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Biopolymers for Responsive Architectural Scaffolds

Rethinking Firmitas

Andrea Ling

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Rethinking Firmitas

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The building is not a static organization or a structure resembling a machine made of more or less permanent 'construction materials' in which 'energetic materials' provided by nutrition decompose to supply the energy needs of vital processes. It is a continuous process in which both construction materials and energetic substances decompose and regenerate.[1]

1 Fernandez-Galiano, Luis. 2000. Fire and Memory: On Architecture and Energy. Cambridge, Mass: MIT Press.

This folio presents the results of a series of material experiments for creating biopolymers that might be developed as new building and production materials. Architecture has long associated solidity and durability of construction as fundamental to good building. Material research in architecture has thus typically been concerned with the development of longer-lasting, lower maintenance, sturdy materials, while contemporary design practice has offloaded the consequences of the production and destruction of these materials away from the construction and maintenance of architecture

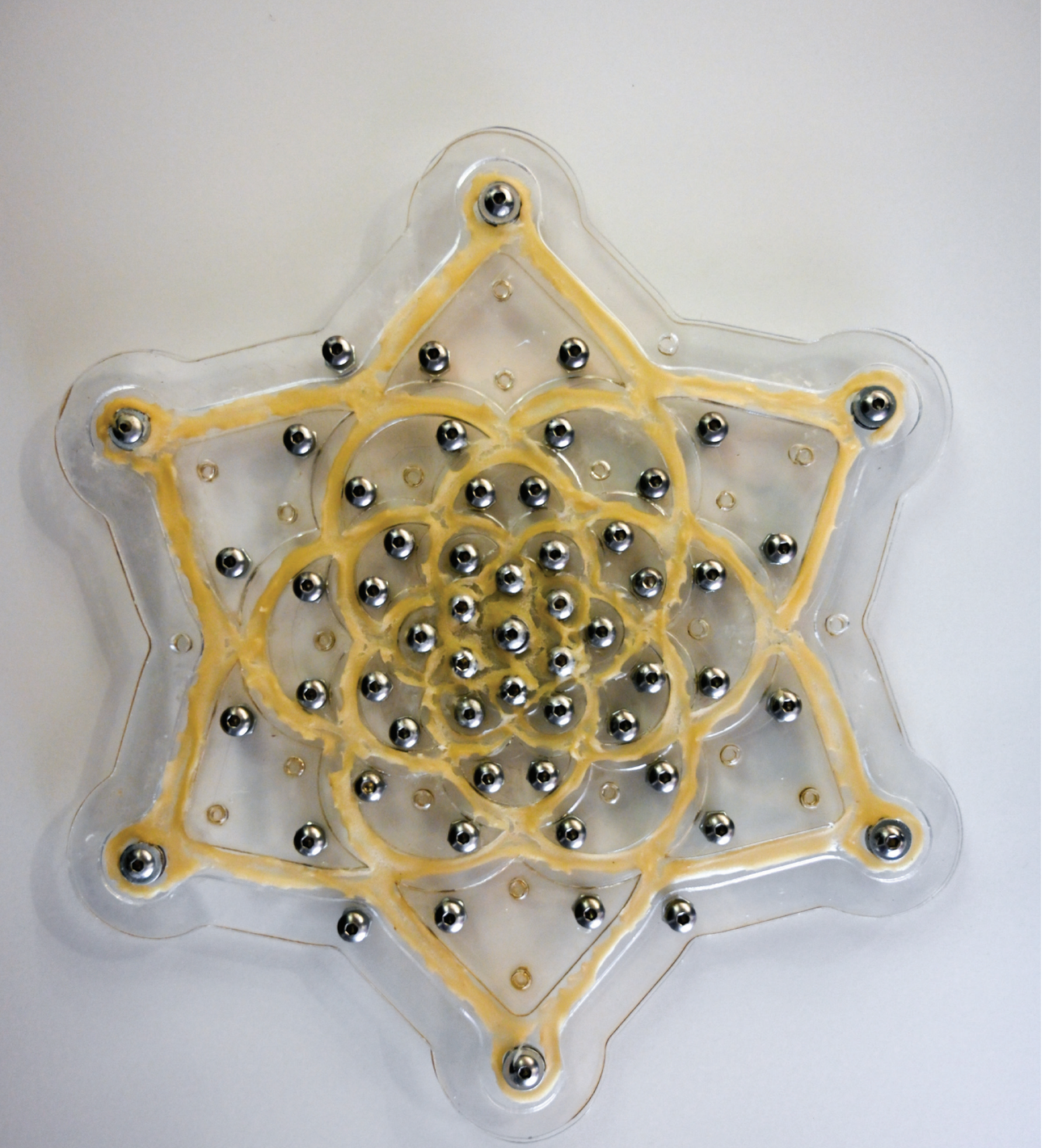


Image 1 (facing page) Chitosan-cellulose composite cast into adjustable 6-sided spar mold

