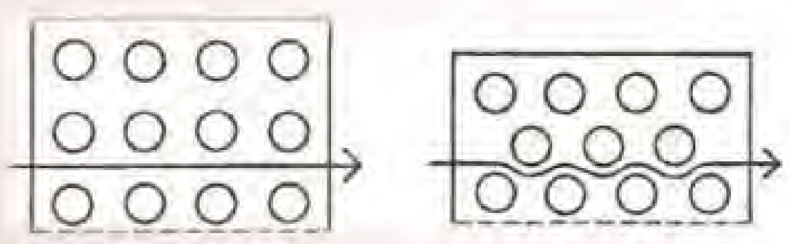
Fractal-based cavities

Fractal structures were extensively studied in anti-noise applications, such as **acoustic damping cavities**. As the sound wave propagates through the highly irregular cavity's cross-section, a remarkable acoustic dissipation occurs [5]. A novel application of these geometries concerns the use as **brick cavities with high thermal inertia**. As suggested by *Bustamante et al.* [6], by increasing the geometric complexity degree of the inner perforations, the heat transmission through the component is hindered as the thermal path is maximized. This effect increases the thermal resistance of the brick. However, the geometrical complexity of fractals makes their reproduction highly difficult. For this reason, in this work, a quasi-fractal geometry called **"Hash"** is proposed. "Hash" cavity has already been designed and tested by the authors as an acoustic cavity in 3D printed Helmholtz resonators for automotive applications [5]. Therefore, this structure could represent a **good match between manufacturing feasibility and thermo-acoustic functionality** in bricks technology.

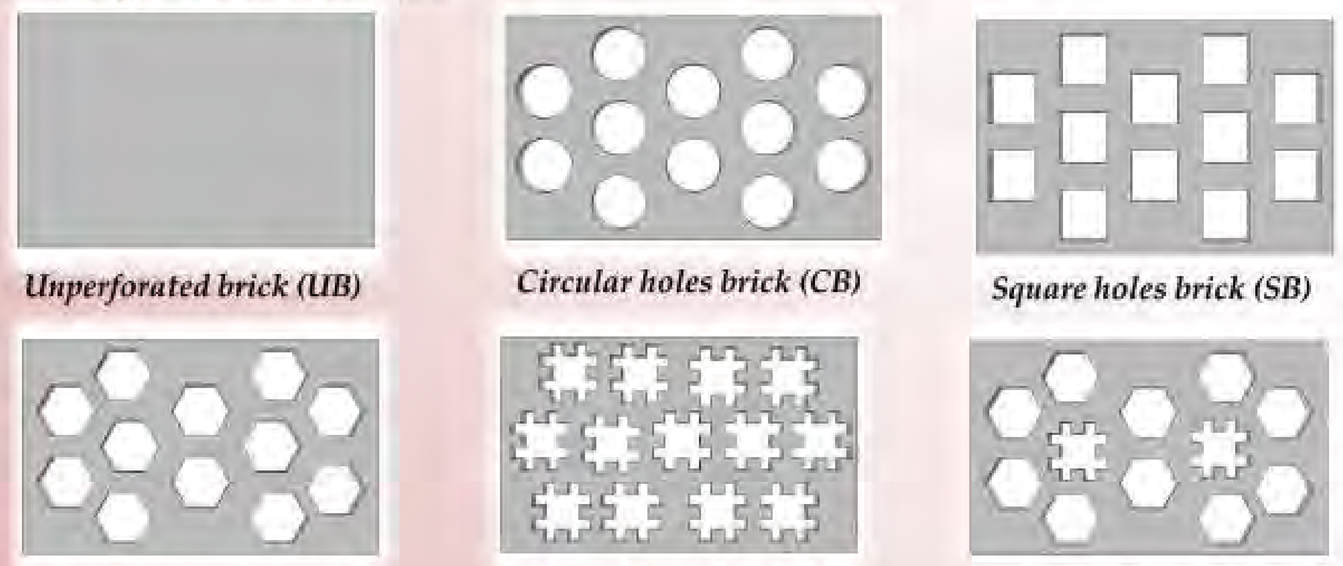
«Hash»-shaped cavity

3. Brick models

Six hollow brick designs (250 mm x 150 mm x 40 mm) were modeled using **3D Geometry Tools** in **COMSOL Multiphysics v5.4**. The prototypes had the same hole concentration ratio (40 %) but different inner architecture. The holes are distributed according to a **"honeycomb arrangement"** to maximize the trajectory of the thermal flow and enhance the **heat insulation performance** [1].



