Self-Cleaning Surface Architectures from Chitin Biomaterials

Computational and experimental methodology

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The current pandemic and the climate crisis urge people to rethink their relationships to the natural and urban environments. In this research we turned to nature for inspiration to find new ways to keep human environments clean and healthy. This paper presents a computational and experimental methodology to design self-cleaning architectural surfaces from chitin biomaterial modeled after butterfly wings. We fabricate surface architectures using parametric modeling, 3d printing, and molding of chitin biomaterial, and assess their performance using mechanical testing, experimental and computational simulations. The goal is to provide an alternative to hydrophobic fossil fuel-based plastics using surface morphologies of biomaterials to achieve structural rigidity and self-cleaning properties in architectural surfaces.

Keywords: *Material-based Design, Parametric Design, Digital Fabrication, Biomaterials, Computational Simulations, Hydrophobicity, Biomimicry.*

INTRODUCTION

This ongoing research study proposes a model for co-creation with nature: including nature's functional strategies in design and architecture. We turned to nature for inspiration to find new ways to keep human environments clean and healthy with a low carbon footprint using functional morphological adaptation strategies inspired by insect wings.

Functional Morphological Adaptation in Spatial Design

Morphology and form are the most common traits to be transferred from natural systems to architecture. However, the most valuable traits of natural systems are their ability to adapt to the environment and serve multiple functions. These traits are rarely retained in the imitated systems (Badarnah & Zolotovsky, 2022).

In recent years several examples for using morphological adaptation strategies from nature in architecture have been proposed that use materials and energy efficiently. For example, Hatton et al (2013) proposed composite windows with artificial vasculature, similar to the one that exists in insect wings, for improved thermal regulation in buildings. Grinham et al., (2020) designed folded origami surfaces to mimic natural surface morphologies (folds, wrinkles, groves) for heat dissipation via convection in architectural facades.

In this paper we focus on insect wings as a model for lightweight architectural membranes with self-cleaning functionality. Insect wings are multifunctional - extremely light and flexible to support flight but also have surface architecture to guide water and dirt off the surface, reflect light and create patterns. Surface architecture can also have anti-bacterial properties – for example, cicada wings have surface micro-architecture that shred bacterial cells to pieces (Quirk, 2013). In fly wings, microstructure on wing surfaces directs the orientation of water drops and facilitates water and dirt removal (Polet et al, 2015). A non-uniform thickness of the chitin surface in the butterfly wings distributes radiative cooling to prevent overheating of the wings (Tsai et al, 2020).

Butterflies need to keep their wings lightweight and clean since any deposit of dirt would not only hide the colorful patterns important for reproduction and territorial display, but also make it harder to fly.

Instead of spending energy on constantly cleaning the wing surfaces, butterfly wings are designed for self-cleaning. Wings are composed of tiny scales, like roof tiles. Both the scale and their microstructure are arranged in a way to direct the flow of water and dirt off the surface of the wing in a specific way.

The microarchitecture makes the wing surface superhydrophobic, or highly non-wettable. There are arrays of micro-grooves that prevent adhesion of dirt, dust, and pathogenic particles, which are collected and removed by the water drops (Saison et al, 2008).

This paper presents a computational and experimental methodology to design self-cleaning architectural surfaces from chitin biomaterial modeled after butterfly wings.

While many bio-inspired microscopically textured surfaces have been previously proposed and developed for self-cleaning purposes, our strategy here offers an efficient design and fabrication route for obtaining large-sized structures for practical architectural applications.

The goal is to provide an alternative to hydrophobic fossil fuel-based plastic using surface morphologies of biomaterials to achieve structural rigidity and self-cleaning properties in architectural surfaces

Computational and Experimental Methodology

The use of computational technologies for capturing, modeling, parameterizing and prototyping membrane systems allowed us to characterize naturally-occurring design principles and apply them to development of novel material composites with enhanced structural and functional properties (Figure 1).

