BIOMIMETIC CONSTRUCTION

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INTRODUCTION

In recent years we have seen a gradual rise of biomimicry as a paradigm for sustainable design strategies. The assumption, or intuition, is that since Nature operates through sustainable systems, our own search for sustainable architecture, whatever that might actually mean, would do well to study and emulate Nature in this regard. This general line of thought has largely played itself out through the use of parametric design software, with an attendant interest in "emergent" self-organizing systems and forms. This represents a significant shift in design thinking and methodology – a consequence of the convergence of ecological thinking, cybernetics, and the computerization of architectural production. The aesthetic charge given by such form-generating programs is considerable, pointing toward new kinds of "organic" architectural form, not simply "inspired" by Nature but somehow *like* Nature in their very generation or operation.

We take this intuited link between sustainable design/construction/life and biomimetics to be a strong one worth following. But we also want to see, as clearly as possible, where this link may or may not be valid. We start with the term *Bio*-mimesis: Since it is now a useful and commonly used term we don't wish to avoid it, but we should be clear from the outset that each of the examples we will offer do not reflect anything like *biological* form generation. Instead these are examples of other natural form-generation processes. Matter itself is always active and in the process of formation, deformation, re-formation - whether it is biologically organized or not. Nature does not need biological systems to organize matter or generate forms. What we are talking about in the broadest possible terms is the generative and transformative capacity of the more-than-human world[1]. With this in mind, we will use the term "*bio*-mimesis" to refer to natural processes quite beyond (or beneath) the strictly biological.

BIOMIMETICS AND BIOPHILIA

We also wish to make a clear distinction between biomimetics (the imitation of Nature) and biophelia (the love of Nature). Simply because a form, architectural or otherwise, bears a visual or geometric resemblance to Nature-like forms and *reminds* one of Nature does not mean it is necessarily biomimetic in any way. While biophelia springs from a deep and enduring aesthetic charge, biomimetics concerns itself with processes of becoming and being in the world that are somehow like those found in Nature. Something may be deeply biomimetic, yet not "look like Nature" in any way.

We also want to call specific attention to the essential distance between the constructions of Nature and those of humans, as well as to some of the less than useful assumptions made by architects about matter. The biologist Steven Vogel points out that natural and human constructions are essentially different in at least three important ways: The things Nature constructs are usually small, wet, and flexible, while the things we make are usually large, dry, and brittle[2]. No matter what we do as architects, we are working very far indeed from the "design" world of Nature – particularly that of the biology.

Then there is the common view of building materials as inert matter to be composed in an X-Y-Z coordinate system. There are fundamental problems with this view of things. One such problem is that inert matter is a fiction. We can refer to the immaculate empiricism of Teilhard de Chardin for clarification.[3] Chardin's concise description of matter sets the following (alternative) truths: 1. matter is everywhere particulate, 2. yet matter is everywhere interconnected, and 3. Matter is always prodigiously active. This view of things re-sets our perception of matter as something living and active – something Nature knows full well, of course, as she continually constructs, destroys, and re-constructs the world from the same particulate and interconnected atoms. The carbon you exhale in your breath may form part of the carrot you eat (and metabolize later in the year), or it may just as well form part of the steel you use to build a building.

This orientation to the problem of biomimetics in architecture sets the stage for a discussion of this subject and our presentation of work as examples of an alternative approach to construction.

We do this knowing full well that we are basically groping in the dark (collectively); that this is a deeply difficult subject to grasp properly, and that what we can best hope for is an insightful discussion with colleagues who are similarly curious and dissatisfied with the range of "questions" and "answers" being offered by the design professions on this subject.

PARAMETRIC DESIGN

Because parametric design (i.e. designing by linked parameters) is systems-based, and output is based on linked contingencies, it is understood by many to be a key tool for biomimetic design, capable of modeling the contingent systems we see at work in natural production and existence.

Early parametric models, such as Antoni Gaudi's hanging chain model for the church at the Colonia Guell, Heinz Isler's hanging membrane sheet models for his funicular concrete compression shells, and Frei Otto's soap bubbles, are all examples of physical "computers" performing parametric "calculations" in a form-finding "program". In all of these examples the parameters are set by the designer (by choice of materials, boundary conditions, length and/or depth of span, loading pattern, and so forth) while Nature, we can say, does the rest as force flows through matter itself. These are all static structures, where what we might call the shape of falling and its resistance converges when the structure finds its own response through form.