such that both designer and user have a fragmented view of the life cycle of the material. By working with biologically derived materials with much shorter and fragile life spans, I am trying to keep those consequences in sight and on-site, developing a type of *firmitas* that is based on a dynamic system of decay and renewal, rather than static permanence, as a means to longevity.[2]

2 Ling, Andrea. 2018. Design by Decay, Decay by Design. Cambridge, Mass: Massachusetts Institute of Technology.

The use of biologically derived materials as making-material is not modern. Bone, wood, grass, and animal skins were what humans used to build their first shelters and artifacts. These simple materials were replaced with metals, stones, and more recently, plastics, which exhibit higher strength performance and durability characteristics. However given that metals, ceramics, and plastics are often more energy intensive, resource expensive, and with high environmental impact, interest in biologically derived materials has been renewed.

Biologically derived materials are materials derived from or created by living organisms, including plant-based cellulose, lignin, pectin, and hemi-cellulose materials and animal-based collagen, keratin, and chitin based materials. Biological materials tend to be environmentally responsive, partially due to the fact that they are derived from living matter whose properties were environmentally dependent. They exhibit a wide range of behavior depending on the environment and are difficult to standardize, due to both their non-standard origins (living things) and environmental responsiveness that makes them fluctuate in dimension, weight, water content, colour or other attributes.

The materials examined in this study as possible making-materials for Living Architecture Systems Group (LASG) testbeds are water-based composites of biological ingredients including casein, chitosan, cellulose, and pectin. These are some of the most abundant biopolymers on the planet, with chitin and cellulose produced as waste products in fishing and forestry respectively. They offer huge diversity in the

natural forms they make, with a large range of physical and mechanical properties[3] depending on water content, additives, and geometry. They are biocompatible, require little processing to use, and have short decay cycles when mixed with water.[4] The rationale for investigating these materials as viable working materials to form testbed components and other artifacts is that they offer new paradigms for design, fabrication, and consumption that contemporary industrial materials do not. Biological materials have the capacity to decay at a much quicker rate, decomposing into constituent elements that then recycle into organized useful output for the microbial agents. Their responsivity highlights the temporality of the artifacts. What they lack in robustness and solidity they make up for with resilience, flexibility, and accommodation. And working with such materials allows designers to create more fragile, filamentous work, beyond the standard capabilities of industrial processing, through the gradation of chemistry rather than only machine or hand-processing monolithic material. The proposed materials in this study include: casein based foam; cast chitosan & cellulose based films that are then molded with humidity; and cast pectin based films.

This study is based on thesis research originally conducted at the MIT Media Lab under the Mediated Matter group and Professor Neri Oxman. While the work at MIT was concerned with the chemical gradation of the materials into flat, heterogenous structures,[5][6][7] this study explores the ability of these natural materials to be shaped into 3D structures through simple material processing techniques such as casting, thermo-forming, and water-based forming techniques. Through this study, we can see if these materials can be used to produce test-bed artifacts for the LASG, particularly spar-type structures and connection details.

3 Ashby, M. F., L. J. Gibson, U. Wegst, and R. Olive. 1995. "The Mechanical Properties of Natural Materials. I. Material Property Charts." Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 450 (1938): 123–40. https://doi.org/10.1098/rspa.1995.0075.

4 Nishiyama, M, J Hosokawa, K Yoshihara, T Kubo, H Kabeya, T Endo, and R Kitagawa. 1996. "Biodegradable Plastics Derived from Cellulose Fiber and Chitosan." In Hydrophilic Polymers, 248:113123 SE – 7. Advances in Chemistry. American Chemical Society. https://doi.org/doi:10.1021/ba-19960248.ch007.

5 Duro-Royo, Jorge, Joshua Van Zak, Andrea Ling, Yen-Ju Tai, Barrak Darweesh, Nicolas Hogan, and Neri Oxman. 2018. "Designing a Tree: Fabrication Informed Performative Behaviour." In Proceedings of the IASS Symposium 2018, edited by Caitlin T. Mueller and Sigrid Adriaenssens. Cambridge: MIT.