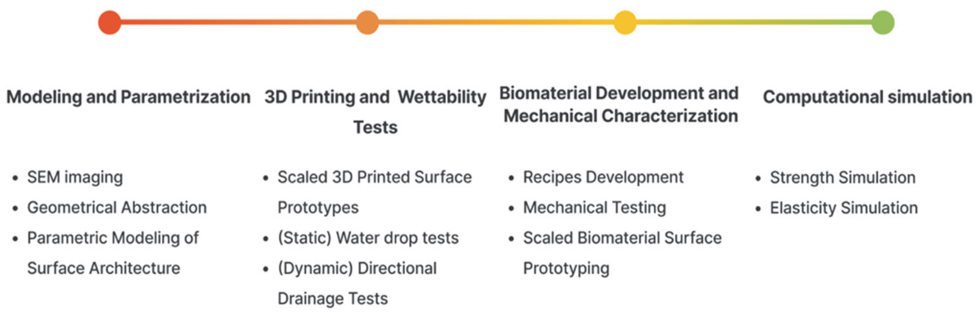


Figure 1
Parametric system and biomaterial development workflow.

First, we use parametric computation to mimic the spatial design strategies of butterfly wings and tune surface morphology and performance. We use 3d printing to fabricate samples with tunable surface architectures. We then conduct wettability experiments using slow-motion digital camera setup to demonstrate how surface architectures repel and guide water depending on surface parameters and orientation.

We cast chitin biomaterial in parametric 3D printed molds to fabricate composite chitin membranes with tunable morphology. We experiment with chitin-based biomaterial recipes to tune material properties to the expected mechanical performance we simulated computationally. We conduct bending testing to verify mechanical behavior. We assess mechanical performance using computational simulations of structural behavior.

The results illustrate how surface morphometry provides a powerful tool to tune hydrophobicity and self-cleaning independent of varying constituent materials composition. Finally, we propose a possible application of the surface morphologies in architectural and product design in larger-scale prototypes.

DESIGN OF THE BIO-INSPIRED SURFACE PROTOTYPE

We used Electron Scanning Microscopy (SEM) to observe several specimens of butterfly wings, including the Swallowtail butterfly (Battus Philenor) and Monarch butterfly (Danaus plexippus) and recorded their hydrophobic performance under high-speed cameras (Figure 2A-C).

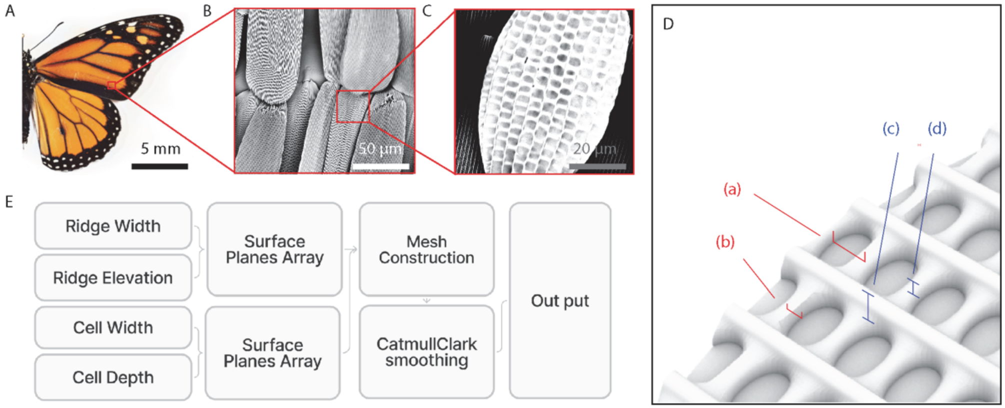


Figure 2
Surface architecture abstraction and parametrization.

We noticed that a butterfly wing has the ability to guide the direction of water flow when it comes into contact with droplet fluid. This characteristic is not solely attributed to either the microscopic surface structure or macroscopic morphology of butterfly wings, instead, it is a combined effort of the hierarchy of structures and their arrangements.

As a primary structure among microstructures of butterfly wings, a layer of small scale-like panels is connected to the wing membrane by short stalks, overlapping each other to create a surface above the membrane (Figure 2B). The panels are arranged radially around the butterfly's torso. The secondary micro-structure, the ridge-like extrusions system on the surface of each panel plays a critical role in the hydrophobic effect (Figure 2C).

