Cellular Building Envelopes

Yasha Jacob Grobman

Abstract The paper argues that the digital revolution in architectural design and manufacturing, particularly the new possibilities offered for the design and manufacture of complex geometry, calls for a re-examination of the traditional concept of the layer-based building envelope which serves only as a barrier. The paper presents a framework for developing building envelopes based on a complex cellular or sponge-like geometry and preliminary design experiments that examine various tectonic approaches to cellular envelopes. The new envelope types, inspired by both cellular/spongy envelopes in nature and monocoque structures in the aviation, automotive and naval industries, are based on simple materials that can be manipulated to generate a complex geometry. The complex geometry of the cellular grid and the cells is developed using parametric digital modeling.

Keywords Cellular envelope · Parametric design · Freeform · Biomimetics

1 Introduction

The building envelope has changed significantly from ancient times to the modern era. It has shifted from being made of massive elements, which were used both for climate control and for structural purposes, into thin elements occasionally made of state-of-the-art materials that do not necessarily have a structural role.

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However, during the entire history of construction, the basic structure of the building envelope, a laminated entity made of different layers that are used as a barrier, has remained unchanged.

Today, the building envelope must cope with increasing demands for performance. The common solution is changing the dimension (mainly thickness) and/or the material of one or more layers that constitute the envelope. This often involves adding advanced high-tech—and thus, usually costly—materials, which pushes up the cost of the entire building. Moreover, the envelopes of contemporary buildings are treated mainly as a threshold that must dispose of rainwater as quickly as possible and avoid vegetation growth (green wall or roof) within the envelope itself. When a green wall or roof is designed, it is added as yet another external layer to the envelope, further increasing the envelope's cost.

The paper argues that the digital revolution in architectural design and manufacturing, and particularly the new possibilities offered for the design and manufacture of complex geometry, calls for a re-examination of the traditional concept of layer-based building envelopes that are used only as a barrier. The paper presents the preliminary results of a research study that develops a building envelope based on complex cellular or sponge geometry. The suggested cellular envelope type, inspired by envelopes in nature, is made from state-of-the-practice simple materials (such as concrete), which can easily manipulated to construct complex form. The final aim of the research is both to develop prototypes for cellular building envelopes and to show that a high-performance façade can be produced by the joint effect of the envelope's material properties and the micro-climate that is being created close to the envelope's surface due to the complex form.

2 Free-Form Design and Manufacturing in Architecture

There is a strong connection between the ability to design a form and the ability to fabricate it. In fact, according to William J. Mitchell, "[a]rchitects draw what they can build and build what they can draw" [1]. Free-form design has been widely used by architects since the end of the 1990s with the introduction of commercial design tools that allow design and manipulation of surfaces based on Non Uniform Rational B-splines (Nurbs). The current decade is witnessing the assimilation of parametric design and Building Information Modeling (BIM) tools and concepts that expand ever further the designer's ability not only to manipulate complex form but also to fabricate it. One can clearly argue that architects today have very few (if any) limitations in formal or geometrical design and manipulation.

One of the most salient advances of the use of parametric design and BIM is the direct connection to fabrication. This allows direct information exchange between architectural design and manufacturing without the need for mediators (construction drawings made by consultants or contractors) [2]. The use of CNC milling machines and other computer-controlled manufacturing machines is being increasingly assimilated into the building industry's standard manufacturing

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process. Moreover, even 3D additive manufacturing machines have reached the size and material capacities of building scale elements and end products.

Indeed, the cost of fabricating a complex form in general and a complex geometry façade in particular is still far more expensive than a traditional orthogonal-layer-based façade. Moreover, the building industry is still oriented toward mass production of standardized elements, and the shift to mass customization, not to mention customized construction, will clearly take some time.

However, it seems safe to argue that the shift toward computer manufacturing and especially large-scale CNC milling and 3D printing will continually reduce this gap. Therefore, given the understanding that the cost of computer-based manufacturing will drop in the near future and the difference between orthogonal form and freeform computer-based manufacturing will diminish if not totally disappear, there is both an opportunity and a need to examine the performance potential of freeform envelopes in architectural buildings.

3 Inspiration from Nature

Building envelopes have numerous distinct functions. Hutcheon [3] organized these functions into two groups with a total of 11 functional requirements.

The first group consists of the items that relate to the facade as a barrier for the control of heat flow; air flow; water vapor flow; rain penetration; light, solar and other radiation; noise; and fire. The second group consists of overall requirements, such as providing strength and rigidity; being durable; being esthetically pleasing; and being economical.

