# Bioinformed Performative Composite Structures

## *From biological micro-structures to material composites and articulated assemblies*


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**Abstract.** *This ongoing investigation aims to learn from nature novel material organizations and structural systems in order to develop innovative architectural system. We focus on biological armored surface as a model system and study the microvascular internal porosity and graded material interfaces as strategies for design of composite material structures. We developed a multidisciplinary approach, using scientific analysis, design research, and prototyping. We use micro computed tomography and scanning electron microscopy to observe microstructures, parametric design to reconstruct the data into digital models, and 3D printing to fabricate prototypes that propose novel gradual material interfaces.*


**Keywords.** *Bioinformed; multi-material; composite; parametrics; performative design.*


## BACKGROUND

Contemporary trends in architectural design, driven by advanced digital drafting and modeling tools, make extensive use of single and double curvature surfaces generating a demand for manufacturing and construction solutions that translate such designs to actual built structures. Frank Gehry's work has for years perfected a technique based on sheet metal "shingles" or overlapping plates, that allow for curvatures to be fabricated out of planar materials. (Most of the surfaces in Gehry's work are developable surfaces, that are curvatures in one of the main directions of the surface. Double curvatures are only very limited in his work and reserved for key elements with high restrictions on the curvatures that can be in fact achieved, due to complexity and cost of manufacturing such custom components.) This approach has been used by many other practices, however it requires a complex "rationalization process" to accommodate flat rigid sheet materials that won't flex beyond certain discrete ranges. (Rationalization implies a reduction in the complexity of the geometry and usually yields a simulated curvature appearance by using faceted strategies in order to use standard flat rigid materials. Tessellation strategies and tiling patterns are usually the final symptom of this situation.)

Moreover, architectural structures are increasingly incorporating performative capabilities that respond to actuation or morphological transformation driven by environmental or programmatic variable conditions: Al Bahar Towers in Dubai by Aedas, Esplanadein Singapore Bay by Michael Wilford & DP Arch, Rijkswaterstaat buildingin Utrecht by Cepezed & Ned Kahn, Cafe Open in Amsterdam by CIE, Q1ThyssenKrupp Quartier in Essen by JSWD Architects, Pola in Ginza by ABI, are some cases that exemplify this phenomenon. Variable formal conditions demand multifunctional strategies and enhanced material properties from the components the structures are made of.

## *Case study of P.senegalus*

This research focuses on an armor design of *P.senegalus*, an ancient "living fossil" fish, that contains unique design principles of double curved surface system covered by articulated scales that are equipped with material and functional differentiation to respond to local functional needs. *P.senegalus* belongs to the Polypteridae family, and it armor remained almost unchanged in relation to similar specimens of its family that lived 96 million years ago during the Cretaceous period (Bruet et al., 2008). While many marine species evolved to have light and flexible protective systems, the heavy armor of *P.senegalus* has proven highly effective and has not been forced to change though evolution. The armor was designed by nature to perform two seemingly contradictory functions: it provides protection and structural resistance from predatory attacks yet allows the fish to remain extremely agile when escaping from one of those attacks.

Nature provides *P.senegalus* with a unique solution to accommodate both protection and flexibility: an articulated armored scale-jacket system that is made from multiple highly biomineralized ganoid scales (Bruet et al., 2008) of convoluted geometry which are imbricated together through articulated joints that enable flexibility of motion for the fish. On the organismal level, the morphological articulation of unit's shapes and the contact surfaces of the joints maintain crucial flexibility for the overall system to adapt to motion. Variation in size, shape, and convoluted connections between units create tailorable anisotropic flexibility across the surface of the scale-jacket.

The squamation of *P.senegalus* has been described in previous studies as following two anatomical body directions, paraserial and interserial and has also been documented that a regular scale from *P.senegalus* has a rhomboid shape, with a protrusion (peg) in the dorsal border or edge and a concavity (socket) in the ventral border or edge (Gemballa and Bartsch 2002; Bruet et al., 2008; Song, 2011). On the paraserial direction, each scale peg (protruding from the dorsal edge) inserts into the socket (concavity located on the ventral edge) of the neighboring scale and form helical rings along the body of the fish (Gemballa and Bartsch 2002; Reichert, 2010). A secondary complementary helical formation in the interserial (isr) direction is produced by overlapping of the anterior edge of the scale over the posterior edge of the adjacent scale. It is mostly responsible for armor flexibility by allowing relative displacement of the scales when curvature of the body of the fish demands for an expansion or contraction of the relative distance between the scales (Figure1a, c). The paraserial helical arrangement of interlocking components provides load dissipation and structural integrity while the interserial secondary articulation order allows great flexibility to the system.