6 Zak, J. Van, Jorge Duro-Royo, Y.J. Tai, A.S. Ling, C. Bader, and N. Oxman*. 2018. "Parametric Chemistry: Reverse Engineering Biomaterial Composites for Additive Manufacturing of Bio-Cement Structures across Scales." Towards a Robotic Architecture.

7 Duro-Royo, Jorge, Laia Mogas-Soldevila, and Neri Oxman. 2014. "Water-Based Robotic Fabrication: Large Scale Additive Manufacturing of Functionally-Graded Hydrogel Composites via Multi-Chamber Extraction." Journal of 3D Printing and Additive Manufacturing 1 (3): 141–51.

Image 2 (facing page)
10% chitosan spar structure made by hydro-forming flat film on six-sided jig

Image 3 (following page) Range of hydro-formed chitosan structures that were made by applying steam to flat, dry chitosan films

Chitosan is a deacetylated derivative of the natural polysaccharide chitin. Chitin is the second most abundant biopolymer on the planet and is structurally similar to cellulose. It is found in arthropod shells, fish scales, and fungal cell walls. Chitin is extremely water responsive – the same material that forms the rigid plates of crustaceans also makes up the flexible material of its joints, depending on how much water the chitin absorbs. Chitosan has a similar level of water responsiveness and exhibits gradable swelling from less than 10% water to over 90% water. It is used in fertilizers, edible films, pharmaceuticals, and biomedical scaffolds as it is highly biocompatible. In an open field, both chitin and chitosan films will degrade completely after six months.[8]

Cellulose is the most abundant biopolymer on the planet and is a polysaccharide that provides stiffness to plant cell walls and is a building block of textiles. The cellulose I use here is a powdered form of white methylcellulose. Cellulose has exceptional biodegradability, with mass losses of over 70% when buried in soil for 70 days.[9]

Pectin is a polysaccharide found in fruit skins and cores as well as in structural complexes of trunks and branches of trees and degrades more quickly than either cellulose or chitosan. It is used in food products and cosmetics. In solution, pectin forms a sticky hydrogel that absorbs water into its fibrous network and sets when cooled.

Casein is a protein found in mammal milk and cheeses that is commonly used as a food additive and in paint, adhesives, and other industrial products. It is known as a natural plastic and binding agent, and some of the first industrial plastics, such as galalith, were made with casein. It is permeable in oil and is hydrophobic.

8 Makarios-Laham, Ibrahim, and Tung-Ching Lee. 1995. "Biodegradability of Chitin- and Chitosan Containing Films in Soil Environment." Journal of Environmental Polymer Degradation 3 (1): 31–36. https://doi.org/10.1007/BF02067791.

9 Kalka, Sebastian, Tim Huber, Julius Steinberg, Keith Baronian, Jörg Müssig, and Mark P Staiger. 2014. "Biodegradability of All-Cellulose Composite Laminates." Composites Part A: Applied Science and Manufacturing 59: 37–44. https://doi.org/https://doi.org/10.1016/j.compositesa.2013.12.012.

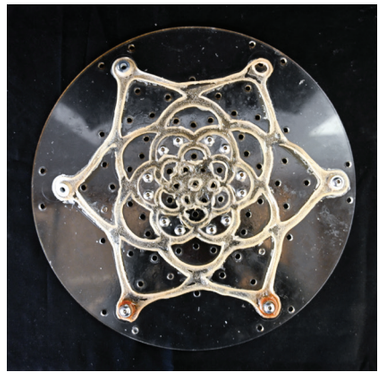


Image 4 (facing page) Casein foam with sodium bicarbonate and acetic acid resulting in contraction of the foam

Image 5 (facing page) Casein foam without sodium bicarbonate and acetic acid, resulting in lighter, less dense foam

Image 6 (facing page) Chitosan-cellulose composite cast into six-sided spar mold

Experiments

The typical mixing protocols for the various water based colloids is as follows:

Casein foam: We use casein pectin powder in a ratio of 50% (w/v (weight to volume)) and sulfur content of 10% to 25% (w/v) and methyl cellulose content of 5% to 15%. 5% KOH is added pellet by pellet into cold water and mixed until the solution is clear. Casein powder is slowly added to the solution and mixed by hand until the solution thickens and foams. Sulfur powder is then added to make the composition more malleable. Cellulose powder is mixed in slowly to add stability in some mixtures. Between 3-10% glycerin (v/v (volume to volume)) is added for flexibility. In one version, baking soda and then acetic acid is added to the mixture, resulting in immediate foam contraction. The foam is then cast into small petri dishes and allowed to dry overnight, covered with lids.

