Load-Responsive Cellular Envelopes with Additive Manufacturing

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Abstract

The last decades have been marked by a growing concern over scarcity of resources caused by the rapid industrialization of emerging economies as well as by the high material consumption at a global scale. These changing environmental conditions have inevitably created new challenges and demands for mediation of the interaction between the natural and the human-made environments. In response to these challenges, designers are currently moving away from conventional top-down design, towards a nature-inspired approach in search of the underlying principles of morphogenesis and materialization inherent to biological entities. Inscribed in this approach, this paper proposes an innovative design-to-fabrication workflow for the conception of nature-inspired load-responsive skin systems which integrates the use of computational tools, Additive Manufacturing, and material experiments with full-scale prototypes. The design phase employs custom algorithms to determine an optimal material distribution for free-form architectural shapes, given a specific loading condition. Through fabrication tests at different scales, the viability of a production system based on Fused Deposition Modelling is demonstrated. Subsequently, the realization of a final prototype of a load-responsive cellular envelope cladded with Fiber-Glass Reinforced Plastic is presented. Opportunities and current limitations of the approach and the emerging architectural system are critically discussed towards future developments.

Keywords

Cellular lattice, Skin System, Digital fabrication, Additive Manufacturing, Computational Design

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1 INTRODUCTION

When modern man builds large load-bearing structures, he uses dense solids: steel, concrete, glass. When nature does the same, she generally uses cellular materials: wood, bone, coral. There must be a good reason for it (Ashby 2000).

Cells are fundamental forms of life, the basic construction units of natural organisms which have been explored diffusely since their discovery by Robert Hooke, described in the seminal work *Micrographia* (Hooke, 1665). In the field of architecture, constructions based on assembly of cells with solid edges or faces packed together to fill a space are called cellular solids (Gibson and Ashby, 1997). Such configuration attracts the interest of designers and scholars due to its inherent mechanical properties, such as high structural stiffness, strength-to-weight ratio, energy absorption, as well as other thermal, acoustic and electrical features (Gibson, 2005). Examples of these structures are widely spread in nature where we can distinguish three main groups: (i) Honeycomb-like materials made up of parallel prismatic cells; (ii) Closed cell foams, and (iii) Open cell foams (Fig. 1). The different level of connectivity of these cells (topology) is the main parameter influencing the behaviour of this type of structure/material, together with its relative density (ρ). The last one is defined as the ratio between the overall density of the cellular material (ρ^*) divided by the one of the solid from which the cell walls are made (ρ_s). When cell walls thicken and the pore space shrinks, the relative density increases. By definition cellular materials have a relative density inferior to 0.3 (Gibson and Ashby, 1997).

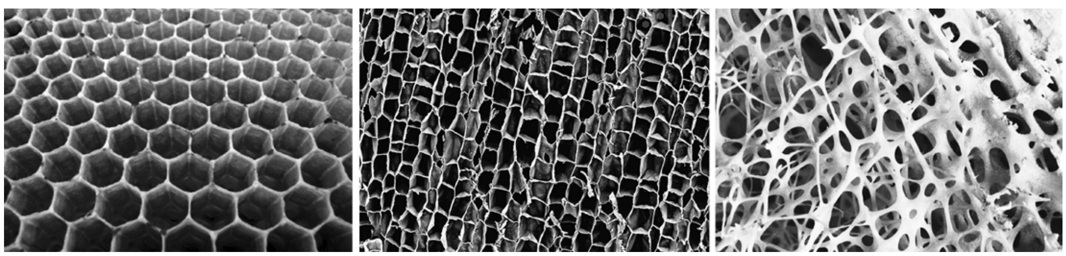

FIG. 1 Type of of cellular structures found in nature. From left: Fig. 1.1a Honeycomb structure of wasp nest; Fig. 1.1b Closed cell structure of cork; Fig. 1.1c Open cell structure in cancellous bone

In this paper, an experimental skin system based on cellular solids is implemented through the combined use of advanced computational design tools and Additive Manufacturing (AM). In particular, the study focuses on the investigation of open cellular solids, based on a lattice structured system, a model that has an efficient way of structuring material (Gibson 2005). Fundamentally, cellular lattice structures are composed of an interconnected network of struts, pin-jointed or rigidly bonded at their connections (Ashby, 2005). At one level, they can be analyzed using classical methods of mechanics, as space frames. On the other side, within a certain scale range, lattice can be considered as a material, with its own set of effective properties, allowing direct comparison with homogeneous materials.

Among the examples of lattice cellular solids, the hierarchical structure of bones is considered as one of the most prominent examples of lightweight and structurally efficient natural systems. Bones are made of a composite material that is about 95% hard calcium-based mineral (hydroxyapatite) marbled with an elastic protein (collagen). The cortical bone makes up the exterior of the bone, while cancellous bone is found in the interior. This has high material efficiency because of its constitutional microstructure based on cells named trabeculae, that are formed through an iterative load-responsive process. Here, an emergent latticework of fibers constitutes a cellular microstructure informed by its loading conditions, which varies in porosity, and in orientation to align with the main stress trajectories to withstand both tensile and compressive forces (Benyus, 2002) (Fig. 2).

