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Functionally Graded Architectures by Additive Construction

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Abstract: The construction industry is increasingly optimizing its performance reducing costs and minimizing its environmental impact. New technologies, growing client expectations and a shift in design thinking are motivating major improvements in the construction sector towards more integrated systems using novel computational fabrication processes. A Rapid Construction System, based on extrusion technologies, was developed to integrate the concept of material space and form to construct eco-efficient buildings with complex forms and geometries. This new 3D digital processing system was used to fabricate functional graded structural components with different material compositions and shape, so its functional requirements can vary with location. The development of this functional design concept, using material gradient and/or geometrical gradient, will enable the fabrication of more efficient structures regarding thermal, acoustic and structural conditions.

Key words: Extrusion technology, functional graded components, computational fabrication

1. Introduction

Design in nature is quite flawless and several engineering design solutions and its applications are frequently inspired in it. Biomimetics investigates the structure and functionality of biological systems as models for the design and engineering of materials and machines. All biological features required for a structure, such as energy savings, beauty, functionality and durability were already created and optimized by nature. In order to replicate nature's design and implement it in an architectural design work, a high level of engineering and biological knowledge is essential. Yet living things in the natural world know nothing about load bearing or architectural principles, in spite of having the capability of adjusting and adapting to new loads. Figs. 1 and 2 illustrates two biologically inspired architectural designs, the Crystal Palace in London and the Munich Olympic Stadium.

One of the topics discussed in biomimetics is Functionally Graded Materials (FGM). FGMs can be found in many natural biological structures, for example bones, bamboo, mollusc shell, etc. These structures present compositional or microstructural gradients, such as the gradation in the density of fibers along the bamboo stems, or the density of the trabecular tissue along the femoral bone (Fig. 3). A continuous bulk functionally graded material has the potential to be an ideal orthopedic implant for load bearing applications.

Fig. 1 The Munich Olympic Stadium is inspired in the Dragonfly Wing design.

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Fig. 2 The Crystal Palace in London was inspired in the Water Lily design.

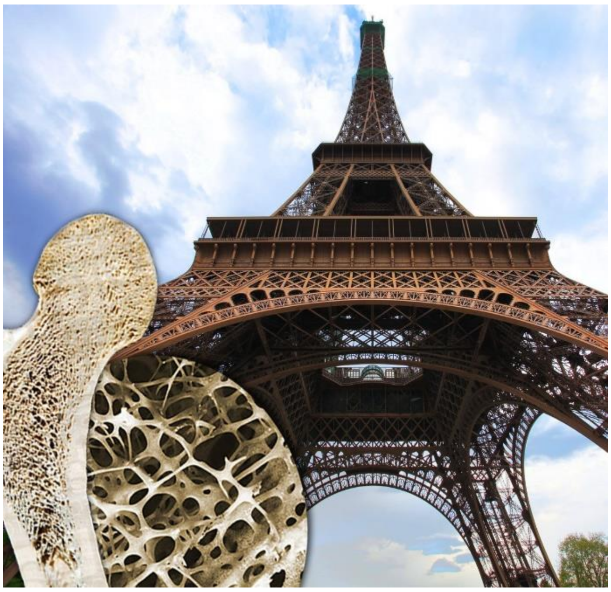


Fig. 3 Section view of a femoral bone combined with a detailed view of the Eiffel Tower.

Architecture and Construction are highly interdisciplinary fields, integrating numerous professionals and engineering domains to produce structures with different levels of scale and complexity. Construction is usually considered very conservative, risk averse and reluctant to invest in new ideas, is facing an increasing pressure to be more efficient to survive in the current economic conditions. Conversely, it needs to address the sustainable and climate change issues, as the environmental impact of the construction sector is huge with buildings accounting for 40% of the European Union energy demand.