In order to further study the performance of the butterfly wing microstructure under macroscopic conditions and to explore the effect of spatial parameters on the hydrophobicity of the material, we designed a parametric system to generate models for 3d printing (Figure 2D). This parametric design system allows us to adjust the scale, size, and arrangement of features while preserving the original structural hierarchy.

We abstracted the secondary structure of the scale surface into disk-shaped panels. On the front side of the disc, the main ridges are arranged in parallel to each other between two edges (parameter (c) in Figure 2D). There are also smaller ridges connecting the main ridges on both sides - the secondary ridges (parameter (d) in Figure 2D).

The secondary ridges are arranged perpendicular to the main ridges, forming small cells of uniform size. The distance between each secondary ridge varies according to the species (parameter (a) in Figure 2D). The 3D model preserves the microstructure of the panel and scales each cell up to a width of about 1mm.

The parametric model was designed using the generative design tool Grasshopper for Rhino 3D software. The parametric script takes four parameters as an input as described in Figure 2C a-d: ridge width and elevation, and cell width and depth. The system then generates arrays of planes in the ratio indicated by inputs, forming a polygonal surface, then converting the surface into mesh and smoothed by the Catmull-Clark algorithm.

We used the parametric model to 3d print a series of disc-shaped samples, varying the ratio of ridge depth and cell depth, the ratio of ridge width and cell width, as well as several samples with an adjusted angle between the main ridge and secondary ridges. The disk-shaped samples resemble individual scale panels on butterfly wings, scaled up to 80mm in diameter (See Figure 3B).

All disk-shaped samples were fabricated with Formlabs Form3 3D Printers, extruded with White Resin filament (RS-F2-GPWH-04) and printed at the fineness of 50 (layer height of 50 microns). This process has helped us create samples of different width and height ratios to observe the effect of one variable on surface properties while controlling for the other. Eventually this process helped us find the best combination in the scale we could fabricate.

TUNABLE ANISOTROPIC SELF-CLEANING

We conducted wettability experiments using a slow-motion digital camera setup to investigate how surface architectures repel and guide water depending on surface parameters and orientation. We performed two kinds of wettability tests. Static Drop-Surface Interaction to demonstrate the hydrophobicity of the surface and to compare between different surface architectures. Dynamic Surface test to characterize the water-guiding behavior of the most hydrophobic surface from the Static Test.

Static Drop-Surface Interactions

We performed the Static Drop-Surface Interaction Test on samples with six different depth and width ratio combinations of ridges to test hydrophobicity when in contact with droplets of water with low kinetic energy (Figure 3A).

All samples were cleaned, dried, and placed on a flat horizontal surface. A droplet of water (approximately 0.05 mL) was released 10 mm above the surface of the sample using a dropper. A front image for each sample was recorded using a high-resolution camera. Based on the image, a water drop profile was drawn for each sample.

The resulting water drop profiles show that all samples exhibit good hydrophobicity in the static droplet test (Figure 3B). Compared with the flat samples used as a control group, the droplets on the surface of all textured samples showed a more rounded morphology, forming a small contact angle with the material (>20^0).

Figure 3C shows water drop profile (Figure 3C(a)) on a butterfly wing surface architecture (Figure 3A(a)) outlined from high-speed experiment video, compared to a drop profile on a flat surface (Figure 3C(b)). During the experiments we observed that the