Chitosan-cellulose composites: We use chitosan powder in a ratio of 6% (w/v) and stir that into hot water with a stir stick. The solution temperature is lowered to 37°C, and acetic acid is added in ratios of two parts chitosan and one part acid. 5% - 20% cellulose powder (v/v) is sifted in slowly to form an extremely viscous hydrogel, which is then homogenized with the mixer.

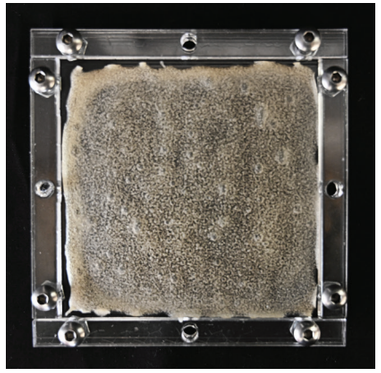
Pectin-chitosan composites: We use apple pectin powder in ratios of 20% to 25% (w/v) and glycerin content of 2% to 5% (v/v). Water is heated to 98oc and glycerin is mixed in. Pectin is added slowly and mixed with a hand mixer until smooth. Next, 2%–8% chitosan (w/v) is sifted in slowly and mixed until uniform. The temperature of the solution is then lowered to 37oc, and acetic acid, in the ratio of two parts chitosan to one part acetic acid, is added as a final step while using the hand mixer to homogenize the solution. The chitosan makes the pectin films stronger and rougher and take longer to degrade.

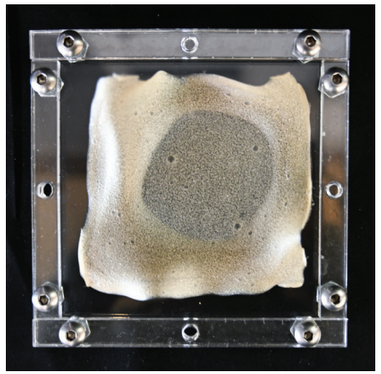
Chitosan hydrogels: We use chitosan powder in ratios of 2% to 12% (w/v). Water is heated to 78oc, at which point chitosan powder is stirred in; at this point the chitosan is not soluble. The solution temperature is lowered to 37oc, and acetic acid is added in ratios of two parts chitosan and one part acid and mixed with a whisk; the acetylation makes the chitosan soluble and the solution thickens immediately. Glycerin is added afterward to increase workability. A 2% concentration solution has a translucent appearance and consistency of thin honey whereas a 12% concentration solution is dark amber brown and an extremely viscous colloid similar to set gelatin.

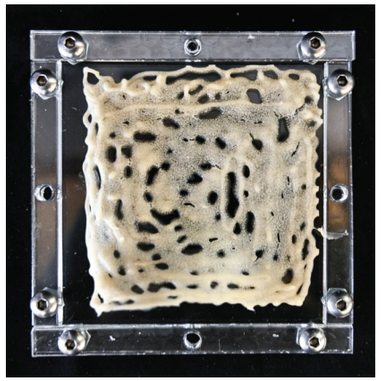
Results

Casein foam: After a few hours of drying, all the samples have a rubbery texture; if exposed to air the foam dries to a hard, dry, light solid similar to a meringue, and contracts in volume. It tends to stick to the dish unless it is removed when partially set. The sample with at 10% methyl cellulose, 5% glycerin, and no baking soda or acetic acid resulted in a light, hard, rigid foam when it was dry, that sticks to the edges of the petri dish it was in. The foam that contained baking soda and acetic acid experienced dramatic contraction while drying and had a consistency of pliant rubber or silly putty as it dried. When dried, it was rigid and hard and denser than the other foam. Further exploration of casting limitations is required with this material.