In today's global economy, the construction industry is increasingly challenged to optimize its performance reducing costs and minimizing the impact on the environment. New technologies and rising client expectations are motivating radical improvements in the construction sector [1]. The industry is currently evolving towards a full digital based design system through a better integration of structure, materials and form through new fabrication technologies, which can create new opportunities and introduce new global challenges to maintain competitiveness.

Additive technologies are a class of manufacturing processes, in which a part is built by adding layers of material upon one another. Additive technologies, usually called rapid prototyping technologies, are one of the most rapidly growing manufacturing technologies in the world [2], due to their capability of producing highly complex geometric products with gradient functionality in terms of material and geometric forms.

These technologies [3, 4] are currently applied in a great variety of industries, such as the aerospace, architectural, automotive or medical fields, though its application for construction industry practices is less suitable for two main reasons: i) they are only used for medium or small-scale objects, and ii) the majority of these systems cannot easily process more than one material. The uniqueness of the construction sector constitutes a challenge for the direct adaptation of these technologies.

A new system was developed to introduce additive manufacturing technologies in architecture and construction, overcoming the limitations of scale and dimension, a new system for automatic construction was developed at Leiria, by the Centre for Rapid and Sustainable Product Development, based on an extrusion process, aiming at the construction of eco-efficient buildings with complex forms and geometries.

2. A Rapid Construction System

The concept of developing highly automated tools and techniques for application in construction is still embryonic. Improving the quality and reliability of manufactured products has been a relevant issue for quite a while. In 1983, Ayres and Miller (1983) [5] reported several advantages on the use of robots in manufacturing, obtained by a detailed survey of 40 major U.S. manufacturers.

It is fundamental to prevent construction site accidents and promote safety for everyone involved in the construction sites, converting the construction activity into a more sustainable one. New challenges and opportunities are emerging to develop modern and innovative methods, which to be successful need to be integrated in a very demanding human and harsh environment.

In recent years, significant advances in technology have created numerous opportunities for innovation in construction automation. Khoshnevis *et al.* (2006) [6] developed a concept for the automatic fabrication of a house called Contour Crafting, consisting of the automatic fabrication of the building walls layer by layer, until the creation of a formwork filled, after the cure, by mortars mainly composed by cement. Lim (2009) [7] developed a concrete printing strategy to produce 3D customized products. This concrete printing system is also based on the extrusion of cement mortars. Dini (2011) [8] developed the D-Shape process that uses a powder deposition binder similarly to the FDM process. In this process, each build material layer is laid to the required thickness, compacted and then the nozzles on the gantry frame deposit the binder in a selective way. Since 2009, the Centre for Rapid and Sustainable Product Development is developing a novel 3D additive technology system, using the know-how acquired in the production of bio-structures for cell support (scaffolds), using materials mainly composed by cement, polymers and clay [9]. This fabrication system, called Rapid Construction, comprises a computer controlled mobile crane integrating multi-deposition heads with various degrees of freedom [10, 11]. This equipment uses fast curing thixotropic materials with low shrinkage [3, 4]. This crane has two parallel rails to enable its movements. This additive manufacturing automation process will allow building house walls layer by layer, in a continuous way. As the head moves along the walls of the structure, the construction material is extruded and troweled using a set of actuated, computer controlled trowels. An extrusion head will continuously deposit material until it approaches a window or door opening space, then it slows down until stopping at these previously selected points [10, 11]. The use of computer controlled trowels allows producing smooth and accurate surfaces. A large scale prototype illustrated in Fig. 4 is being tested for material deposition strategies. Fig. 5 illustrates the proposed system at real scale.

The optimization of this new system aims at integrating the concept of material space, material composition information of building heterogeneous

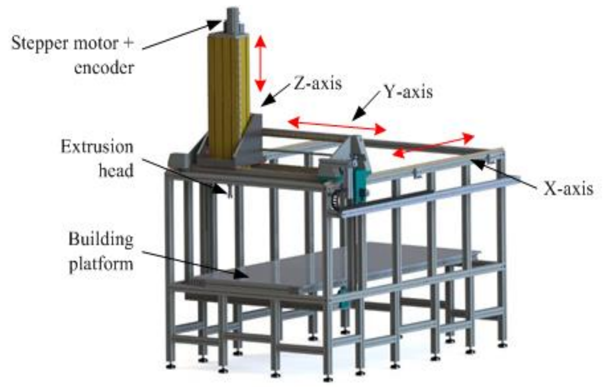


Fig. 4 Large scale prototype of the rapid construction system.

