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Employing Mesh Segmentation Algorithms as Fabrication Strategies. Pattern Generation Based on Reaction-Diffusion Mechanism

This paper examines how the evolution of architectural generative design processes aim to apply similar physical and geometrical principles of biological processes taking place during development and to translate them to fabrication processes. In analogy to the reaction-diffusion mechanism for biological pattern prediction, the logic of stripe is used as construction system and examined for its structural behaviour. Both, mesh relaxation processes and weighted mesh graphs representations are employed as design tools for the construction of a minimal thin shell structural skin with branching topologies. Eventually the design workflow is extended to engage also collaborative fabrication processes and to steer the design based on intuition, knowledge of the fabrication tools, properties of the materials, manufacturing simulations and logic of assemble. This approach could lead to the optimization of material usage and machine time and facilitate the assembly process of a physical object which integrates the whole process into its form. The outcomes have been used to fabricate a prototype, using three different materials and digital fabrication methods, to examine the stability and the mechanical connectivity by taking in count the tolerances. The paper argues that biological skin patterns and segmentation in fabrication open a new field of interdisciplinary investigation and architectural applications.
Keywords: *Fabrication methods, Stripes, Skin pattern, Morphogenesis, Shell structure.*

1. INTRODUCTION

Architectural design processes and workflows are goal-directed and traditionally driven by optimizing the functional requirements and the structural hierarchy of materials. The process of biological evolution, on the other hand, is blind to any future goals and proceeds by tinkering and reusing previous structures, thus being subject to historical contingency. It is impartial to the complex sequences of the synthesis of materials, which are instead integrated in the coherent, non-linear and often self-organized process of morphogenesis [1]. Generative architectural design processes aim to apply the principles of biological morphogenesis to the design and fabrication of architectural structures. However, despite the revolution in computation aided design and interdisciplinary upgrades of digital fabrication technologies, they fail to acknowledge materials, tools and construction logic in an early stage of the design process, as manifested in nature. As a result, the realization of specific fabrication processes and their individual constraints often lead to amendments to an already established workflow by making desperate adjustments to rationalize the design.

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One of the objectives of this paper is to re-examine the design workflow, as part of a digital fabrication course, with the integration of three digital fabrication techniques (CNC milling, laser cutting and 3D printing). Taking in count the material properties, tolerances, constraints, capacities of the machines and interactivity between them, to steer the design and the construction of minimal surface structures and landscape design. The method also tries to implement biologically processes, such as the reaction-diffusion (RD) mechanism, as fabrication process, incorporating three different materials and procedures in a single parametric workflow to manifest a unified patterning system. Examining the work of Marc Fornes [2] and Vlad Tenu [3], stripe patterns have many advantages as a construction logic, like minimizing of material and connections, assembly efficiency and structural stability. Besides the unlimited variations evident in nature, the aesthetics and visual effects may act also as a form of motion camouflage [4].

In order to understand the morphogenetic process, this research refers to the RD pattern mechanism, the available simulation models and also the computational tools to generate them. Secondly, describes the evolu–tion of how those patterns are incorporated in a form finding process of minimal surfaces, from simple to more complex, to the fabrication. And thirdly, the real fabrication process. In addition, a qualitative compa–rison of the shell FEM analysis model, the stress lines diagrams and segmented pattern of stripes of the phy–

sical model is offering some potential hints of extracting useful information about stress lines and segmentation relation, the skin and stripe structural performance, and the shell with the landscape continuity.

