Scutoid Brick

The Designing of Epithelial cell inspired-brick in Masonry shell System

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This paper focuses on the design of individual bricks in a masonry shell system that are inspired and informed by the reorganization of epithelial cells within tissues. Starting from a newly discovered shape called "Scutoid", we first investigated how epithelial cells within living animals are packed three dimensionally within tissues. We focused on the living mechanisms within these cells that facilitate tissue curvature in the creatures' organs, skin, and blood vessels. By utilizing this generative geometric approach, we created a series of parametric generators and modeling kits to represent this mechanism and process. We then explored the potential for adopting this mechanism into larger-scale settings. Meanwhile, we discovered that the deformation of individual epithelial cells during the bending process generates an intriguing triangular connection along the bending direction. We managed to translate this unique feature to the architectural scale as a joint system for connecting bricks in a masonry shell structure. Based on the above findings, we designed and fabricated a set of models for the masonry shell structure that are generated from scutoid bricks and this unique joint. The geometrical characteristics of scutoid bricks allows the packing of four bricks with just two joints. The work that we have generated thus far contributes to solving issues of shell design and fabrication from the perspective of individual units. The result of the shell structure model demonstrates that applying the epithelial cell inspired-block masonry system is a feasible approach for the construction of shell structures.

Keywords: *Epithelial cell, Scutoid, Bio-inspired Design, Generative Design, Masonry shell*

INTRODUCTION & BACKGROUND

Due to the limitation of imaging technology at the nanoscale, a comprehensive visualized description of epithelial cells' three-dimensional appearance has been missing from the field until recently. Most biological researchers understood the shape to be similar to columnar prisms or a frustum shape. In 2018, through the approach of mathematical modeling, A group of scientists from Universidad de Sevilla (G´omez-G´alvez, Pedro, et al, 2018) unexpectedly predicted that as the curvature of these epithelial tissues increases, some of the epithelial cells would likely develop into forms other than columnar prisms and frustum shapes. The research claims that this unique three-dimensional geometry is a transition volume between a pentagon and a hexagon with an added vertex (Figure 1). Researchers named the shape "scutoid" because the backs of some insects (Protaetia speciose) have a similar mini-triangular shell. Additionally, researchers successfully found that some of the epithelial cells present the same shape in several highly curved epithelial tissues in various creatures such as drosophila and zebrafish's renal tubule and thyroid follicles. The discovery of the scutoid has brought new geometric inspiration to understand the three-dimensional structure of epithelial tissues. Epithelial cells are one of the most critical cells in the early stages of every animal. They are capable of reorganizing themselves into different shapes to envelop cavities. This capability allows epithelial tissue to establish barriers for the creature's body from the external environment and deform the barriers to fit with the environment.

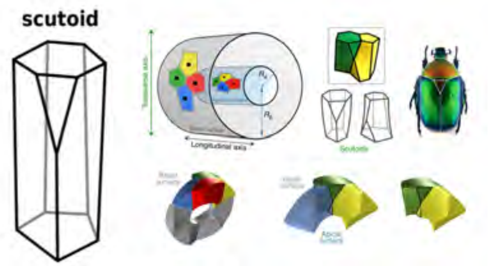

Figure 1
The findings of scutoid, photo credit to Gómez-Gálvez, Pedro, et al (2018)

There are two parallel goals in this paper. First, we aim at investigating the deformation mechanism of epithelial cells to enrich our overall understanding of how the epithelial cells present the scutoid shape by setting up a series of parametric models and visualized generators from the perspective of design research instead of cell biology. Specifically, this paper looks into dialectical relations between global morphology and individual units at a micro-scale. Meanwhile, situating this from a design perspective, the paper aims to adapt the deformation mechanism of epithelial tissues and the concept of the scutoid into a novel design application. Notably, inspired by Scutoid geometry, we designed a new masonry system termed Scutoid Bricks. The system can be used to enhance a joint in a masonry structure, as the scutoid shape in epithelial tissue exhibits certain impressive features that we can potentially enlarge to a macro scale.