Similar functional requirements exist in the natural world. During evolution, living organisms developed various approaches and strategies to fulfill these requirements. Architecture has a long history of looking at nature for inspiration. Some approaches concentrated on the rather formal aspects of nature or natural form. These approaches include, among others, art nouveau architecture [4], organic architecture [5] and zoomorphic architecture [6]. The focus of this research is a different approach, generally called biomimicry, which examines the performative aspects of natural form and tries to extract insights for creation of architectural form and processes [7, 8]. More specifically, this research examines skins and envelopes in flora and fauna as a possible inspiration for the performance of a building façade.

A recent review by Gruber and Gosztonyi [9] presented a summary of the sparse existing academic research and studies related to biometric façade and compared the functions of skins of organisms and their analogy in architecture. A more specific study by Badarnah et al. [10] examined various strategies for thermoregulation based on insights from nature and shading strategy based on organizational feature in leaves [11]. Laver et al. suggested a cellular structure for a high-performance masonry wall system based on insight from termites and barrel

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cacti [12]. None of the above described research suggested an overall framework or an argument for a shift to a cellular approach in building envelopes.

4 Why Cellular or Spongy Envelopes?

Ever since the modernist separation between the structure and the building envelope, the development of building envelopes has concentrated mainly on finding new materials, combining materials, or shear optimization of the performance of the building envelope's various layers and their combined performance.

Knippers and Speck [13] argue that traditional architecture and civil engineering define construction in two separate categories: material and structure. They claim that this separation is impossible in natural world structures, which could be divided into five to twelve interconnected hierarchical levels in different scales/levels (biochemical level, microscopic level and up to the ultra-structural level). They define an important characteristic of natural system as being multi-layered and having a "finely tuned and differentiated combination of basic components which lead to structures that feature multiple networked functions."

Comparing building envelopes and natural envelopes or skins, one can clearly see that one of the main differences between the two has to do with the cellular-based structure. Natural skins or envelopes—and in fact, a large percentage of natural tissues—are based on cellular units [14]. These cells are characterized by complex 3D freeform (as opposed to the flat envelopes of buildings), which is based on geometric and material logic; multi-functionality; structural and formal heterogeneity; and multilevel hierarchical structure that consists of both isotropic and anisotropic structure according to local needs (the characteristics are based on Knippers and Speck's design principles of natural systems).

As opposed to the complex cellular structure of natural skins, traditional building envelopes are typically based on flat (extruded 2D) orthogonal geometry, repetition, limited functions (usually as a barrier) and structural homogeneity (frequently the envelope does not have a structural role). Developing cellular building envelopes that are based on a number of natural cellular skins principles and cellular/sponge-like geometry [15] could facilitate a multifunctional envelope system that could offer the following advantages:

- A single spatial structure—This could function as a barrier, water collector, shading mechanism and green wall. This represents a shift into more efficient building structure based on ideas implemented in monocoque structures, which are currently used in the naval, aviation and automotive industries.
- More than a threshold—The suggested envelope changes the narrow perception of the building envelope, which is currently regarded almost exclusively as a threshold. It challenges the perception that rainwater must be avoided and/or

disposed of rapidly in building envelopes by allowing a certain amount of water to be collected inside the cavities, where it will be used for cultivation of plants. Thus, the envelope itself also turns into a green wall (as opposed to the current need to construct a special layer for plants). Previous research has shown that green walls offer considerable benefits by reducing heat islands, helping to conserve animal habitats and saving on infrastructure costs (by retaining some of the water and reducing demands, especially in extremely rainy conditions) [16].

- Microclimate—There is a possibility of using the air flow close to the envelope's surface to create a microclimate. As opposed to the traditional layering approach, a parametric complex geometry approach to the building envelope is fundamentally based on a cellular or perforated surface in which the spatial relationship between the filled spaces and the hollow spaces is controlled parametrically and is used to create a microclimate. The microclimate can be optimized for insulation, ventilation, light, draft, water conservation and the cultivation of vegetation (green wall) according to the demands [17, 18].
- Form heterogeneity—There is a possibility of creating a variation of envelope cells that would be customized to deal with changing local conditions within the building envelope.
- Simple materials—In terms of materials, the suggested approach suggests a shift to building envelopes based on a small number of simple, widely used materials, such as concrete. This could have significant ramifications, since the creation of high-performance, low-cost envelopes could considerably decrease the buildings' energy consumption.
- Decrease of the environmental impact/footprint of building—This would occur due to the increase in performance and the possibility of embedding green walls and using storm water collection [19].

