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# Topology-optimized insulating facebrick with aerogel filling

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**Abstract.** This research presents the design of a new clay brick filled with aerogel. The design has been performed using multi-objective topology optimization that considers both stiffness and thermal conductivity. The current research uses the free-form design method of topology optimization with set boundary conditions for the evaluation of the stiffness and thermal conductivity. The internal structure of a standard-sized brick filled with aerogel is designed in this work. The article also offers numerical evaluations that compare the performance of the new optimized design to a standard full brick. A topology optimized-brick design is presented and shown to significantly improve the thermal insulation. Suggestions for future research include performing experimentally validations.

**Keywords:** topology-optimization, standard brick, burnt brick, aerogel, historical materials, heritage, preservation.

## 1. Introduction

Bricks are universal construction elements, which have appeared independently in many cultures, have evolved through ages and survived centuries. Bricks are still widely popular throughout the world and represent the local characteristic atmosphere of many different places. This includes both towns and the countryside, and uses within various building types such as accommodation, public buildings and industrial facilities. The recent increase of standards in fire safety, sustainability, thermal insulation properties, etc. have limited the use of the traditional brick as a load carrying construction element. Today bricks are more used as cladding for their aesthetic appearance, user-friendliness and low-maintenance demanding surface. However, if the thermal insulation properties are improved, bricks have the potential to become desirable structural elements again.

Where the availability of stone and timber is low, local clay has for centuries been a logical alternative. Bricks are easy to form from local clay, easy to burn and to subsequently handle and



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assemble during construction. They even offer an opportunity for reuse when a structure reaches its end-of-life. Both historically and today, traditional bricks have been and are popular for both interior and exterior use.

During the industrial revolution the use of bricks shifted from having mainly been used as a structural and loadbearing element towards becoming filler components within the final structure (Fig. 1). In metal frame construction, bricks were e.g. used for interior separations and for weather protection on facades. Since bricks at this time were also still used as common construction elements, the use of bricks diverged into having various main functions and specialized designs began to emerge.

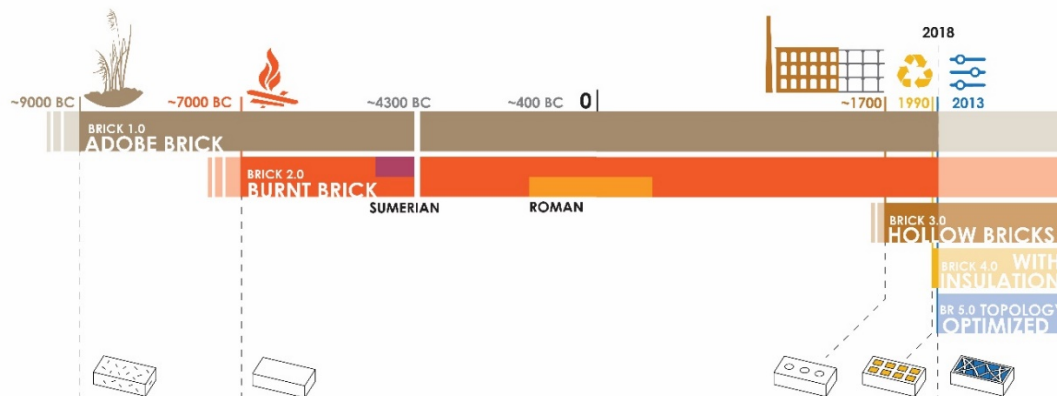
Today, the building envelope is a major source of energy loss within the built environment. Between 2020-2030 the International Energetic Agency's agenda urges researchers and manufacturers to: *"develop advanced aerogel insulation that has high performance, lower cost, and offers greater benefits for space constraint applications"* [1] [2]. Our research addresses this challenge by interdisciplinary cooperation within engineering.