2. SIMULATION OF BIOLOGICAL PATTERNS

Only until the discovery of the gene regulatory networks (GRNs) emerged the idea of thinking about biological morphogenesis in purely mathematical terms. This allowed to establish a formal parallelism between the GRN dynamics and the logic gates in computation theory, paving the way for new approaches, such as the introduction of 2D cellular automata [5] for the simu–lation of biological pattern formation. More recent research includes the morphogenetic engineering field [6] which explores the possible parallels between natu–rally-evolved and artificially-engineered systems and synthetic biology construction [7], a new engineering design process. This goes beyond finding inspiration from biological systems and propose a system in which both modelling and manufacture are combined into an engineered biological system. Bionic basic principles are found in mechanical engineering also and especially in robotics. Research was carried out on the movement of different biological systems, which have legs. By observation, it is attempted to define some general principles that are necessary for the task of moving legged robots. [8]

2.1 Reaction-Diffusion (RD) Mechanism

In order to find a way of implementing the stripe patter–ning logic to fabrication, this research seeks to under–stand the underlying mechanism of skin formations from scientific and mathematical references. The semi–nal 1952 article of Alan Turing, “The chemical basis of morphogenesis”, [9] base a whole notion of natural patterns, such as the zebra's stripes, on the relationship between two competing tendencies: one that activates the growth of an effect and one that it inhibits it. The mechanism is called reaction-diffusion (RD) system and mathematical analysis shows that a RD mechanism can generate a wide variety of spatial patterns by varying the few parameters involved, giving this model the po–tential for application as an experimental working hypothesis in a wide variety of morphological pheno–mena. [10] The formation of pigmented biological pat–terns, like the stripes or dots on furs, the rings on the butterfly wings, the skeletal elements in vertebrate limbs, the scutes in turtle’s shells and even the cusps in mammalian teeth, has become accessible to modelling by means of certain RD equations. [11]

Nowadays, the RD mechanism is computationally accessible, and there are many programming languages, and mathematical models, like the Gray-Scott RD mo–del, with the ability to produce a varied number of bio–logical looking (and behaving) patterns, both static and constantly changing, or have developed fast and compu–tationally efficient finite difference method for the Turing pattern on curved surfaces in the three-dimen–sional space. [12] Although a striking resemblance are often found between the biological pattern and its simu–lation, the actual mechanism of pattern formation has still to be confirmed experimentally by means of empirical studies. [13]

2.2 Animal Skin Patterns

Patterns are all different but share some specific characteristics, like the zebra's stripes (Fig. 1) which are perpendicular to a centre-line running through each of the more tube-like parts of the body: the neck, legs, and middle part of the torso. The morphogenetic process runs quite uniformly over these more Euclidean areas, and as parts merge smoothly, the pattern on the zebra’ s back must transform from vertical stripes to horizontal ones that wrap the hind legs, bending the stripes into a C- figure, by deforming the pattern over the haunches, or transforming front legs to Y-figures. Figures play the role of the joints in the tessellated model and the pattern should be constantly modified and adapted deformed and transformed. Whenever the system cannot manage the changes in geometry by stretching and deforming the stripes, the pattern does it by inserting an extra stripe, i.e, transforming. [14]

But how this mechanism could be computationally applied to generative architectural design and especially as fabrication procedure? From a scientific point of view, RD simulation is much easier in 2D than other phenomena occurring in 3D [15], revealing a surprising variety of irregular spatiotemporal patterns of numerical simulations [16] to generate the shell surface and landscape. The design strategy extract processes from fundamental principles that govern both the biological and the fabrication machine. By doing such an geo–metrical abstraction, one can capture the essence and reveal the rules underlying the apparent complexity.

Figure 1. The pattern on the zebra’ s back must transform from vertical stripes to horizontal ones that wrap the hind legs, bending the stripes into a C- figure, by deforming the pattern over the haunches, or transforming front legs to Y-figures. Grevy's Zebra Stallion. (commons.wikimedia)