A shift to building envelopes based on freeform cellular geometry and logic also entails some challenges or disadvantages. One of the main challenges has to do with the programmatic flexibility of customized complex forms. As it is suggested that the envelope would be tailored to fit both the external and internal needs of a specific program, one can assume that during the buildings' lifetime the internal program is liable to change. This might change the demands, for example, for natural illumination. In traditional buildings where all openings are similar, this would not be a problem, but in customized buildings, the opening demands of one programmatic function might not well serve other functions.

Another disadvantage is cost. Although it is expected that the cost of fabricating complex geometry will be reduced substantially when computer-based fabrication becomes widespread, it is logical to expect that there would be a cost difference as compared with manufacturing an envelope based on repetitive elements.

Other possible challenges have to do with the fact the living envelope has to be carefully maintained and that complex form might not be well accepted by the client that who is accustomed to traditional orthogonal buildings.

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5 Precedents for Cellular or Spongy Building Envelopes

Although freeform architectural design in general and freeform cellular or spongy form in particular demands computer-based manufacturing for its realization, the notion of cellular buildings and building envelopes is not a new one. The following sections will briefly describe precedents for cellular or freeform envelopes.

While freeform architecture was not common in the post-industrial revolution period, architects such as Antoni Gaudi, Eladio Dieste and others were able to design and build highly articulate building forms and building envelopes. However, even though the entire form of some of their buildings was complex, the envelopes of these buildings were still based on traditional building methods and did not try to postulate better performance as a result of the form.

At first glance, one might consider Gaudi's well-known Casa Mila project (La Pedrera in Barcelona, Spain, 1910) as an example of a complex cellular façade due to the formal complexity of the envelopes. Nonetheless, a deeper examination reveals that the façade design is driven by solely formal aspects and that no argument was suggested by the designer for the performative aspects of this type of envelope.

Erwin Hauer's work and research on complex 3D wall systems (mainly for interiors) can be considered one of the early examples of cellular complex 3D logic in building walls [20]. He developed and implemented complex 3D repetitive units, mainly from concrete, back in the 1950s (see Fig. 1). His walls are principally orthogonal, but the units or cells that populate the grid he creates within the wall are formally complex. His work has been an inspiration to later research that tried to use parametric design tools to examine possibilities of creating both complex wall systems (as oppose to Hauer's orthogonal walls) and replacing the repetitive grid and tile with parametrically modified ones [21].

A different perspective on cellular approach to building envelopes is derived from Leatherbarrow and Mostafavi's idea [22] of the "denial of the frontality of the façade" in relation to Le Corbusier's introduction of the *brise-soleil*. The façade's frontality and flatness is replaced in this case with a space that acts as a light control mechanism but also challenges the notion of the flat building envelope. A more general perspective regarding this notion could refer to kinetic building

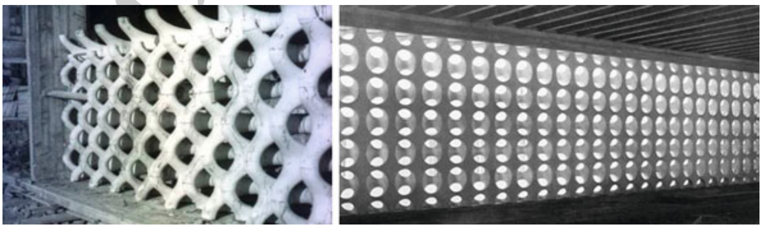

Fig. 1 Erwin Hauer—church in Liesing, Vienna, Austria, 1952 (*left*). Church in Erdberg, Vienna, Austria, 1954 (*right*). *Source* www.erwinhauer.com

envelopes. A well-known example in this realm is Jean Nouvel's Arab World Institute (Paris, France, 1987). An earlier but comprehensive discussion on kinetic building and envelopes can be found Zuk's book on kinetic architecture [23].

The introduction of computers to architectural design and particularly the use of parametric design "offers a high degree of geometric control combined with ability to rapidly generate variations" [24]. According to some researchers, the assimilation of parametric design methods and tools in architectural design and manufacturing has introduced a new "style" called Parametricism to architectural design and stimulated experiments in both urban and building (mainly envelope) scales [25, 26]. Parametric tools such as ParaCloud generative modeler (GEM) and Grasshopper (generative modeling tool for Rhino) have made it possible to generate complex geometry and to connect the architectural form to simulation software [27]. Parallel to research that concentrated on the geometric aspects of building envelopes, a considerable amount of research has been dedicated to the idea of performance in architectural [28, 29] and computational material [30, 31]. The new direct data exchange between these ideas and tools and computer-aided manufacturing tools, such as CNC milling machines and laser cutters, has fostered a flurry of parametrically designed and computer-manufactured structures, mainly in pavilion or installation scale, over the last 5 years [32, 33].