Figure 3
Static drop-surface interaction

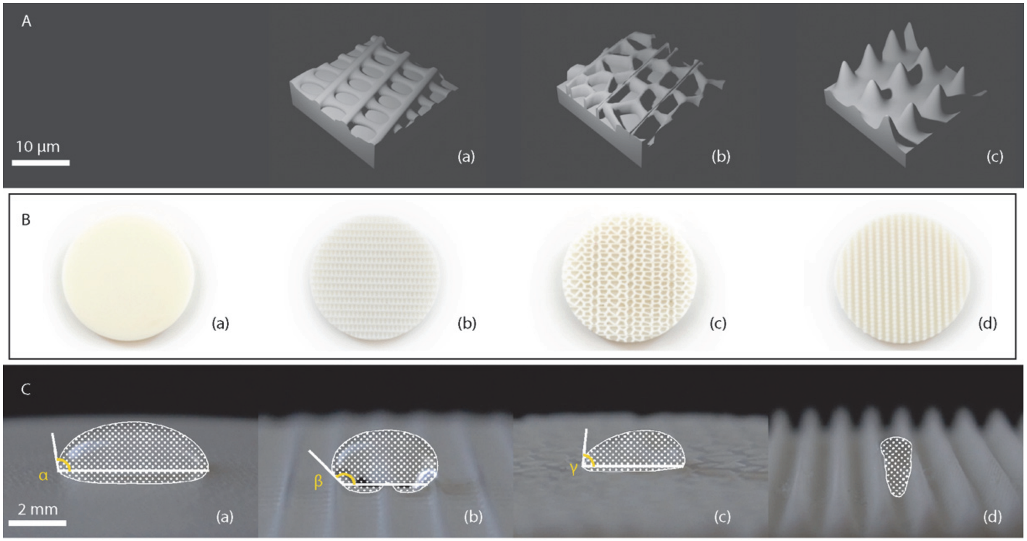
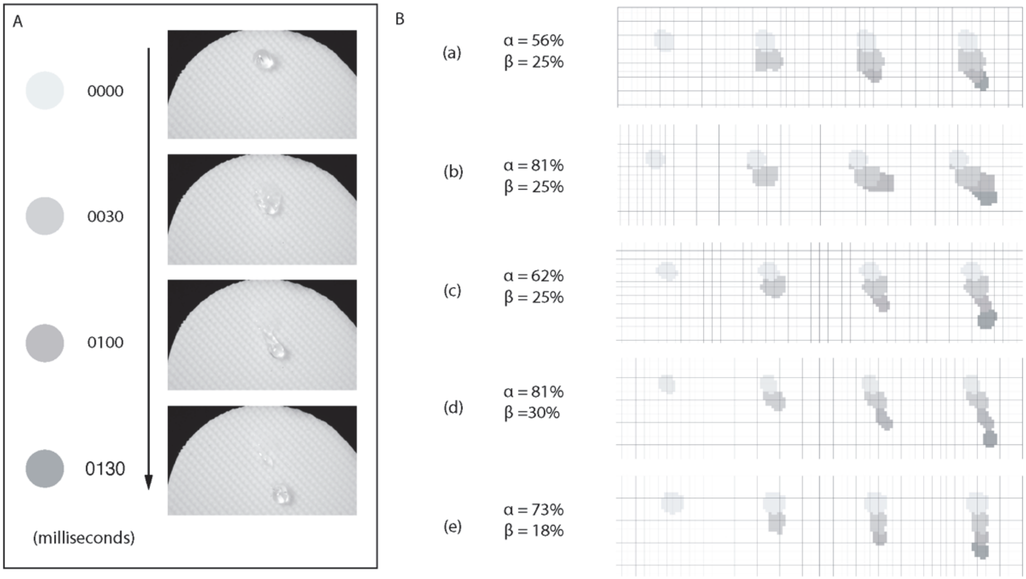


Figure 4
Dynamic surface interaction test



small cells on the surface of the sample catch the air and form small bubbles when in contact with water, greatly reducing the contact area between the material and the liquid.

Dynamic Surface Behavior

To further test the hydrophobicity of samples when in contact with droplets of water and its performance of directional fluid channeling, we performed the Dynamic Surface Interaction test.

Disk-shaped samples were set up at a 45-degree angle on a horizontal tabletop, while the pattern was oriented to have the main ridge at a 45-degree angle.

A water droplet was released from 200mm above the surface of the tested sample and the contact point on the upper half of the surface was recorded. High-speed camera footage was captured and analyzed to determine the wettability and fluid interaction of a sample.