What is key here, and what we will return to later, is the fact that the materials engaged in these "calculations" (soap films, chains, textiles) are flexible. Specifically, they offer no resistance to force except through pure tension.

MODELING REALITY

The advent of computer-based, parametric design seems to herald a new horizon for architecture, not only in terms of form and geometry, but also in the very role of the architect, and indeed in what constitutes "creativity" in the production of architectural forms and ideas. Yet in all cases there are significant problems to be dealt with. For example, physical parametric models, though driven by natural law and producing immaculate geometric and structural outcomes, do not produce any numerical information about their geometries. All numerical 3-D information must somehow be extracted (historically through photography and painstaking scaled measurements). Digital models are *made* of numerical quantities and do not present this problem at all. Digital scanners can short cut the job of extracting numerical data from physical parametric models.

Both physical and digital models, however, present the problem of scaling-up and transforming these geometries into full-scale building constructions. The distance from model to built reality may be greater or smaller depending on how the model and its parameters are treated, though not on whether the model is physical or digital. Gaudi understood the links of his chains as masonry units; Isler his resin or gypsum-soaked textiles as reinforced concrete, and Otto his soap films as prestressed cable nets or structural fabrics.

Many computer-based parametric models, however, are developed in a purely three-dimensional geometric world, offering a visually compelling, idealized, output with no actual link to a material existence. It is as if there is a kind of geometric intoxication in these kinds of experiments with parametric form finding. The trick will be to link parameters of the physical world to those of pure geometry. This is being done in engineering models, and will be discussed briefly below.

In terms of geometric production and architectural forms, computer-based parametric designs are free to partake of three-dimensional geometries that are both new to the formal language of architecture and highly complex compared to the largely prismatic geometries offered by the history of human constructions.

The factory-based architecture of machine modernism, to which we are heir, is almost entirely based on the processes and productions of single axis mills: saw mills, rolling mills, extrusions, etc., linked to the single axis rotations and basic powertrains of the watermill, windmill, combustion engine, and electric motor. The single axis mill, by its nature, produces uniform sections and prismatic forms perfectly aligned not only with the construction tools and methods of an industrialized building culture but also with our drawing tools as well. So, for example, both the T-square and the computer cursor are direct geometric/productive kin to a circular saw's blade, along with its fence and set square. By contrast, the drawing tools used in computer-based parametric design can easily produce intricate curved forms that may approach the complexity of natural, biological structures. Though these shapes can be mathematically described in Cartesian 3-dimensional space, they are very difficult and expensive to build using the conventional/ traditional industrial production tool kit. Once the size limits of digital production tools are superseded (such as CNC router beds for example), these geometries are almost always extravagant things to construct.

The problem, of course, is that constructing such complex shapes at the scale of architecture is exceedingly difficult. When construction is attempted at all, it tends to use cast reinforced concrete poured into sacrificial, segmental, polystyrene moulds. Each foam block is separately carved by multi-axis CNC routers. These need to be sealed, assembled, and eventually removed (demolished) from the final structure. What appears in the computer as an elegant, minimal, optimized structure is constructed using the "brute force" of high-capital tooling, excessive construction waste, and materials being treated as passive participants (both in the formwork and the forming material) in the design process. The disconnect between the digital promise and the physical reality could not be clearer.

What we find is that as architecture is beginning to fundamentally rethink its relation to Nature through the adoption of emergent and biomimetic paradigms and the more complex geometries these may entail, their *constructed* outcomes remain thoroughly enmeshed in a culture of excess rather than in simplicity and reduction. And while the result may look like a biomimetic, "natural" form, any true link to biomimetics (or sustainability) is lost during the construction process.

FORM FINDING AS FORM CREATION

What we offer here are some approaches to parametric form creation the authors are exploring in an effort to develop a biomimetic design and build process. This work attempts to collapse the previously described acts of design and building as separate events, where the parametric actions of the design process are abandoned in order to reproduce the discovered form with entirely different techniques of making. What we are exploring is an approach where the actions that generate a *form finding* exercise are the same ones used to arrive at a *form making* result. The materials that allow this to be possible are, as Steven Vogel describes, *flexible*, and *wet* – namely fabric, concrete, FRP rods, and ice.