This research focuses on the hypothesis that it is practically possible to meet the Vitruvian virtues of "durability, function and aesthetics" in one construction element or material. The aim is to improve the thermal characteristics of a facebrick by re-designing a new void pattern with topology optimization. This will ensure that the loadbearing properties remain and hence that bricks can be used as structural elements again. The thermal performance is further improved by filling the voids within the designed pattern with the super insulating material silica aerogel. Other paragraphs are indented

### 1.1. History of Brick Design

Globally and throughout history, various materials have been used to form blocks for building construction including stone, clay, turf and snow. Clay is the most affordable material in areas where wood or stone are not readily available. Burnt bricks can be considered as one of the very first "pre-fabricated" universal construction elements, which on site offer easy assembly, high durability and an enormous universality of usage [3].

The historical design evolution of bricks is shown in Figure 1. Burnt bricks started to be used as nomad populations settled into an agricultural life-style. The burning of clay at high temperatures made the bricks more durable, increased the strength properties and provided fire resistance. Burnt bricks were used without any significant design changes as universal construction components till the 18th century.



**Figure 1.** Scheme of basic brick types through the history where evolution steps are consequences of technological improvement.

Since the industrial revolution, the use of bricks has undergone significant changes. Prior to the industrial revolution, the perimeter walls of a structure were most often both loadbearing and a means of weather protection. As large scale metal and cement production became possible, framed constructions systems made first of cast-iron and later steel and concrete became popular. The new skeletal structures were loadbearing and any brickwork became a filler in the envelope, offering rich aesthetics and durability. The new framed construction thus relieved bricks of their loadbearing function.

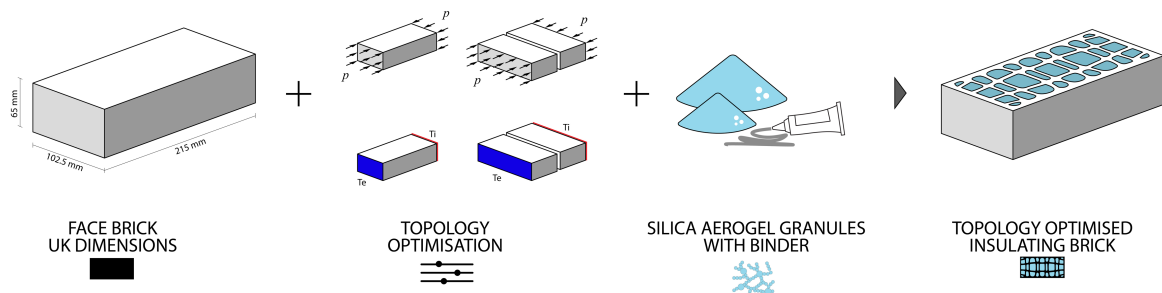
This allowed the design of bricks to evolve and introduced lighter hollow and perforated facebricks (Figure 1). These brick types demand a lower use of clay and less energy is necessary to burn them. Within the last decades, a new generation of bricks have started to appear with light hollow designs that focus on improving the insulation properties. However, most designs focus solely on the thermal performance and neglect the accompanying possibility for re-introducing bricks as loadbearing elements. This work therefore focuses on using topology optimization to control multiple parameters in brick design.

### 1.2. Silica Aerogels

Silica aerogel is a nanostructured open-porous material with remarkable insulating properties. For building construction, aerogels as superinsulation materials have emerged on the market within the last decade and are typically characterized by thermal conductivities around  $14.4 \pm 1.0 \text{ m}\cdot\text{W}/(\text{m}\cdot\text{K})$  [4]. After the aerogel blanket, new aerogel-based products (ABPs) in various forms have appeared for applications in architecture and construction. Research on applications of aerogel has also significantly increased. The combination of vapor openness and the super hydrophobic property of the granules of silica aerogel makes it desirable to use as a filling material for hollow bricks as it may improve the thermo-hygic properties. The thermal conductivity of bricks is around  $860\text{--}700 \text{ m}\cdot\text{W}/(\text{m}\cdot\text{K})$ . Since this is significantly higher than for silica aerogel, a two-material brick design offers immense possibilities for improvement of the thermal conductivity.