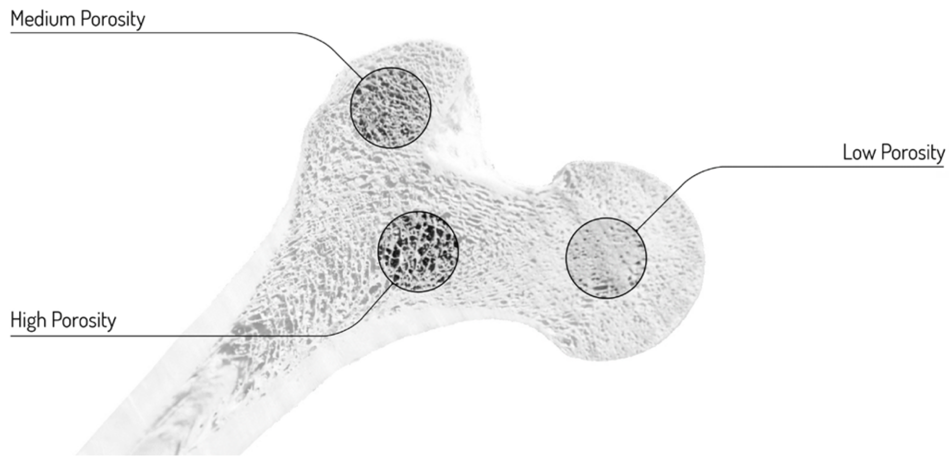

FIG. 2 Section of a human femur bone showing degrees of porosity according to a load-responsive material organization

Interestingly, the process of bone remodelling is responsive to variable loading conditions which an individual can encounter during our life. In particular, this process is subjected to the simultaneous action of two cells - osteoblasts and osteoclasts, that are evaluating local strain values within the bone trabecular structure and adding or removing material accordingly. High strain levels indicate that the bone is weaker than expected and osteoblasts will compensate by adding material in order to reduce strain. Analogously, excessively low strain levels show an unneeded over-mineralization, and the need for osteoclasts to remove material. The balance between these two processes therefore provides a converging point where function and structure are optimized (Turner, 2012). This specific formation process can be synthesized in an algorithm which constitutes the procedural base for the generation of the load-responsive cellular envelope tackled in this paper (Fig. 3).

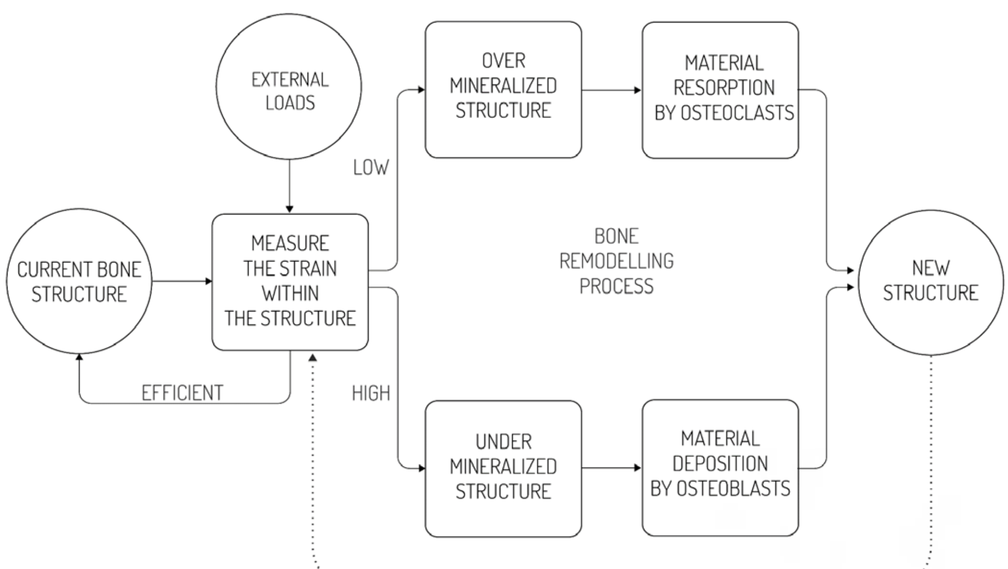

FIG. 3 The algorithm that interprets bone remodeling process (adapted from J.S. Turner, 2012)

2 METHODOLOGY

Specific logics pertaining to the bone remodelling process, such as the informed variation of porosity/relative density and orientation are here developed into a computational workflow for the design, optimization and fabrication of a functionally graded cellular envelope, an innovative system for building skins (Fig. 4). This methodology aims at implementing a biomimetic formation process rather than focusing into mimicking resulting forms. As in nature, the goal is to provide a general method of sustainable materialization to be applied to a potentially infinite variety of formal and loading conditions. This involves the elaboration of a custom algorithmic workflow to generate and materialize lattice cellular solid structures informed by specific mechanical behaviour. In analogy with the bone remodelling process, a method which performs an iterative macroscale mechanical analysis with Finite Elements Methods (FEM) is proposed to compute a specific material optimization of free-form building envelopes. The outcome of this analysis is then directly translated into a lattice cellular microstructure which, in common with the trabecular bone, varies in porosity according to local stress values, and in size to best fit specific shape features. In this process, main input parameters are material properties and fabrication constraints of AM, overall geometry and boundary conditions. Variations in any of these would generate different outputs. Morphological, material and performance information is read, analyzed and modified iteratively.