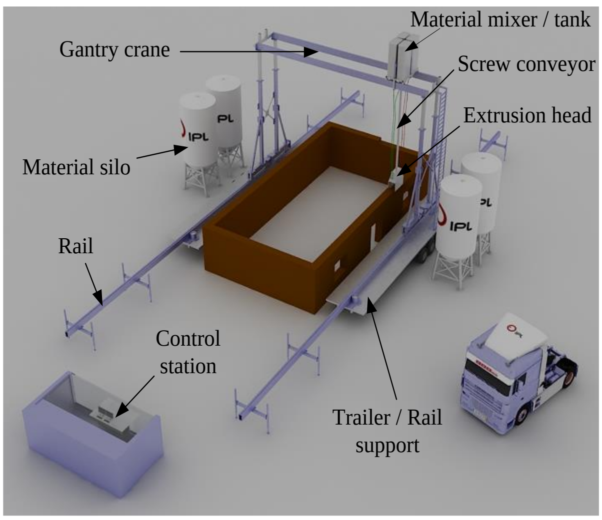


Fig. 5 The proposed system for the automatic construction of a building (real scale).

components with geometry information, assigning different spatial features according to requirements. The proposed multi-material deposition system will enable the construction of more efficient buildings regarding thermal, acoustic and structural conditions. Fig. 6 illustrates a building concept capable of being produced by the Rapid Construction System.

3. Functionally Graded Design

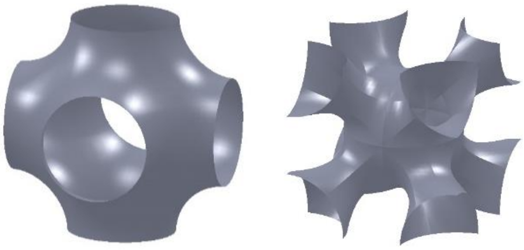
Functionally Graded Design can be achieved through two concepts, by either geometric shapes and forms or material density variations. In this research work, both concepts are presented.

3.1 Graded Shape Functionality

In the last decade, Hyperbolic Surfaces attracted the attention of many researchers from several engineering domains. Hyperbolic geometries commonly exist in natural shapes and structures. Among the several existing Hyperbolic Surfaces, Minimal Surfaces are the most studied. If a Minimal Surface has a space group symmetry, it is periodic in three independent directions, and is often called Triply Periodic Minimal Surfaces (TPMS) [12]. TPMS describe several natural shapes, such as lyotropic liquid crystals and colloids, zeolite sodalite crystal structures, diblock polymers, silicates, lipid bilayers bicontinuous composites, detergent films, hyperbolic membranes (found in the prolamellar structure of choloroplasts in plants), echinoderm plates (interface between the inorganic crystalline and organic amorphous matter in the skeleton), cubosomes and certain cell membranes [13, 14]. Two important sub-classes of TPMS are the so-called Schwartz and Schoen primitives, considered in this research work (Fig. 7).