At the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba Faculty of Architecture, the authors have been exploring the creation of efficient structures using fabric-forming techniques that employ both ancient and recent materials and methods in form creation. In fabric formwork construction a flexible membrane is stretched into shape by a supporting frame and receives a wet cementatious material, like concrete. The tension resistance of the textile surface combined with the imposed load and hydrostatic pressures generate complex forms of resistance and response. In these structures, the fabric's intrinsic ability to respond to force flows with form naturally generates shapes of structural resistance. Each wrinkle is a reaction to the forces the surface experiences and the pregnant curves created can follow the exact force flow it will carry when solidified. In this way, although seemingly arbritraryarbitraryThis method allows for the design and creation of highly efficient structural forms in a direct and unified process, the complex surface forms of the fabric formwork can actually be highly efficient structural forms.

Because these construction materials are flexible, their forms react in real time to the forces they are introduced to. As a result, those involved with its construction are witness to their behavior and this helps shape their intuitive understanding of the construction's geometric and structural response.

Professor Mark West has developed numerous techniques for casting concrete structures in flexible textile molds. These include methods for constructing reinforced concrete, columns, beams, walls, slabs, and shells for both cast-in-place and precast construction. One salient example is his development of thin-shelled fabric formed concrete panels and vaults. What is common to all these methods is a combination of controlled construction, designed and set by rigid boundary conditions, and self-forming constructions where the fabric and concrete *find*, or *arrive*, at a final form during the act of construction.

In this instance, it is the self-forming aspect of this work that is of interest. The example chosen here is a method for making funicular compression vault molds from a hanging flat sheet of fabric.

Figure 1. Examples of fabric formed columns and thin shell structures developed at CAST by Professor Mark West.

Briefly, a hanging flat sheet of fabric is loaded with a uniform layer of concrete (for example), producing a funicular tension shape in response to the imposed load. When this construction is inverted, it presents a mold for the precast production of funicular compression vaults.

Like Gaudi's chains, or Isler's hanging sheet models, these are physical parametric constructions. The ability to make such vault structures was developed at CAST, with Research Associate Ronnie Araya and numerous student research assistants, through the construction of small-scale (generally 1:10) gypsum plaster models using light fabrics. These small models, though essentially engaged in the same mechanics as Isler's hanging sheet models, are fundamentally different because in this case there is no need to translate the parametrically derived form into a different system of construction; the materials and the act of construction itself directly activate the form-finding. Both the smaller models and larger structures are resolved at their own respective scales under the influence of identical parameters. Scaling factors, of course, apply but both the events *and manner of construction* are congruent.

This last point is particularly important. Because the small-scale parametric models are simply miniatures of the full-scale parametric