The wet area from water drop interaction with the sample surface was recorded in 30ms increments. Figure 4A shows experimental time lapses for sample B(d). Figure 4B shows the wettability plots for 5 different samples with tunable parameters: alpha = depth ratio (cell depth/ridge height) and beta = width ratio (ridge width/cell width)

The results show that when the depth ratio (Cell depth/Ridge Height) is relatively large, the surface of the material has the greatest impact on the droplet movement in the horizontal direction, but at the same time loses a part of its hydrophobicity; When the beta width ratio (ridge width/cell width) is smaller, the material has the best hydrophobicity, but at the same time almost completely loses its fluid directing ability.

After several adjustments, we found that the samples B(d) had the most balanced performance in directionality and hydrophobicity as measured by the smaller number of wet area pixels and the largest number of pixels on the 45-angled path. To conclude, the set of width ratio 30, depth ratio 81, for samples with ridge width of 300µm, was found to be the most effective in directing fluid while maintaining excellent hydrophobicity.

Chitin Biomaterial Architectures

Traditionally, we achieve hydrophobicity by applying mostly petroleum-based materials, however, nature organizes biomaterials into efficient structural solutions to achieve the same. Our ultimate goal was to create hydrophobic surface structures that were created from biological materials. to include the diversity of functions they serve in nature. Beyond being lightweight, biodegradable, and functionally graded, these materials can serve additional functions – they can self-clean, self-heal, and interact with their environment.

For biomaterial fabrication, we focused on the surface morphology that had the optimal tradeoff between hydrophobicity and fluid direction, as revealed from our Dynamic Surface Interaction test (see previous section), using a chitin biomaterial.

Chitin was chosen as the main feedstock to experiment with as it is the dominant component of insect wings and is not innately hydrophilic.

Chitin Biomaterial Casting

To create our chitin biomaterial 90% deacetylated chitosan was mixed with potato starch and glycerin in a 5% acetic acid solution with a ratio of 1:1:2:75 = chitosan: starch: glycerin: acetic acid using a magnetic stirrer. The mixture was heated to 180F. Once it reached a gel state, the mixture was cooled to room temperature and then poured into the 3D printed mold which was lightly greased with petroleum jelly. After 72 hours of air drying, the sheet was unmolded (Figure 5A). We observed significant shrinkage in the volume of the dried biomaterial, but the surface architectures were unaltered (Figure 5B).

Mold Fabrication

The 3D printed mold was printed as the negative of the desired surface architecture, with a surface dimension of 100 mm by 60 mm, including a wall thickness of 3 mm (Figure 5A). The 3D printing method is described in the Design of the Bio-inspired Surface Prototype section.

Static Drop-Surface Interaction Test

We performed the Static Drop-Surface Interaction Test (see section Static Drop-Surface Interactions) on the chitin biomaterial sample. We observed that the droplets on the surface of the sample showed similar rounded morphology to the 3D printed samples, with a low contact angle (see Figure 5C).