On the microscale level, this system presents material organization principles of multi-material

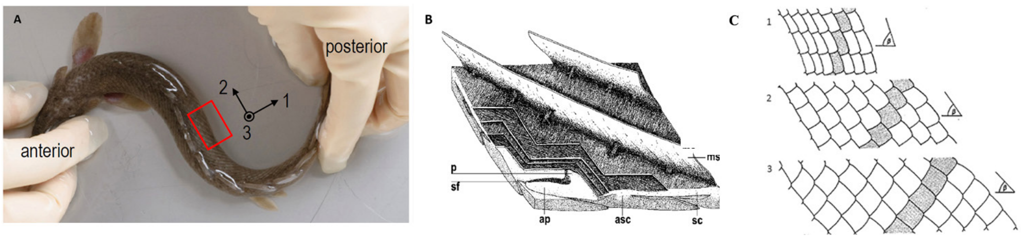


*Figure 1*
*(A) Anesthetized P. Senegalus showing extreme body curvature (Reichert, 2010). (B) Network of fibrous tissues, skin tissue and scales are connected: Fibrous tissue from Stratum Compactum (sc) composed by 4 layers, each layer oriented in one of the two crossing directions. Myosepta (ms) runs parallel to one of the directions of S. Compactum (sc). and Sharpey fibers connect to scales at attachment points (Gemballa and Bartsch, 2002). (C) Scale system showing (1) extreme compression and overlapping due to body curvature, concave side (2) resting position of scales and (3) maximum lateral flexion stress on convex side of body curvature (Gemballa and Bartsch 2002).*

layering, internal porosity with vascular structure and gradual transition between materials with different properties. Gradual transitions from flexible material regions to rigid material regions as observed in the scales of *P.senegalus* are related to two different aspects. First, each ganoid scale that forms the armor is made by a highly efficient material composition and microstructure to resist attacks from its predators. The scale is composed of four layers of composite inorganic-to-organic nano-composite materials: ganoine, dentine, isopedine and a bone basal plate (Bruet et al., 2008). This composition outperforms other heavier and stiffer systems from other species, by combining the stiffness and hardness of the mineral ganoid layer with the energy dissipation of the more flexible underlying layers, creating a plywood-like with enhanced material performance, that among other properties, prevents material fracture and cracking propagation, while being 20% lighter than its bi-layer analogues.

Second aspect of the rigid to flexible interface is the weaving of organic fibers that intertwine the scales and the underlying layer called *stratum compactum* in the interserial direction (Figure1b) (Gemballa and Bartsch, 2002). The alignment in the direction between these fibers and the internal structure of *stratum compactum* suggests that the cross-direction of the entire interserial articulation system (Figure 1c) is guided by the orientation of the *stratum compactum* fibers (sc) which in its turn is aligned with the myosepta, muscles attachment sites that guide the locomotion.

The study of the graded rigid-to-flexible material interfaces and the weaving patterns of the fibers through scales is the main focus of this paper. This paper presents a unique collaboration between design research and scientific research to translate these naturally occurring material organization principles into adaptive synthetic designs. This paper describes work-in-progress and preliminary results regarding the application of such principles through advanced multi-material 3D printing technologies. We believe this approach offers unique opportunities to reduce complexity in assemblies while enhancing the performance of polyfunctional and multimaterial constructs. The longer vision is to be able to apply such constructs to performative architectural envelopes. Physical principles are scaleless and relatively context independent. The study of this fish and its protective armor system is but a medium to explore more general structural principles and material compositions occurring in nature but that may apply to engineering and architectural scales and contexts.

## METHODS

### *MicroCT analysis*

To study the internal porosity structure and the fibrous rigid to flexible material transition on the scale-to-scale interface, we used microcomputed tomography (microCT), then processed to reconstruct the CT data as a voxel data using the scanner's Scanco software, and then translated into a three-dimensional mesh model to be finally parametrically rebuilt in macroscale resolution using 3D software Rhinoceros 3D, v.4.0 from McNeel & Associates. The microCT system used for this purpose was a Viva CT40 scanner (e.g. a Viva CT40, Scanco Medical AG, Bassersdorf, Switzerland), and was operated by Juha Song.