Epithelial cells deform and proliferate themselves into multicellular tissues during embryonic development (Lecuit, Thomas, and Pierre-Francois Lenne., 2007). These tissues will eventually become various organs in our body. Primarily, serving as a medium to isolate different biological tissues as epithelial cells constitute the surfaces of creatures' organs and blood vessels. They form the skin of the creature, establishing a barrier for the creature's body from the external environment. Epithelial cells have other chemical and physical mechanisms, such as regulating the exchange of chemicals inside tissues and body cavities, etc. Our project specifically focuses on the mechanism that allows epithelial tissue to deform itself into complex geometry. To achieve the wide range of functions mentioned above, epithelial tissues have evolved to develop complex and diverse cellular structures that exhibit unique structural features at multiple dimensions. These features allow epithelial tissues to form into a complex surface to fit with a given environment.

In 2D space, considering a single layer of epithelial tissue as two-dimensional lamellar, it can be represented by a two-dimensional sheet. Studies found that the deformation capability of epithelial tissue as a 2D lamellar is achieved through its cell rearrangement. As the primary mechanism of tissue deformation, epithelial cells rearrange themselves to a new position without being separated from the adjacent cell according to a topological T1 transition (Kong, D., 2017). A single layer of epithelial tissue is composed of adjacent and closely connected epithelial cells. In this two-dimensional cell model, isolated cells can be approximated as circles. When two cells engage with each other, their common boundary can be represented by a straight line. The length of this common boundary depends on the distance between the geometric centers of the two cells. The closer the two cells are, the longer the common boundary is. When four cells are packed together, cells squeeze each other in both horizontal and vertical directions. If two of the four cells are neighboring with each other horizontally, the other two cells are isolated vertically. The distance of isolated and neighboring cells are inversely proportional. The closer the geometric centers of neighboring cells are, the further away the isolated cells are (Figure 2).

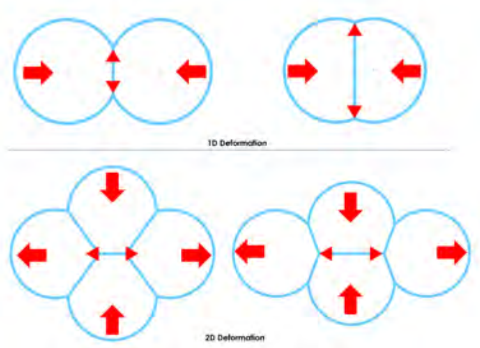

Figure 2
1 and 2-dimensional deformation of cells

Expanding this into 3D space, for most healthy epithelial cells, the columnar appearance of epithelial cells is one of the critical morphological features. Geometrically, a columnar epithelial cell is composed of basal and apical surfaces, and the deformation process of epithelial tissue is a surface that, with thickness, bends at a particular position. When the tissue is bending, the basal and apical surfaces associatively perform the T1 transition to rearrange its position. Epithelial cells often have significant polarity, which is not only presented in the different functions and structures of basal and apical surfaces but also the various movement tendencies. The basal and apical surfaces of any pair of adjacent cells, that share one common boundary, will have a different motion tendency. If the tissue is bent toward the basal surfaces (Figure 3), the basal surfaces of the two cells will two-dimensionally squeeze each other. At the same time, the apical surfaces will tend to separate from each other. However, due to the presence of adhesion forces between cells, adjacent cells will not be immediately isolated and their common boundary will not disappear quickly. In the process of tissue bending, with the increasing curvature of the tissue towards the basal surface, the boundary line between the two adjacent apical surfaces will gradually become shorter (Figure 4). Until the curvature reaches a certain level, both apical surfaces are separated. The basal surfaces that two-dimensionally squeeze against each other will produce longer boundary lines. When four such cells are packed together, two cells that don't align along the bending direction will also have different motion tendencies on the basal and apical surfaces. The two apical surfaces that get closer with each other will occupy the space that is vacated after the detachment of apical surfaces. As the tissue bends, the basal surfaces that squeeze each other will occupy the space left by another pair of basal surfaces.