UB identified the unperforated block. *CB* model is composed of circular holes with 13 mm radius. In *SB* block, the side of the squares is 33 mm. The hexagons side in *HB* model is 20.5 mm. The edge of "Hash" structures in *FB* brick is 8 mm. *HFB* combined design consisting of an array of ten hexagonal holes containing two fractal cavities.



Unperforated brick (UB) — *Circular holes brick (CB)* — *Square holes brick (SB)*

Hexagonal holes brick (HB) — *Fractal holes brick (FB)* — *«Hybrid» brick (HFB)*

4. Material properties

Physical, mechanical, and thermal experimental properties of **3D printable Portland-based mortar** were used as input data in FEM analysis.

Compressive test

3D printing process for specimens manufacturing

Thermal conductivity analysis

Bulk density (ρ)	1927 kg/m³	BS 1881-114
Porosity (φ)	33.1 %	ASTM C1220
Compressive strength (σ_c)	63.1 MPa	ASTM C109
Elastic Modulus (E)	5.56 GPa	ASTM C348
Uniaxial tensile strength (σ_t)	7.61 MPa	Empirical
Biaxial compressive strength (σ_{bc})	76.1 MPa	Empirical
Thermal conductivity (k)	1.321 W/m K	ASTM D7984
Heat Capacity (Cp)	0.0016 J/kg K	ASTM D7984
Emissivity	0.9	Empirical

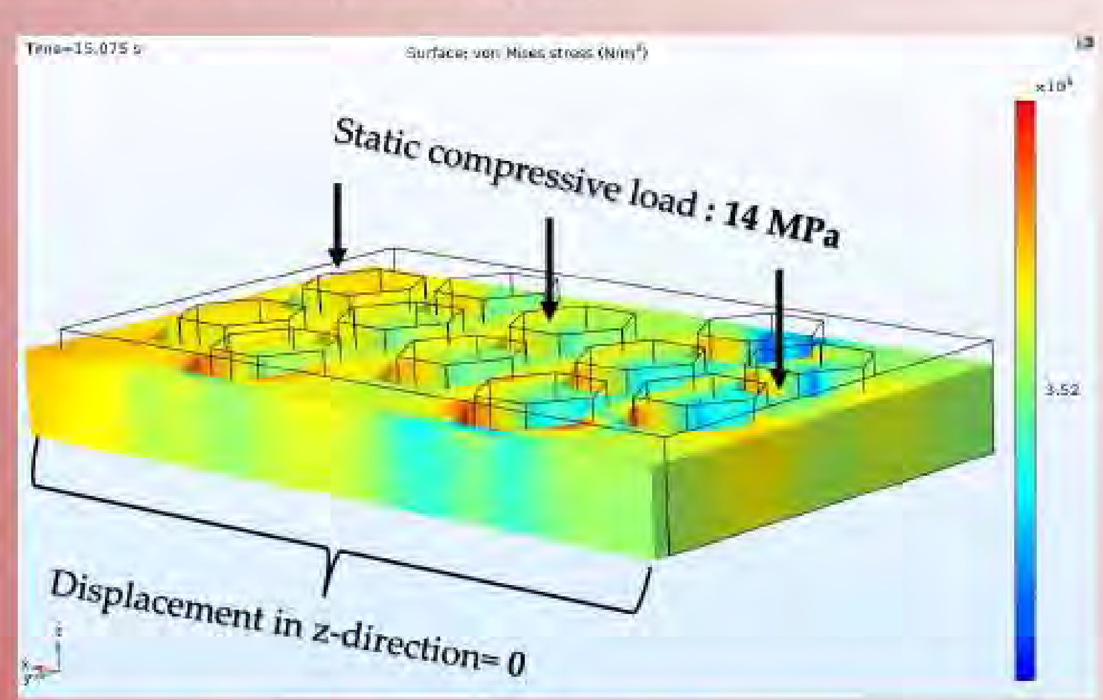
Material input data for mechanical and thermal FEM analysis