### *3D printed prototyping*

For experimental prototyping we used 3D printing with multiple materials. Current 3D printing technologies enable deployment of two, three or more materials while manufacturing a single part or object. In the course of this investigation we have used a number of 3D printing technologies (Table 1).

## RESULTS AND DISCUSSION

### *Scientific study of fish armor and bio-inspired design research*

In this research project, the observation and characterization of the structure and geometric principles of the scales system was acquired by producing a digital three-dimensional reconstruction from mi-

| Technology | Materials |
|---|---|
| Z-Printer 450 (3D Systems) | ZP 150 High Performance composite |
| | ZB 59 Clear Binder Solution |
| Dimension 1200 ES (Stratasys) | ABS Plus thermoplastic as printing material |
| | SST 1200es as soluble support material |
| 3DTouch3DPrinter (3D systems) | ABS 3.00mm filament |
| | PLA 3.00mm filament (soluble and biodegradable) |
| Objet Connex 500 (Stratasys) | TangoPlus FLX930 (rubber-like translucent amber) |
| | TangoBlack FLX973 (rubber-like black opaque) |
| | VeroClear RGD810 (rigid translucent amber) |
| | VeroWhitePlus RGD835 (rigid white opaque) |

*Table 1*
*3D printing technologies used.*

croCT scans of individual scales (Figure 2). The microscale material articulation principles of the armor were observed through X-ray capturing with microcomputed tomography, processed and reconstructed into STL files. The digital reconstruction was 3D printed in order to fully understand the intricacies of the geometry, and then abstract and synthesize new design parameters and relations. The output of this analytical process was used to re-design a synthetic articulated scale system, its parameterization, assembly and prototyping.

To study how the collagen fibers interfaced with the scale, we performed consecutive cross-sections every 20 microns on a three-dimensional reconstruction of microCT data of the scale, which showed that these points of contact for fibers are in fact inter-connected through internal conduits that conform a large vascular network and microporous structure. While the presence of collagenous fibers is apparent in several areas on the inner side of the scale, it is most noticeably found in regions parallel paraserial ridge in bands along the edges of the scale and also along two parallel region alongside the peg-socket ridge (Figure 2).

These sections clearly depicted a vascular convoluted and yet continuous internal microstructure of interconnected pores with some defined areas of connection to the exterior both on the subducting edge of the scale and along the ridge of the peg-and-socket joint. This latter area is known to have Sharpey's fibers connecting the scale to the dermal layers of the fish, specifically to the *stratum compactum* (Gemballa and Bartsch, 2002). Therefore, it is assumed that the internal porous structure is related to the fibers that connect the mineralized scales to the soft organic tissue of the skin of the fish.

The study of the parallel section of the scales shows that the distribution of the internal microporous structures is clearly allocated anisotropically within the scale volume. The scales show a higher density toward the anterior subducting edge and progressively diminish in density of porosity and in area of occupancy toward the exposed posterior edge of the scale. While the porous structure seems to concentrate on an area parallel to the surface of the scale, and not centered within the section but closer to the exterior, its shape follows the external side of the scale. The internal microporous structure is clustered in four different groups that present different morphological characteristics, transitioning gradually in size and formal aspects from the anterior subducting edge towards the posterior edge, it was separated by cluster (Figure 3). By isolating each cluster in combination with the parallel sections, measurement and characterization of the micropores was carried out.

The first cluster showed the largest pore formations, spheroid in shape and interconnected through narrow stenotic passages that varied in size between approximately 50 and 90 micrometers (pm). The second cluster presented more continuous pores that were also connected through stenotic connections but that were less structures penetrating from the subducting edge of the scale