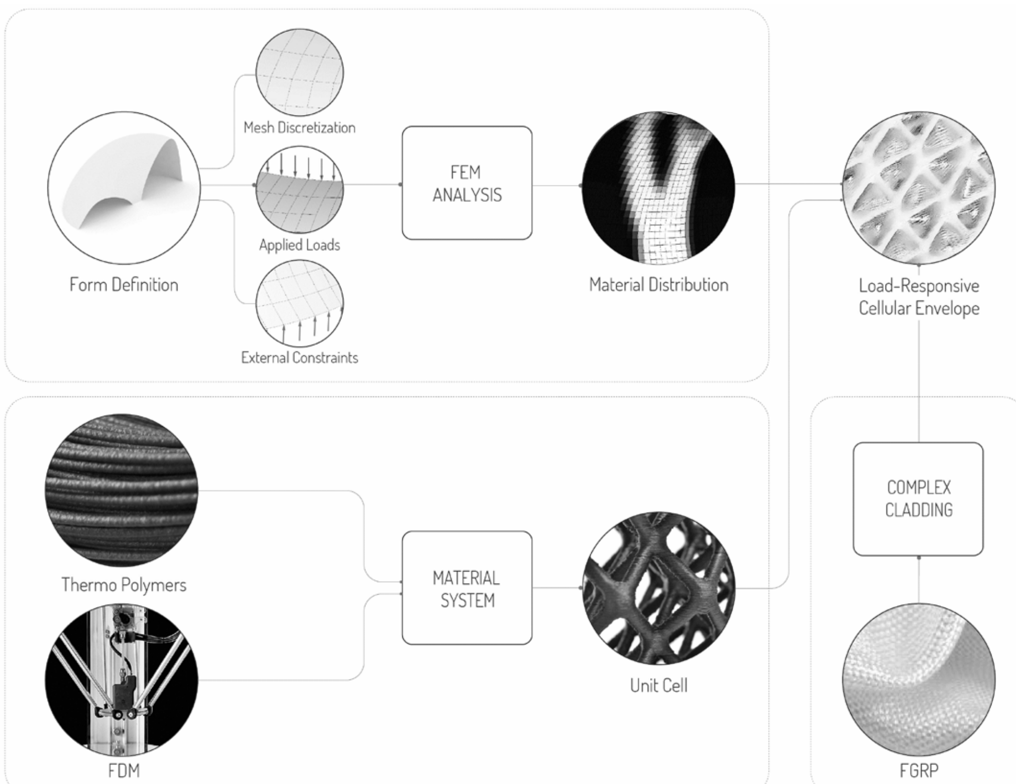

FIG. 4 Scheme of the overall design workflow, involving computational tools, fabrication procedures and material information

This approach has the advantage of being applicable to a wide range of materials. Indeed, mechanical properties of cellular structures are surely governed by those of the material from which they are made of, but most importantly by their topology and relative density. In brief: form does matter, more than material. For this reason, the investigation focuses on the use of Fused Deposition Modeling (FDM) with thermo polymers - an additive method that ensure high complexity and control, relative geometrical freedom, and the use of weight and cost effective materials. This naturally takes advantage from the fact that thermoplastic polymers can be modeled into any desired shape while almost entirely preserving mechanical and thermal properties. The focus is questioning and proving the viability of FDM within the context of a laboratory prototype. Naturally, the application of such technique into real buildings would require further research in the material formulation which exceeds the agenda of this paper. In the workflow of realization of these cellular structures is finally proposed and discussed the integration with a composite cladding system, an external protective layer of glass-fiber reinforced plastic (GFRP).

3 EXPERIMENT / RESEARCH

3.1 MATERIAL SYSTEM OF ADDITIVELY MANUFACTURED THERMO POLYMERS

Within the field of constructions, the shift from prototyping to direct manufacturing is mainly connected to material improvement, which in comparison with product design is more complicated to achieve. Material characteristics and behaviour, mechanical properties and dimensional requirements are key elements in evaluating the use of AM for large scale applications (Naboni & Paoletti, 2015). Therefore, the exploration of a material system should be held in order to understand the way it can be exploited, with a rigorous multi-scalar analysis of the material coupled with the fabrication system that will be used (Hensel, 2011). This process starts with analyzing the materialization process through fabrication experiments and the observation of their geometrical and mechanical characteristics. As result, a set of specific boundary conditions for the fabrication systems, involving machinic, software and material interdependencies is defined.

In the frame of this research it is used a delta-robot, a typology of printer intrinsically agile that guarantees an ideal travel speed for the production of discontinuous geometries such as the lattice structures. The employed material is High Performance PLA (Polylactic Acid), a polymer with discrete mechanical properties which are leveraged by its superior printability. An extensive campaign of fabrication tests have been conducted with it to define print settings in relation to geometric constraints, printing time, printing resolution and mechanical resistance of the lattice microstructure. Among various aspects, an important one emerged in the necessity of evaluating models to be printed according to geometry limitations in overhanging angles, to avoid the need of support geometries with consequent inefficiency in the use of material. The relation between the deviation angle from the vertical axis and the number and thickness of shell elements is fundamentally driving the resolution and refinement of the production (Fig. 5).