2.3 Graphical Computation Tools and Fabrication

There is a long history of the equilibrium analysis of structural systems with graphical methods. (Fig.2) According to Block, an application of thrust lines emp–hasizes the relationship between the forces and geometry of structures with the key mathematical principle of use of graphical analysis and interactive computer methods to determine possible equilibrium states. [17] The three new ideas of this approach are: the interactive graphic statics, geometry controlled loads, and animated kinematics. He mentions also about the challenge when working with new efficient materials, that scaling the problems is not possible anymore, since stresses do not scale linearly. The equilibrium shapes are correct, but how to assign the material becomes now an issue. Not only stability, but also material stresses, including buckling of compression elements will have to be checked. [18]

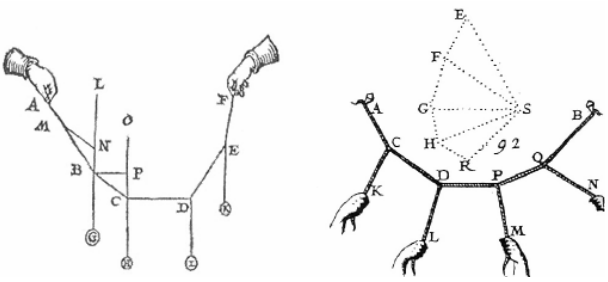

Figure. 2. (Left) One of Stevin's drawings of force equilib–rium of hanging weights on a string (1586), and (Right) an illustration by Varignon showing a graphical analysis of a funicular shape (1725). [17]

Another recent research demonstrates that approaches bringing together mesh and graph representations drawn from computer graphics can be effective within the domains of applications for which they have been developed [19], [20]. The dual graph concept implemented as a data object that is called MeshGraph (MGraph) corresponds to the specific purpose of unfolding surfaces and segmentation of triangular meshes. The application is running inside Grasshopper platform and could generates stripe formations in an early design phase, giving at the same time the CNC cut designs, connection system and logistics. In this case, the application of edge weighted meshes representations provides an efficient design workflow of generating the stripe patterns for fabrication. The network of the connected mesh faces and edges is a simplified representation of architectonic elements, such as structural framing or facade panels and could be applied to any shell form.

3. DESIGN METHODOLOGY

This research offers a methodological framework of identifying a suitable surface pattern with similar fea–tures like a RD-based stripe formation to be used as fabrication logic. The patterning algorithm was compu–tationally explored and geometrically defined using both force-based relaxation processes and mesh segmentation algorithms to generate a shell skin pattern. Eventually, to give the desired stripe effect, the mesh relaxation process is linked with the segmentation process and the fabrication process in one unified system in equilibrium.

3.1 Mesh Relaxation Process for the Shell Structure

To generate in a simple and intuitive way a structure in static equilibrium, with minimal surface properties, dynamic relaxation physical load force of gravity was applied using Kangaroo physics engine inside Grasshopper [21]. The initial input geometry/topology consisted of a bottom and a top voronoi system joined with columns and beams with boundary conditions defined by three bottom strong anchoring points and nine weak anchors in the top.

The objective was to investigate the limits for constructing tubular minimal forms with branching connections using the stripe logic and the specific material. The bottom boundary geometry of the struc–ture was modified to achieve stability and continuity with the landscape pattern. During this phase, the dyna–mic physics engine allowed to visually and intuitively interact in real-time with the "virtual" physical forces applied to the pre-defined geometry input and to trans–late the mesh lines and vertices to a network of springs and particles. The load, spring length and strength was controlled by the algorithm, to gene–rate the proper height of the structure. From the relaxa–tion process emerged an organic structural system of triangulated mesh faces, with surface curvature arriving to almost zero mean. This was achieved by applying extra stren–gth and variant anchor's strength to the boundaries to control the geometry output. (Fig. 3)