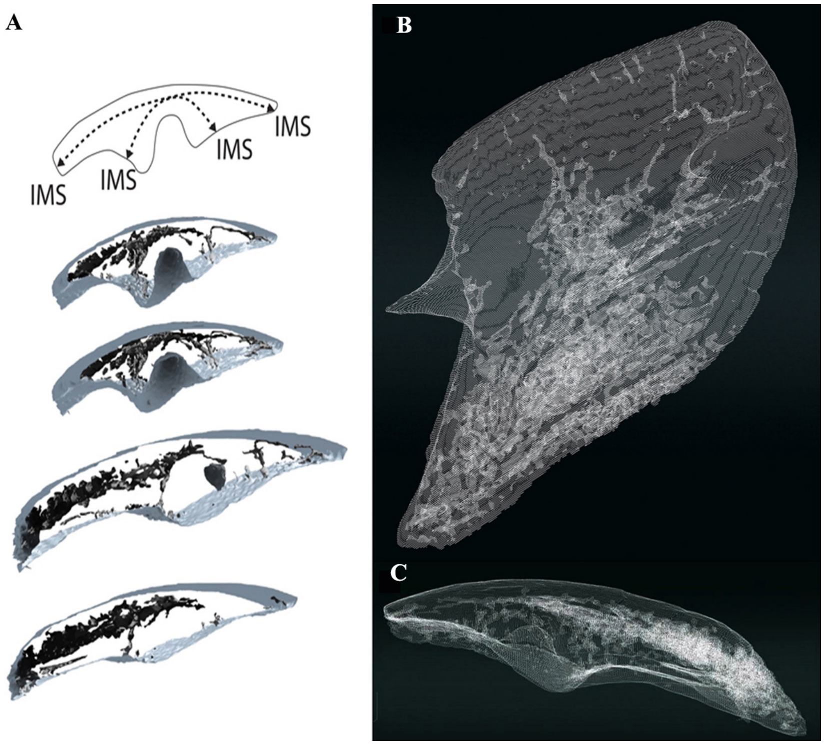


*Figure 2*
*(A) Three-dimensional reconstructive section depicting for different sections the entrance and egress of organic fibrous tissues (ims) into the scales. (B)(C) Three-dimensional reconstructions of internal structures showing anisotropic micropores of organic/biomineralized configuration. All diagrams by author.*

pronounced. The pores in the second cluster were also less spheroid and more tubular in shape. The third and fourth cluster were smaller in size and area, and the pores progressively become more of a continuous flat cavity with some interruptions. The pores on this cluster were clearly aligned with the external side of the scale. Connections from these two clusters with the posterior exposed edge and the central axis ridge links these structures with the external surfaces of the scale. Through isolation of these porous structures we observed a pattern of gastrulations and tubular conduits, clearly demonstrating that the pores play a role in the adhesion and connection of the scale to the fibrous connective tissue of the *stratum compactum*.

The scale morphological features were reconstructed physically by prototyping the external surface of the scale and then the internal microporous structures but leaving void the solid tissue composed by the multilayered composite (ganoine, dentine, isopedine, bone), in order to understand the morphological relations between the external surface features and the internal microstructures (Figure 4).

## ***Reconstruction through Multimaterial Fabrication and new Synthetic Models***

The current results are still preliminary but yield some promising evidence. We prototyped several "articulated scale systems" using a bio-inspired scale design (Reichert, 2010) using a refined peg-socket joint connection from previous design (Reichert, 2010) and including a continuous parametric interserial soft/flexible articulation mechanism (Figure