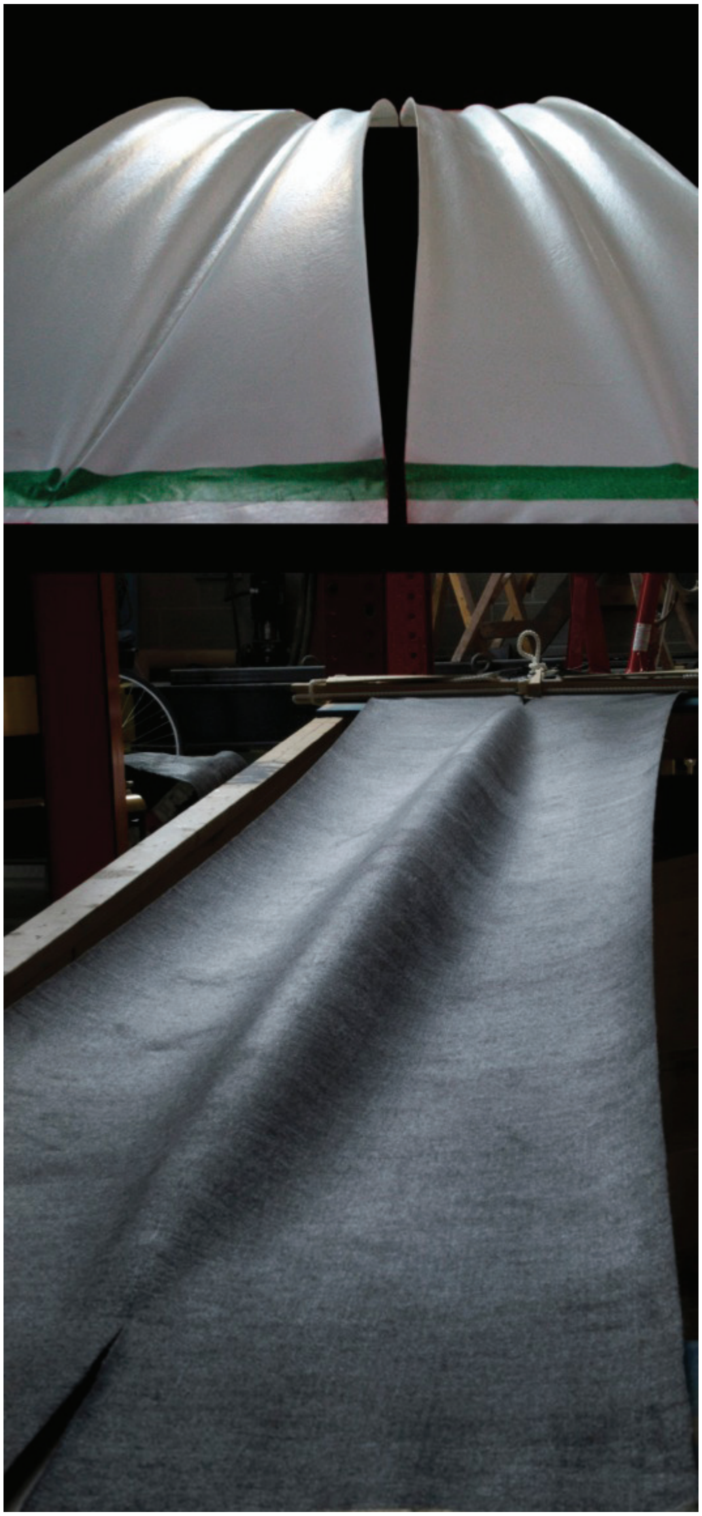

Figure 2. *Plaster study models of fabric formwork vaults (top); Full-scale PE fabric formwork vault ready to receive application of concrete (bottom).*

construction, the techniques one develops to manage the dynamic materials of a plaster model are in themselves a discovery of the construction methods required at a larger scale when working with concrete and industrial fabrics. The designer becomes a student ready to listen and learn from the materials and forces that reside in a more-than-human-world. Other kinds of parametric models cannot supply this kind of information and knowledge. This is particularly true of virtual models, which are devoid of physical “feedback”.

Figure 3. Concrete cast of a vault being liftedmade from an inverted fabric formed concrete mould (and modeled in plaster fromduring the initial study in (Figure 21).

Digital design and analysis software will, of course, be required to adapt these methods to contemporary industrialized design practice. This work is currently underway at the ETH Zurich by Mr. Diederik Veenedaal, under the supervision of Philippe Block. It will be noted that in the case of such software, the parameters in play are those not just of pure geometry but of the physical world of construction. In either case, physical or digital, the prize will be models and tools that close the gap between form-generation in the design and construction of those forms in the physical world. The closing of this gap is, in a sense, a prerequisite for a biomimetic construction, which after all is not merely about form but about process and the means of becoming.

ICE SKINS AND WOBBLY FRAMES

Exploring parametric designs at a building-scale reveals many important lessons that cannot be found in a plaster study model, however prototyping at a building size with concrete presents many challenges; it is heavy, burdensome, and is a massive undertaking yielding permanent results that are difficult to store or discard. Assistant Professor Lancelot Coar’s work at CAST has involved exploring alternative building materials that are easy to work with and temporary in nature.