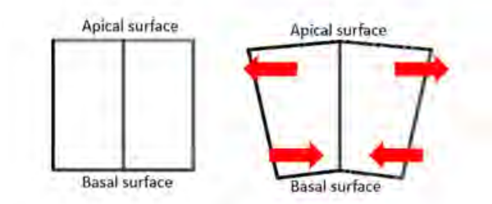

Figure 3
The tissue is bent toward the basal surfaces

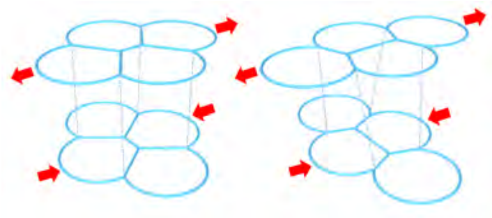

Figure 4
3d deformation on apical and basal surfaces

Studies (Rupprecht, Jean-Francois, et al. 2017) also found that such polarity can not only be observed on basal and apical surfaces. This is observed inside of the epithelial cell cluster with the help a microfluidic device. The common boundary between adjacent cells exhibits various lengths at different depths (Figure 5). Given the fact that cells are competing for space under geometric constraints, we realized that at a certain depth within a group of cells, the length of the common boundary would reach 0. It means the initial adjacent cells are connecting through a vertex, while the formerly separated cells that are perpendicular to the bending direction are also connecting through the same vertex. Our initial modeling strategy is based on the geometrical feature described in (G´omez-G´alvez, Pedro, et al, 2018), where the scutoid is a volume that transitions from a pentagon to a hexagon. We found that the vertex mentioned above plays a critical role in the modeling process of a given scutoid shape. Deeper within the cells, two of the hexagonal neighboring vertices on a surface merge to the mentioned vertex. By doing so, the hexagon on the apical surface converts to a pentagon in the middle of the cell's volume and keeps this formation until it reaches the basal surface.

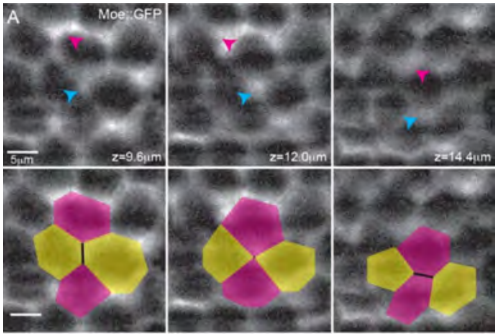

Figure 5
The common boundary between adjacent cells exhibits various lengths at different depths. Photo credits to Rupprecht, Jean-Francois, et al (2019)

Furthermore, based on the above researches and our deduction, we can conclude that the T1 transition of cells rearrangement is achieved through cell revolve and squeeze. Cells vertically revolve along the horizontal axis resulted in different movement tendencies on apical and basal surfaces. Adjacent cells revolve toward the inverse direction resulted in boundary length change. As for the classic scutoid shape, the triangular that transitions from hexagon to pentagon is also generated by cells squeeze. (Figure 6)

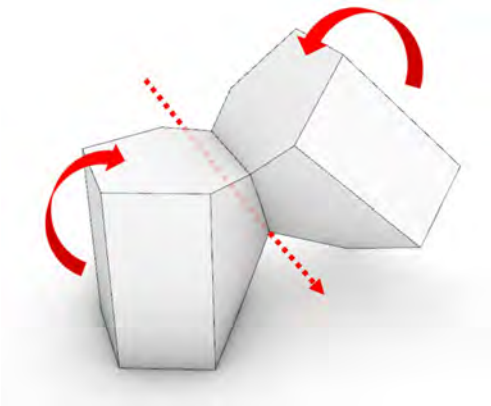

Figure 6
Cells vertically revolve along the horizontal axis resulted in different movement tendencies on apical and basal surfaces.