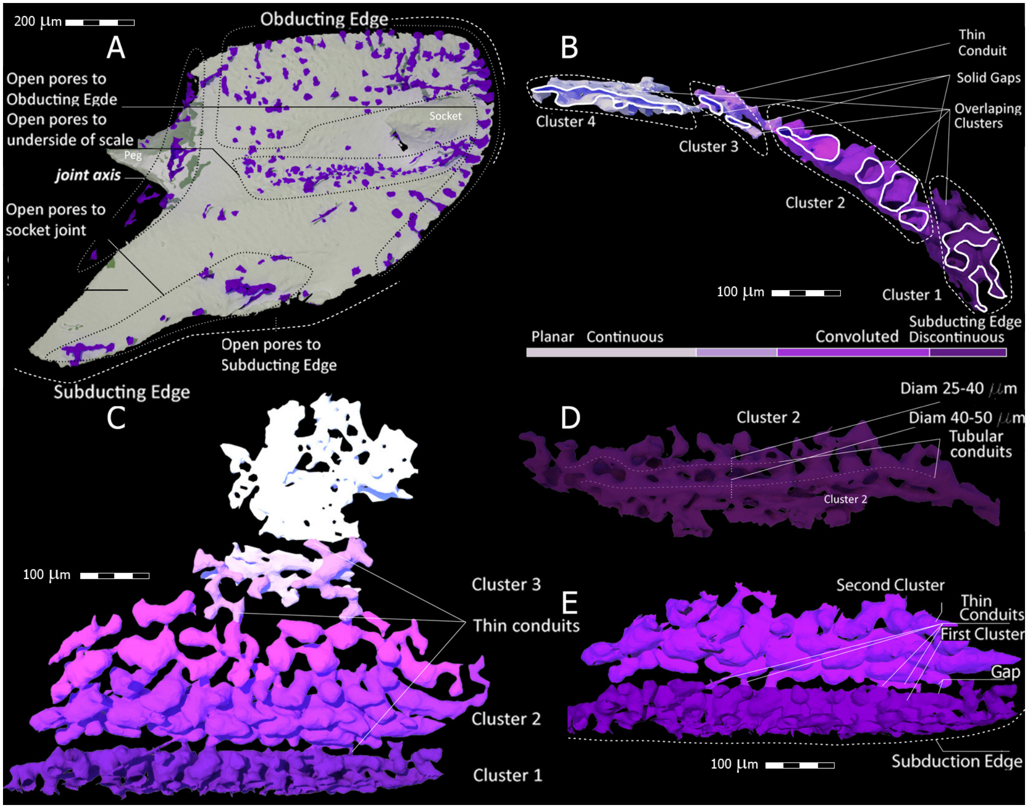


*Figure 3*
*Digital reconstruction of internal microporosity in P. Sengalus scale, responsible for dynamic articulation through organic fibers passing through: (A) internal view of points of access or egress of fibers, clustered around regions parallel to edges of scale and also parallel and on both sides of peg-socket ridge in paraserial axis; (B) lateral view of isolated internal microporosity composed by four sequential clusters gradually varying in size and morphology; (C) top view of isolated internal microporosity and all four clusters of micropores; (D) shows internal view of cluster 2 and longitudinal conduit parallel to scale edge on paraserial orientation and (E) shows top view of cluster 1 and cluster 2 connected by thin conduits evidencing the gap between clusters. All diagrams by author.*

5a) that connects the system scale-to-scale. In this arrangement, the "flexible fibers" go in through the subducting edge of the scale, passing through it and existing on the obducting edge of the scale, only to re-enter the next scale on its subducting edge, and continue sequentially. Different "flexible fiber" configurations have been printed and tested (Figure 5b-f), varying in number, vascular configuration and proportion, location and distribution in the scale, and material properties of the fibers themselves (Figure 5f, k). The process involves observation, characterization, abstraction, parameterization and translation of geometrical, material, and functional parameters into new models. The detailed characterization of the morphological and biomechanical features of the articulated armor in *P.Senegalus* offers interesting and relevant design principles for structural yet flexible and adaptive architectural structures.

The peg-socket paraserial articulation mechanism provides a great mechanism to dissipate loads by engaging the whole system at once when in compression. The interserial articulation mechanism provides flexibility and the capability to achieve high grade curvatures either in compression or tension. The double helix arrangement of the system provide perfect load dissipation, especially if in a synthetic model, the helical structure was oriented vertically (like in a tall building as opposed to the fish where the main axis is almost always horizon-