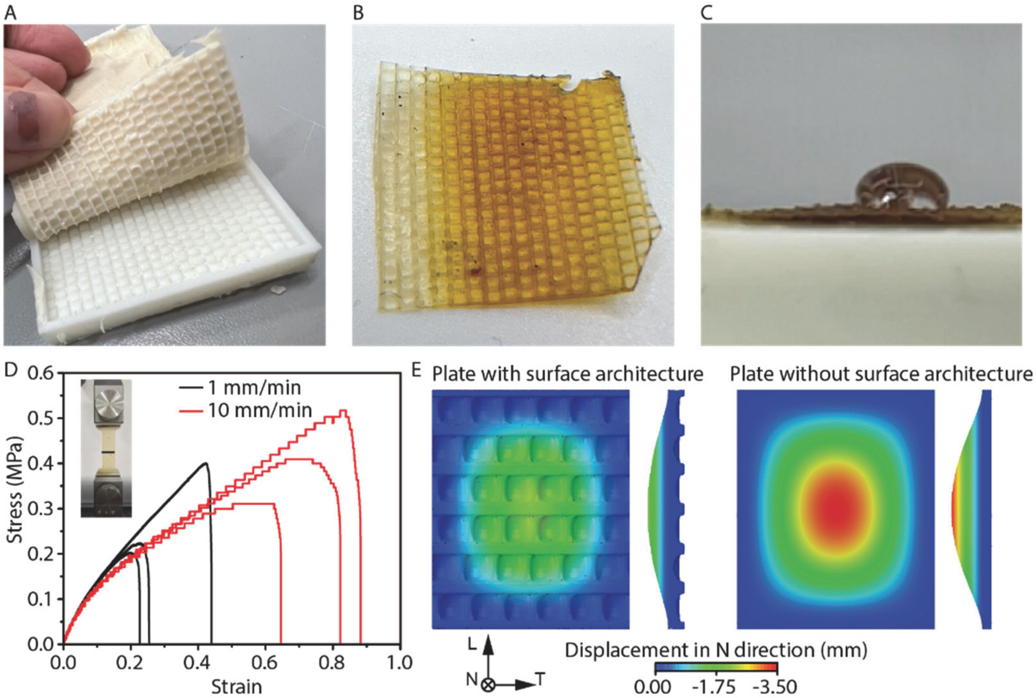


Figure 5
Chitin surface architecture fabrication and characterization

Mechanical Testing

To extrapolate the mechanical properties of the chitin biomaterial we conducted tensile tests and simulations.

Mechanical tension tests were carried out on the artificially fabricated and dry chitin samples, which are in dog-bone shape (inset, Figure 5D), using loading rates of 10 mm/min and 1mm/min, respectively.

An Instron 5942 machine was used to conduct the tests. The stress-strain curve of each test was then obtained in Figure 5D, which shows that the increase of loading rate yields significantly increased extension and stress. Therefore, we considered the 1mm/min loading rate provides quasi-static results for chitin material.

The elastic modulus and strength of the chitin are higher than those of the low-density polyethylene (LDPE), polystyrene, and the blends of LDPE and polystyrene (Barenstein, 1973) , as well as natural rubber (Sengupta, 2007), yet lower than those of the expanded polystyrene (Chen, 2015), and high-density polyethylene (HDPE) (Kalay, 1999). Specifically, compared to LDPE (0.910-0.925g/cm^3) where the increase of strain rate increases the elastic modulus, yield strength, failure strain, and ultimate tensile strength, the strain rate seems to only influence the ultimate tensile strength and failure strain (Jordan, 2016).

COMPUTATIONAL SIMULATION

We carried out mechanical simulations on the rectangular model with hydrophobic surface texture to explore its mechanical properties including elastic modulus and stress distributions. The model is shown in Figure 5E which can be described as a periodically arranged concave surface separated by vertical and horizontal ribs as reinforcement. A control model of plate without surface architecture, which has the same material volume as the one with surface architecture, was also constructed for comparison. The input elastic modulus and Poisson's ratio are 1.87MPa and 0.49, respectively, based on the experimental measurement and mechanical behavior as shown in Figure 5D.

Considering the application of our surface architecture as a canopy or tent, we expect the bending with distributed load along the out-of-plane direction (i.e., N direction) and with fully fixed boundary conditions as the typical loading mode (Figure 5E). Therefore, we applied distributed load of 0.001MPa on the simulation models with all sides fully fixed (i.e., no rotational and translational displacements of the nodes at the boundaries) and measured the deflection in N direction.

We found that the maximum deflections for plates with and without surface architecture are 2.23mm and 3.45mm, respectively, which demonstrates an increased bending resistance of the surface architecture model. This can be further confirmed by the N-directional displacement distributions of the models where the plate with surface architecture shows significantly reduced deformation (Figure 5E). This improved bending resistance is expected as the rib design on the plate provides enhanced area moment of inertia of the plate and hence the improved bending stiffness. Therefore, our surface architecture not only provides hydrophobicity but also improved structural rigidity with consideration of its potential applications and typical loading mode.