The discovery and research above allows us to establish a framework for building a parametric model of Scutoid geometry. Our initial model is composed of three layers. Besides the two necessary outer layers to form the basal and apical surface, we also set up an intermediate layer to arrange the key vertex. On both outer layers, we defined eight fixed vertices and two dynamic vertices to form a pair of adjacent hexagons, where the length of the common boundary can be changed. Perpendicular to two adjacent hexagons, we defined another four fixed vertices to form the associated pentagons which are separated from each other. However, on the intermediate layer, we identified 13 fixed vertices and formed four pentagons which are sharing the center vertex. The formation of these four pentagons on the intermediate layer won't be impacted by the movement of vertices on the outer layers. By connecting the center vertex on the intermediate layer with the dynamic vertices on both outer layers, and then connecting the remaining fixed vertices, we established a parametric wireframe model of scutoids that represent four epithelial cells packed together (Figure 7). The morphology of each cell in the cluster is determined by the length of the common boundary of adjacent hexagons. When the cluster model starts folding towards the basal surface, according to the T-1 transition, two hexagons on the apical surface detach from each other. The common boundary gets shorter and the pentagons on the same layer merge closer. Conversely, the common boundary of adjacent hexagons on the basal surface becomes longer as hexagons are further apart, while the pentagons on the basal surface separate from each other.

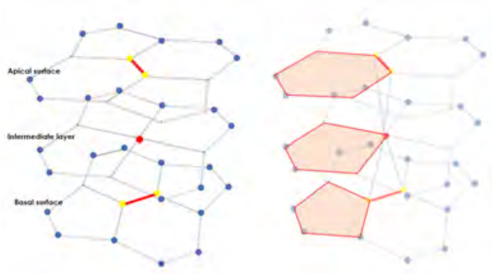

Figure 7
The framework of the parametric model of Scutoid

RELATED WORK

As a recent discovery, scutoid related studies are still at an early stage. Yet, there are still some associated works that positively support our investigation. (Mughal, A., et al.2018) successfully reproduced the scutoid-like soap bubbles between curved surfaces on a larger scale, as they inject soap water between two highly curved surfaces, which have an 18mm distance in between. The scutoid bubbles can be observed directly in the soap water without the usage of any device. But in the controlled experiment, no scutoid-like soap bubbles can be found in between two flat surfaces. As the discovery of scutoids can only occur in highly curved epithelial tissues, this experiment verified that curved space is a necessary condition of generating scutoid. In other words, locally converting columnar prisms to scutoids can facilitate the overall curvature of global geometry that is packed by individual units. Furthermore, this study validates the existence of scutoid in a non-bio setting yet with less discussion of practical potentiality or quantitative description of scutoid.

Parallel to experimental verification, (Subramanian, Sai Ganesh, et al.2019) started looking at the potential applications of scutoid in a more practical spectrum. They proposed a 3D space-filling approach by applying scutoid as its modular structure. They hope to develop new component-based space-filling tiles to compensate for the limitations on the structure's reliability and strength that is led by traditional prismatic filling units (like rectangular brick). Researchers have developed an algorithm that takes as input two planes containing Voronoi tessellations and inserts tiling between the top surfaces based on the distribution of points, then lofted each contour profile generated through the previous step into a 3D volume. This project didn't realize the fact that the form generation of apical and basal surfaces isn't conducted through the Voronoi algorithm in epithelial tissue, although it looks very similar. Also, this project proposed a 3D space-filling approach without giving an application scenario. But still, through this paper, we realized that Scutoid shape has its potential to be designed as component-based space-filling tiles for assembling global geometries to overcome the drawbacks of cubic tiles such as regular bricks. In terms of morphology, we argue that the scutoid, as a widely existing geometry, should not be limited to the initial description of the transition from the pentagon to the hexagon. A more arbitrary geometrical definition of scutoid is still missing within this subject. According to our investigation, the number of polygon segments at the basal and apical surfaces of a prismatoid is an essential factor that determines the scutoid. We defined two conditions that are required for prismatoid-like geometry to be recognized as scutoid. First, the numbers of the polygons segment are not equal on apical and basal surfaces; second, two vertices on one surface can be merged into one vertex on the intermediate layer to equalize the polygons segment.