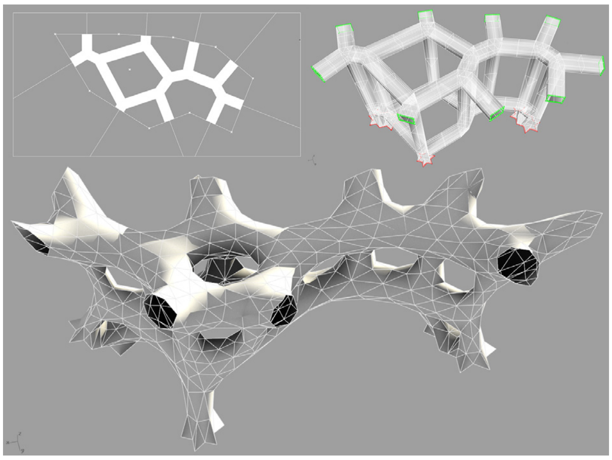

Figure 3. Initial voronoi points and lines selected (Top left). Top right, shows the two sets of voronoi trusses connected with vertical columns. The green naked edges are anchors with not much strength and the red naked edges of the base have very strong strength. (Bottom), the triangulated mesh obtained after the relaxation method described. (Image by authors).

1.2 Mesh Segmentation Process for the Shell Skin

In a second phase, computational techniques of weigh-ted-mesh representations, using IVY plugin [19,20] inside Grasshopper, were employed for the generation of stripe configurations on the surface, analogous to the skin patterns emerging from a RD mechanism. As a construction logic, each stripe was conceptualized as a ruled surface (developable, with zero Gaussian curva–ture). The relaxed mesh in equilibrium was given as input for the MGraph creation, where face centers beco–me nodes in the graph and mesh topological edges be–come edges. Custom weight was applied to the edges using the Orange Peel Edges (OPE) to generate ripples. This algorithm separates layers, creating a pattern of nodes that develop concentrically, radiating from a set of specific input vertices. The input mesh vertices were defined as the naked edges of the top voronoi of the shell to achieve a pattern of stripes that starts as rings from the top and arrive to the bottom legs perpendicular to the ground (Fig. 4).

Using as primary segmentation the MST Kruskal (mstK) Minimum Spanning Tree disjoint algorithm, the graph was separated into subgraphs while transforming it into a tree and in parallel removing edges. The goal was to arrive to the least amount of stripes with the most vertical strength given by the connection system of screws and bolts, along the edges of each stripe. This required two inputs: (G) MGraph – the MGraph object and (W) Weight Limit – the interval of weights to considered, giving as output: (G) MGraph – the tree/trees MGraph object.

A secondary segmentation algorithm, the Weight Deviation Split Graph (DevSplit), splitted the tree MGraph into more subgraphs by deleting more edges with a specified edge weight larger or smaller than the previous. This required three inputs: (G) MGraph – the MGraph object, (D) Deviation – the amount the edge weight needs to deviate from the previous one in order to be deleted, and (M) MinFaces – the minimum num–ber of nodes/mesh faces a piece needs to have in order for the split to be validated, giving as Outputs: (G) SubGraphs – the list of MGraph pieces.

The numbering order of the 28 stripes, before the unrolling, was arranged to give the black and white effect and the same arrangement was used to facilitate the assembling.

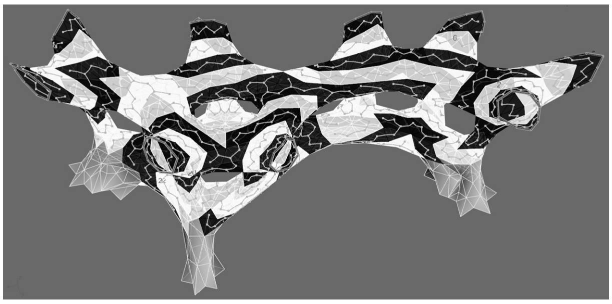

Figure 4. Image showing the naked edges on green, in which the (OPE) starts striping selection towards the center and perpendicular to the legs. (Image by authors)