## 2. Methods

This study uses topological optimization to generate new brick designs within pre-specified design operating and boundary conditions. The new designs consist of two material phases; burnt clay and silica aerogel and are designed to improve both stiffness and thermal conductivity. The clay mass is required to be reduced by approx. 50%. The design problem was formulated considering four load cases where two are thermal and two are mechanical (see Figure 2). This was done to ensure even performance, regardless of the bricklaying direction in the cladding of the wall.



**Figure 2.** Facebrick with UK dimensions has been redesigned with topology optimized for four load cases [5]. The designs have two base materials such that bricks filled with silica aerogel are obtained.

### 2.1. Topology Optimization

Topology optimization is a computational structural design method, which is used to design high performance elements. It is a free-form design approach, in which the designer is not required to have a preconceived notion of final design layout. It has been known to lead to new and surprising solutions that typically outperform conventional low weight designs [6]. Most topology optimization approaches only require the designer to define a design domain with applied loads and boundary conditions. A formal optimization problem is then posed and a rigorous mathematical program is used to guide the design decisions of where material is placed within the design domain. The design evolution for the new brick is shown in Figure 3 where the final material placement within the design domain constitutes the layout of the optimized design.

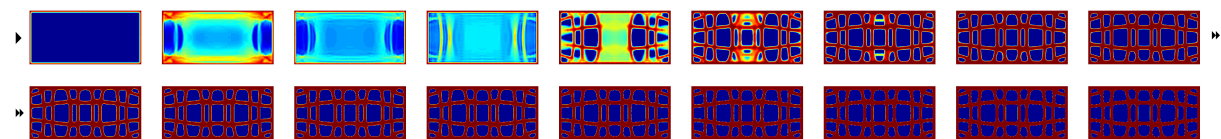
Researchers have previously suggested to improve the properties of bricks and blocks by using topology optimization [7][8]. Additionally, improvements of existing brick patterns by adding insulation material, including aerogel filling, have previously been described and measured [9]. However, this work is novel in coupling the use of topology optimization and silica aerogel filling in brick design.

## 2.2. Thermal Simulations

After the topology-optimized designs were achieved, thermal simulations were performed to evaluate the temperature redistribution and heat flux within the new brick. The simulations were performed using the Therm program and the results were compared with the design output.