Chitosan-cellulose composites: Composites of 6% chitosan with 5%, 10%, 15%, and 20% (w/v) concentrations of powdered methyl cellulose were cast onto 100mm x 100mm plates and left to dry overnight. All compositions warped during drying. The 5% cellulose composite initially had the most workability and poured the most easily into the dish, it warped as dramatically as the more viscous and slow moving 15% and 20% concentrations. When the 20% cellulose composite was cast into a spar template, the mixture contracted and pulled away from the mold. The more cellulose there







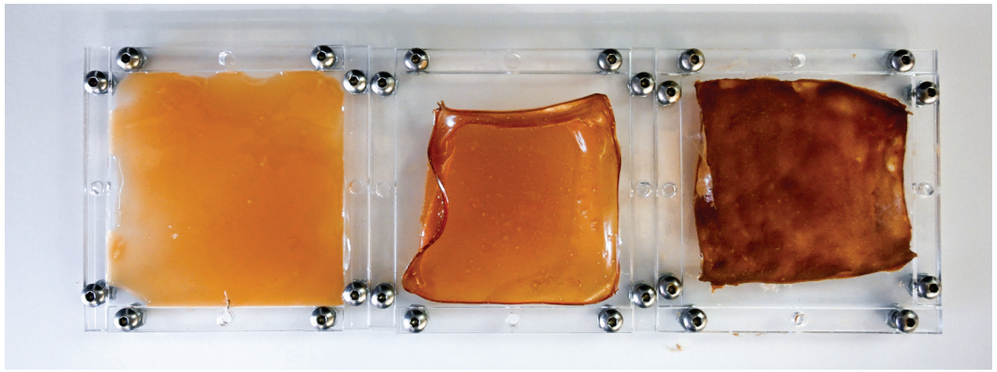


Image 7, 8, 9 (facing page) Chitosan-cellulose composites cast in 100mm x 100mm molds, Cellulose concentration varies from 5% to 20% where lower concentrations result in runnier hydrogel and higher cellulose concentration results in more viscous hydrogel that does not fill out the entire mold

Image 10 (above) Pectin-chitosan composites of 25% pectin with (from left to right) 2%, 4%, and 8% chitosan concentrations cast into 100mm x 100mm plates

Image 11 (above) Chitosan hydrogels in 4%, 6%, 8%, and 10% concentrations

was in the composite, the more difficult it was to hydroform into a 3D form.

Pectin-chitosan composites: Composites of 25% pectin with 2%, 4%, and 8% chitosan were cast onto 100mm x 100mm plates and left to dry overnight. All three compositions deformed considerably when drying, contracting and pulling away from the mold. When cast into a spar template, the mixture contracted and pulled away from the mold and in susceptible areas would tear apart. Because the initial mixtures are too runny to be able to print into a spar form without the use of a walled mold, we did not try to make spar forms

Image 12 (top left) Dried pectin-chitosan composites of 25% pectin with (from left to right) 2%, 4%, amd 8% chitosan concentrations

Image 13 (above) Three-pronged chitosan tripod made by hydro-forming dried film onto three holed jig

Image 14 (left) Dried chitosan films (from left to right) in 2%, 4%, 6%, 8%, and 10% concentrations, showing how increasing chitosan concentration causes increase in deformation

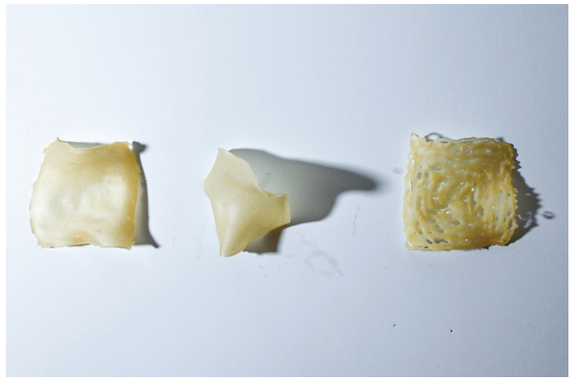
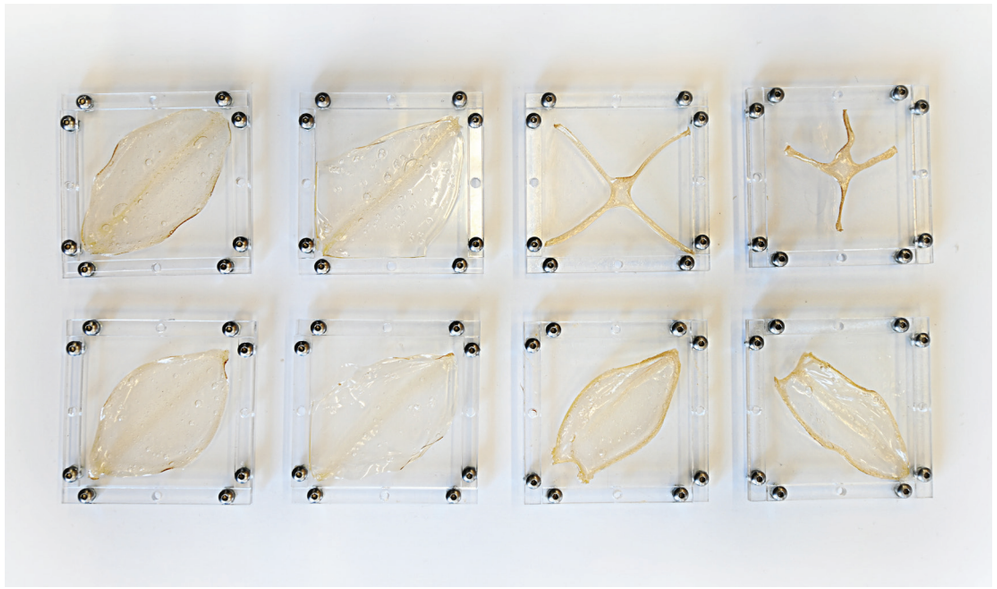