As we aim to adapt epithelial tissue deformation into a design space, we also examined previous work that borrows findings from biological models into architectural design research. Taking the mammary gland as a starting point, Sabin and Jones (2008) in-

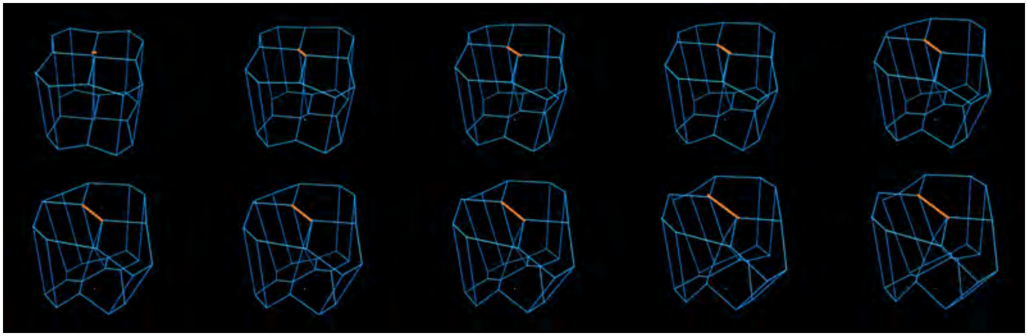

Figure 8
A matrix drawing of a wireframe model of a cluster of 4 cells packing together

vestigated the mechanism of how mammary glands respond to global and local stimulation to change its structure by taking advantage of dynamic parametric 3D modeling. Furthermore, the authors expanded the observations into the design of a set of deployable structures and simulated how the surface structure responds to environmental factors. It is truly a novel approach and workflow that adapts the cell behavior into an architectural structure and design process to bridge the gap between micro-scale biology and macro-scale architecture application.

METHOD

Through the process of developing the scutoid parametric model, we propose that one of the necessary features of the scutoid is that either two vertices on the basal or apical surfaces merge into the center vertex on the intermediate layer. The connection between the three vertices creates a triangle that is partially bridging two epithelial cells. When four epithelial cells are packed as a cluster and bend toward the apical surface, the common boundary between the pair of adjacent hexagons becomes extended, and the area of the connection triangle is larger (Figure 8). In addition, we also examined that as novel component-based space-filling tiles, Scutoid shape's application to assemble other masonry constructions such as walls, pavements. But given the fact that epithelial tissue often presents highly curved formation, applying Scutoid shape as component-based space-filling tiles in flat settings is not the most suitable application for embodying its morphology features. Thus, we focused on further investigation on the application scenario of scutoid in a masonry shell system. This scutoid mechanism creates an intriguing joinery method where two pairs of epithelial cells connect in a bending environment. Greater curvature within the cell cluster also generates a larger area of triangular connection, thereby creating a more stable connection between two epithelial cells. The features mentioned above are well suited for application in masonry shell systems as one of the main concerns when designing a masonry shell is to avoid sliding failure within the bricks (Rippmann, M. and Block, P., 2013). (Figure 9)

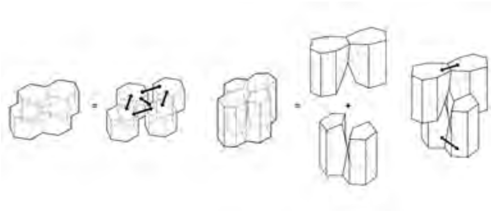

Figure 9
Two pair of scutoids are stacking with each

It is noted that as we are examining the application of scutoids as space-filling tiles for masonry shell, we are not focusing on the geometrical optimization of shell/vaults geometry. Instead, we are focusing on designing and generating scutoids as space-filling tiles to assemble curved global geometry. We propose a novel design and assembly of bricks for the fabrication of a masonry shell with the geometric features of Scutoid. Beyond the building of a parametric model based on four epithelial cells packed together, we further explored the subdivision of a free form surface into unit blocks embedded with scutoid features that can be connected and assembled. Our exploration can be summarized in the following two methods.

A. Voronoi-Based Scutoid Generator

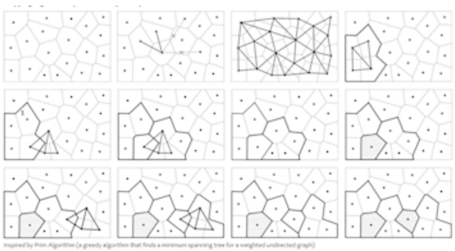

Figure 10
Utilizing the greedy algorithm for selecting any four cells as a cluster in 2d space