3.2 STUDY ON LATTICE CELL TYPOLOGIES

A critical phase in the development of a cellular solid structure is the definition of the base unit cell. In nature this is direct expression of a material system, which accommodates the biological and mechanical needs of an organism. This implies that the above-mentioned geometry constraints of FDM are to be taken first into account in this evaluation. A comparative multicriteria analysis of typical three dimensional cells have been conducted, with an evaluation of printability, relative density and visual permeability. Eight typologies have been analyzed: orthogonal grid (A), star (B), tesseract (C), octahedron (D), cross (E), octet (F), vintiles (G) and diamond (H) (Fig. 6). Each specimen is bounded in a 10 000 mm^3 cube and all the struts have a sectional diameter equal to 10 mm.

An analysis of the geometry constraints has been carried out, focusing on the evaluation of overhanging angles. Considering the XY plane as the leaning plane, a critical threshold for printability is set at 65° angle deviation from the vertical axis. Printing angles below this value guarantees production speed and quality, whereas larger angles can be problematic, in particular with thicker layer heights, as emerged in the description of the material system. From the cell analysis, the octahedron (D) and diamond (E) cells show optimal features for this fabrication process.

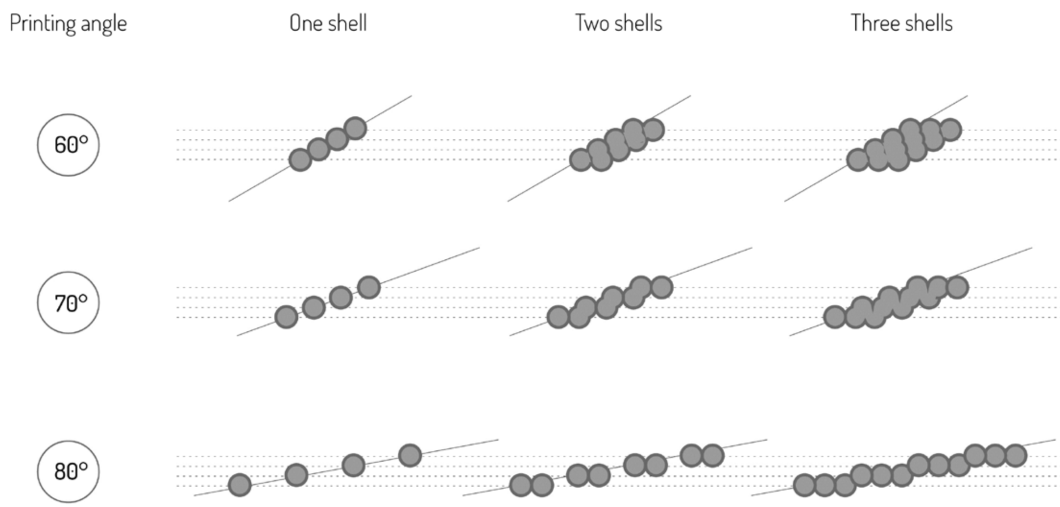

FIG. 5 The scheme shows the geometrical discretization of inclined geometries with FDM. For a printing configuration with 0.7 mm diameter of nozzle extrusion size, and 0.5 mm extrusion height, angles larger than 60 degrees from the vertical axis require the use of multiple shell elements.

In the analysis of relative density are highlighted large differences: on one hand, the Octahedron and Diamond have the lowest relative density of 0.18 and 0.10. On the other hand, cells such as the Octet and the Tesseract have the highest relative density over 0.50, meaning that more than half of the bounding box is occupied by the cell struts, resulting in a stiffer but heavier structure.

Finally, visual permeability is measured in respect to the projection of the unit cells on a vertical plane using a 30° angle of view. This analysis highlights again strong differences among the samples, being the dimensions of the projected areas ranging from 4 900 mm^2 to 12 100 mm^2. Considering that the projected area of the bounding box is 16 600 mm^2, the octahedron with its area of 4 900 mm^2 obstructs about 1/3 of the visual field, while the octet cell blocks around ¾ of the view with a projected area of 12 100 mm^2. Everything examined, octahedral cells have proven to be ideal to guarantee a streamlined production while offering a degree of freedom allowing variable mechanical and visual features.