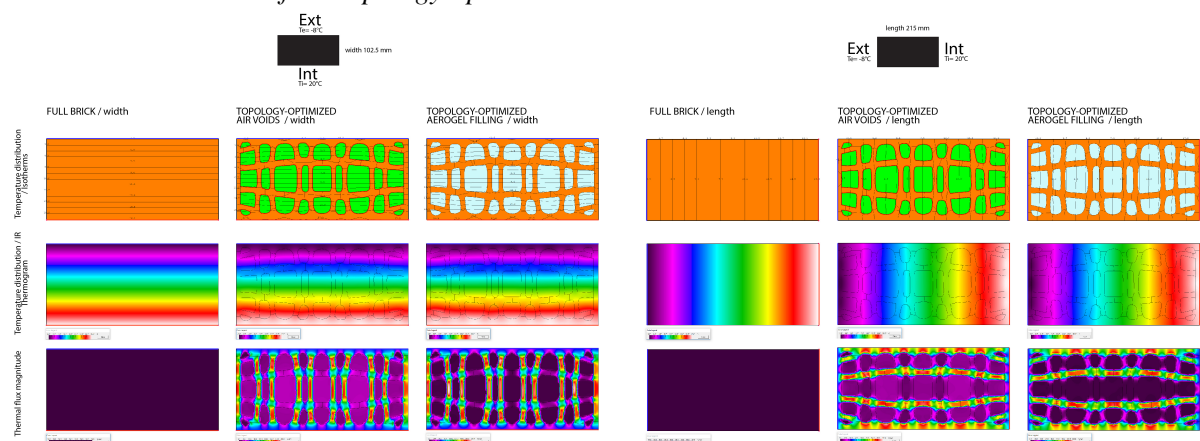
## 3. Results

The design problem was defined using the dimensions for a standard UK brick (65x102.5x215 mm, see Fig. 2). The aim was to design a thermally insulating face brick with a high stiffness. As mentioned, two mechanical and two thermal load scenarios were considered. Constraints were formulated such that even performance would appear regardless of the bricklaying direction [5]. The weighted importance of stiffness improvement versus thermal performance was shifted to obtain several design options. In all generations, the maximum amount of clay was limited to 50% of the design domain. For this work, the design shown in Figure 3 was found to exhibit the best combined behavior of thermal and mechanical properties. The thermal transmittance of the topology-optimized facebrick is found to be reduced by more than 65% when compared to a standard brick [5]. The weight is also reduced from 2.86 kg for a full brick to 1.51kg of the topology-optimized design. Of these, 1.45 kg represents burnt clay and 0.06 kg is silica aerogel in ideal granular form.



**Figure 3.** Evolution of topology-optimized design (red= burnt clay, dark blue=aerogel, green = fictitious material).

### 3.1. Thermal simulation of the topology-optimized brick

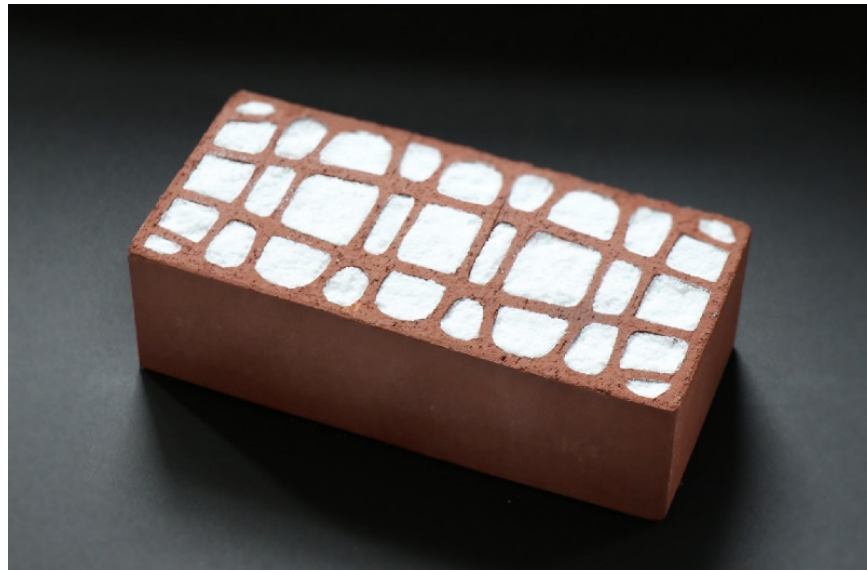


**Figure 4.** Thermal simulation of designed brick pattern, cross heat transfer, longitudinal heat transfer, Condition of Thermal simulation Clay=0.8 W/mK, Aerogel granules=0.014 W/mK, Cavity=still air  
 $T_i = 20^\circ\text{C}$ ,  $T_e = -8^\circ\text{C}$ ;  $R_{si} = 0,13 \text{ m}^2\cdot\text{K}/\text{W}$ ;  $R_{se} = 0,04 \text{ m}^2\cdot\text{K}/\text{W}$

The results of the thermal simulations conducted on this new brick design are shown in Figure 4, where the thermal performance of a full brick is compared to the performance of the new design with air voids and filled with aerogel. Two bricklaying directions are considered in the figure. The first row of the