4. FABRICATION PROCESS

Current design to production processes do not take into account the machines to use on the fabrication. Design procedures have to be aware of the fabrication methods, such as CNC milling, 3D printing and laser cutting, which are mostly used nowadays in architecture and de–sign. These workflows need to be combined and per–formed in a seamless process in order to process data without any noise. [22] Merging digital manufacturing methods have the advantage of understanding the machines' working area and the permissible range of variation in the projects dimension, besides under–standing the importance of preparing geometry for different fabrication methods. [23] This requires more time to understand deeply the potential applications for prototyping. The combination of three materials with different geometrical aspects of connectivity and three manufacturing techniques add more complexity to the process. In order not to multiply errors, geometrical configurations require to consider the tolerances toget–her with the machine procedures and material behavi–our, like, polypropylene's (PP) material expansion. [22]

4.1 CNC Milling Method

The profiled lines of the landscape were designed for a 2x1m polystyrene foam panel adapting a different logic and milled utilizing various tools and methods. The lines were inputted as tool paths generated using RhinoCam2016. Some of the strategies used for the CNC milling were Horizontal roughing, Parallel finishing, Pocketing and Engraving. Different types of drill bit were used to perform the specific strategies. The entire process was simulated in the RhinoCam2016 environment to check for clashes and machine times. The pockets to accept the structural legs were slightly modified to avoid clashes with the steeper angles of the overall geometry and the 3D printed piece. This could be dealt more effectively by modifying the pattern on the Polystyrene. The mountains and valleys on the pattern were slightly decreased in height and depth towards the sides, so as to minimise material erosion and maintain stability. This could also have been dealt with by modifying the pattern to accommodate the overall stability. The entire CNC milling process took two days for the result.

The most important aspect of this part of the production is the reducing of machinic time. If more than one tool is used for machining a single part, the total machining time for that part will be considerably longer compared to the situation when one complex-geometry tool is used. A complex-geometry tool, on one hand, can replace several tools but, at the same time, it reduces the total machining time, the most significant reduction being that of idle times. [24] In the case of the pavilion made of aluminum sheets, for further contribution to the market, would have been to design and digital fabricate different types of mass production aluminum profiles so each piece would not need to be CNC machined. [25] In such cases a complex-geometry tool in combination with design adaptations would be a meaningful solution for reducing cutting time.

4.2 Laser Cutting Method

The unrolled surfaces generated by implementing MGraph, were systematically numbered and labelled so as to create assembly guidelines. The primary segmen–tation produced 28 stripes, but the unrolling generated some overlapping. These overlapping were non-conducive to the laser cutting. After re-numbering from one end to another and separating the overlapped pieces, the definition generated 108 stripes. After being labelled in the 3D and 2D design, the unrolled surfaces were treated as individual 2D shapes, to which additional semi-circular loops were added to the naked edges of each triangulation. At the assembly stage these loops served as overlap washers. An empty pattern was added at the center of each face, to reduce the overall weight. The stripes were then arranged on 1050x750mm sheets, using RhinoNest. This stage helped in nesting the sha–pes on the available sheet size of PP for optimization of material use. The nested geometries were then exported to Autocad 2007 file to be fed into the laser cutter. The thickness of the PP sheets, 0.8mm and the melting point of the material dictated the speed of cutting, the overall outcome and the level of detail obtained. The laser cut pieces were then arranged based on the label numbers and connected to each other by means of 2.5mm diameter screws and nuts. To help in the assembly process, the screws were inserted pointing outwards rather than inwards, so that the bolts could be comfortably fastened. The entire laser cutting process took 6 hours for the result.

From assembly perspective, more holes, not just at the naked edges, but also at the vertices of the naked edges would have been more effective. This would have made stripes more prominent and structure more robust. The order of assembly of the stripes was depended hea–vily on the fabrication workflow and the manual pick-and-chose process. The numbering and labelling system could be optimized to make the assembly process more fluid.