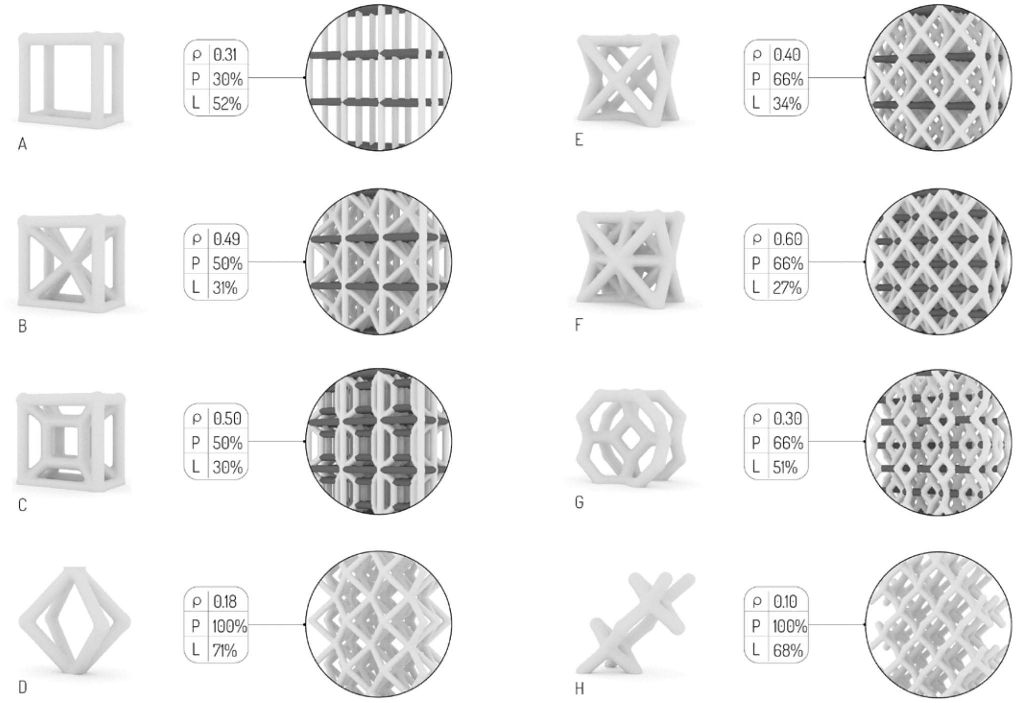

FIG. 6 The image shows eight different unit cells typologies for the Cellular Lattice Structure and their observed characteristics; first column shows unit cell types: A - orthogonal grid, B - star, C - tesseract, D - octahedron, E - cross, F - octet, G - vintiles and H - diamond; second column shows the relative density (ρ), printability (P) and light permeability (L); third column shows the repeated unit cell in a skin system, highlighting in red elements that are not possible to be fabricated with FDM

3.3 FABRICATION EXPERIMENTS OF CELLULAR COMPONENTS

Cellular structures based on the selected octahedral cells have been subsequently tested in different scale of fabrication, starting from samples inscribed in a cuboid with length 150 mm. At this scale, different options of shell thickness and infill patterns have been tested in order to define convenient strength to weight ratio (Fig. 7). In order to evaluate stiffness, lightness and permeability at full scale according to variation in porosity (relative density), larger samples of cellular structures have been manufactured inscribed within a 500 mm wide cuboid component (Fig. 8). Interestingly, same relative density can be reached with different cells size, and very different visual perception. These test samples contributed to the definition of an optimal fabrication resolution, with a measured tolerance of 0.1 mm using an extrusion height of 0.5 mm and a nozzle diameter of 0.7 mm. This configuration proved to ensure the best compromise between production precision and printing speed, with an average production time of fifteen hours.