The first method is a Voronoi-based subdivision solution, as the discoverers of scutoid G´omez-G´alvez, Pedro et al. (2018) assume that the apical and basal surfaces of epithelial tissue behave as Voronoi diagrams and generated the computational model of the apical and basal surfaces through Voronoi diagram in the research. To achieve an optimal result, we utilize this well-known algorithm as a geometric filter to select any four cells as a cluster in 2D space to then generate scutoids from. The eventual goal of the selection is to attain the optimal configuration of the cell clusters. Cells that have specific eigenvalues are eligible to merge as a scutoid cluster. We execute step-by-step to verify the number of neighboring cells based on the eigenvalues of each cell. We choose those cells that have two eigenvalues as the first batch to generate Scutoids. When one cell has been merged into a Scutoid cluster, the eigenvalues will be affected by minus one. And if we continue this process, the selection process will eventually reach the optimal result when there are no more eligible cells in the Voronoi diagram (Figure 10).

We then generated an automatic workflow to form a three-dimensional scutoid embedded surface subdivision and translated this into a C-sharp code component in Grasshopper and Rhino environment (Figure 11). Based on the selection process we have developed above, the scutoid generation starts with an initial input that changes the curvature of the surface. In this component, it is necessary to implement a simple associative data structure (the Graph). It is a spring force model of a dynamic system combined with nodes and edges in this case. The surface is interpreted as a simple non-interacting particle system where each element is a simple point whose location changes over time as a response to external forces applied to it obeying Newtonian physics. Some collections of objects can be updated in real-time. The initial spring force structure contains multiple polygons that are optimized from the Voronoi diagram. The cells on the margin are fixed. Then, external forces are applied to each node in the spring structure, which makes it bend gradually. During this process, for cells that have edges and nodes that are overextended, a trigger function is added to generate scutoids (two vertices on outer surface merge into one vertex in the middle of cell). Hence, the Scutoid generator becomes functional when the overall surface is about to lose the stability of the original form.

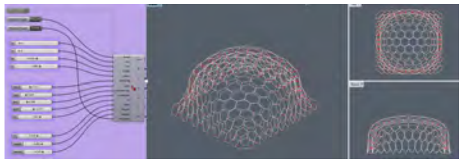

Figure 11
An automatic workflow to form a three-dimensional scutoid embedded surface subdivision and turn it into a C# code component in Grasshopper/ Rhino environment.

After successfully establishing a Voronoi-based scutoid generator to create scutoid shapes within a curved surface, we designed several trials to prove the efficiency of this generator and to optimize the workflow. We conducted a comparison when some specific input elements are changed. A preferred model was printed as it best reflects the morphology relationships between local connections of Scutoid bricks. However, from a simulation perspective, the above method has less practical potentials.

B. Rational-Based Subdivision Scutoid Generator

Compared with the Voronoi diagram-based subdivision solution, the second method attempts to subdivide the overall surface in a rational and practical approach instead of starting from random points. The method creates more accessibility for fabrication, as the sub-divided components are unified into variable modules. This method aims to generate scutoid bricks for a static double-curved shell so that blocks can be interspersed with each other without the risk of sliding failure.

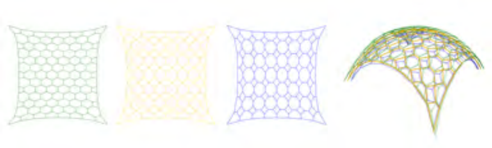

Figure 12
Three layers of sub-division of shell geometry

Previously, we defined that the parametric model of a scutoid cell cluster can be recognized as a three-layer structure. Two essential conditions for determining a scutoid are: 1) the number of the polygonal segments are not equal on apical and basal surfaces; 2) two vertices on one surface can be merged into one vertex on the intermediate layer to equalize the polygon segments. Based on the above rules, we first extracted the three layers of a given shell geometry. Then, we sub-divided the apical surface into hexagons and the intermediate layer into a variable grid of diamond shapes with hexagons and basal surface into a grid of diamond shapes and octagons (Figure 12). Finally, we merged the two vertices of each hexagon on the apical surface with the vertex of each diamond shape on the intermediate layer, and connected the same vertex of each diamond shape with the two vertices of the octagons on the basal surface.

The above sub-division and connecting method creates two types of scutoid bricks: one with the arrangement of hexagon-diamond shape-diamond shape, and the other with the arrangement of hexagon-diamond-octagon (Figure 13). Despite the two different arrangements, both types of scutoids have two connection triangles allowing these scutoids to be continuously assembled.