At the outset of the computer's assimilation to architectural design and manufacturing in the late 1980s, design experiments initially concentrated on creating new types of building layers, such as inflated materials (for example, the Beijing Olympic swimming pool by PTW Architects (Fig. 2) [34], Allianz Arena by Herzog and De Meuron architects [35] and the Eden Project by Grimshaw-Architects [36]. Subsequent experiments with complex geometry façades concentrated on the new potential for manipulating complex forms that required almost no attention to the envelope's performative aspects [37]. See also, for example, Migrating Formations wall by Contemporary Architecture Practice (Fig. 3) [28], KOL/MAC Architecture's INVERSAbrane building envelope [28], Greg Lynn's Blobwall [28] and Gramazio Kohler's The Dissolved Wall/Screens projects [37].

Fig. 2 PTW architects—watercube—Beijing National Aquatics Center, Beijing, China, 2003. *Sources* http://www.ptw.com.au, http://www.terrywier.com/, http://www.flickr.com/photos/xiaming/484446352/lightbox/

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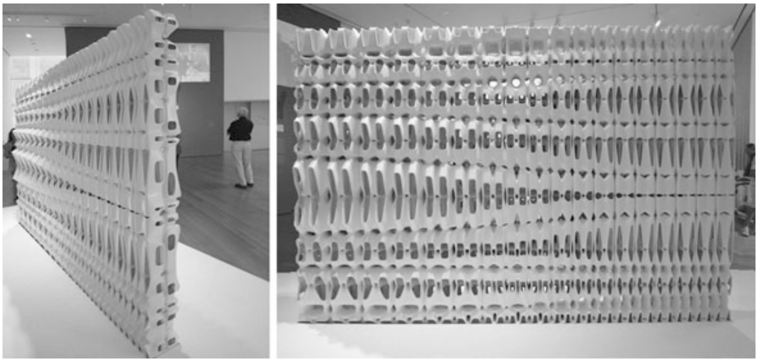

Fig. 3 Contemporary architecture practice (CAP)—migrating formations, New York, USA, 2008. *Source* Grobman and Neuman [28], p. 97

6 Cellular Envelope Design Experiments

The following section presents preliminary design experiments that examine the potential and trajectories in the design of cellular building envelopes. The method used in the design process of these projects combines digital form-finding methods with more traditional formal design methods. It thus combines ideas from research by design approach [38, 39] and digital and non-digital form-finding [27]. The design method used for these experiments is based on "populating" cellular elements on the cells of a grid that was generated for each of the experiment's envelopes. The rather complex grid that is used in each of the experiment is developed from initial regular grid that was modified according to performance criteria such as orientation, program (of the spaces behind the façade) and function of the specific areas of the facade. For example, an area which is intended for utility equipment does not usually needs a similar amount illumination as areas which are used for offices. Each of the final cells in the grid was populated by a different cellular element according to its location and function (type of space served by the specific cell of the envelope).

Each one of the three different experiments examines a different approach to cellular envelopes. In the first approach, the grid is used as a structural element and the cellular elements are inserted in the spaces created by the grid. As opposed to the duality characterizing structure and cells suggested in the first experiments, in the second and third experiments the grid serves as both a structure and a barrier.

6.1 Experiment No. 1

A cellular unit is populated inside a Voronoi based geometry grid (Fig. 4). Each unit is unique and made to fit a specific position in terms of size and performance.

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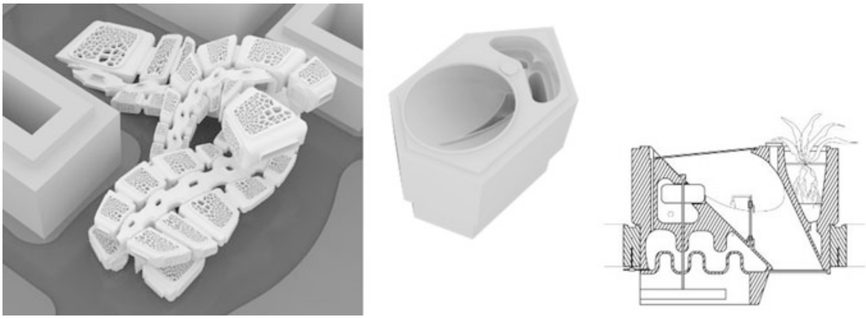


Fig. 4 Experiment no. 1 envelope with a structural cellular grid based on Voronoi algorithm geometry (*left*). Isometric view of a cell unit (*middle*). Section of a cell unit (*right*)

The unit presented in Fig. 4 contains the following elements: a place for a plant; a solar radiation system based on heating water by means of focusing the solar radiation using a circular surface; and a ventilation heat-exchange system based on a turbine. A cell unit can contain these entire features or any a combination of them, based on local need.