4.3 3D Printing Method

The 3D printed legs were the structural interface between the cut stripes and the milled landscape (Fig.5). This required the design of the structural legs to mediate between the structural properties of the polystyrene foam and the PP stripes to accommodate their respective design. The three designed structural legs were made to be water-tight by closing all naked edges. To create the G-code, Simplify3D platform was used for slicing. During this process, the slicing simulation allowed to optimize geometrical and printing time issues.

The legs were then printed using FDM (Fused deposition modelling) additive printing on two Felix 3.1 printers with a build volume of 255x205x225 mm, extrusion speed of 15mm3/s and motion speed of 150mm/s. The material used was PLA (Polylactide) filament with 1.75mm diameter requiring working temperature of 190°C-210°C and platform temperature of 50°C-60°C. Owing to the higher complexity and steeper angles (the angles were designed to arrive to no smaller than 45 degrees) of the geometry, the prints were done with structural supports, which were easily removable by hand. The screw holes for anchoring to the landscape required sanding and smoothing with a drill machine. The entire printing process took three days.

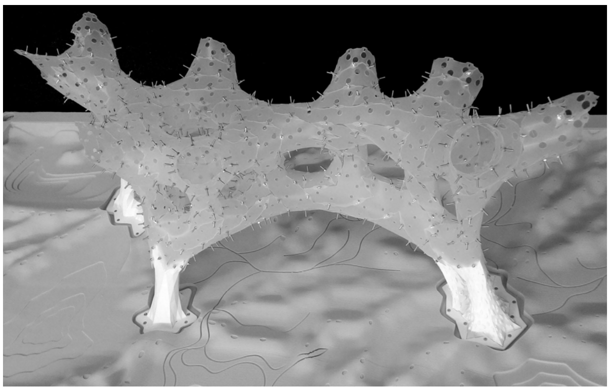

Figure 5. Perspective view of final prototype. (image by authors)

The printed pattern on a structural leg was being isolated from the whole system, which made it redun–dant. If, it was emerged from the concept of MGraph, it would have effectively maintained the continuity. The selection of the printed parts from the whole structural mesh was made so that geometrically will require:

- to fit the printable area of the Felix 4.0.
- the angles to be minimum 45° to avoid, or minimize supports.
- to weave the PP and PLA for stability reasons and continuity.

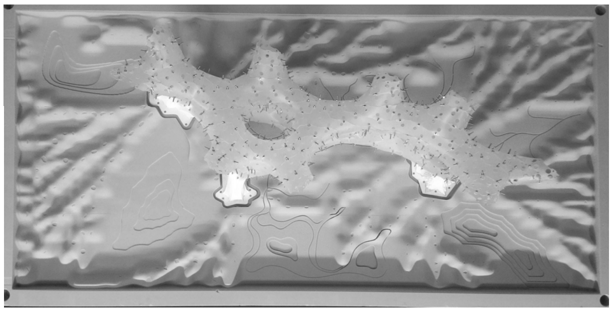

Figure 6. Final assemble. (Image by authors)

1.3 Assembly Process

During the construction, three student teams, repre–sented the simultaneous fabrication with the three ma–terials, polystyrene foam, PP sheets and PLA filament and delivered the G-code of each fabrication techniques vis. CNC milling, laser cutting, 3D printing respec–tively. The outcome prototype, (Fig. 5,6) required full coordination of all the teams in a collaborative assembly process where the sequential roles and responsibilities of each material were fulfilled. The three legs were con–nected on the shell and then mounted to the polystyrene foam by means of fisher screws. The entire assembly process was finished in 12 hours, without any eventual amendments to the already established workflow. The stripe formation not only generated the shape, but also aided in the assembly, and reducing time. Owing to the impetus on a predetermined fabrication and assembly strategy that relies on material properties and manu–facturing simulations the assembly culminated as one unified fabrication process in spite of unclear intero–perability between materials and machines.