Material input data for mechanical FEM analysis

Material input data for thermal FEM analysis

5.1a FEM-based mechanical analysis

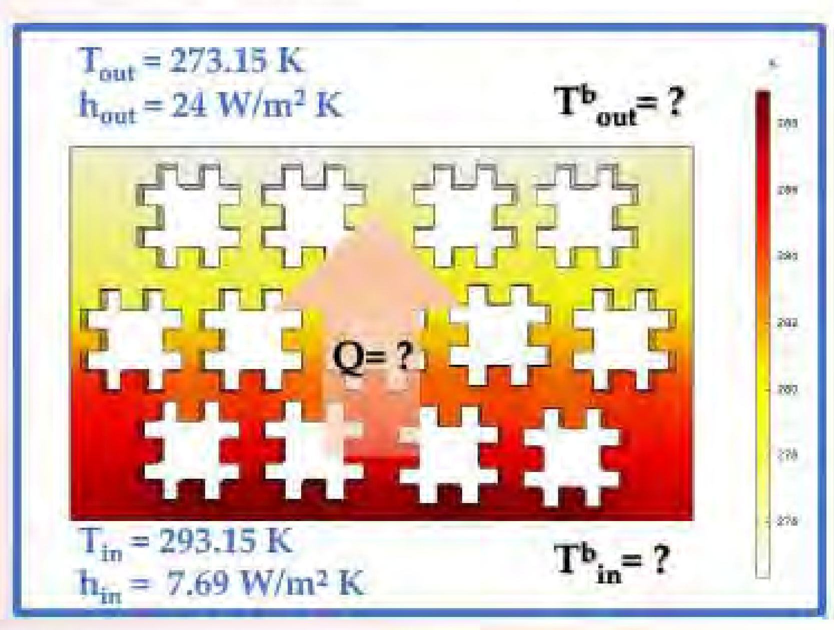
3D FEM-based mechanical analysis was performed using the **Structural Mechanics Module** of **COMSOL Multiphysics v5.4**. Static compression test was simulated on the brick models considering the laboratory conditions in **ASTMC 67-03a standard** (*Standard Test Method for Sampling and Testing Bricks and Structural Clay Tile*).

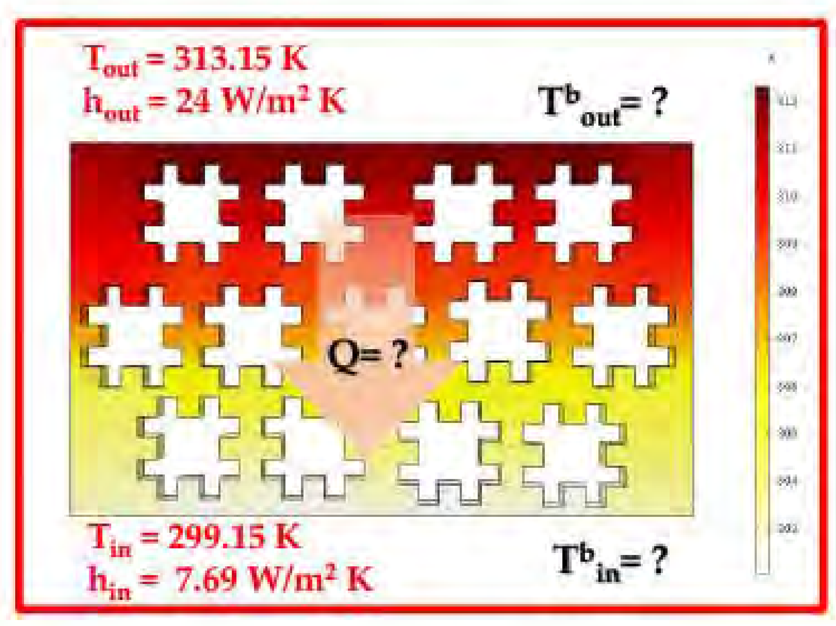


FEM-based mechanical analysis details	
Failure criterion	William-Warnke yield criterion
Mesh type	Fine Thetraedral
Resolution of the analysis	4 stress-strain data every 10 seconds

5.1b FEM-based thermal analysis

FEM-based thermal analysis was performed using the **Heat Transfer in Solids Module** of **COMSOL Multiphysics v5.4**. To evaluate the thermal insulation performance of brick prototypes, **Thermal Resistance (R_T)** was determined through steady-state analysis, as suggested by **ISO 6946 standard** (*Thermal resistance and thermal transmittance — Calculation method*). FEM study included the average climatic conditions (winter and summer) in Italy.