Image 15 (left) Dried chitosan-cellulose composites; cellulose concentration (from left to right) 5%, 10%, 15%.

Image 16 (facing page) Drying chitosan films made by depositing higher concentration gel as center "structural lines" and lower concentration gel on periphery as "leaf" body

Image 17 (facing page) Chitosan films from image 19 in dried leaf form. Curl is controlled by the center higher concentration deposition



without the use of the mold and none of the flat patterns that resulted were usable (without tears), so no attempt to thermo- or hydro-form the spars was made.

Chitosan hydrogels: 2%, 4%, 6%, 8%, 10%, and 12% concentrations of chitosan hydrogels were cast onto 100mm x 100mm plates and left to dry overnight. The more concentrated the chitosan solution, the more it warped as it dried. Attempts to cast the chitosan into the spar molds were unsuccessful as the gels would tear apart during the drying process. Instead, the gels were deposited onto templates such that they would be free to contract as they dry without having a mold to restrict movement. This method worked well with the higher concentration solutions (8-12%) but not with the more liquid lower concentration solutions. The successfully dried patterns could be removed from the acrylic templates and then hydro-formed into 3D shapes. Hydro-forming involved steaming the dried patterns for short periods of time until the chitosan film was malleable and pulling it into shape and letting it dry for a few minutes in that form. Aluminum jigs were used to pull six-sided spars and three-sided tripods into tall forms. Differential contraction rates were also explored as different concentrations of chitosan solution were cast into the same 100mm x 100mm mold and allowed to dry. For instance, a central diagonal band of 10% solution would be extruded surrounded by thin 6% solution in the rest of the plate. As the sample dried, the higher concentration chitosan would contract more dramatically and cause a leaf-like structure to emerge with the perimeter rippling. Different variations of this system were tested with different contraction results.

Conclusions

The working of the different films had varying degrees of success. When hydro-forming the chitosan artifacts, the higher concentration solutions proved to form more robust structures but were also more prone to deformation than the