5. DISCUSSION

Similar to a previous project of connected PP stripes [26], the intention was to examine how a thin structural shell behave without extra supporting structure, only relying on the equilibrium stage of the relaxation pro–cess, that is, in geometry and the stripe logic. However, a discussion is raised about the stripes topology and direction. In comparison with the previous project in which the stripes were rings, the performance of a more complex stripe pattern with boundary rings, does not appear to affect the structural behaviour, at least of the prototype. A parallel goal was, taking in count the tole–rances, to test the stability between the three materials and the mechanical connectivity of screws, taking in count the tolerances. During the construction, the stripe formation not only generated the shape, but also aided in the assembly, reducing time.

4.4 Structural Model

In this project, the minimal branching topologies were examined with a very fast linear analysis of shell elements, made with Millepede [27] plugin to extract useful information. For the FEM analysis, material data of PP was used (elasticity, density and yield strength [28] and poisson’s ratio [29]). The distribution of deflection across the structure revealed some of the structure's vulnerable areas. (Fig. 7). In the physical prototype though, such problem was not observed. The plugin also generated stress lines, curves that at each point are tangent to one of the principal stress directions. In relation with those stress (force) lines, we observe concentration of lines on the deflected areas. Also, in the stripes diagram, (Fig.8) in most cases, the lines are perpendicular to the direction of the stripes. The direction of the stress lines and the direction of stripes have definitely a relation, but in this case this is not very clear. According to Tam and Mueller, the noise of the stress lines is due to the low-resolution and mesh topology. Also, there is no guarantee that the produced stress lines, from conventional tools integrated with parameterized design interfaces available to designers for generating stress lines, such as Millipede and Karamba will lead to usable structural patterns, nor is there documentation evaluating the performance of stress line generation methods. [30]

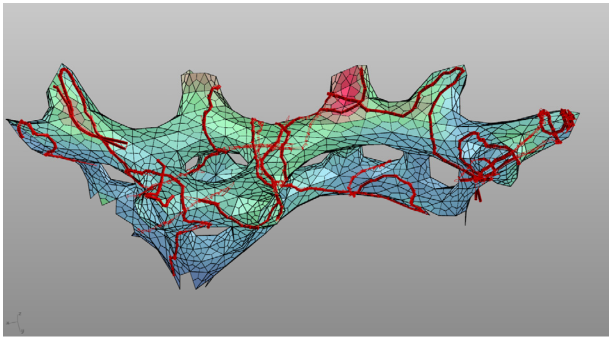

Figure 7. Stress lines and deflection. (Image by authors)

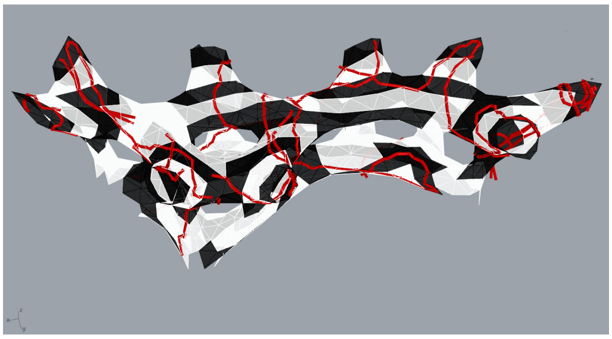

Figure 8. Stress lines and stripes. (Image by authors)

If we assume that the stripes are reinforced on their naked edges with the overlapping material and screw connectivity, then the direction of the stripes is also important to analyse for structural reasons. The para–metric model allowed the extraction of data information for the analysis of the verticality of the connections that are under compression. Figure 9 demonstrates the diag–ram of the extracted angles. An experimental way of translating this data shows on the graph (Fig. 10). The comparison here is between the average angles between each stripe’s naked edges and the X vector (top, dashed line), and the average angles between the faces of each stripe (bottom line). The closer to 1.58 radian average, stripes are mostly vertical, so pulling forces are applied to the screws. The bottom line shows the curvature continuity for each stripe, indicating that all are near to minimal surfaces.