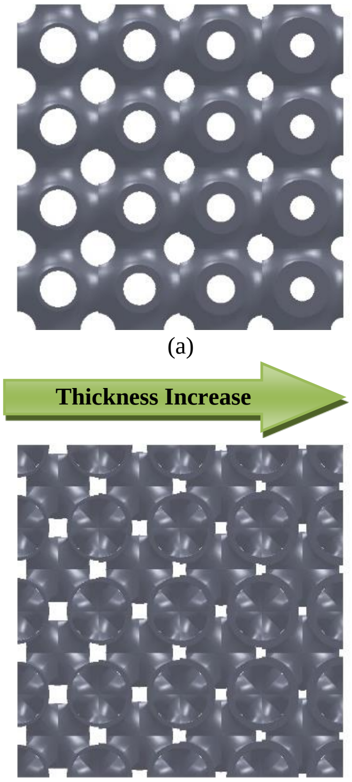
The geometric modelling of the Schwartz and Schoen models were obtained through a commercial CAD software. Fig. 8 illustrates Boolean operations by the addition of the basic units into an arbitrary unit, with thickness variation resulting in a construction block with a thickness gradient. Fig. 9 illustrates the production of both construction blocks through an extrusion-based additive manufacturing system.

Fig. 6 Building concept capable of being produced by the rapid construction system.



(a) (b)

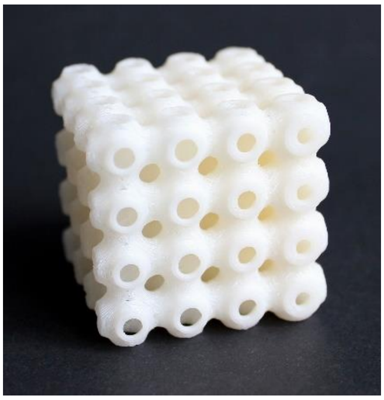
Fig. 7 (a) Schwartz and (b) Schoen TPMS primitives.



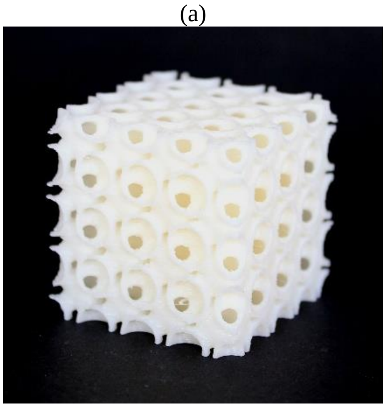
(a)

(b)

Fig. 8 CAD models illustrating thickness gradient within the structures for the a) Schwartz and b) Schoen geometries.



(a)



(b)

Fig. 9 Physical models of a) Schwartz and b) Schoen geometries produced through extrusion-based additive manufacturing.

To get a better understanding of the structural behavior proposed for the construction blocks, structural simulations were performed to understand the influence of the thickness gradient. A displacement solicitation along the direction of the thickness gradient was defined to undergo the simulations. Results show that as the thickness of the elementary units in both construction models increase, the tensile variation tends to lower in value, becoming more homogenous as illustrated in Fig. 10.

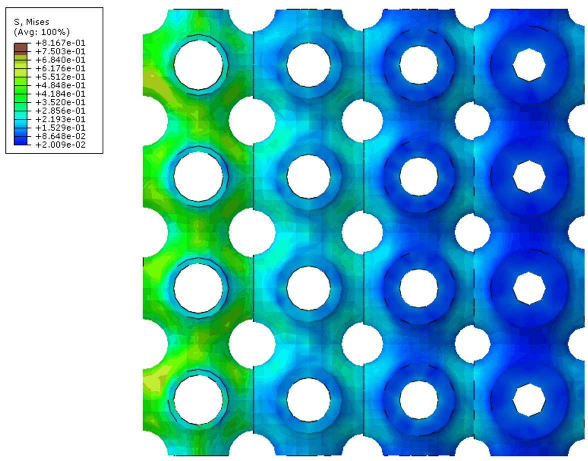
Fig. 11 illustrates a building concept based on TPMS surfaces where these natural surfaces can be well combined with existing cities such as Lisbon.