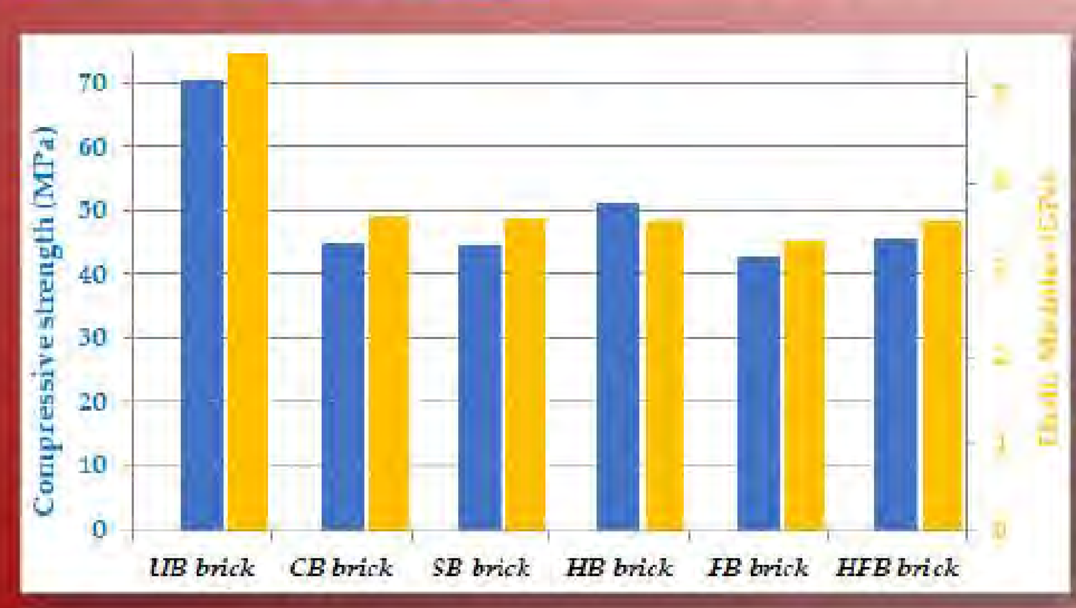
FEM-based thermal analysis: ambient conditions	
Average wind velocity	3.6 m/s
Normal solar irradiance (summer)	236 W/m²
Diffuse solar irradiance (summer)	93 W/m²
Normal solar irradiance (winter)	64 W/m²
Diffuse solar irradiance (winter)	28 W/m²

Thermal Ohm's law

$$R_T = \frac{A}{Q} \times (T^b_{in} - T^b_{out})$$

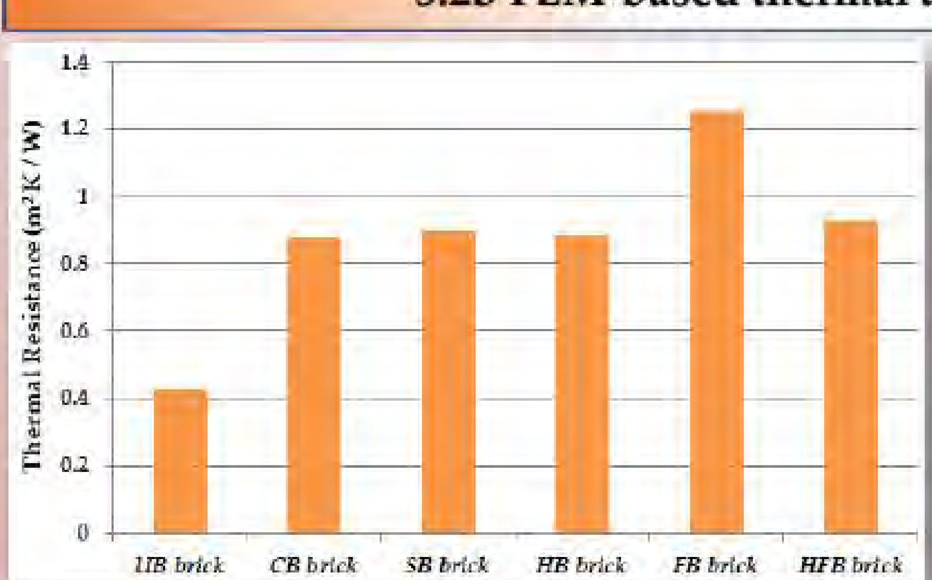
A = cross-sectional area perpendicular to the path of heat flow (m²)
Q = thermal power (W)
$T^b_{in} - T^b_{out}$ = temperature gradient between the boundary surfaces (K)

5.2a FEM-based mechanical analysis: results and discussion



- Cavities reduce the mechanical strength of the component but improve its **deformability properties** and **post-cracks performance**
- Among the perforated designs, the **hexagonal structure (HB)** exhibits the best mechanical behavior
- **HFB** model "ranks" second in terms of strength properties of hollow bricks

5.2b FEM-based thermal analysis: results and discussion



- **Air cavities** in hollow bricks act as **high-thermal inertia sites**, improving the thermal insulation properties than the unperforated model
- High geometric complexity of the inner **"Hash" cavities** maximizes the thermal path of heat flow, resulting in **greater thermal attenuation** than the other architectures
- **HFB design** exhibits intermediate R_T*-value* between FB and conventional designs. This inner configuration combines **the mechanical efficiency of hexagonal holes with the thermal performance of the fractal ones**

References:
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