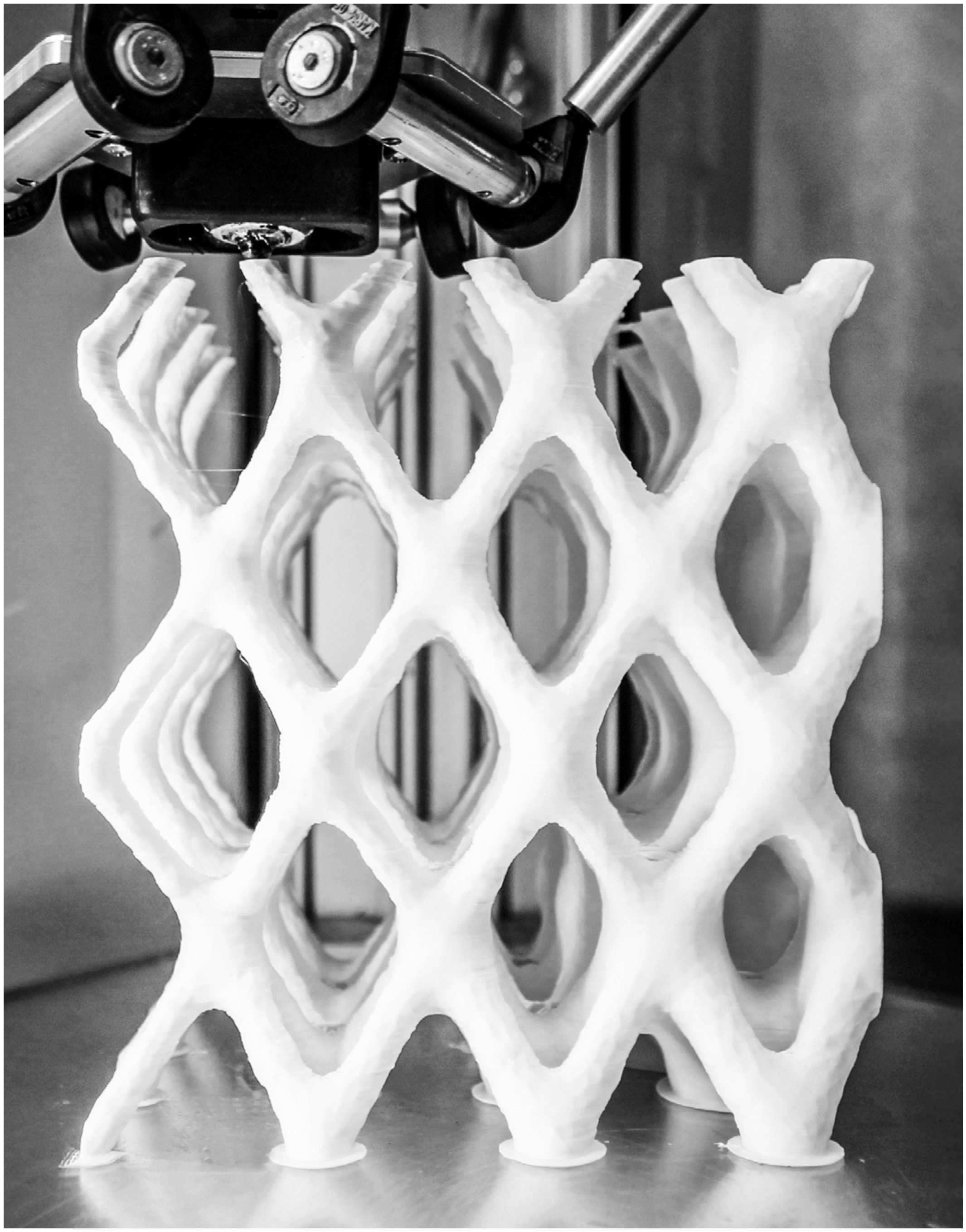

FIG. 7 A small scale sample of cellular structure based on octahedral cells produced with FDM

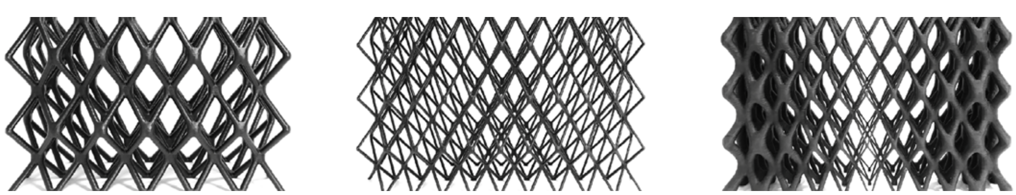

FIG. 8 Prototypical components 500 mm wide with different relative density: from left - $\rho = 0.04$, $\rho = 0.05$, $\rho = (0.04 \text{ to } 0.06)$

3.4 DESIGN AND FABRICATION OF LOAD-RESPONSIVE CELLULAR STRUCTURES

Findings on the fabrication experiments have been implemented in a larger mock-up, realized implementing the overall design workflow outlined in the methodology section. Starting from the selection of a free-form shape, this is evaluated under different external loading conditions, added to its self-weight, obtaining different patterns of material distribution. In the case of this mock-up, it is chosen a configuration emerging from the of dead and live vertical loads (1KN), out of different loading conditions. The algorithmic workflow generates a grayscale representation of the desired stiffness values, which informs the sizing of each single strut diameter (Fig. 9). A portion of this envelope design is prototyped in scale 1:1 to address construction aspects of the load bearing structure (Fig. 10).

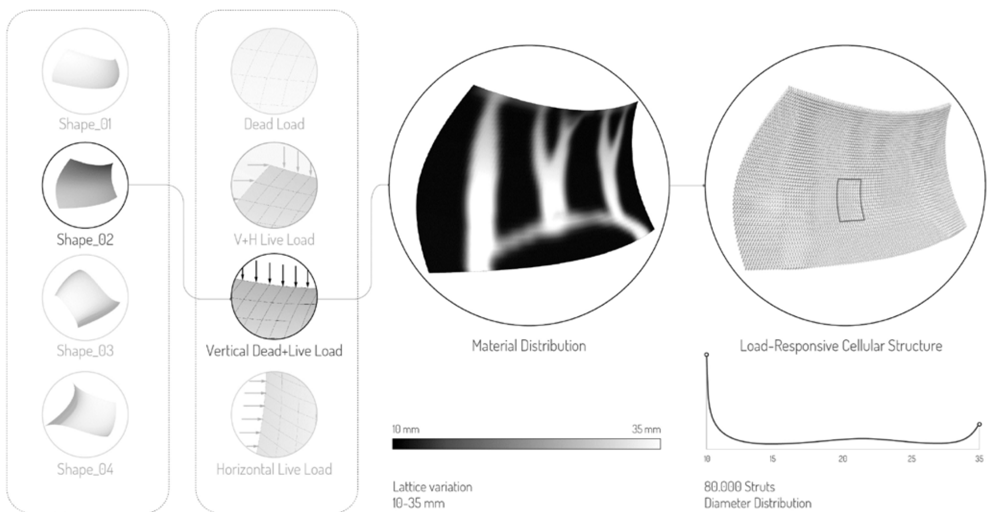

FIG. 9 Workflow of the lattice cellular structure generation from the initial shape definition