Parallel to the Voronoi-based scutoid generator, we built a rational-based subdivision scutoid generator component in Grasshopper/Rhino environment. Several physical models of 3D printed shells are fabricated and assembled for evaluation purposes.

In addition to the advantage of the connection triangles preventing sliding failures, we also discovered another benefit of the scutoid bricks in shell systems when making physical models. The connection triangles of both types of scutoid bricks (hexagon-diamond shape-diamond shape, and hexagon-diamond-octagon) aligned with two bending directions (U and V), as the given shell geometry is a doubly-curved surface. The two types of scutoid bricks share a bridge of connection triangles along the respective axes. Meanwhile, the connected scutoid bricks on both directions act like multiple arches that are perpendicularly mortising together. The above configuration formed a space grid structure that is believed to have greater structural stability (Figure 14).

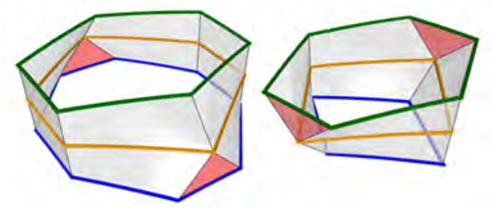

Figure 13
Two types of scutoid bricks

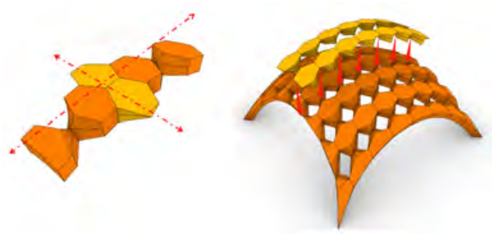

Figure 14
The connected scutoid bricks on both directions act like multiple arches that are perpendicularly mortising together

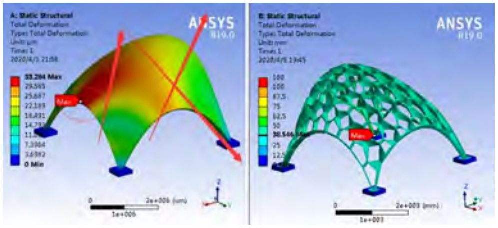

Figure 15
FEA of shell model

For testing the structural stability, we conducted finite element static analysis on the selected shell model with ANSYS, and mainly focused on the total deformation and equivalent stress. In the controlled experiment, we calculated the force situation for a non-masonry shell. We found in a particular area that the total deformation is significantly higher than average. However, in the experiment of the masonry shell that is made up of scutoid bricks, we found the deformation ratio on each scutoid brick of the shell is relatively even (Figure 15) Meanwhile, we also conducted an initial stress test on a 3D printed and assembled scutoid masonry shell model. Each scutoid brick of the masonry shell model is 3D printed with PLA with a 20% infill, and the total net weight is 1.8 lb. The model surprisingly supported the payload of a pair of 40-pound dumbbells without any damage (Figure 16). According to the results of FEA analysis and physical model testing, we can assume that the use of scutoid bricks in the masonry shell system can distribute a sudden change in stress more evenly than a non-masonry shell.

CONCLUSION

The work that we have generated thus far contributes to and enhances our understanding of how deformation mechanisms within epithelial tissue structures local and global change due to changes in local geometry and global surface curvature. We also opened up a new channel that builds upon rigorous observations of cell behavior to then apply these findings in design research for architectural potential. Most importantly, we contributed a novel approach for shell structure design and fabrication from the perspective of individual scutoid units. These outcomes demonstrate that the epithelial cell inspired-brick can be applied in a masonry shell system and is a feasible and innovative approach for the fabrication of shell structures.

Future work will include full-scale testing and digital fabrication accompanied with detailed design and technical drawings. Fabrication methods, material studies for constructing a masonry shell with both semi-rigid and rigid scutoid bricks will be investigated at full scale. Notebly, this study of scutoid bricks shows us that this unique geometric system does not only pertain to biological models. A comprehensive investigation requires interdisciplinary teamwork .

Figure 16
Testing with
physical model

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