3.2 Graded Material Functionality

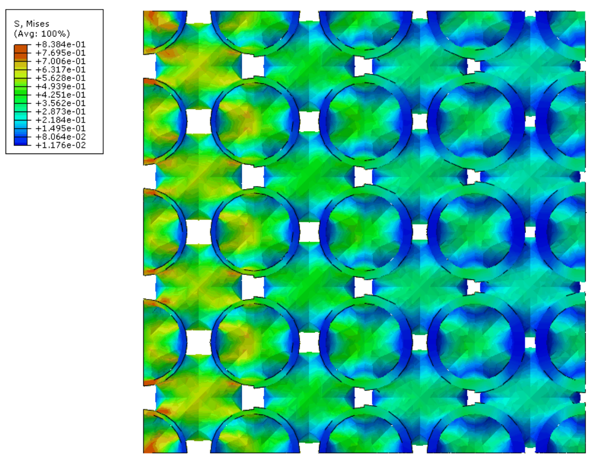
There is an increasing interest in tailoring building structures so the functional requirements can vary with location [15]. In a functionally graded material (FGM), both the composition and the structure can gradually change over the volume, resulting in varying material properties.

The processing system [3, 4] combines mixing and extrusion processes to enable the continuous manufacturing of finished components using different materials in a one-step process. The raw materials can be varied continuously (Fig. 12) or by using multiple extruders with different raw materials to build up walls with material variations with the required characteristics.

The direction of the gradient can determine its features, allowing predefining a more advantageous direction regarding a better thermal insulation, for instance. The same material can be lighter, with more gaps, in a specific location, so more weak and be denser



(a)



(b)

Fig. 10 Variation of Tensile Stresses along the thickness gradient for both structures the a) Schwartz and b) Schoen geometries.

Fig. 11 Building concept inspired on TPMS primitives.

Fig. 12 Representation of a material with a functional gradient.

in another position and stronger. The use of lighter materials can reduce the building weight without compromising its structural safety. The material distribution can be optimized, using the same or different materials according to structural, thermal or acoustic needs (Fig. 13).

A functionally graded component was fabricated using PU polymers with different compositions (Fig. 14). This pilot test was inspired by the biomedical cell supports (scaffolds), though the layer thickness needs to be reduced to allow a better control on the spatial properties of the material.

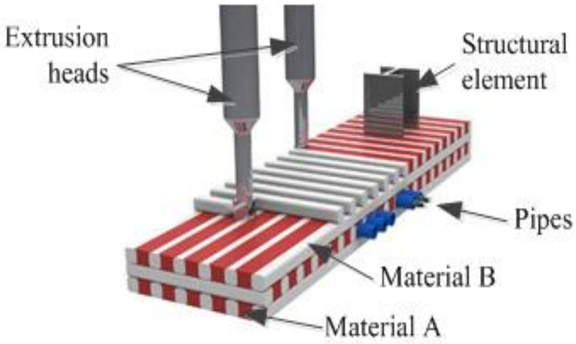


Fig. 13 The concept of FGM applied to a building wall.

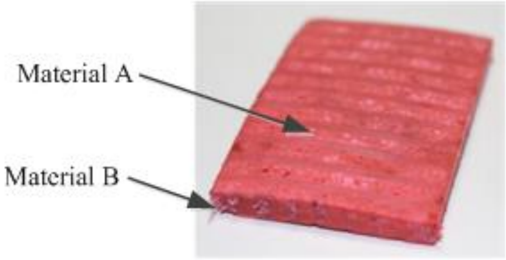


Fig. 14 PU polymers with different compositions.

4. Conclusions

Modern information technologies and the rapid progress of computer-aided design (CAD), with the advances in digital design and fabrication are motivating a shift in architecture and design towards the production of full integrated buildings. The industry is currently evolving to new processes of design fabrication combining material, form, structure and construction, creating new business opportunities. High public expectations and the dynamic nature of the construction industry are motivating new advances in building technologies, introducing an increased efficiency and competitiveness.

The Rapid Construction system, a multi-material deposition equipment based on extrusion-based technologies, presents several advantages over traditional approaches, namely greater geometrical freedom, structural optimization, multi-material, faster and lower construction costs.

The optimization of this new system enable to design and construct complex and best-adapted buildings, regarding thermal, acoustic and structural conditions.

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