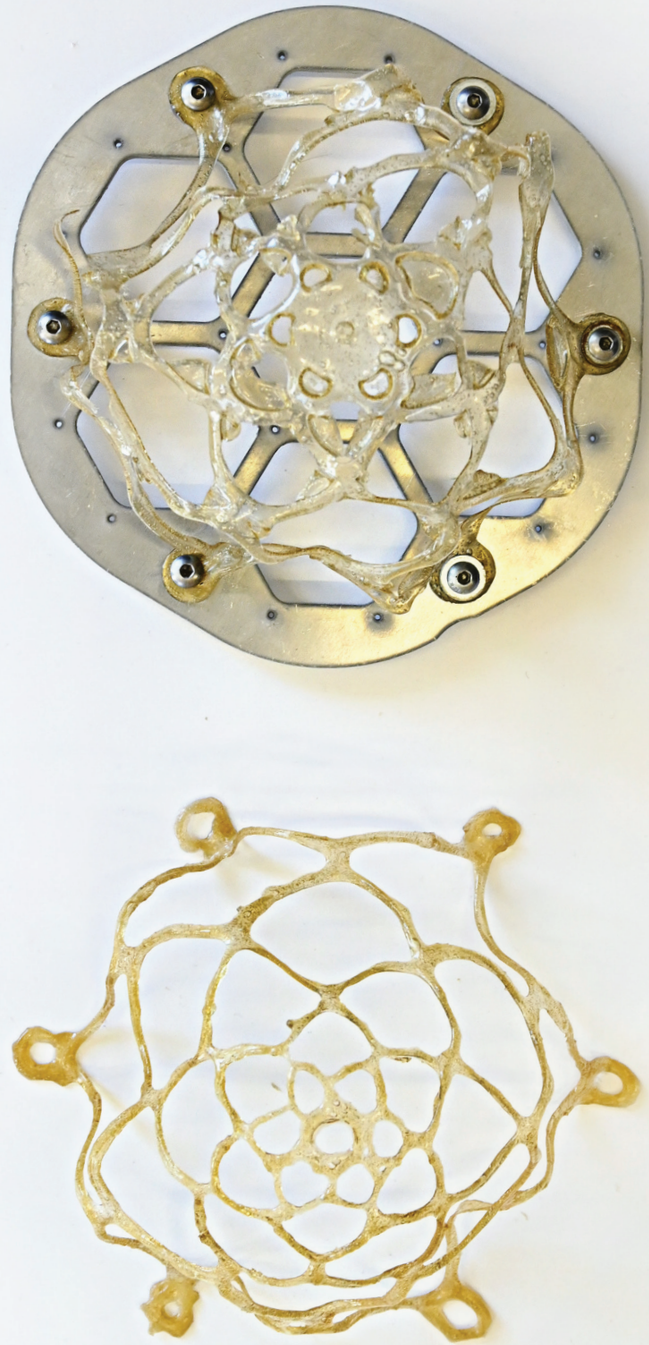


Image 18 Steel Jig used for hydro-forming

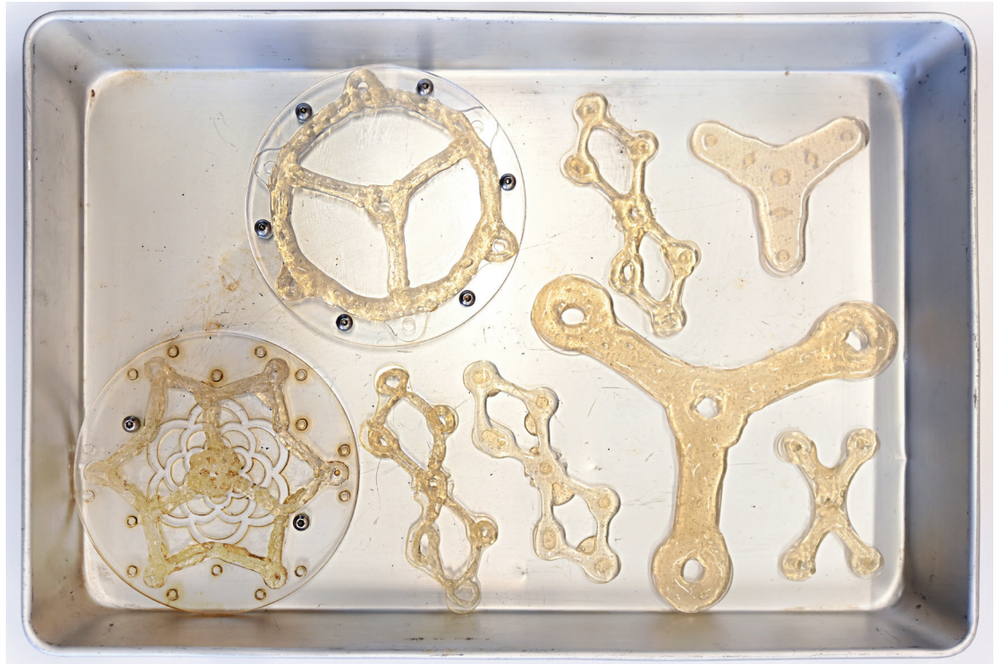


Image 19 Manually deposited chitosan gels on simplified templates to be used for three- and four-pronged structures

more fragile, lower concentration films. Forming the structures was highly imprecise, even with the use of a jig. For instance, the six-sided spar structures lack the consistency of an acrylic spar, cut in the same pattern and thermos-formed with a jig. Simplifying the extruded forms into three-sided tripods made for more even results, however, there is still a degree of warping in the tripod structures, despite reducing complexity and increasing the size and width of the part.