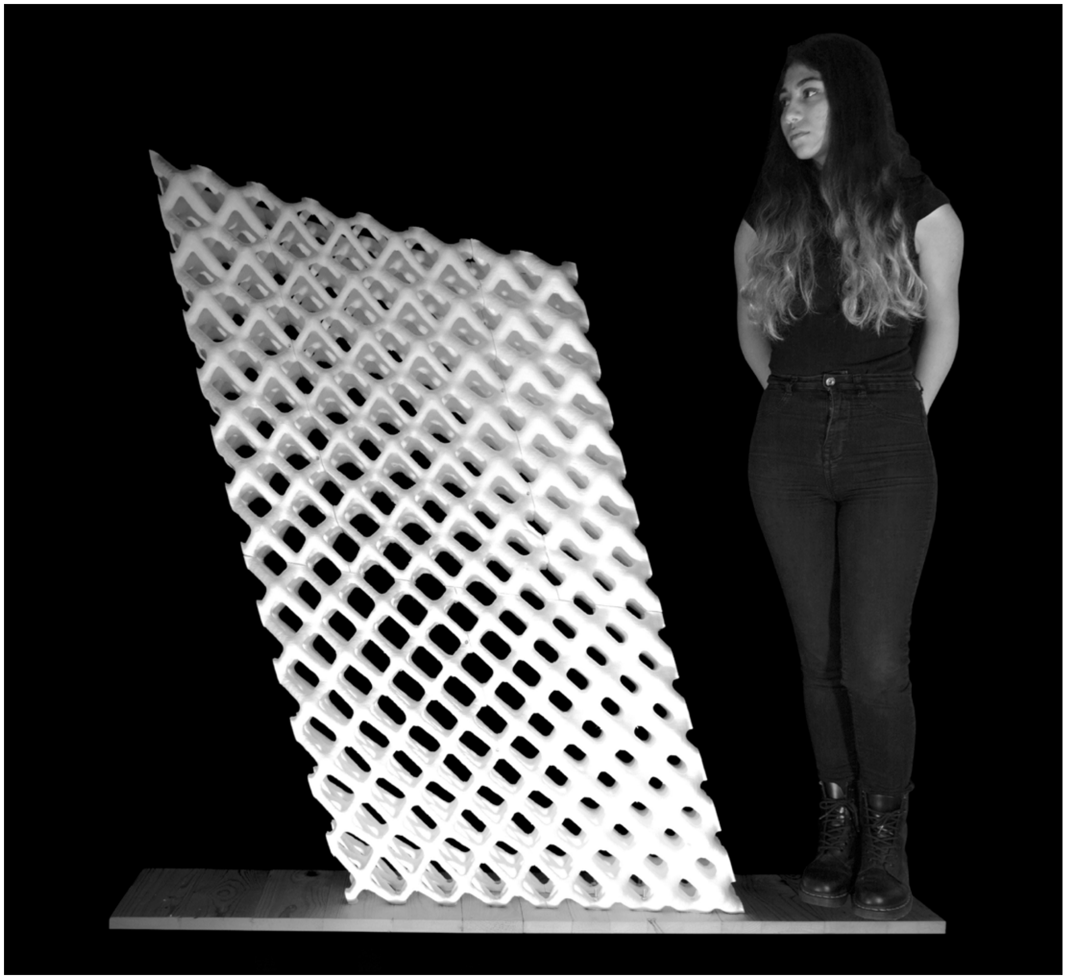

FIG. 10 Full scale mock-up of a 3D printed Load-Responsive Lattice Structure

3.5 INTEGRATION OF A COMPLEX-SHAPED COMPOSITE CLADDING

On the base of the load-responsive cellular structure which was manufactured, a cladding solution is proposed to complete the lightweight building skin with an external protective layer. Visual permeability, allowing light transmission, and exhibiting the constructive geometry of cellular solids, is a required performance. In this sense, it is excluded a solution based on 3D Printing the external skin layer along with the structure, which, because of the layered deposition of material, would result in insufficient light transmission. Referring to cladding solutions instead, the main challenge is geometry-related: the output of the method presented in this paper can be of any shape and curvature. Moreover, cells are different in size and orientation, meaning that no standardized solution can be adopted. The use of Fiber Reinforced Plastics (FRP) has been selected as an optimal solution because of its formability and the chemical compatibility with most of the thermoplastics employed in FDM.

The forming of the composite layer over the cellular structures is made through hand lay-up: a manual process of placing the fiber cloth over the lattice and impregnating it using a brush. This is applied progressively, to ensure the adhesion of the fibreglass to the external cell struts, and to allow the fabric to self-organize in a doubly curved surface in between the cell voids.