WATER GUIDING ARCHITECTURE PROPOSAL

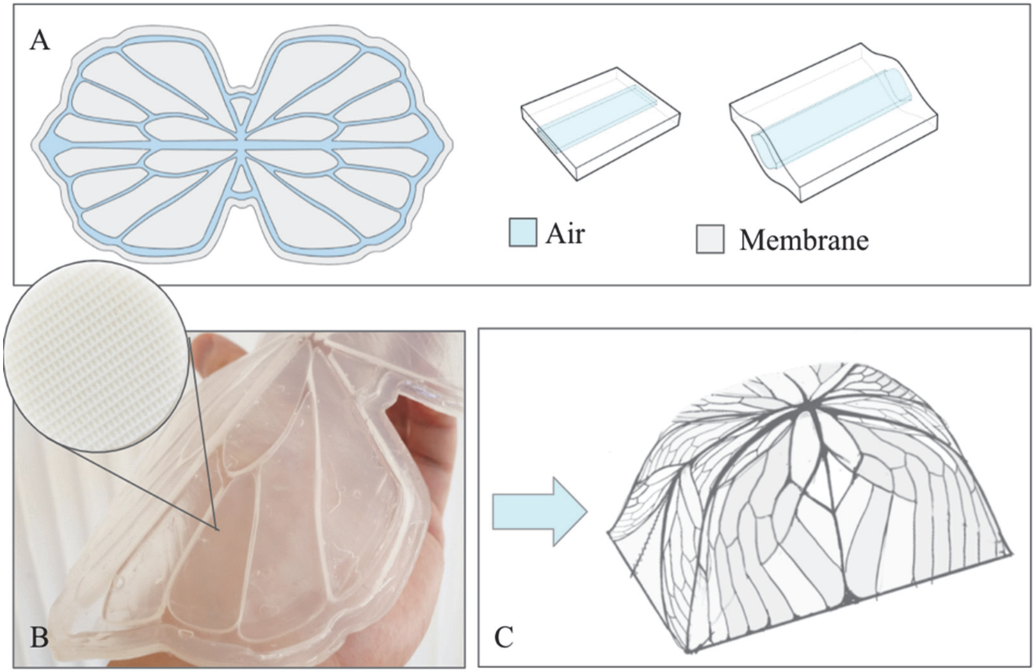
The biodegradability and resultant ephemerality of the chitin biomaterial lends itself to use in impermanent structures. We looked at urban unofficial settlements in Dharavi, India that have densely packed makeshift shacks made from found materials and have poor hygiene due to lack of drainage during the monsoons. Taking inspiration from the inner fluid system that provides butterfly wings with their rigidity, we designed an inflatable tent structure that achieves rigidity by inflating its vein-like air channels (Figure 6A-C).

The main axes of the tent are defined by larger primary channels that branch into smaller secondary channels which define the overall structure. Networks of tertiary channels provide planar integrity to membranous faces of the tent. This strategy reduces the installation footprint and cost as no heavy machinery or additional infrastructure is required for their construction.

Additionally, we leveraged the ability of the wing microstructures to direct water and chose to align the ridges of our surface architectures parallel to the desired direction of water drainage to create canopies that would collect rainwater for domestic purposes as well as guide the excess water through a proper drainage system to prevent street flooding.

These tents can be deployed in a decentralized manner but arranged in a configuration that maximizes regional drainage and water collection. Considering the biodegradability of our material we propose the use of these chitinous structures in cases where transience is advantageous, such as in relief shelters, unofficial settlements and outdoor pavilions.

Figure 6
Proposal for water guiding inflatable architectures



CONCLUSIONS

In this paper we present surface architectures for self-cleaning and water-collecting properties. The results illustrate how surface morphometry provides a powerful tool to tune hydrophobicity and self-cleaning behavior.

We organize weak biomaterials into parametric surface architecture to achieve water-guiding properties and tunable mechanical performance. We combine scientific analysis with parametric design research and prototyping to characterize the behavior of the biomimetic surface architectures. The goal is to adapt natural modes of combining weak and biodegradable materials with parametric articulation of surfaces to achieve multi-functionality. We focus on butterfly wings as a model for lightweight tough architectural membranes with water-collecting and self-cleaning functionality.

In this paper we demonstrate how to imitate the water-guiding properties of butterfly wings on a macro scale using chitin biomaterials architecture. However, the challenge of scaling up to realize the architectural proposal in the previous section still remains open. Our future work will be developing a functional prototype of a hydrophobic chitin surface on an architectural scale.

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