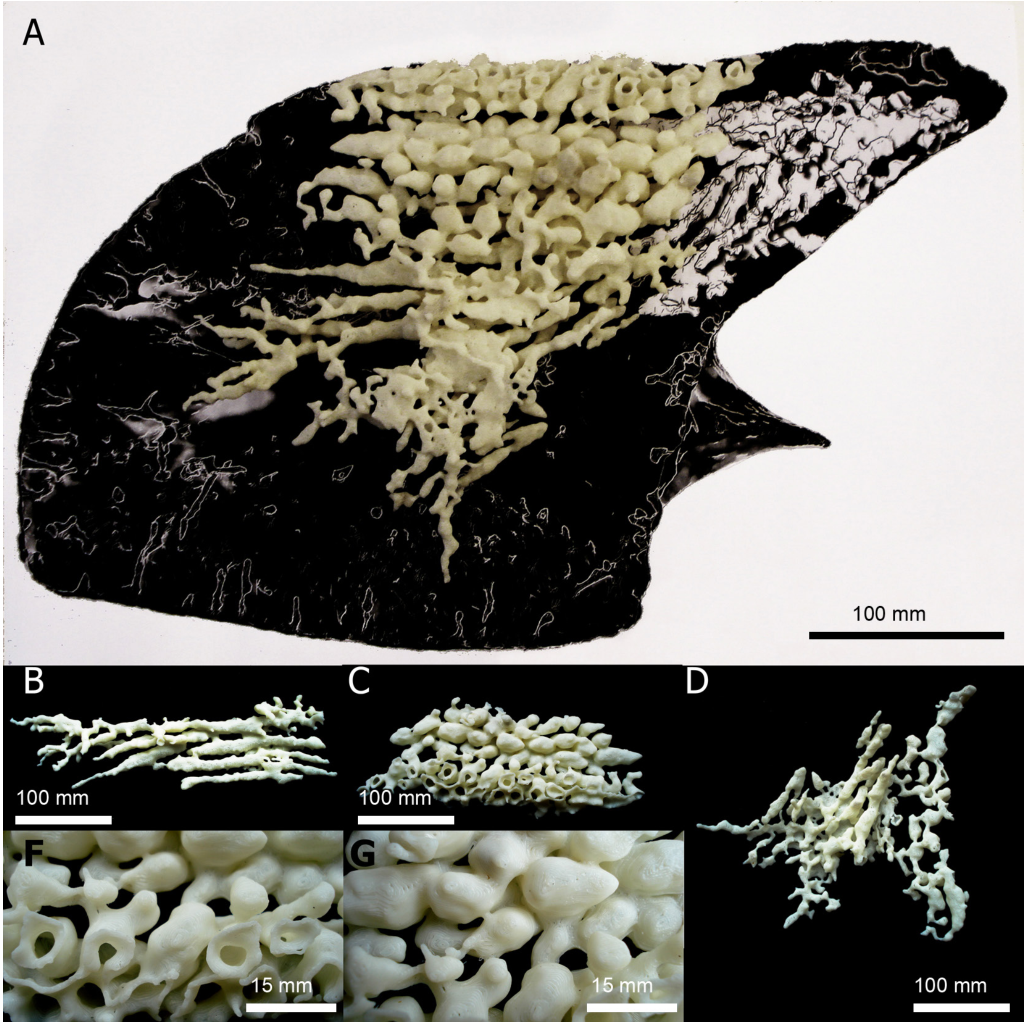


*Figure 4*
*3D printed reconstruction of internal microstructure of internal microporosity relative to fibers that connect the scale to the integument of the fish, specifically to the stratum compactum. (A) four clusters of micropores and counduits 3D printed and assembled over plotted top view of scale; (B)(C)(D) 3D printed cluster of internal micropores and conduits pre-assembly; (F)(G) details of micropores and conduits showing (F) open pores as they open out to the exterior of the scale allowing for fibers and organic tissue to penetrate through the cavities and (G) closed pores that contain organic tissue and fibers as they pass through each scale. All diagrams by author.*

tal) (Figure 5 d-f). This helical configuration would very effectively transfer loads vertically down. Even multiaxial loads would be successfully transferred by engaging the system in a "cohesively rigid" state produced by the load transfer from scale to scale through the peg-socket connection. Previous research from the first author (Araya, 2005; 2006) on tall building façade systems and responsive façade systems have been developed using diagonal grids as optimal structural designs. This double helix configuration is potentially an optimal structural model for such endeavors.

The flexible overlapping articulation mechanism offers opportunities to explore an adaptive and flex-