Herein lies the problematic heart of working with biologically derived materials within a system of product making that demands uniformity: it is difficult to reconcile variation and some of the dynamic advantages these materials have within a building methodology that prefers the inert and static. For the purposes of this study, it is questionable if this is the correct strategy with these materials. Unlike the other materials that make up the existing testbeds of the LASG, these materials are intrinsically responsive. They have been or are capable of supporting life and fluctuate in tune with their environment. The trick then is to understand when to coax behavior from the material and when to let go. For in this fragile mutability and difficulty is the opportunity to rethink what can be made durable and what is maintained. If maintenance was done not to make something seem always the same, but instead to accommodate adaptation and change, facilitated by organisms that use the old to build anew, and building was a process that required many small incursions of energy that shaped material gradually rather than one huge initial output of it that formed it dramatically, would that change what could be made durable? Could we rethink *firmitas* then, not as a static condition of robustness, but as a dynamic state, based on a system of many weak redundant members that are dependent on renewal for longevity?

Designers are reaching a point where biological tools are now accessible yet they demand a different design process to use them successfully. In comparison with previous design methods involving contractual drawings where we specify materials that are homogenous and often agnostic to environmental conditions, assembly systems that depend on standardization and locations that are fixed or at least predictable, we cannot design with biological materials in the same prescriptive fashion. We cannot be certain of the outcome in the same way we are certain about the outcome of, for example, a structure that depends on metal extrusions from a factory or laser-cut and assembled plastic. We can however, be precise about the process that we use to design with, mediating and responding to the idiosyncrasies of the biological system and the environmental conditions with synthetic and designed intervention.[10] In pursuing the use of biological materials in structures we are trying to embrace mutability as a desired quality in the built world as well as guarantee that the mechanisms of constructive renewal will be embedded into the artifact.

10 Ling, Andrea. 2018. Design by Decay, Decay by Design. Cambridge, Mass: Massachusetts Institute of Technology

The goal is to support an alternative mode of design practice where the process of making things is not only consumptive but also provisional and where we work in symbiosis with the underlying logic of natural systems rather than try to subjugate them. The struggle is to learn to be comfortable with the tensions embedded in this mode of practice, where material and biological agency sometimes work in contradiction to what we planned. But perhaps, not necessarily in contradiction to what we need.

Andrea Ling is an architect and installation artist from Toronto working at the intersection of design, digital fabrication, and synthetic biology. She is interested in material research, bottom-up design processes, and making things by combining technological and biological tools with traditional techniques.

She is a recent graduate of the MIT Media Lab where she worked for Professor Neri Oxman, designing artifacts that leverage the logic of natural systems with the use of biologically derived materials, biological agents, and novel digital fabrication technologies. Projects at MIT include a series of architectural scale artifacts made of 3D printed biologically derived materials, deploying water-based structures in zero-gravity and textile experiments using silkworms as bio-fabricators. Prior to the Media Lab, Andrea was a project lead at Philip Beesley Architect in Canada where she worked on a series of kinetic immersive installations as well as a series of wearables for techno-centric fashion designer Iris van Herpen.

Andrea is an architect with the Ontario Association of Architects and a founding partner of designGUILD, an artist collective, based in Toronto, Canada, that focuses on large-scale public art projects. Andrea has a MS from MIT, and her M.Arch and B.E.S. from the University of Waterloo with a background in human physiology from the University of Alberta in Canada.

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This folio presents the results of a series of chemical experiments for creating biopolymers that might be developed as architectural building materials. By working with biologically derived materials the experiments explore the possibility of an architecture based on a dynamic system of decay and renewal as a means to longevity rather than solidity and durability of construction.

Organic materials such as casein, chitosan, cellulose and pectin decay more quickly than traditional construction materials, but what they lack in robustness and solidity, they make up for in resilience, flexibility and accommodation. Their fragile mutability presents an opportunity to rethink what can be made durable and what is maintained. Could we rethink the concept of firmitas not as a static condition of robustness, but as a dynamic state, based on many weak redundant members that are dependent on renewal for longevity? Can we support an alternative mode of design practice where the process of making things is not only consumptive but also provisional and that works in symbiosis with natural systems rather than trying to subjugate them?

The Living Architecture Systems Group (LASG) is an interdisciplinary partnership of academics, artists, designers and industry partners dedicated to researching and developing next-generation architectural environments. The LASG disseminates its work through exhibitions, publications and events. It is generously supported by the Social Sciences and Humanities Research Council of Canada (SSHRC), the University of Waterloo and many other partners and supporters.

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