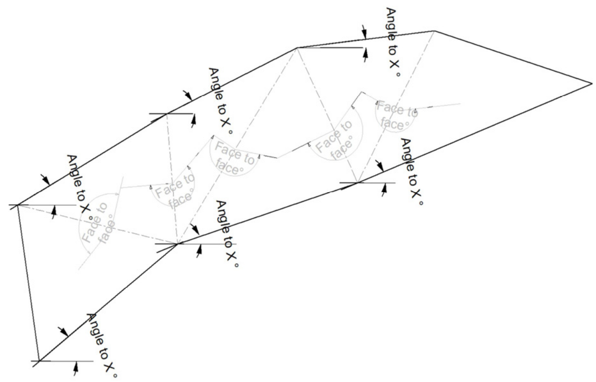

Fig 9. Each stripe is analyzed in the naked cantilever with the X axis, and in the folding angle between faces. The average angles are compared in the graph (fig.10). (Image by author)

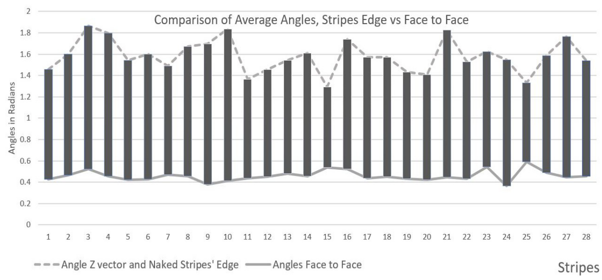

Figure 9. Comparison of average stripe’s edges angles vs. face-to-face angles (rad). (Graph by authors)

6. CONCLUSION

Biological morphogenesis has been raised in discourses on computational methods in architectural design thro-ugh the paradigms of parametric and procedural mode-ling of form. A distinction needs to be made, however, between what might be described as bio mimicry of form and morphogenesis, [28] or bio inspiration. Since architectural practice is still depending on the process of breaking things into discrete elements as a way of construction, design workflows, as the one described in this paper, could offer many design applications as stripe organization for fabrication, thus opening a new field for multidisciplinary investigation between engi-neers, programmers, scientists and fabricators.

Future work could include dynamic changes of the pattern applied to adaptive design systems and 3D simu-lation techniques of other biological patterns found in nature, with similar structural characteristics like stripes.

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ПРИМЕНА АЛГОРИТАМА СЕГМЕНТАЦИЈЕ МРЕЖЕ КАО СТРАТЕГИЈА ЗА ФАБРИКА–ЦИЈУ. ГЕНЕРИСАЊЕ УЗОРАКА НА ОСНОВУ МЕХАНИЗМА РЕАКЦИЈЕ-ДИФУЗИЈЕ

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Овај рад испитује како еволуција процеса архитектонског генеративног пројектовања има за циљ да примени сличне физичке и геометријске принципе биолошких процеса који се одвијају током развоја и да их преведе у процес производње. Аналогно са механизмом реакције-дифузије за предвиђање биолошког обрасца, логика пруге користи се као конструкциони систем и испитује се њено структурално понашање. И процеси релаксације мреже и репрезентације пондерисаних мрежних графова користе се као пројектни алати за конструкцију оплате са минималном дебљином љуске са разгранатом топологијом. На крају се радни процес дизајна проширује како би се укључили и процеси колаборативне израде и да се управља дизајном на основу интуиције, познавања алата за израду, својстава материјала, производних симулација и логике састављања. Овакав приступ би могао довести до оптималне употребе материјала и времена строја и олакшати процес монтаже физичког објекта који интегрише цели процес у његов облик. Резултати су коришћени за израду прототипа, употребом три различита материјала и дигиталне методе израде, како би се испитала стабилност и механичка повезаност узимањем у обзир толеранција. У раду се тврди да биолошки обрасци и сегментација у производњи стварају ново поље интердисциплинарних истраживања и архитектонских апликација.