Located in central Canada, the extreme winter temperatures in Winnipeg (reaching to -40°C) makes it possible to investigate ice as a building material suitable to emulate concrete for such structures. For the past few years Professor Coar has experimented with constructing building-scale fabric formed structures using ice instead of concrete. The ice not only provides an effective and extremely workable alternative liquid-to-solid materials but it also has revealed its own potential as a robust building material for temporary structures in cold climates. Previous research by Heinz Isler in the 1960's[4], and more recently by Arno Pronk and Dirk Osinga[5] have revealed how ice can help to form, support, and coat fabric membrane structures when exposed to both natural and artificially generated cold temperatures (below -10°C). Since ice begins in a liquid state, contributing hydrostatic and liquid properties to a flexible membrane before solidifying, it behaves as a biomimetic medium like the fabric formed concrete methods previously described.

Another area of Coar's research is in the potential participation that the temporary support structures, usually made from rigid scaffolding, can have in the form-finding abilities of a parametric structure. With 7m long fiberglass reinforcing bars, typically used to reinforce concrete structures, Coar uses constructs flexible structural frames that support a fabric skin to receive a self-hardening building material like concrete or ice. With this building system, the fiberglass bars establish a a very flexible and lightweight, yet strong, frame that guides the fabric along its curving geometry. However when sprayed with water, the weight of the frozen liquid adds new stresses the fiberglass causing–gravity induced deflections to become a stiffened post-tensioned structure. When controlled properly the loads imposed by the liquid material can generate complex parametric forms not achievable through simple pole assembly alone.

Figure 4. Fiberglass framing being installed on the frozen Assiniboine River in preparation for fabric formwork layer to be received.

When combined, the ice and fiberglass have allowed for the creation of building-scale structures (7m tall, 4m wide, 12m long) in a relatively short time (3 days) and with little to no waste. Because the fiberglass framing remains imbedded within the fabric membrane, the scaffolding, that normally would be used to temporarily support the fabric formwork before being taken away, adds to the strength of the newly formed ice structure. Because of the lightweight and compact nature of the 2cm diameter rebar, as well as the fabric formwork, this material combination allows for the possiblity of transporting and constructing building-scale parametrically formed structures with minimal resources that can be rapidly assembled. While the fiberglass presents a number of new opportunities to establish complex geometries not achievable with rigid orthagonal framing, this flexible material also creates new challenges and new learning that must be acquired in order to control and master it's potential.

Figure 5. Coar spraying river water onto the fabric skin of the fiberglass framed structure (from Figure 1). The structure acted as a skating tunnel for the Warming Huts Competition in Winnipeg, Manitoba in 2011.

There are of course many challenges when working with such a physically determined design approach. One of which is the infinite range of solutions that might present themselves within a set of constraints introduced by a designer. In addtion, the physical limitations of the scale of construction can restrict the size of the structure explored unlike a virtual model which has no such limits. Also, since the *wet* and *flexible* materials participate in the formation of the physical models, there will always be inherent limitations in the range of forms that are able to be explored based on the degree to which we can negotiate with the materials through technique and process.

CONCLUSION

The two building methods developed at the CAST Lab/Studio described above offer examples of how the biomimetic aspects of parametric design can find congruent methods in flexible systems of construction. Here flexibility is key as it allows the mechanisms of form-finding and structural response in materials to emerge and become active in the design process. Similarities of this approach to ancient and primal building materials (as opposed to Industrial material and methods) and the adoption of physical parametrics (rather than virtual/digital parameters) in a sense orients this work towards the past. But this work looks directly towards the future. We do not wish to confuse innovation (i.e. newness) with progress. A biomimetically informed mode of creation will require, to a great extent, a retooling and re-thinking of how we approach both design practice and the practice of construction. Like other strategies for sustainability, the past holds the knowledge we may need most in the future.

From our research the simultaneous acts of form-finding and form creation points towards one way we might learn from Nature. The merging of these two acts is a fundamental characteristic of Natural processes and, we expect, the clearest path toward establishing a truly biomimetic method of creation. With this way of working, we open ourselves to an attentive relationship with the more-than-human world and recognize it as a deeply complex, mysterious, and "intelligent" collaborator (even guide) in design. By treating material, and our world, in this way, we might continue to learn from it, realizing that the true *translation* that we must seek is the interpretation of how Nature's deep and fundamental efficiency and beauty can inform our own desire for similar results.

ENDNOTES

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