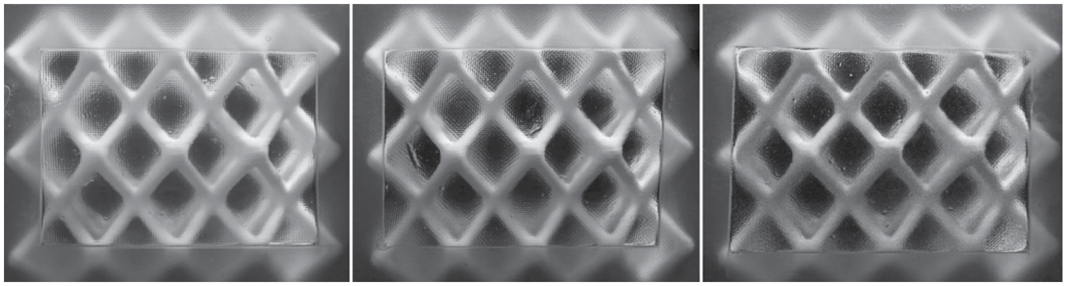

FIG. 11 Experiments on transparency and impact resistance of woven roving: Flat layout (from left) 160 g/m2, 80 g/m2 + 80 g/m2 at 0° and 80 g/m2+80 g/m2 at 45°

The application of a layer of woven glass fibers integrated within a matrix of epoxy resin has been investigated in various densities, in order to define an optimal configuration in function of three main parameters: formability, transparency and impact resistance. A range of levels of transparency and strength of the woven rovings were obtained by experimenting with different thickness of the fibreglass, layout, resin type - especially its own degree of transparency, colour and viscosity - and the amount of it absorbed by the fabric. The layout is characterized by the amount of layers employed, their orientation, and the relation between one another. The rotation of fibres is taken into consideration because combining fabrics with an orientation of 45° improves the strength of the resultant glass-reinforced plastic composite (Kim, Kim and Lee, 2012). Single fiberglass sheets of 80 g/m^2, 160 g/m^2, 290 g/m^2, 390 g/m^2 as well as combinatorial configurations such as 80 g/m^2 + 80 g/m^2 or 160 g/m^2 + 80 g/m^2 at 0° and 45° fiber orientations have been evaluated.

From these experiments emerged that glass reinforced composites made of an overall fibreglass layer with a nominal density inferior to 100 g/m2 are weak and respond poorly in terms of impact and tear resistance. Finally, a 290 g/m2 woven roving is chosen as most proper GFRP configuration for the cladding system of the lattice structure due to its drapability properties, strength and preferable transparency. A clear-glass resin with additives that protects from UV-degradation has been finally chosen. The ultimate configuration resulted in a highly precise cohesion of the fiberglass to the complex doubly-curved lattice configuration that ensured high degree of resistance and structural stiffness with an engaging degree of translucency and pattern exposure.

FIG. 12 GFRP cladding system for lattice structures: 160 g/m² woven roving with single curvature layout

4 RESULTS

The research develops a system for free-form building envelopes based on cellular lattice structures. The design process is inspired by the load-responsive formation of cellular bone microstructure, in particular in the creation of gradients of porosity and cell orientation to improve the response to variable loading conditions. A novel algorithm-based workflow for the design of complex building skins is introduced. This is articulated in: an iterative procedure for FEM analysis of complex envelope shapes, which suggests optimal material distribution; a process of analysis of FDM material system to define base unit cell for the cellular system; the integration with a formable GFRP protective layer. Lattice samples at various scales are successfully prototyped and tested towards the validation of their application in construction. A final full scale mock-up is produced as a proof-of-concept for the load-responsive cellular envelope system, which highlights interesting properties in terms of weight to area ratio, equal to 11 kg/m^2. This is compared with traditional construction skin systems for an intuitive analysis, showing a considerable mass reduction (Table 1). The employed material, High Performance PLA, exhibited ideal characteristics in terms of printability for such geometries, as well as good stiffness and impact resistance

CONSTRUCTION SKIN SYSTEM	WEIGHT TO AREA RATIO [KG/M^2]
Plastered brickwork	339
Curtain Wall	68
Balloon frame construction	73
Cellular Concrete	142
Lightweight Concrete	268
Precast Concrete [hollow planks]	36
Load-responsive Cellular Envelope [Mockup]	11

TABLE 1 Weight to Area ratio values of typical construction skin systems in comparison with the realized mockup of Load-Responsive Cellular Envelope

5 CONCLUSIONS

AM methods have undoubtedly introduced novel materialization processes, where logics of sustainability and efficiency typical of mass-production are no longer applicable. Unprecedented control, precision and freedom of this manufacturing allow the conceptualization of unseen architectural systems. Taking inspiration from the remodelling process of bones, a design methodology which adapts to different shapes and loading conditions is developed. The outcome of this process is an envelope system, which allows the creation of light-permeable load-bearing facades with reduced material usage. This experimental approach challenges current design paradigms of lightweight architecture: complex shapes are neither pre-optimized by shape, nor post-rationalized to meet manufacturing constraints. The system has been successfully tested in a laboratory setup. However, its implementation in operative conditions in buildings would require further developments in terms of material and fabrication equipment. This approach can be easily adapted to the use of metal 3d printing, to offer a more robust material option at current time. However, the rapid development of thermo polymers for 3d printing with increased chemical, mechanical and weather resistance, offers interesting perspectives of application with FDM. Further development of this work will involve the testing in a relevant environment through a full scale architectural demonstrator, where a wider set of evaluative criteria are to be involved. In the long-time perspective, this research offers an alternative approach to the problem of scarcity of resources by shifting the design towards a higher scale of resolution, inferior to 1 mm. At this scale, nature prefers to operate by articulating material into complex formations to minimize the use of material. With this open perspective, complexity in architecture can be considered as a beautiful opportunity.

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