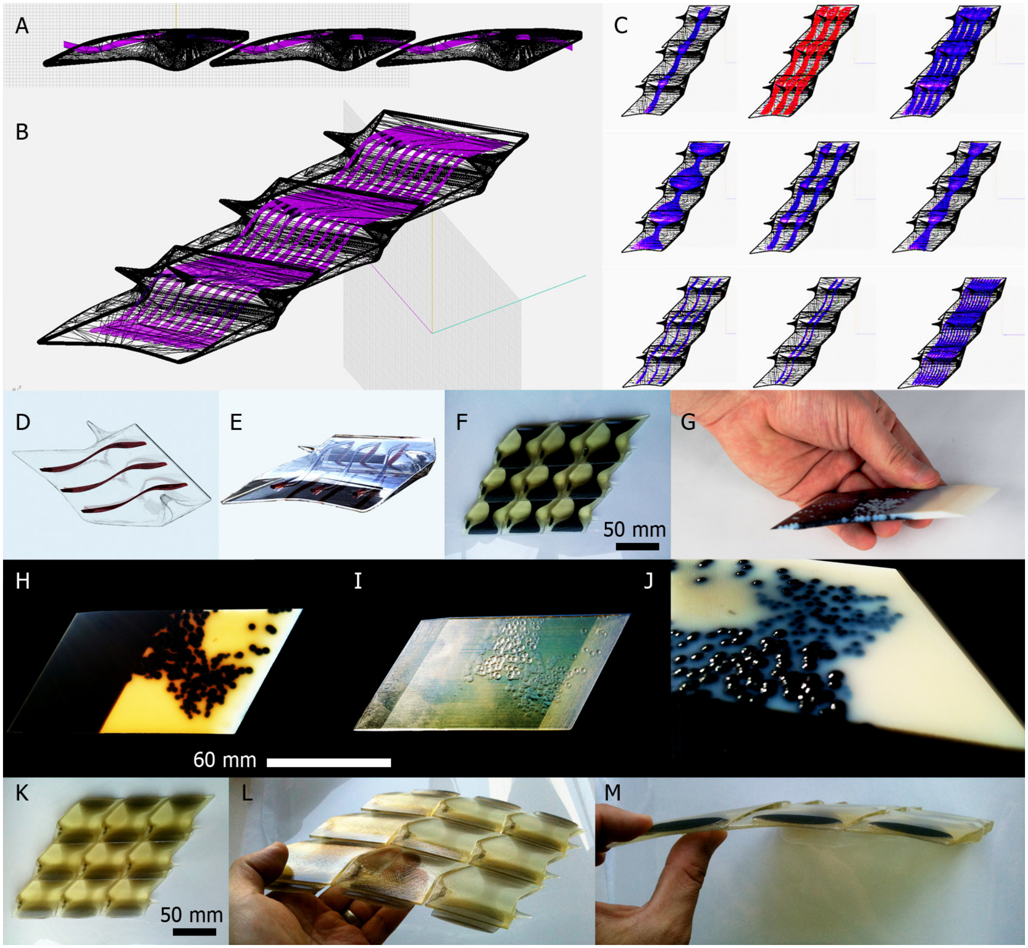


*Figure 5*
*3D printed solid multimaterial composite prototypes. (A)(C) Material test using Tango Black (rubbery flexible) and Vero White (rigid translucent). (B) Material test using Tango Plus (flexible high translucency) and Vero Clear (rigid high translucency). (D)(E)(F) Assembly test using Tango Plus 80%+Tango Black 20% and Vero Clear (rigid translucent), model shows flexible behavior in serial orientation even without load being applied to it.*

ible system, while remaining sound structurally. By allowing ranges of motion and flexibility, a structure equipped with such system would be able to oscillate, shift, turn, move and even vary its cross-section, while retaining its integrity. This again is contrasted with previous studies (Araya, 2006) where triangulated double curved surfaces through diagonal grids, had a better performance in terms of adaptive capabilities, than their quadrangular and orthogonal counterparts.

Lastly, one of the most interesting aspects explored is the capacity of gradually, not discretely, transitioning from one type of structure or material quality, to another. This exploration manifests itself in the prototypes that explore gradual transition from rigid and structural to flexible and adaptive, and even from transparent to gradually more opaque (Figure 5g-j). This prototypes performed well in gradually transitioning from a flexible quality to a rigid quality, through a material diffusion pattern based on the morphological principles from *P.Senegalus* (Figure 5h) and was particularly successful when both materials had the same visual appearance and optical refraction but different stiffness properties (Figure 5i). In this last case, the transition from flexible to rigid was invisible, but performed particularly well because the flexible material allowed for intense curvature and bending while on the rigid end, there was no deformation to load. The multimaterial diffusion interface proposed by the new algorithm shows promising results in preventing delamination—a common problem when the material interface is flat and orthogonal to both materials. This approach offers the opportunity to algorithmically localize areas where flexibility might be required for functional and performative reasons, and stiff and rigid areas where structure is required, smoothly transitioning from one condition to the other without flat and discrete material interfaces.

Further research on available materials for 3D printing processes is required, and possibly the development of custom materials in order to obtain better performance with seamless integration, as was the case in the current prototypes.

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