6.2 Experiment No. 2

The envelope is created from a family of cellular units, which are used both as a structure and as an infrastructure for functions such as shading, growing plants and isolation. The envelope's front view in Fig. 5 shows an example of the parametric approach to populating the cells in which the designer can choose a specific member from a unit family for every position in the envelope. The units' function can vary; it can serve as a passage, a room/space or a balcony.

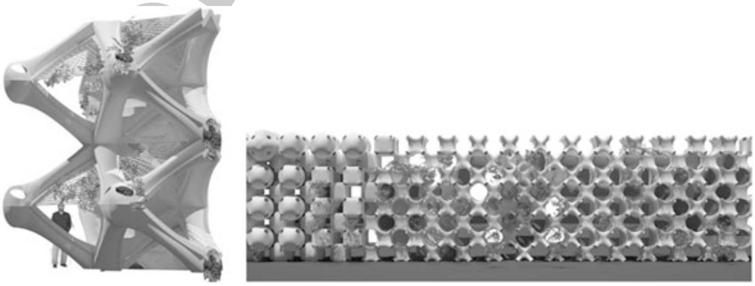


Fig. 5 Experiment no.2—Isometric view of an envelope unit (*left*) and a front view of an envelope (*right*)

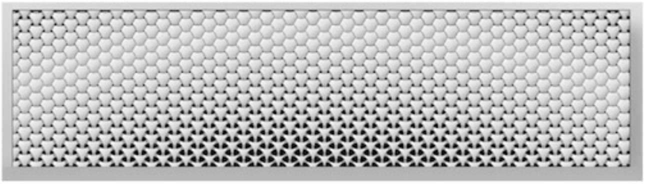
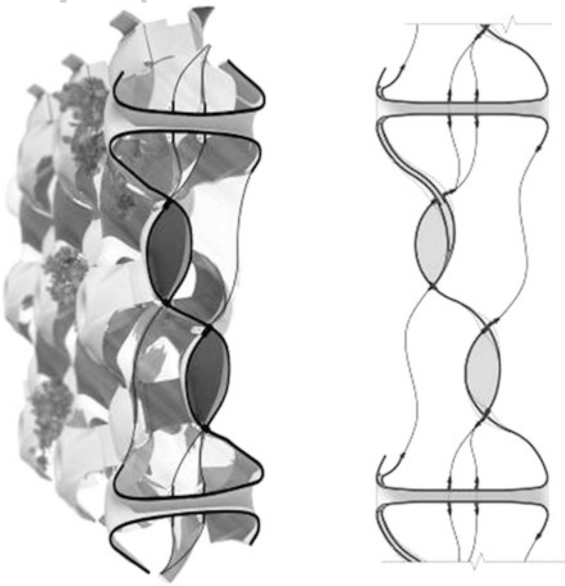


Fig. 6 Experiment no.3—envelope, front view

6.3 Experiment No. 3

This experiment presents a similar system to the one developed for the previous experiment in terms of the parametric population of the cells within the grid and the multifunctionality of the cellular unit. The main difference between the two experiments is that the current cell system is based on a singular unit that allows a gradual change in its dimensions. This allows the creation of a continuous variation in the envelope units, which in turn gives the envelope a more organic formal expression (see Fig. 6). The system is built from a structure of fiberglass and metal, which create the structure for Ethylene Tetrafluoroethylene (ETFE) air cells that are used both for thermal isolation and for transferring natural light (see Fig. 7).

Fig. 7 Experiment no.3—section (*left*) and isometric rendered section in the envelope (*right*)



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7 Conclusion and Future Research

The approach and the design experiments described above present the initial framework and possible trajectories for developing cellular building envelopes. Although several design directions have been developed and the concept seems plausible from the design and manufacturing viewpoints, the next stages of the research has yet to prove the possibility to reach similar performance in various environmental criteria as in traditional envelopes.

The significance of the proposed approach lies in the centrality of the building envelope to the design, manufacturing and performance of buildings. The resulting shift in the traditional concept of building envelopes could potentially improve the building's overall energetic performance, decrease urban heat islands by allowing vegetation to grow over the envelope and reduce the infrastructure needed for handling rainwater. Moreover, the new possibility of creating low-cost complex geometry envelopes that embed vegetation as an integral part of the envelope itself could trigger a dramatic change in the way our built environment looks and behaves. From the current strict division between built and green areas, our built environment would become—to a certain extent, at least—all green.

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