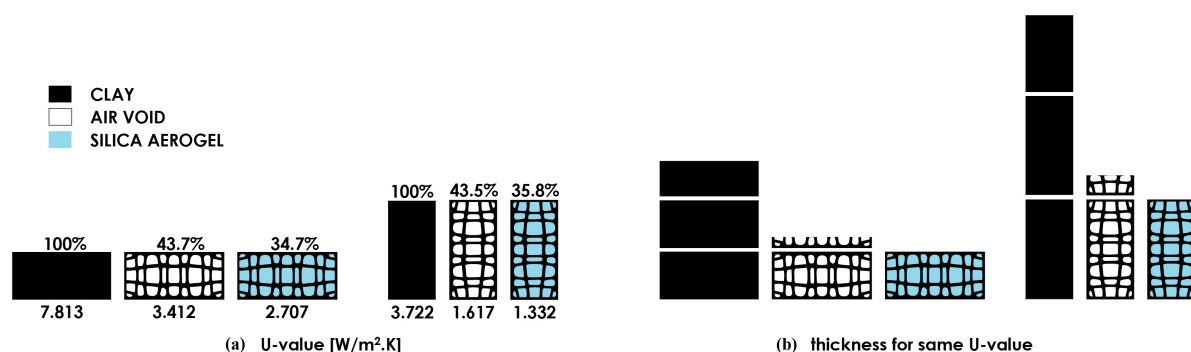
figure shows the distribution of the different materials (clay and air voids – 2<sup>nd</sup>, 4<sup>th</sup> column, aerogel respectively) and the temperature distribution represented by isotherms. The second row also shows the temperature distribution, but in thermogram form. The temperature distribution (2<sup>nd</sup> row) is homogenous close to the outer surface of the brick, which is beneficial for the bricks weathering and controlled thermal performance. The third row shows the heat flux through the brick. Some parts of the new design are more thermally stressed than others. The heat flux path through the internal parts is seen to be strongly dependent on the direction of heat flow (2<sup>nd</sup>, 3<sup>rd</sup> and 4<sup>th</sup>, 5<sup>th</sup> column, 3<sup>rd</sup> row).



**Figure 5.** Topology-optimized face brick prototype with reduced U-value, filled with high performance thermal insulating silica aerogel.

#### 4. Discussion

A prototype of the chosen design has been fabricated and is shown in Fig. 5. Since it is a loadbearing, thermally insulating and aesthetic construction element it meets Vitruvian virtues of "Strength, Functionality and Beauty". In Fig. 6 the thermal performance of the new brick is compared to a full brick. It is seen to have a much smaller U-value regardless of the bricklaying direction, and thus that much thinner walls can be constructed with the same thermal behavior.



**Figure 6.** Comparison of a full brick and the new topology-optimized brick without filling and with silica aerogel. In (a) the improved U-value is shown for the cross and longitudinal directions of thermal loads; and (b) gives a comparison of necessary thickness required to achieve the same U-value.

A future direction of this research is to investigate the Life Cycle Assessment of the new topology-optimized brick in an effort to holistically estimate the amount of preserved energy. Additionally,

experimental measurements of a real scale mock-up wall will bring comprehensive validation and insight to potential problems with cold bridge formations.

The current price of aerogel results in a high initial cost for the filling of the new brick that is approx. four times higher than a regular brick. However, the price of aerogel granules has a decreasing trend and this new design therefore has the potential to become an affordable construction component.

## 5. Conclusions

Topology optimization offers new possibilities for design of high-performance construction elements. A thermally improved topology-optimized burnt brick can help decrease built energy consumption while preserving the traditional cultural appearance of local significance, the "genius loci", and thus help to maintain local identity of the built environment. The herein designed topology-optimized brick significantly improves the thermal properties compared to a full brick. It additionally generates the potential for loadbearing brick construction to reemerge as a sustainable, insulating, vapor-open, user-friendly and aesthetic technology.

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